Trabajo Fin de Máster
Ingeniería Aeroespacial

Analysis of Distance Measures for Detection of Manoeuvres for Satellites in Low Orbits with Radar Data

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El tribunal nombrado para juzgar el trabajo arriba indicado, compuesto por los siguientes profesores:

Presidente:

Vocal/es:

Secretario:

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El Secretario del Tribunal

Fecha:

Resumen

Título: Análisis de Medidas de Distancia para la Detección de Maniobras para Satélites en Órbitas Bajas con Datos de Radar.

Resumen del trabajo: Uno de los principales problemas del sector espacial actualmente es la gran población de objetos y basura espacial que se encuentra orbitando la Tierra, y que se prevee que continue creciendo en el futuro. A causa de ello, la detección de maniobras se ha convertido en un tema de actualidad en el sector; ya que permite mejorar la conciencia situacional reduciendo el número de objetos no correlacionados. Este trabajo se centra en un algoritmo de detección de maniobras en órbita baja usando datos de radar. La idea principal del mismo es la comparación, mediante una distancia estadística, de los datos esperados según los parámetros iniciales de la órbita y los datos obtenidos por el radar en la siguiente pasada. El objetivo del trabajo es caracterizar la dependencia de los resultados en función de los diferentes parámetros de los que depende el algoritmo, destacando entre ellos, la distancia estadística empleada.

Palabras clave: Detección de Maniobras, Divergencia de Kullback-Leibler y Distancia de Bhattacharyya.

Conclusiones: Las tres distancias empleadas en el proyecto obtienen buenos resultados en la detección de maniobras con datos sintéticos. Con todas ellas se obtiene un elevado valor del *F-score*, especialmente con la distancia de Bhattacharyya, que resulta ser también la que ofrece mejores resultados en el caso de escenarios con datos reales. El desempeño del algoritmo se reduce considerablemente en estos últimos casos. En concreto, utilizando la divergencia de Kulback-Leibler no se logra detectar prácticamente ninguna maniobra. Por otra parte, se ha comprobado que, así como la órbita afecta de forma considerable en los resultados, los parámetros de propagación parecen no impactar en la detección de maniobras. El otro aspecto importante tratado a lo largo del proyecto es la propagación de la incertidumbre. La elección de este método repercute tanto en los resultados como en el tiempo de computación. Se ha detectado que el orden de Taylor aumenta considerablemente este tiempo, sin embargo, no incrementa el número de maniobras detectadas ni disminuye el número de falsos positivos. Concluyendo así, que establecer el segundo orden de Taylor es la mejor opción. Por otra parte, el método de *unscented transform* consigue reducir el tiempo de computación en un 35% con respecto al álgebra diferencial de Taylor y Montecarlo, sin detrimento de los resultados.

Abstract

Nowadays, one of the main problems in the space sector is the amount of space objects and debris in orbit about Earth, which will increase continually in the future. This is the reason why manoeuvres detection has become a topic of broad and current interest, because it can enable to improve the space situational awareness by reducing the number of uncorrelated targets detected. This project focuses on an algorithm for manoeuvres detection for satellites in Low Earth Orbit from radar data. The main idea of this algorithm is the comparison, using a statistical distance, between the predicted orbit from the initial data and those obtain from the radar in the next track. The aim of the project is to characterize the impact of different parameters of the algorithm on the results, highlighting among them, the statistical distance used.

Contents

1 Introduction

One of the main problems in the space sector is the amount of objects in Earth orbit. Currently, there are tens of thousands of satellites in orbit around the Earth, and the number will increase continually in the future. Some of these space objects might perform manoeuvres for some purpose occasionally, like station-keeping or orbit transfer. This rising space objects population increases the potential threat to all space vehicles and launches, and makes satellite operation activities more and more challenging.

Moreover, the space population is not just made up of active satellites, there is a great number of space debris in Earth orbit. Orbital debris is any human-made object in orbit around the Earth that is no longer useful. The number of space debris object in Earth orbit is estimated to be around 29000 for objects larger than 10 cm, 670000 larger than 1 cm and more than 170 million larger than 1 mm [1]. They are, for instance, non-functional spacecraft, launch vehicle stages or fragmentation debris. In fact, most debris is originated by break-ups in orbit, explosions or collisions. These objects travel at very high speed (in particular, in Low Earth Orbits, they are placed in different orbital planes so the impact at this height can occur at up to the order of km/s) so the collision with an operating satellite or spacecraft can cause great damage [2].

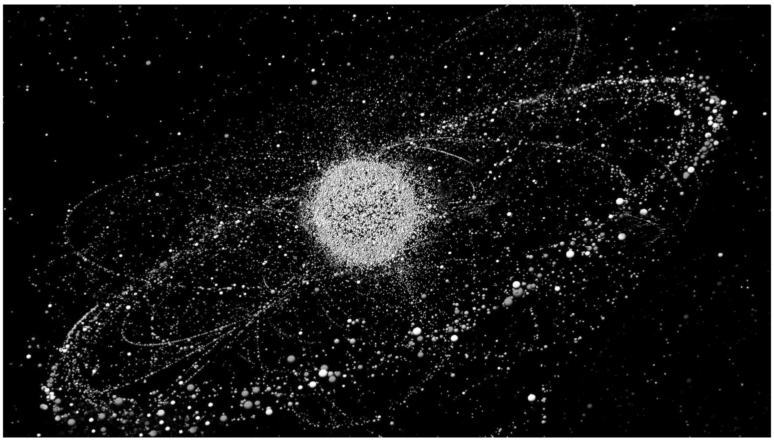

Figure 1.1 Objects in orbit around Earth [1].

These are the reasons why the space situational awareness is very important, and it is necessary to keep the catalogs updated. The manoeuvre detection is of utmost important in the field of Space Surveillance and Tracking (SST). For instance, it makes possible to identify fragmentation. Moreover, when a satellite perform an unknown manoeuvre, trying to associate the new observations collected with the previosly known reference orbits is challenging. One of the main reason of the importance of manoeuvre detection is that it can reduce the number of uncorrelated targets detected. Most of these objects are just known satellites, which have performed unpublished manoeuvres, thus, their new orbits do not match with the predictions [3].

Nowadays, several methods are being developed for the detection of manoeuvres. This project focuses on the algorithm 1 presented in [3], a method for the detection of manoeuvres in Low Earth Orbit from radar data. This algorithm is applicable to objects whose orbit is known. The main idea is to compare the predicted position of the satellite, which is computed by the propagation of its orbit, with the next track obtained from the radar. This comparison is carried out with the Mahalanobis distance. However, there are some other metrics used to determine whether an object is correlated or not with a previously tracked object. The Kullbak-Leibler divergence and the Bhattacharyya distance are some of them [4].

This algorithm is applied to synthetic data, but also to real data. Those are provided from S3TSR, the Spanish surveillance radar developed by Indra with the funding of the Spanish Government and tecnically managed by ESA. It is a ground-based radar capable of providing positional information of orbital object. It provides surveillance and tracking of space objects in Low Earth Orbit, from 200 km to 2000 km of orbit height above Earth [5].

1.1 Scope of the project

The final aim of this project is to use radar data to detect possible manoeuvres of known objects in Low Earth Orbits; the idea is to compute a probability of manoeuvre occurrence. The project is based on the algorithm developed in [3]. One of the main pieces of this algorithm is the measurement of the distance between the propagation of the orbit and radar data. It is here where the objective of this project lies. This work seeks to determine which statistical distance (the original one, the Mahalanobis distance, or the other two distances aforementioned, the Kullback-Leibler divergence and the Bhattacharyya distance) offers better results, i.e., detects a greater number of manoeuvres and avoids a higher number of false positives.

The algorithm depends on other parameters, both satellite scenario data and specific aspects of the algorithm. Some of the parameters that define the scenario are the orbit or the physical characteristics of the satellite, its mass or its ballistic coefficient. On the other hand, the computation of the covariance matrix is an aspect of the algorithm that needs to be considered. This project also pretends to characterize the impact of these parameters on the detection of manoeuvres.

1.2 Document structure

The organization of the document and a brief description of the content of each chapter are presented below:

- Chapter 1: Introduction. It is the current chapter. It contains an explanation of the context in which this project is located. The problem of the increasing population of space objects and orbital debris is introduced. The chapter also establishes the scope of the project.
- Chapter 2: Preliminary concepts. It is contains a review of the theoretical background of the project, including orbital mechanics and basic concepts of statistics needed to work with the statistical distances. Some tools needed on the project are also introduced in this chapter.
- Chapter 3: Algorithm for manoeuvre detection. Here, the description of the algorithm for manoeuvre detection is laid out. In addition, the Theory of attributables and the Theory of distances, which are employed by the algorithm, are also presented, as well as the concept of F-score.
- Chapter 4: Results. In this chapter, the results of applying the algorithms to a number of synthetic and real scenarios are presented, as well as the analyses of the distances and the impact of the parameters .
- Chapter 5: Conclusions and future work. This final chapter closes the document with the conclusions obtained from the project. In addition, possible future considerations are mentioned in order to improve the study.

- Appendix A: Distances and probabilities table. This appendix contains the values of the distances and the probabilities of manoeuvre occurence of all the analyses performed.

- Bibliography. It contains the reference documents used through the report.

2 Preliminary concepts

In this chapter, an introduction of the theoretical background of the project is posed, together with the explanation of some tools used for the development. It is structured as follows: Section 2.1 contains a brief explanation of orbital mechanics. Basic statistics concepts are introduced in Section 2.2. Sections 2.3 and 2.4 contains a brief introduccion of OREKIT and Distribution Fitter MATLAB App, respectively. In Section 2.5 Taylor differential algebra is explained and the unscented transform is described in Section 2.6.

2.1 Orbital mechanics

Thi section contains the introduction to orbital mechanics, in order to define the orbits and positions of the satellites detected by the radar, taking also into account the considered orbital perturbations.

2.1.1 Reference Frames

First of all, different reference systems used in the project will be defined. Depending on the situation, one reference frame or another may be better. For instance, radar data is always given in its corresponding topocentric frame, however, the propagation algorithms usually need to be expressed in an inertial frame.

Earth-centred inertial frame

The Earth-centred inertial frame (ECI) has its origin at the Earth's centre of mass. XY-plane contains the Equator, X-axis points in the direction of the Vernal equinox (♈ point) and Z-axis is orthogonal to the former ones, so the system is directly oriented. Moreover, Z-axis points towards the celestial north pole.

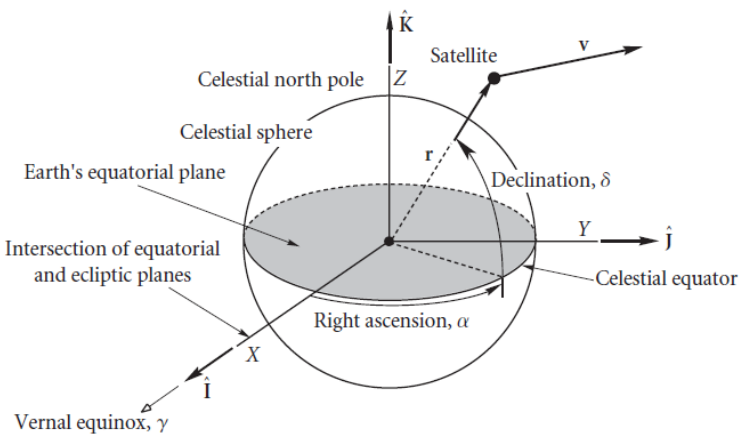

Figure 2.1 Earth-centred inertial frame [6].

The modulus of the position vector and two angles are necessary to describe the position of a certain point on this frame:

- Right Ascension (α): it is the angle between X-axis and the projection of the position vector on the equatorial plane.
- Declination (δ): it is the angle between the vector position and the equatorial plane, XY-plane.

Earth-centred Earth-fixed frame

The Earth-centred Earth-fixed frame (ECEF), known as well as Geographic equatorial frame, also has its origin at the Earth's centre of mass and its XY-plane contains the Equator. However, the X-axis passes through the intersection between the Equator and the Greenwich meridian, thus, it rotates with the Earth.

The following variables are used to define the position of a satellite on this frame:

- The modulus of the position vector.
- Longitude (λ): angle between X-axis and the normal plane to the Equator which contains the satellite.
- Latitude (ϕ): angle between the vector position and the equatorial plane, XY-plane.

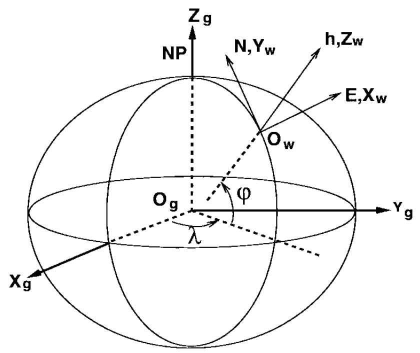

Figure 2.2 Earth-centred Earth-fixed frame ($_g$) and topocentric frame ($_w$) [7].

In the project, conversion between this frame and the Inertial ECI frame is provided by OREKIT (a tool explained in Section 2.3). It takes into account the effects of precession and nutation, as well as the poles' wandering displacement with precision, and the ellipsoidel shape of the WGS84 Earth.

Topocentric frame

As it was said at the beginning of this section, the radar data are always expressed on the topocentric frame corresponding to it. The origin of the frame is placed on the position of the radar. The XY-plane is tangent to the Earth's surface, taking into account that, in this project, it has been approximated by the shape of the WGS84 Earth. X-axis points to the East and Y-axis to the North. Z-axis is orthogonal to the tangent plane and points up, to the *zenith*. This frame is also represents on Figure 2.2, with the suffix w.

The three coordinates that define the position on this frame are the following:

- The modulus of the position vector.
- Azimuth (Az): angle between North and the projection of the position vector on the XY-plane, positive clockwise.
- Elevation (El): angle between XY-plane and the position vector.

Other important concepts are the variation of these coordinates over time:

- Range-rate ($\dot{\rho}$): is the radial component of the velocity.
- Azimuth-rate ($\dot{Az}$): is the time derivate function of the azimuth angle.
- Elevation-rate ($\dot{El}$): is the time derivate function of the elevation angle.

Local-vertical local-horizontal frame

Local-vertical local-horizontal frame (LVLH) is placed on the target point, in this project, on the satelite. Z-axis points down, to the Earth centre, *nadir*. Y-axis is orthogonal to the orbit plane and X-axis completes the reference frame. This frame is usually employed to define manoeuvres.

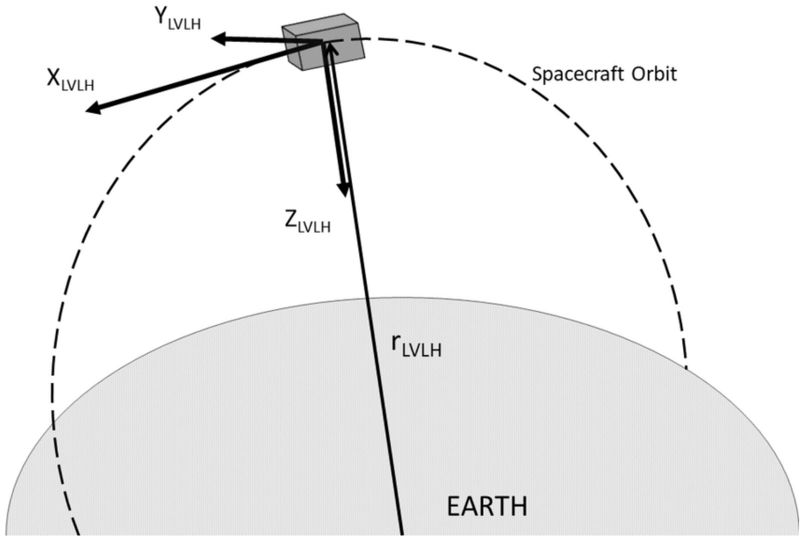

Figure 2.3 Local-vertical local-horizontal frame [8].

2.1.2 Two-body problem

The aim of the two-body problem is to determine the motion of two massive objects in the space. It is assumed that the system is isolated from the rest of the Universe, only their own mutual gravitational attraction force is taken into account. The masses are considered punctual and located in their centers of mass or equivalently sphere with density depending only on the radius.

Equation of motion

As it has been said, the gravitational force is the main element of the orbital motion of bodies. This force describes the attraction between two bodies by the simple fact of having mass. It is directly proportional to each of their masses, m_1 and m_2, and inversely proportional to the square of the distance between them, r.

$$\vec{F}_1 = G \cdot \frac{m_1 \cdot m_2}{r^2} \cdot \frac{\vec{r}}{r}; \qquad \vec{F}_2 = -G \cdot \frac{m_1 \cdot m_2}{r^2} \cdot \frac{\vec{r}}{r} \tag{2.1}$$

Where G = $6.67 \cdot 10^{-11}$ Nm^2/kg^2 is the gravitational constant and $\vec{r}$ is the vector going from the first body to the second one, $\vec{r} = \vec{R}_2 - \vec{R}_1$, as it is shown in Figure 2.4.

Thus, the equation of motion of each body with respect to an inertial reference frame defined by Newton's second law is the Equation 2.2.

$$m_1 \ddot{\vec{R}}_1 = G \cdot \frac{m_1 \cdot m_2}{r^2} \cdot \frac{\vec{r}}{r}, \qquad m_2 \ddot{\vec{R}}_2 = -G \cdot \frac{m_1 \cdot m_2}{r^2} \cdot \frac{\vec{r}}{r} \tag{2.2}$$

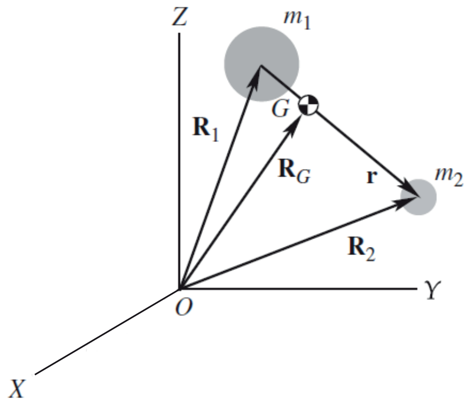

Figure 2.4 Two masses located in an inertial frame [6].

The coordinate origin of the reference frame can be translated to the center of mass of the system, and the frame will remain inertial. Equations 2.3 are obtained by redefining the position vectors of both bodies.

$$\vec{r}_1 = \vec{R}_1 - \vec{R}_G = -\vec{r} \cdot \frac{m_2}{m_1 + m_2} \qquad \vec{r}_2 = \vec{R}_2 - \vec{R}_G = \vec{r} \cdot \frac{m_1}{m_1 + m_2} \tag{2.3}$$

If the mass of one of the bodies is much greater than that of the other, $m_1 \gg m_2$, it can be assumed that the center of mass of the system coincides with that of the most massive body. Approximating the problem to that of the relative motion of one body around a massive one.

$$\ddot{\vec{r}} = \ddot{\vec{R}}_2 - \ddot{\vec{R}}_1 = -\frac{Gm_1}{r^2}\frac{\vec{r}}{r} - \frac{Gm_2}{r^2}\frac{\vec{r}}{r} = -G(m_1 + m_2)\frac{\vec{r}}{r^3} \tag{2.4}$$

Whether the gravitational parameter, μ, is defined by Equation 2.5,

$$\mu = G(m_1 + m_2) \tag{2.5}$$

the equation of motion can be written as Equation 2.6.

$$\ddot{\vec{r}} = -\mu \frac{\vec{r}}{r^3} \tag{2.6}$$

As with the center of mass of the system, if one body is more massive than another, the gravitational parameter is practically function of the greater mass only, $\mu \simeq \mu_1$. Taking into account that the two bodies involved in this project are the Earth and the satellites, due to the difference of masses, $M_\oplus >> m_{sat}$, the gravitational parameter is defined by the Earth mass (as expressed in Equation 2.7).

$$\mu \simeq GM_\oplus = 3.986004 \times 10^{14} \, \frac{m^3}{s^2} \tag{2.7}$$

Angular momentum and orbit equation

Defining the angular momentum of the orbit with Equation 2.8, which is constant (see [6] for the demonstration), and taking the cross product of the equation of motion with $\vec{h}$, the orbit equation (which is the Equation 2.9) can be determined . It defines the path of the orbiting body, the satellite, around the massive body, planet Earth, relative to the second one.

$$\vec{h} = \vec{r} \times \dot{\vec{r}} \tag{2.8}$$

$$r = \frac{h^2}{\nu} \frac{1}{1 + e\cos\theta} \tag{2.9}$$

The orbit equation represents the parametric equation of a conic curve, where e is the eccentricity, related to the type of conic curve and θ is the true anomaly, which is the angle between vector $\vec{r}$, position of the object, and position vector of the periapse (perigee on Earth case).

Position as a function of time

The definition of the variation of the position in time depends on the conic curve type. The satellite orbits around Earth are for the most part elliptical, so this is the only case explained in this project (see [6] for parabolic and hyperbolic orbits). First, some previous concepts are established.

- Mean motion: average angular velocity in elliptical orbit. This velocity is equivalent to real angular velocity in circular orbits,

$$n = \frac{2\pi}{T} = \sqrt{\frac{\mu}{a^3}} \tag{2.10}$$

  where T is the period and a the semimajor axis

- Mean anomaly: angle between the position of a fictitious body moving around the ellipse at the constant angular speed, n. For a circular orbit, the mean anomaly, M, and the true anomaly, θ, are identical, for elliptical orbit, this is true solely in periapsis and apoapsis.

$$M = n\Delta t \tag{2.11}$$

- Eccentric anomaly: it is the angle E shown in Figure 2.5. Drawing the circumscribed circumference to the ellipse and a perpendicular to the mayor axis through point S (the location of the object defined by the true anomaly) is determined point Q. The angle between the apse line and the radius of the circle that passes through Q is the eccentric anomaly, E.

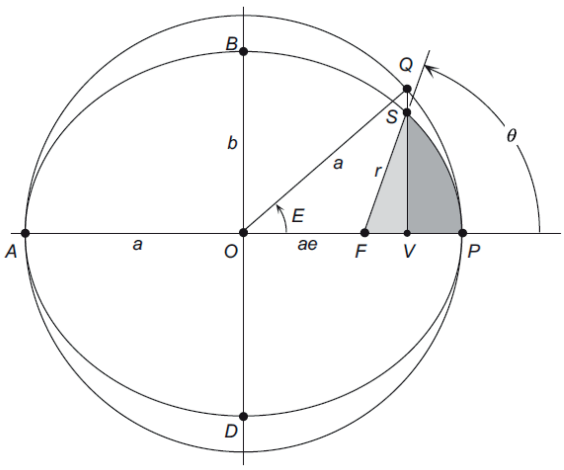

Figure 2.5 Eccentric anomaly definition [6].

The eccentric anomaly and the true anomaly are related by Equation 2.12.

$$\tan\frac{\theta}{2} = \sqrt{\frac{1+e}{1-e}}\tan\frac{E}{2} \tag{2.12}$$

Now, by means of Kepler's second law, the relationship between time increment and the eccentric anomaly can be established, as expressed in Equation 2.13.

$$\Delta t = \frac{E - e\sin E}{n} \tag{2.13}$$

Finally, combining Equation 2.12 and 2.13 and the definition of mean anomaly results in Equation 2.14. called Kepler equation relates the true anomaly, θ, with the mean anomaly, M:

$$M = E - e\sin E \tag{2.14}$$

2.1.3 Orbital elements

Orbital elements is the minimum data set, together with the epoch, that allows to define the position of a body in an orbit at a certain time.

Two parameters are necessary to define the orbit in the plane, the semimajor axis, a, and the eccentricity, e. Sometimes a can be replaced by the angular momentum, h, the period, T, or the average angular velocity, n (the last two can only be used if the orbit is elliptical). Then, a third parameter is required to define a specific point on the orbit. This parameter is the true anomaly, which is the angle between the perigee and the body position. It can be replaced by the mean anomaly, M, the eccentric anomaly, E or the increment of time, Δt. Three additional parameters are requiered in order to describe the orientation of a plane in three dimensions, known as *Euler angles*.

The intersection between the orbit plane and the reference plane is known as *the node line*; for terrestrial orbits, the reference is the equatorial plane. The intersection between the orbit and this line are two points. The one where the orbit crossed the equatorial plane from below to above is called *the ascending node*, ☊, and the other one *the descending node*, ☋. The node line vector, $\vec{n}$, extends outwards from the focus through the ascending node. Thus, the angle between the positive X-axis and the node line vector is the *right ascension of the ascending node*, Ω, positive counterclockwise.

The eccentricity vector, $\vec{e}$, intersects the orbit at perigee. Then, *the argument of perigee*, ω, is required to determine the orientation of the orbit. This is the angle between the node line vector, $\vec{n}$, and the eccentricity vector, $\vec{e}$, and it is positive in the movement direction.

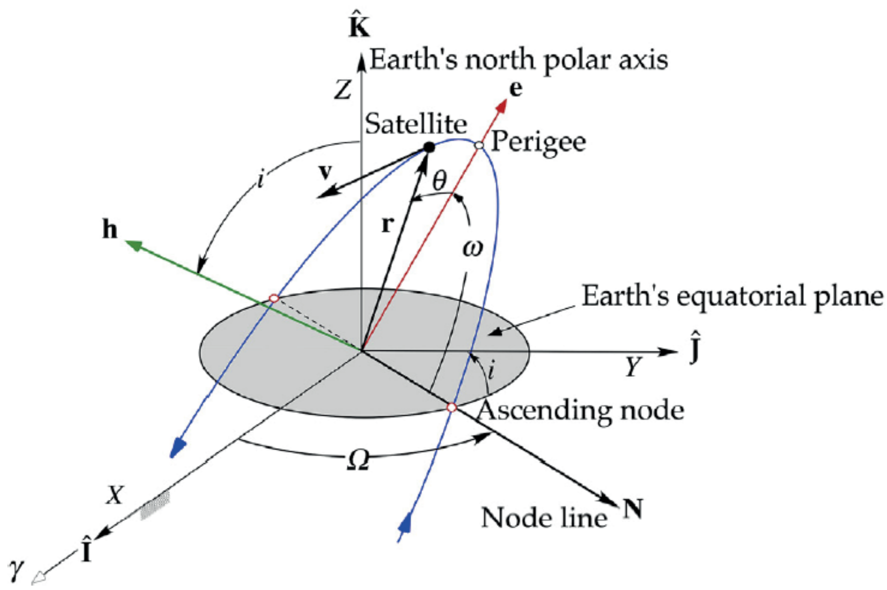

Figure 2.6 Keplerian orbital elements [6].

Finally, the angle between the reference plane, equatorial plane, and the orbit plane is *the inclination*, i, positive in the direction indicated by $\vec{n}$.

In summary, six orbital elements are required to define the position of a body in a certain orbit (Figure 2.6 shows all of them). The Keplerian elements are:

- a: semimajor axis.
- e: eccentricity.
- θ: true anomaly.
- Ω: right ascension of the ascending node.
- ω: argument of perigee.
- i: inclination.

There are special orbits where some Keplerian elements are not well-defined.

- Elliptical equatorial orbit: inclination is equal to 0 so the orbit is contained in the equatorial plane, i.e. there is no node line. Thus, the argument of perigee and the right ascension of the ascending node are not well-defined.
- Circular non-equatorial orbit: there is no perigee, consequently, the argument of perigee and the true anomaly are not well-defined.
- Circular equatorial orbit: there is neither perigee nor line of nodes. Therefore, neither right ascension of the ascending node, nor argumen of perigee, nor true anomaly are well-defined.

There are other representations of orbital elements which removes these singularities. In particular, in this project the Equinoctial element set is used, [9], which removes the mathematical singularities at e = 0 and i = 0 and 90 degrees. Therefore, it is especially well adapted to orbits with small eccentricity and small inclination.

- a: semimajor axis
- $ey = e \cdot \sin(\Omega + \omega)$
- $ex = e \cdot \cos(\Omega + \omega)$
- $hy = \tan\left(\frac{i}{2}\right) \cdot \sin(\Omega)$
- $hx = \tan\left(\frac{i}{2}\right) \cdot \cos(\Omega)$
- $lv = \theta + \omega + \Omega$

2.1.4 Orbital perturbations

The two-body problem is not realistic. One of their main assumptions is to consider the system isolated from the rest of the Universe, which allows the forces to be reduced only to the gravitational force between the two bodies. Nevertheless, there are many other forces acting on the system, for instance, gravitational force exerted by other bodies, such as the Sun or the Moon, atmospheric drag, quite significant in Low Earth Orbits, or solar radiation pressure.

The other essential assumption is to consider the masses punctual and located in the center of mass. This statement is valid just if the bodies are homogeneous solid spheres. Typically, neither planets nor satellites are perfect spheres.

All these factors are called perturbations and it is necessary to analyze them in order to get a precise position of the satellites.

Atmospheric drag

Atmospheric drag is the most important perturbation for Low Earth Orbits, the subject of this project, and very eccentric orbit, whose perigee radious is very low. Over 99.99 % of the Earth's atmosphere is located below 100 km, nevertheless, the air density at that altitud is sufficient to exert drag on satellites moving at orbital velocity. The density depends on the altitud and there are different models which describe its variation. Figure 2.7 shows the US Standard Atmosphere 1976.

Harris Priester and Marshall model are the ones employed in this proyect. The Harris Priester model is based on theoretical temperature profile solutions of the heat conduction equation under hydrostatic equilibrium conditions. On the other hand, the Marshall model is based on the MSFC Solar Activity Future Estimation model, which estimates the intermediate-term and long-term behavior of the solar radio flux, the relative sunspot number and the geomagnetic index.

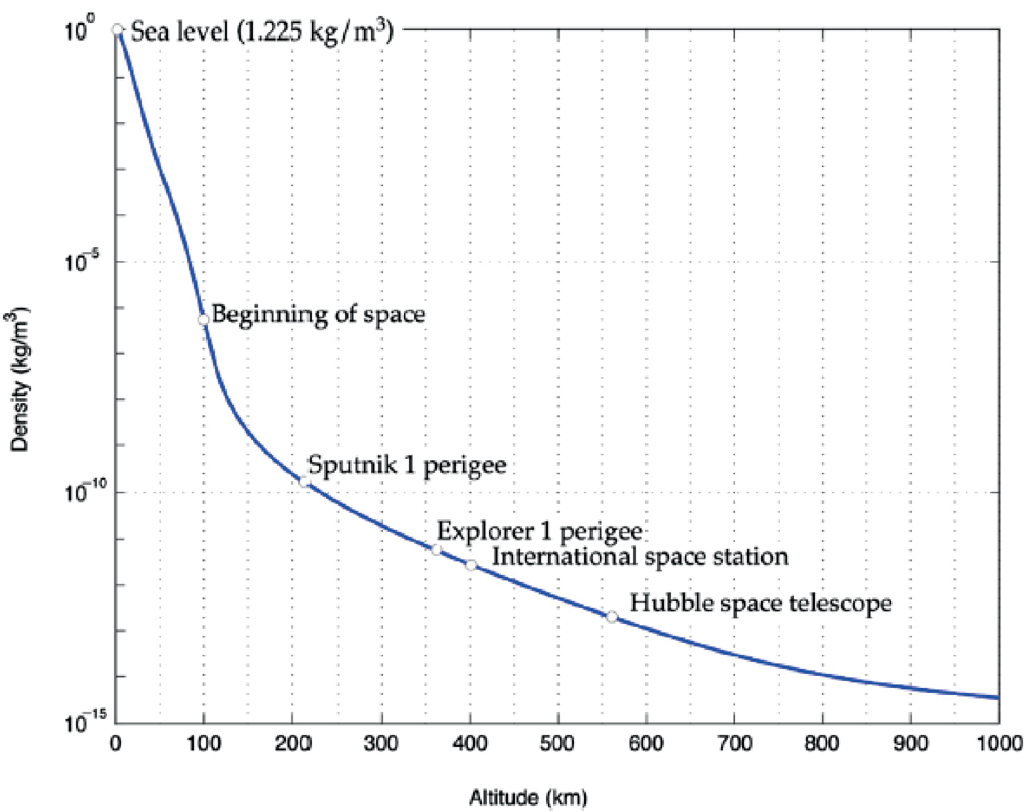

Figure 2.7 US Standard Atmosphere 1976 [6].

The drag force, $\vec{D}$, has the opposite direction of the velocity vector relative to the atmosphere, $\vec{v}_{rel}$, so it can be express by Equation 2.15.

$$\vec{D} = -D\vec{v}_{rel} \tag{2.15}$$

Under the assumption that the atmosphere rotates with the Earth, the relative velocity is expressed by Equation 2.16.

$$\vec{v}_{rel} = \vec{v} - \vec{\omega}_{\oplus} \times \vec{r} \tag{2.16}$$

Where $\vec{v}$ is the inertial velocity of the object, $\vec{r}$ is its position vector and $\vec{\omega}_{\oplus}$ is the rotation speed of the Earth.

Knowing the drag coefficient of the body, C_D, the force can be estimated by Equation 2.17. Where ρ is the atmospheric density and A is the frontal area of the object.

$$D = \frac{1}{2}\rho v_{rel}^2 C_D A \tag{2.17}$$

Now, Equation 2.18 determines the perturbing acceleration, $\vec{p}$, due to the drag force.

$$\vec{p} = -\frac{1}{2}\rho v_{rel}\left(\frac{C_D A}{m}\right)\vec{v}_{rel} \tag{2.18}$$

The quotient between the product of the drag coefficient and the frontal area, and the mass is defined as ballistic coefficient, B (as expressed in Equation 2.19). This is a parameter that just depends on the body and its attitude.

$$B = \frac{C_D A}{m} \tag{2.19}$$

Gravitational perturbation

The gravitational potential energy of a spherical, homogeneous body can be expressed by Equation 2.20.

$$V = -\frac{\mu}{r} \tag{2.20}$$

Thus, the gravitational acceleration can be computed by its gradient, as expressed in Equation 2.21.

$$\vec{a} = -\mu\frac{\vec{r}}{r^3} \tag{2.21}$$

However, the bodies are generally not perfect spheres, in particular, the Earth is more similar to an oblate spheroid. Therefore, the gravitational field varies not only with the radius, but also with the latitude. Rotational symmetry has been considered, so the gravitational field does not depend on the longitude. Thus, the gravitational potential can be written by Equation 2.22. Where the first term represents the potential of a sphere and the second term the desviation of the perfect model.

$$V(r,\phi) = -\frac{\mu}{r} + \phi(r,\phi) \tag{2.22}$$

The second term can be calculated with J_k, known as zonal harmonics, and P_n, called Legendre polynomials, (as expressed in Equation 2.23). The zonal harmonics are unique to a planet. Table 2.1 shows the first harmonics of the Earth.

$$\phi(r,\phi) = \frac{\mu}{r}\sum_{k=2}^{\infty} J_k \left(\frac{R}{r}\right)^k P_k(\cos\phi) \tag{2.23}$$

Zonal harmonic	Value
J_2	1.08263×10^{-3}
J_3	-2.534×10^{-6}
J_4	-1.620×10^{-6}
J_5	-2.273×10^{-7}

Table 2.1 Earth zonal harmonics.

The Legendre polynomials can be computed using Rodrigues' formula, which is shown in Equation 2.24.

$$P_k(x) = \frac{1}{2^k k!} \frac{d^k}{dx^k}(x^2 - 1)^k \tag{2.24}$$

Solar radiation pressure

Solar radiation comprises photons, which are massless particles but its energy and momentum are not zero. The solar radiation pressure is obtained by dividing the energy flux transported by photons across a surface normal to the radiation direction by the speed of light.

The force due to this pressure can be computed by Equation 2.25. A is the area of the satellite where the radiation hits and P_{SR} is the solar radiation pressure. The shadow function, ν, is equal to zero when the satellite is in the shadow and one otherwise. The radiation pressure coefficient, C_R, takes a value between 1 and 2. It takes 1 when the surface is a black body and 2 when all the incident is reflected. Finally, $\vec{u}$ is the unit vector going from the satellite to the Sun.

$$\vec{F} = -\nu P_{SR} C_R A \vec{u} \tag{2.25}$$

This perturbation has a greater influence on high orbits, where the atmospheric drag is practically negligible. Thus, this perturbation is not so relevant in Low Earth Orbit, which are the target orbits of the project.

Lunisolar perturbation

The two bodies that most affect satellites movement around the Earth are the Moon and the Sun. Let consider three body system comprissing, for instance, the Earth, the satellite and the Moon. Following the same procedure as that of the two-body problem, the equation of motion of the satellite can be computed by Equation 2.26.

$$\ddot{\vec{r}} = -\mu \frac{\vec{r}}{r^3} + \mu_x \left(\frac{\vec{r}_{x/s}}{r^3_{x/s}} - \frac{\vec{r}_x}{r^3_x} \right) \tag{2.26}$$

The first term of Equation 2.26 is the fundamental equation of Keplerian motion and the second one the perturbation force which is exerted by the third body. μ_x is the gravitational parameter of the third body, $\vec{r}_x$ is the vector from the Earth to the third body and $\vec{r}_{x/s}$ is the vector from the satellite to the third body.

The order of magnitud of this perturbation can be estimated by referring to the Keplerian force. Thus, the perturbation due to the Moon in Low Earth Orbits is in the order of 10^{-7}, and to the Sun of 5×10^{-8}.

Comparison of perturbation effects

Finally, Figure 2.8 shows the effect of the different perturbations in Low Earth Orbits. The most relevant perturbations are those due to gravitational potential and atmospheric drag. These two are the perturbations that are considered in this project for sythetic data, disregarding the solar radiation pressure and the lunisolar perturbation. In real cases, the complete model is used, considering the four perturbations.

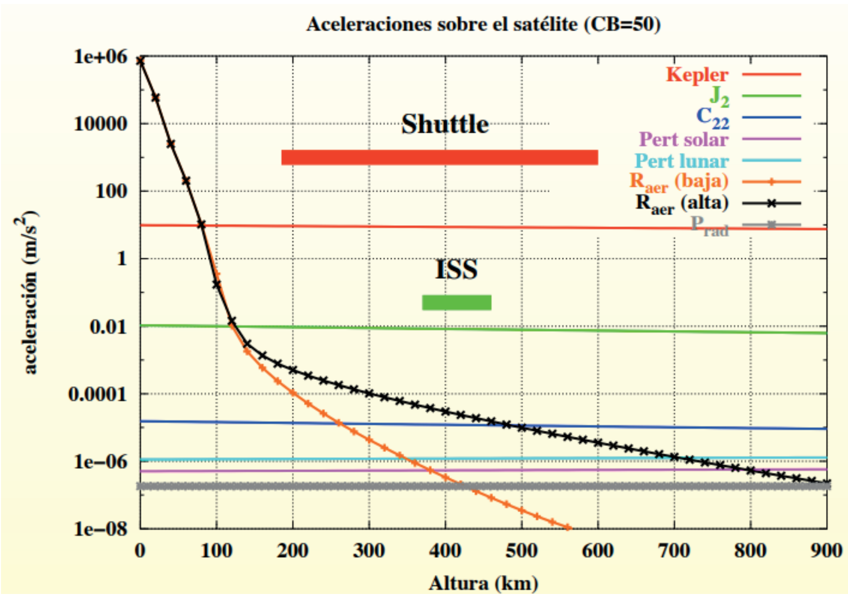

Figure 2.8 Perturbation effects in Low earth Orbit [10].

2.1.5 Orbital propagators

It is necessary to use an orbital propagator to know the orbital elements at an instant of time, epoch, and their evolution. This is an algorithm that allows to compute future ephemeris from the orbital element set given at a certain epoch.

Regardless of perturbations, this algorithm is simple, the basic keplerian or two-bodies propagation. Nevertheless, taking into account some perturbations, the model becomes more complicated. Therefore, there are numerous models for orbital propagator.

Considering the altitudes of the orbits taken into account in the project, the most relevant perturbations are the first tesseral Earth harmonics and the atmospheric drag. These perturbations are the ones include in the project for orbit propagation when synthetic data are used. In case of real data, solar radiation pressure and the lunisolar perturbation are also included for orbital propagators.

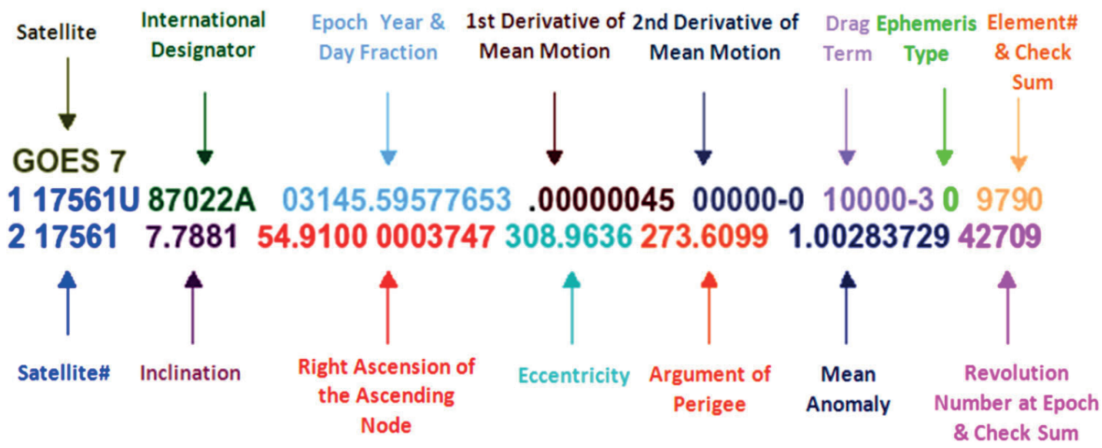

Figure 2.9 Two-line element set format [11].

A common orbital format has been used, the two-line element. A two-line element set, TLE, is an encoded data format that contains a list of the orbital elements of an object in orbit about the Earth at an instant of time. This data format gather the orbital elements of the object into two lines of 69 columns preceded by a title line. This title line is not required, as each data line includes a unique object identification code.

2.1.6 Visibility

Another important concept of orbital mechanic for radar is the visibility. Since the project is based on radar data, it is important to know in which condition the radar can take them. Radar can only obtain satellite data when this one is placed in a visible interval. In general, this happens when the vector from the station to the satellite, $\Delta\vec{r}$, is above the geographic horizon of the station [10] (in particular, the visibity of the S3TSR is defined by the elevation-azimuth mask explained in Section 2.1.7). The angle between vector $\Delta\vec{r}$ and the horizon, θ, must be higher than a minimum value determined by instrumentation and topography, α (Figure 2.10 shows a scheme of these parameters).

Angle θ is the arcsine of the scalar product of the vector from the radar to the satellite and the unit vector from the Earth centre to the radar (as expressed in Equation 2.27).

$$\theta = \arcsin(\Delta\vec{r}\cdot\vec{c}), \qquad where \qquad \vec{c} = \frac{\vec{r}_{site}}{R_\oplus} \tag{2.27}$$

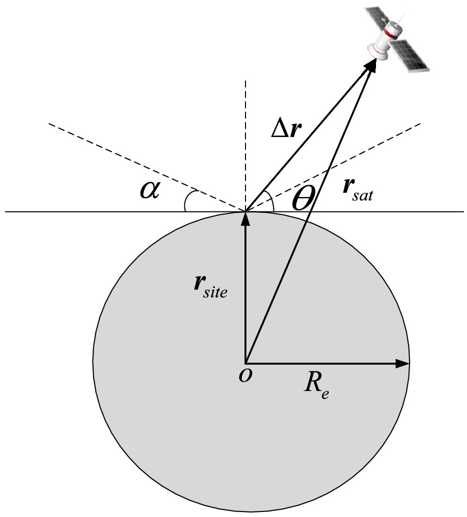

Figure 2.10 Satellite visibility from Earth station ($R_e = R_\oplus$) [12].

The vector from the station to the satellite, $\Delta\vec{r}$, can be expressed by Equation 2.28. Thus, tthe angle between this vector and the geographic horizon of the station can be computed by Equation 2.29. Where r_{sat} is the module of satellite position vector, ψ is the angle between this vector and the station position vector, r_{site}, and $R_\oplus$ is Earth radius (Earth radius is denoted by R_e in Figure 2.10).

$$\Delta\vec{r} = \frac{\vec{r}_{sat} - \vec{r}_{site}}{\sqrt{r_{sat}^2 + R_\oplus^2 - 2R_\oplus r_{sat}\cos\psi}} \tag{2.28}$$

$$\theta = \arcsin\left(\frac{\vec{r}_{sat}\cos\psi - R_\oplus}{\sqrt{r_{sat}^2 + R_\oplus^2 - 2R_\oplus r_{sat}\cos\psi}}\right) \tag{2.29}$$

2.1.7 Radar simulation

The main analyses of this project have been performed with synthetic data. A radar data simulation tool implemented on MATLAB by the advisor's group has been employed to obtain these scenarios. Following the concept of visibility aforementioned, the radar is modelled by an Azimuth-Elevation mask, and the tool detects when the satellite crosses this mask.

The main idea of this tool is to find the zero crossing for the function $g(el,az) = el_{max}(az) - el$, where $el_{max}(az)$ represents the maximum elevation value for a given azimuth, i.e., the superior limit of the mask. This is solved by iterating between instants before and after the crossing up to an arbitrary precision. The same procedure is followed with the inferior limit, just changing the elevation function depending on azimuth, $el_{min}(az)$.

The mask is shown in Figure 2.11 in an Azimuth-Elevation plot. If the radar were omnidirectional and the elevation was limited only by topography, all azimuths and all elevations greater than a constant minimum value would be visible. However, the radar employed in the project is the S3TSR and its mask is defined as an area with mean azimuth of 180 degrees, so it is pointing South, a mean elevation of 60 degrees and swept angle span, referred to main antenna planes, not lower than 43 degrees in left-right direction and not lower than 15 degrees in up-down direction [5].

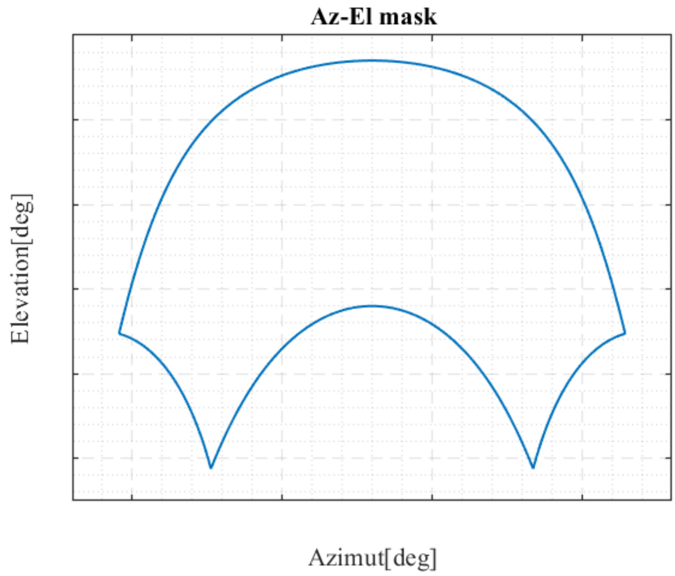

Figure 2.11 Elevation-azimuth mask.

2.2 Statistics

In manoeuvres detection, errors of different nature have to be taken into account; for instance, those introduced by radar measurements, or by propagation in orbit. Furthermore, the algorithm uses a statistical distance and its probability has to be computed. Thus, an introduction of statistics concepts is presented in this section.

Firstly, some basic concepts of statistics are briefly defined [13].

Definition 2.1 A *random variable*, X, is a measurable function defined on a probability space which assigns real numbers to the outcomes of an experiment.

Definition 2.2 The *cumulative distribution function (cdf)*, F, is a unique function which computes the probability that a random variable takes values less than or equal to some value, x:

$$F(x) = P(X \leq x) \tag{2.30}$$

Definition 2.3 The *probability density funtion (pdf)*, f, is a function which computes the probability that a random variable, X, takes some value, x:

$$f(x) = P(X = x) \tag{2.31}$$

Different distributions are used in the project; both to characterize the errors and to compute the probabilities from the statistical distances. These distributions are defined below.

Definition 2.4 The *normal distribution* is a type of continuous probability distribution for a real-value random variable. Its pdf and its cdf are given by Equations 2.32. Where μ is the mean value, σ is the standard deviation and erf is the related error function, which is defined by Equation 2.33.

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \quad F(x) = \frac{1}{2}\left[1 + erf\left(\frac{x-\mu}{\sigma\sqrt{2}}\right)\right] \tag{2.32}$$

$$erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt \tag{2.33}$$

This distribution plays an important role in classic statistics due to the *Central Limit Theorem*, which is explained in Theorem 2.1. Furthermore, an important property of this distribution is that the sum of normal distributions is also a normal distribution. That means, whether $X \sim N(\mu_x, \sigma_x^2)$, $Y \sim N(\mu_y, \sigma_y^2)$ and they are independents, then $Z = X + Y$ is distributed as a normal; $Z \sim N(\mu_x + \mu_y, \sigma_x^2 + \sigma_y^2)$.

Theorem 2.1 The *central limit theorem* establishes that the sum of random variables, with any kind of distribution, tends towards a normal distribution.

Definition 2.5 The *gamma distribution* is a two-parameter family of continuous probability distributions. Its pdf and its cdf are given by Equations 2.34. Where α is the shape parameter, β is the scale parameter, Γ is the gamma function and γ is the lower incomplete gamma function. These two functions are defined by Equations 2.35.

$$f(x) = \frac{x^{\alpha-1}}{\beta^\alpha \Gamma(\alpha)} e^{-\frac{x}{\beta}} \quad F(x) = \frac{\gamma(\alpha, \beta x)}{\Gamma(\alpha)} \tag{2.34}$$

$$\Gamma(\alpha) = \int_0^\infty t^{\alpha-1} e^{-t} dt \qquad \gamma(\alpha, \beta x) = \int_0^{\beta x} t^{\alpha-1} e^{-t} dt \tag{2.35}$$

Definition 2.6 The *chi-squared distribution* with k degrees of freedom is the distribution of a sum of the squares of k independent standard normal random variables. It is a special case of the gamma distribution with $\alpha = \frac{k}{2}$ and $\beta = 2$.

Definition 2.7 The *exponential distribution* is a particular case of the gamma distribution, with $\alpha = 1$ and $\beta = \frac{1}{\lambda}$. λ is the parameter of the distribution, called rate parameter. Its cdf is defined by Equation 2.36.

$$F(x) = 1 - e^{-\lambda x} \tag{2.36}$$

In addition, the variable of this project is not one-dimentional. Thus, multidimention random variables are also introduced. Moreover, since the large-scale errors come from the sum and accumulation of many small-scale errors, the *central limit theorem* justifies the use of the normal distribution as error model. Hence, the multivariate normal distribution is also explained.

Definition 2.8 Let $\vec{X} \in \Re^n$ be a *multivariate continium random variable*, each component of it follows an unidimensional distribution. As in one-dimensional case, a joint distribution function is defined, which is computed by the density function.

The two important parameters are, the mean, which is defined by Equation 2.37, and the covariance matrix, that is characterized by Equation 2.38. The covariance matrix is always symmetric and positive semi-definite. The diagonal values represent the variance of each component of $\vec{X}$. The rest of the matrix elements are the correlations between two components of $\vec{X}$; the component ij of the covariance matrix is the correlation between the components X_i and X_j.

$$\vec{\mu}(\vec{X}) = E\left[\vec{X}\right] = \int_{\Re^n} \vec{y} f(\vec{y}) dy \tag{2.37}$$

$$\Sigma(\vec{X}) = E\left[\left(\vec{X} - \mu(\vec{X})\right)\left(\vec{X} - \mu(\vec{X})\right)^T\right] \tag{2.38}$$

Definition 2.9 The *multivariate normal distribution* is expressed as $\vec{X} \sim N_n(\vec{\mu}, \Sigma)$ and its density function is defined by Equation 2.39.

$$f(\vec{x}) = \frac{1}{Det(\Sigma)(2\pi)^{n/2}} e^{\left(-\frac{1}{2}(\vec{x}-\vec{\mu})^T \Sigma^{-1} (\vec{x}-\vec{\mu})\right)} \tag{2.39}$$

Finally, some additional important concepts for the error model are introduced [14], [15].

Definition 2.10 A *stochastic or random process* is a time-dependant random variable, $\vec{X}(t)$. Thus, the mean and the covariance also depend on time, $\vec{\mu}(t)$, $\Sigma(t)$.

The autocorrelation for a process is defined by Equation 2.40. It shows how much the past history affects its current value. Whether a stochastic process is distributed following a multivariate normal, it is called *gaussian process*.

$$R(t, \tau) = E\left[\vec{X}(t)\vec{X}(\tau)^T\right] \tag{2.40}$$

Definition 2.11 A process, $\vec{v}(t)$ is called *white noise* if it verifies the following characteristics:

- $E\left[\vec{v}(t)\right] = \vec{0}$.
- $E\left[\vec{v}(t)\vec{v}(t)^T\right] = \sigma^2 Id$.
- $R(t, \tau) = E\left[\vec{v}(t)\vec{v}(\tau)^T\right] = \delta(t - \tau)\sigma^2 Id$, where $\delta(x) = 1$ if x = 0 and $\delta(x) = 0$ otherwise.

The last condition means that a white noise at a certain instant is independet of its value at any previous instant. Finally, a *gaussian white noise* is a process which satisfies the previous conditions and is also a gaussian process.

2.3 OREKIT

The language chosen for the development of the project has been MATLAB. Moreover, an important tool for this has been OREKIT (ORbit Extrapolation KIT) [16], a low level space dynamics library written in Java which can interfaced with MATLAB. It aims at providing accurate and efficient low level components for the development of flight dynamics applications. OREKIT provides basic elements, like orbits, dates or frames; and various algorithms to handle them, such as conversions between different frames or analytical and numerical propagation. OREKIT has been developed by the CS GROUP.

Some of the elements of OREKIT which are used in the project are the definition of the different frames, that are explained in Section 2.1.1 (Earth-centred inertial, Earth-centred Earth-fixed, topocentric and local-vertical local-horizontal frame); or the conversions among them. For instance, it provides the transformation between the ECEF frame and the inertial frame, taking into account the effects of precession and nutation, as well as the poles' wandering displacement with precision. OREKIT also includes absolute propagators in cartesian coordinates or orbital elements and a Taylor differential algebra framework (an other important tool of the project which is explained following in Section 2.5).

Furthermore, OREKIT allows to include all basic perturbations models when propagating orbits. For the altitudes in the scenarios cosidered in this project, LEO propagation, the most relevant perturbations are the first tesseral Earth harmonics and the atmospheric drag. For the atmospheric model, it has been used the standar Harris-Priester model and the Naval Research Laboratory Mass Spectrometer and Incoherent Scatter Radar Exosphere (NRLMSISE) model, in particular the Marshall Solar Activity Future Estimation (MSAFE) for the empirical solar data. Both models are included in the OREKIT library.

2.4 Distribution Fitter MATLAB App

The Distribution Fitter App is a tool from MATLAB that allows one to fit distributions to the data. This app has been employed to compute the distribution of one of the statistical distances used in the project.

Firstly, you have to introduce the target sample data in the app. There are two options for this purpose; a vector of the data can be created directly in the app or it can be imported from the MATLAB workspace. It is necessary to choose a distribution to create the fit. Moreover, the results, both the data and the fit, can be displayed on the app. You can choose to display, for instance, the density (pdf) or the cumulative probability function (cdf).

The fit can be improved by excluding certain data. For example, bounds for the data to exclude can be specified or data can be excluded graphically. Additional fit can be created and certain parameters of the fit can be changed manually (See [17] for more information about this app).

2.5 Taylor differential algebra

One of the basic problem in dynamics, in particular, in satellite dynamics, relies on the fact that, even if the physical laws of motion are well-known with reasonable accuracy and the algorithm is precise enough, the set of initial data at a given epoch always contains a certain amount of uncertainty. The aim of this section is to explain a method to propagate the data with its uncertainty along time to a future epoch.

The set of initial data are expressed with their nominal value, and the uncertainty with respect of this value is define by a covariance matrix (symmetric and positive semi-definite matrix, whose main diagonal contains the variance of each component and the other elements represent the correlations between two components).

There are several methods to achive this goal. A typical one is the Montecarlo-like procedure, which consists in sampling the domain of initial data and propagating along time each point independetly (as seen in Figure 2.12). Nevertheless, it is easy to notice that this Montecarlo-like procedure is an expensive computational process.

In this project, an alternative method that can reduce this cost is used. This method is known as jet transport, which is a flexible, accuracy and efficient method, and it is based on high-order Taylor expansions. It is known that, for instance, computations of Lyapunov exponents or solution of boundary value problems by shooting requiere the use of first order variation equation. The jet propagation is a generalization of this idea to higher order, so it is not just based on the linear approximation around the nominal solution.

Let x_0 be the initial data and ε the initial uncertainty on a given domain. The main idea of the jet transport is to propagate this initial data expressed like $x_0 + \varepsilon$ along time and to obtain its evolution. The Montecarlo-like procedure would sample the domain and propagates for many ε values (this procedure is represented by Figure 2.12). On the other hand, jet transport uses arbitrary high-order variational equations to express the solution at any time as a Taylor series expansion in ε around the nominal solution, truncated at the desired order [18] (Figure 2.13 represents this method). Besides, the coefficients of the Taylor series are computed along the nominal trajectory as extended states using a suitable numerical scheme.

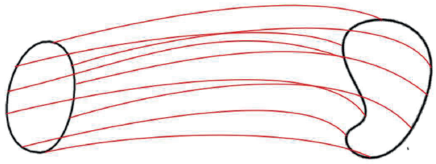

Figure 2.12 Montecarlo-like procedure [19].

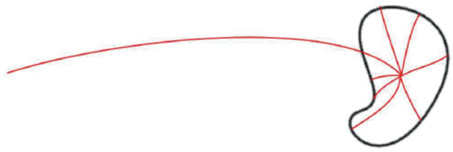

Figure 2.13 Taylor based jet transport [19].

Once the coefficients are computed, the series is defined. At that point, the computational effort involved in propagating a small sampled initial domain is reduced to the direct polynomial evaluation. With respect to accuracy, it can be controlled by the step of the numeric scheme or by the order of Taylor expansion.

A further advantage is that the effect of parameters can be included with the same methodology, in addition of the inicial condition. This means that more in-depth and detailed analyses can be performed.

It is important to take into account that Taylor's method is not always a better option than the typical Montecarlo procedure. Montecarlo procedure is faster than jet transport for low orders and low number of variables. However, for samples of moderate to high size the Taylor-based method becomes competitive. Due to project conditions jet transport technique using Taylor differential algebra will be one of the method employed.

2.6 Unscented transform

The purpose of this section is to explain another method to propagate the uncertainty along time to a future epoch, called unscented transform. This project pretends to compare the results obtained with both methods and their computation times.

The unscented transform (UT) was originally prosed by Jeffrey Uhlmann as part of his PhD thesis (Uhlmann, 1995). The basic premise of the UT is that it easier to approximate a Gaussian distribution than it is to approximate an arbitrary density after a nonlinear transformation [20].

The problem that solved the UT is the following: having some n-dimensional Gaussian distributed variable, as expressed in Equation 2.41 (where μ_X is the mean and Σ_X is the covariance marix), a nonlinear transformation is applied to it, as shown in Equation 2.42. The aim of the problem is to estimate the density distribution of this new variable.

$$x_k \sim N_n(\mu_X, \Sigma_X) \tag{2.41}$$

$$y_k = f(x_k) \tag{2.42}$$

The main idea of the UT is to compute a subset points, called sigma points $S = \{s_i\}_{i=1}^{2D+1}$, and propagate them through the nonlinear map $f(\cdot)$. Then, it is necessary to estimate a Gaussian distribution, as expressed in Equation 2.43 (where μ_Y is the sample mean and Σ_Y is the sample covariance matrix).

$$\begin{aligned} &y_i = f(s_i), \forall i \in 1,...,2D+1, \\ &y_i \sim N(\tilde{\mu}_Y, \tilde{\Sigma}_Y) \end{aligned} \tag{2.43}$$

There are different proposals to choose sigma points. In this project, a weighted unscented transform is used, so it is also necessary to compute the weights associated (w_i) to the sigma points (X_i). Equation 2.44 shows how to compute them:

$$\begin{aligned} X_0 &= \bar{x} & w_0 &= \frac{k}{n+k} \\ X_i &= \bar{x} + \left(\sqrt{(n+k)\Sigma_X}\right)_i & w_i &= \frac{1}{2(n+k)} \\ X_{i+n} &= \bar{x} - \left(\sqrt{(n+k)\Sigma_X}\right)_i & w_i &= \frac{1}{2(n+k)} \end{aligned} \tag{2.44}$$

where $\left(\sqrt{(n+k)\Sigma_X}\right)_i$ is the ith column of $\sqrt{(n+k)\Sigma_X}$. k is a free parameter, which has been set $k = n-3$ to minimize the fourth-order moment mismatch [21].

Next step is to propagate the sigma points through the nonlinear map, as expressed in Equation 2.45.

$$y_i = f(X_i) \tag{2.45}$$

Finally, the sample mean of the transformed sigma points and the sample covariance can be computed by Equations 2.46 and 2.47, respectively.

$$\bar{y} = \sum_{i=0}^{2n} w_i \cdot y_i \tag{2.46}$$

$$\Sigma_y = \sum_{i=0}^{2n} w_i (y_i - \bar{y})(y_i - \bar{y})^T \tag{2.47}$$

In this project, the nonlinear map is a combination of the propagation along time of position and velocity, and the trasformation from these variables to range-range rate. The dimension of the variable is 6, hence, 13 propagations are needed.

3 Algorithm for manoeuvres detection

This chapter is about the algorithm for manoeuvres detection employed in this project. The Theory of attributables is posed in Section 3.1. In section 3.2, the algorithm itself is explained. In section 3.3, the different statistical distances, which are going to be analyzed, are explained; as well as the computation of the probability that a manouevre has been performed. Finally, the concepts of precision, recall and F-score are defined in Section 3.4.

3.1 Theory of Attributables

The aim of the attributable is to condense the information of all measurements and obtain a singe, virtual one [22]. The radar provides range, ρ, range-rate, $\dot{\rho}$, elevation, El, and azimuth, Az, and together with the chosen reference epoch, t, the attributable can be computed (as expressed in Equation 3.1).

$$\mathscr{A} = \{t, \rho, \dot{\rho}, El, Az\} \tag{3.1}$$

The fit to an observable's measurement vector is computed with an unweighted linear least squares approach for a polynomial of degree n based on a Taylor series (as expressed in Equations 3.2). Moreover, if the definition of the range-rate is included into the modelling, it is possible to improve the uncertainty of the resulting virtual measurement; in this case, the observables range and range-rate share the parameters, because range-rate is the time derivative of range.

$$\begin{aligned}
\rho(t) &= \rho_0 + \rho_1 \cdot t + \rho_2 \cdot \frac{t^2}{2!} + ... + \rho_n \cdot \frac{t^n}{n!} \\
\dot{\rho}(t) &= \rho_1 + \rho_2 \cdot \frac{2t}{2!} + ... + \rho_n \cdot \frac{nt^{n-1}}{n!} \\
El(t) &= El_0 + El_1 \cdot t + El_2 \cdot \frac{t^2}{2!} + ... + El_n \cdot \frac{t^n}{n!} \\
Az(t) &= Az_0 + Az_1 \cdot t + Az_2 \cdot \frac{t^2}{2!} + ... + Az_n \cdot \frac{t^n}{n!}
\end{aligned} \tag{3.2}$$

For the fitting process, the origin of time is at the middle time of the tracklet. The classical least squares algorithm is employed to compute the parameters, using the Equation 3.3.

$$\vec{m} = \begin{bmatrix} \vec{\rho}_* \\ \vec{El}_* \\ \vec{Az}_* \\ \vec{\dot{\rho}}_* \end{bmatrix} = A_{SYS}\, \vec{p} + \vec{v} = \begin{bmatrix} A & 0 & 0 \\ 0 & A & 0 \\ 0 & 0 & A \\ A_{\dot{\rho}} & 0 & 0 \end{bmatrix} \begin{bmatrix} \vec{\hat{\rho}} \\ \vec{\hat{El}} \\ \vec{\hat{Az}} \end{bmatrix} + \vec{v} \tag{3.3}$$

In Equation 3.3, $\vec{m}$ contains the measurements of all observables, $\vec{p}$ are the parameters which are going to be computed (named ρ_0, ρ_1, El_0, Az_0,... in Equations 3.2) and the matrices A and $A_{\dot{\rho}}$ have coefficients found from the attributable time-varying formula for (ρ, El, Az) and $\dot{\rho}$, as expressed in Equation 3.4 (where m is the number of observables). Finally, $\vec{v}$ contains the error, which follows the distribution of the measurements.

$$A = \begin{bmatrix} 1 & t_1 & \frac{t_1^2}{2!} & \cdots & \frac{t_1^n}{n!} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 1 & t_m & \frac{t_m^2}{2!} & \cdots & \frac{t_m^n}{n!} \end{bmatrix} \qquad A_{\dot{\rho}} = \begin{bmatrix} 0 & 1 & \frac{2t_1}{2!} & \cdots & \frac{nt_1^{n-1}}{n!} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 1 & \frac{2t_m}{2!} & \cdots & \frac{nt_m^{n-1}}{n!} \end{bmatrix} \tag{3.4}$$

As the measurement errors are uncorrelated (its covariace matrix, Σ_v, has only elements on the main diagonal); the problem is posed (as seen in Equation 3.5) as weighted least-squares, whose solution is well-know (as expressed in Equation 3.6).

$$\min_p \vec{v}^T \Sigma_v^{-1} \vec{v} = \min_p (\vec{m} - A_{SYS}\,\vec{p})^T \Sigma_v^{-1} (\vec{m} - A_{SYS}\,\vec{p}) \tag{3.5}$$

$$\vec{p} = (A_{SYS}^T \Sigma_v^{-1} A_{SYS})^{-1} A_{SYS}^T \Sigma_v^{-1} \vec{m} \tag{3.6}$$

Finally, the covariance matrix of the parameters, Σ_p, can be computed directly from the covariance matrix of the measurements, with the expression shown in Equation 3.7.

$$\Sigma_p = (A_{SYS}^T \Sigma_v^{-1} A_{SYS})^{-1} \tag{3.7}$$

3.1.1 Position and velocity from attributables

In this section is explained how to compute the position and the velocity of the satellites from their attributables.

As it has been mentioned the range rate value can be derived from the parameters of the range attributable. Thus, in order to obtain approximately a complete representation of the satellite state, the same computation can be done with elevation and azimuth. Then, the definition of the attributable is expressed as Equation 3.8.

$$\mathscr{A} = \left\{t, \rho, \dot{\rho}, El, \dot{El}, Az, \dot{Az}\right\} \tag{3.8}$$

Radar data are given in its topocentric frame. Thus, it is necessary to go from this frame to the Earth-fixed and then to the inertial. The satellite coordinates ($\vec{s}^g$) in topocentric frame are shown in Equation 3.9.

$$\vec{s}^g = \rho \cdot \begin{bmatrix} \cos(El)\cdot\sin(Az) \\ \cos(El)\cdot\cos(Az) \\ \sin(El) \end{bmatrix} \tag{3.9}$$

The satellite position in the Earth-fixed frame is expressed as Equation 3.10. Where C_g^e is the rotation matrix from the topocentric to the Earth-fixed frame, and $\vec{x}_{radar}^e$ is the vector from the radar to the satellite, both are defined with the coordinates of the radar in the Earth-fixed frame.

$$\vec{x}^e = C_g^e \cdot \vec{s}^g + \vec{x}_{radar}^e \tag{3.10}$$

The translation from the Earth-fixed frame to the inertial frame depends on the epoch. In the project, OREKIT has been used to compute the rotation matrix required, C_e^i. The satellite coordinates in the inertial frame are computed by Equation 3.11.

$$\vec{x}^i(\mathscr{A}) = C_e^i \cdot \vec{x}^e = C_e^i C_g^e \cdot \vec{s}^g + C_e^i \vec{x}^e_{radar} \tag{3.11}$$

Now that the position is computed, the velocity can be calculated by differentiating it, as expressed in Equation 3.12; where $\frac{d}{dt}(\vec{s}^g)_g = [\vec{s}^g_\rho, \vec{s}^g_{El}, \vec{s}^g_{Az}] \cdot [\dot{\rho}, \dot{El}, \dot{Az}]^T$.

$$\vec{v}^i(\mathscr{A}) = \frac{d}{dt}(\vec{x}^i)_i = C_e^i \cdot \frac{d}{dt}(\vec{x}^e)_e + \vec{w}^i_{e/i} \times \vec{x}^i = C_e^i C_g^e \cdot \frac{d}{dt}(\vec{s}^g)_g + \vec{w}^i_{e/i} \times \vec{x}^i \tag{3.12}$$

Also the uncertainty information of the attributable can be passed on to the inertial frame. Let $\vec{X}^i = [\vec{x}^i, \vec{v}]^T$ be the complete satellite state in cartesian coordinates, the covariance matrix can be computed with Equation 3.13, where $\frac{\partial \vec{X}^i}{\partial \mathscr{A}_s}$ is the jacobian of the complete transformation.

$$\Sigma_{\vec{X}^i} = \left(\frac{\partial \vec{X}^i}{\partial \mathscr{A}_s}\right) \Sigma_{\mathscr{A}_s} \left(\frac{\partial \vec{X}^i}{\partial \mathscr{A}_s}\right)^T \tag{3.13}$$

3.2 Algorithm for manoeuvre detection

In this section the employed algorithm for manoeuvre detection is explained. The algorithm employed in this project is based on comparing the attributable obtained from the real measurements taken by the radar and the one obtained from the predicted states at the time of the measurements. It has been applied computing the attributable only with range and range rate, only with azimuth and elevation, and using all the variables. At the end of the project we will see that the most important one (with the best results) is the range-range rate attributable.

The inputs requiered by the algorithm are the following:

- The satellite's orbit before the measurements with its uncertainty information. As it has been mentioned above, the data are expressed in TLE format in case of synthetic data, and the uncertainty in the form of a covariance matrix.
- The satellite's measurements, together with its associated uncertainty in the form of a covariance matrix.

The output of the algorithm is the probability that a manoeuvre has been performed by the object.

Moreover, the following assumptions are taken into account:

- Measurements come from radar data. It is considered that the measurements contain quite accurate range and range rate measurements and rather imprecise elevation/azimuth angle measurementes.
- Only one manoeuvre at most happens in between measurements.
- Manoeuvre are approximated as impulses.

Using the idea of the Theory of Attributables, from the measurements at certain time, the attributable of range, range-rate, azimuth and elevation can be obtain at the middle of a tracklet, as well as the associated uncertainty, which is expressed in the form of a covariance matrix, Σ. The scope of this algorithm is to obtain a predicted measurement from the initial value of the reference orbit, which is known with quite some accuracy.

The initial condition is sampled, obtaining m sampled points. These point will be denoted as $\vec{x}_{0j}$ for j = 1, . . . , m. Thus, the set of initial conditions is approximated by these points.

The sampled points are propagated using an OREKIT propagator up to time t_f. This computation can be made using different methods. The original algorithm employed Taylor differential algebra. In this project, the unscented transform is also used, in order to compare both procedures. Predicted values at measurement times are obtained as a cloud of points $\vec{x}_j(t_i)$. The density of points gives an approximate measure of the probability associated to the real trajectory.

Once it has the sampled orbit, the measurements at the attributable time can be computed. A "cloud" of measurements has been obtained, so its mean can be computed $(\hat{\rho}_0, \hat{Az}_0, \hat{El}_0, \hat{\rho}_1)$, as well as the covariance matrix which expresses the uncertainty. This value would be the expected one whether the satellite had not performed any maneuver, given the starting point of the orbit. Finally, the attributables and the predicted measurements can be compared. If there is no manoeuvre, both values are expected to agree. This can be defined by Equation 3.14.

$$(\Delta\rho_0, \Delta Az_0, \Delta El_0, \Delta\rho_1) = (\rho_0, Az_0, El_0, \rho_1) - (\hat{\rho}_0, \hat{Az}_0, \hat{El}_0, \hat{\rho}_1), \quad \Delta\Sigma = \Sigma + \hat{\Sigma} \tag{3.14}$$

Thus, under assumption of normality and whether the satellite has not performed any manoeuvre, $(\Delta\rho_0, \Delta Az_0, \Delta El_0, \Delta\rho_1)$ is expected to belong to a normal distribution of zero mean and covariance matrix $\Delta\Sigma$. This can be checked computing a statistical measurement. It is precisely here where the aim of this project lies. Together with the Mahalanobis distance, the Bathacharyya distance and the Kullback Leibler divergence are the statistical distances used in the project. All of them are explained in the following section.

3.3 Theory of distances

In Statistics, the study of distances is of fundamental importance in solving practical problems. Statistical distances are measurements that quatify how close two statistical objects are, which can be, for instance, two random variables or two probability distributions.

From the point of view of Geometry, a metric is define as follows:

Let M be a non-empty set, a distance function or metric over M is an application $\delta : M \times M \longrightarrow \mathbb{R}$ if the following conditions are satisfied for all x, y, z $\in M$.

1. $\delta > 0$ if $x \neq y$, and $\delta(x,x) = 0$;
2. $\delta(x,y) = \delta(y,x)$, (symetry);
3. $\delta(x,y) \leq \delta(x,z) + \delta(z,y)$, (triangle inequality);

Then, statistical distances are mostly not metrics because they lack one or more properties of proper metrics. A metric is distinguished from a *semimetric* when the application does not satisfy the triangle inequality and from a *quasimetrics* when it does not achieve the symmetry condition. Statistical distances that just fulfill the first property are referred to as *divergences* [23].

In this project, three statistical distances are used. The Mahalanobis distance (MD), which is the original one used by the algorithm; and the Kullback-Leibler divergece (KLD) and the Bhattacharyya distance (BD), which are those that will be studied in the project. As it has been explained before, the scope of the algorithm is to compute the distance between the attributables and projected measurements and make an estimation of the probability of manoeuvres occurrence.

3.3.1 Mahalanobis Distance

The Mahalanobis distance is the original one employed in the algorithm. The MD is a measure of the distance between a point x and a distribution. If the distribution has mean μ and covariance matrix Σ, the MD is define as expressed in Equation 3.15.

$$MD = \sqrt{(\vec{x}-\vec{\mu})^T\Sigma^{-1}(\vec{x}-\vec{\mu})} \tag{3.15}$$

In the project, the radar measurements have also error which is defined by a covariance matrix. Thus, the matrix Σ of the Equation 3.15 is define, under a Gaussian hypothesis, as $\Sigma = \Sigma_1 + \Sigma_2$, [24]. Where Σ_1 and Σ_2 are the covariance matrices of the radar measurements and the predicted ones.

Probability associated with the MD

In particular, if the ditribution is a multivariate normal, as the distribution of the project data, the square of the MD has a χ^2 distribution with n degrees of freedom, being n the number of variables. Then, the probability of manoeuvre is computed by Equation B.1

$$PR = \max\left\{0,(\chi^2(MD^2,n)-0.5)\cdot 2\right\}\cdot 100 \tag{3.16}$$

Finally, to reduce false positive, if the MD has a probability of 50% or less of occurring, it is assumed that there is no manoeuvre. Conversely, if the probability is more than 50%, then one substracts 50 from the probability and multiplies it by two.

3.3.2 Kullback-Leibler divergence

The Kullback-Leibler divergence, also called relative entropy, is a measure of the similarity or difference between two probability distributions, [25]. It is a divergence, since it does not satisfy the condition of symmetry, $\delta(x,y) = \delta(y,x)$, nor the triangular inequality, $\delta(x,y) \leq \delta(x,z) + \delta(z,y)$.

For two continuous random variables, P and Q, whose probability density funtions are p(x) and q(x), the Kullback-Leibler divergence is computed by the Equation 3.17.

$$KLD(P||Q) = \int p(x)\log\frac{p(x)}{q(x)}dx \tag{3.17}$$

Its value is always greater than or equal to zero and the equality will be fulfilled only when the two distributions are identical.

As the working distributions are multivariate normal, the divergence between these two distributions, with means μ_1 and μ_2, and covariance matrices Σ_1 and Σ_2, not singular, is defined by Equation 3.18, [26].

$$KLD(P||Q) = \frac{1}{2}\left[\log\left(\frac{\det(\Sigma_2)}{\det(\Sigma_1)}\right) + \mathrm{tr}(\Sigma_2^{-1}\Sigma_1) + (\mu_1-\mu_2)^T\Sigma_2^{-1}(\mu_1-\mu_2) - k\right] \tag{3.18}$$

Probability associated with the KLD

The distribution of the KLD is unknown. Thus, the determination of the probability distribution of this distance has been done experimentally.

The Distribution Filter App from MATLAB, which is explained in Section 2.4, has been used. The KLD has been computed for 5 satellites; it has been used 27 different scenarios with manoeuvre for each satellite and 102 scenarios without manoeuvres in total. Only the values of the KLD below 200 has been used for the fit, because high values, which appear in some scenarios, worsen the fit. Figure 3.1 shows the histogram of the KLD. It can be noticed that the shape of the virtual envelope curve is similar to the gamma distribution, whose probability density function can be seen in Figure 3.2 for different values of the shape and scale parameters. Then, this is the distribution chosen for the fit.

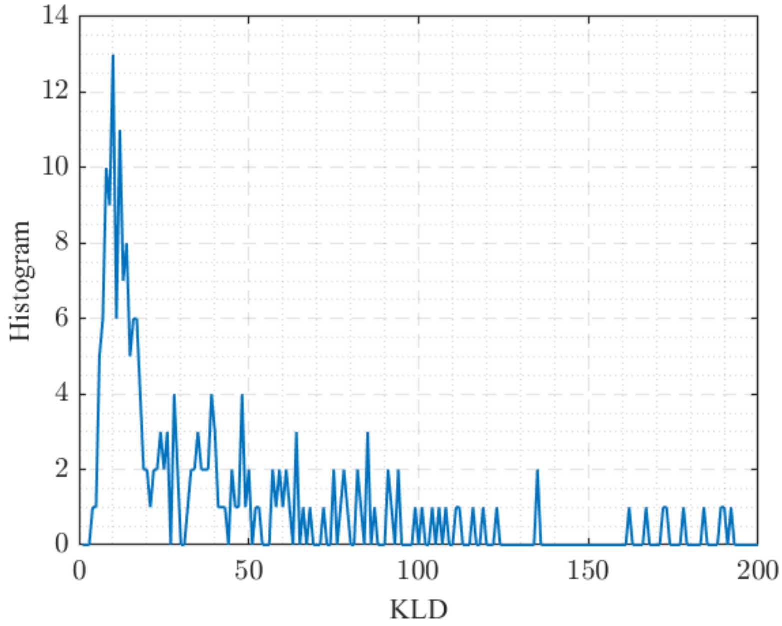

Figure 3.1 Histogram of the KLD.

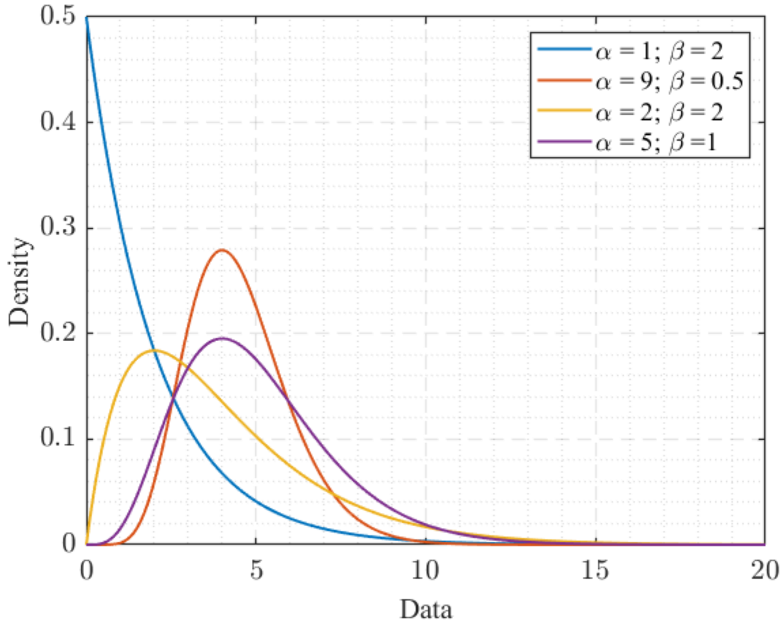

Figure 3.2 Probability density function of the gamma distribution.

Figures B.1 and B.2 show the cumulative distribution function and the probability density funtion, respectively, of the data and the fit. The tool computes the shape and the scale parameters of the distribution, obtaining $\alpha = 0.6328$ and $\beta = 183.7$.

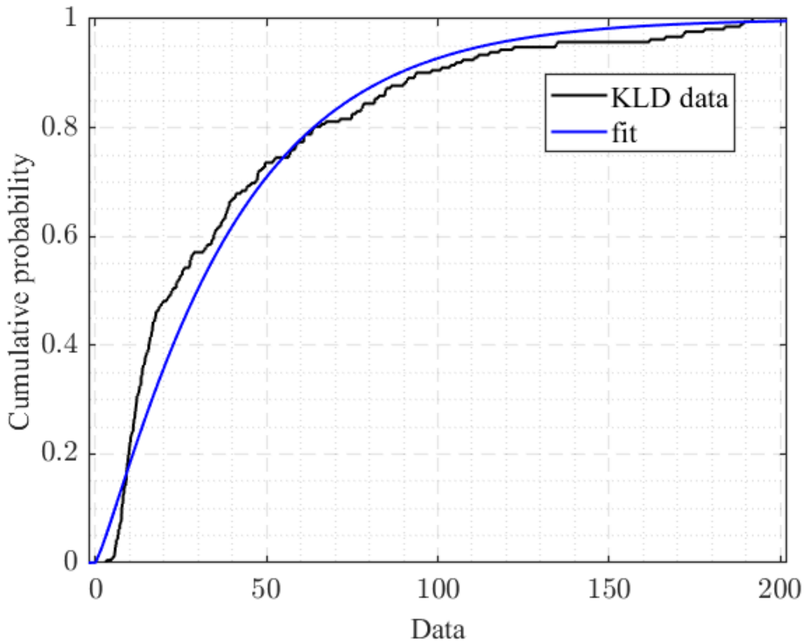

Figure 3.3 Cumulative density function of the KLD.

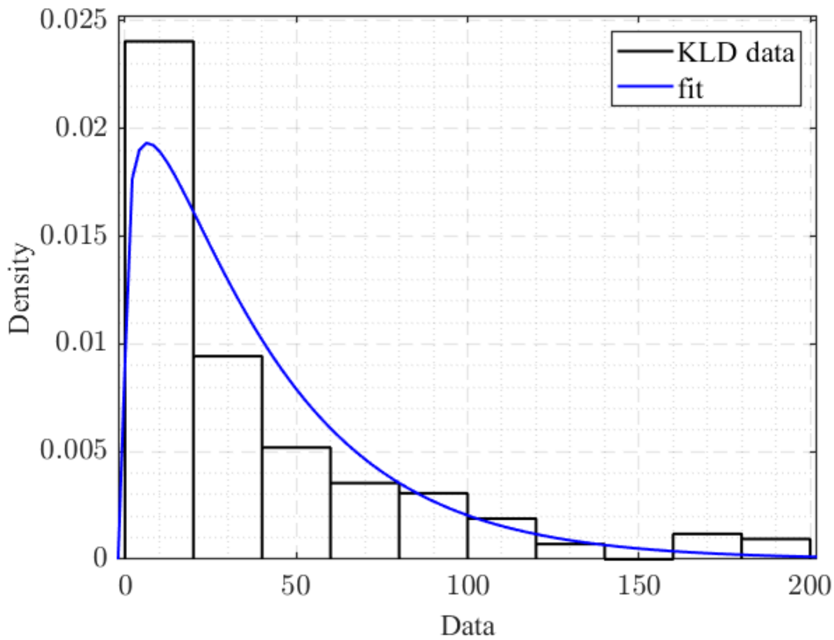

Figure 3.4 Probability density function of the KLD.

In the same manner as before, the probability is scaled to reduce false positives. If the KLD has a probability of 50% or less of occurring, it is assumed that there is no manoeuvre. If it has a higher probability of happening, then one substracts 50 from the probability and multiplies it by 2, to rescale the probability and keep it between 0 and 100%. Thus, the probability is computed by Equation B.2.

$$PR = \max\{0, (\Gamma(KLD, 0.6328, 183.7) - 0.5) \cdot 2\} \cdot 100 \quad (3.19)$$

3.3.3 Bhattacharyya Distance

In statistics, the Bhattacharyya distance is used to measure the similarity between two probability distributions. It is closely related to the Bhattacharyya coefficient, which measures the overlap between two statistical samples [27], [28].

Being p and q the densities of two continuous probability distributions, the Bhattacharyya coefficient is defined by the Equation 3.20. Establishing this definition, the BD can be computed by the Equation 3.21.

$$\rho(p,q) = \int \sqrt{p(x)q(x)}dx \quad (3.20)$$

$$BD(p,q) = -\log(\rho(p,q)) \quad (3.21)$$

Note that the coefficient is bounded, $0 \leq \rho \leq 1$, taking the value 0 when the distributions do not have any overlap, and 1 when they are identical. However, the distance can take any value greater than or equal to zero. Furthermore, since this distance does not fulfill the triangular inequality condition, it is a*semimetric*.

Both the attributables and projected measurements follow a multivariate normal distribution, $p_i = N(\mu_i, \Sigma_i)$. With this distribution, the distance can be computed by Equation 3.22.

$$BD = \frac{1}{8}(\mu_1 - \mu_2)^T \Sigma^{-1} (\mu_1 - \mu_2) + \frac{1}{2}\log\left(\frac{\det(\Sigma)}{\sqrt{\det(\Sigma_1)\det(\Sigma_2)}}\right) \quad (3.22)$$

Where μ_i and Σ_i are the means and covariace matrices of the distributions and Σ is defined as $\Sigma = \frac{\Sigma_1 + \Sigma_2}{2}$.

Equation 3.22 shows that the first term is related to the MD, and the second one is cancelled when the covariance matrices of both distributions are identical, since the MD is a particular case of the BD.

Probability associated with the BD

As it has been mentioned, the aim of computing the distance is to obtain the probability of manoeuvre ocurrence. The distribution of the BD is unknown. Nevertheless its coefficient, ρ, is bounded by the range 0 to 1, so it is quite simple to compute a probability from it.

The Bhattacharyya coefficient will be 0 if there is no overlap, and equal to 1 if both distributions coincide. Thus, the probability that a manoeuvre has been performed is $1 - \rho$. Computing this probability for different scenarios, it has been noticed that the value moves in a very small range, being the minimum value reached 0.9. Thus, to distribute the resulting values over a wider range, a scale coefficient, α, has been introduced.

The BD has been computed considering *range-range rate*, *elevation-azimuth* and *all data*. The results show that the distance is bigger when *all data* are used, hence, the number of variables, n, has to be considered in the likelihood computation. It has been decided to introduce these coefficients, α and n, as exponents of ρ, due to the similarity between the expression of the probability, $1 - \rho$, and the density function of an exponential distribution.

The coefficient α has been experimentally estimated. The distance has been computed also for 5 satellites; 27 different scenarios with manoeuvres for each satellite have been used, together with 102 scenarios without manoeuvres, like with the KLD. As the distirbution depends on the number of variables, it has been decided to employ just the BD computed with range-range rate and elevation-azimuth.

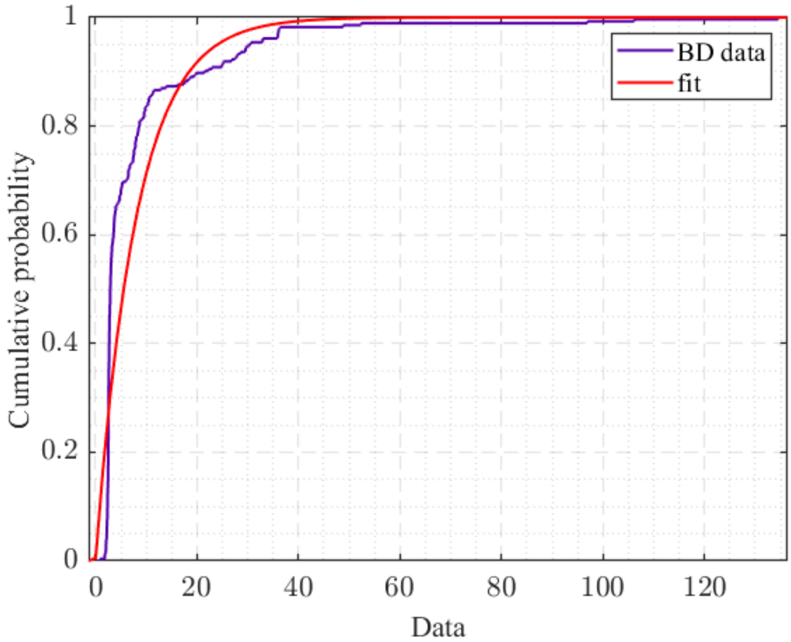

Figure 3.5 Cumulative density function of the BD.

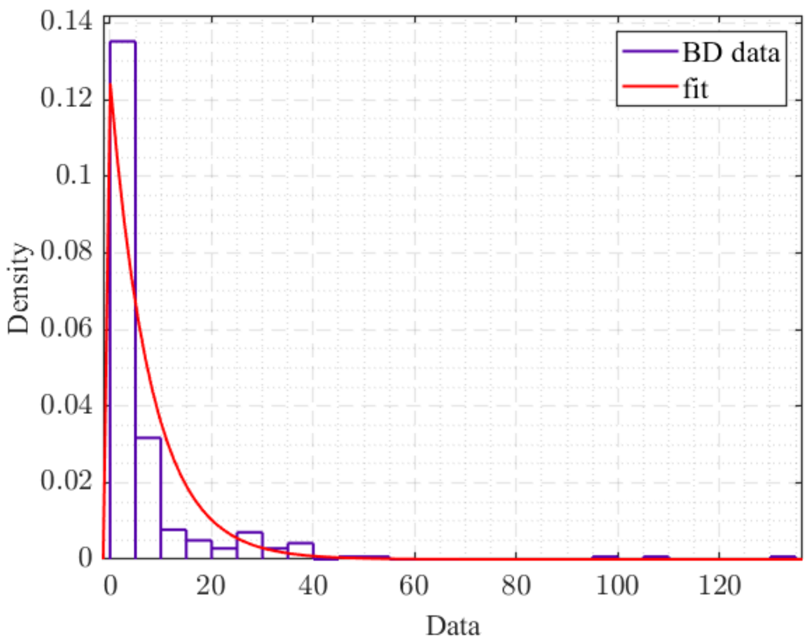

Figure 3.6 Probability density function of the BD.

The Distribution Filter App from MATLAB has been used, computing the fit with an exponential distribution. Figures B.3 and B.4 show the cumulative distribution function and the probability density function, respectively, of the data and the fit. The tool computes the mean, obtaining $\mu = 8.007$.

Whether one compares the expression of the probability density function of the exponential distribution, which is shown in Equation 3.23, and the expression to compute the probability of the BD, as expressed in Equation 3.24, the rate parameter, λ, is related to α by Equation 3.25. In addition, it is know that the rate parameter is the inverse of the mean. Thus, being $\mu = 8.007$ and the number of variables 2, α is set at 4.

$$F(x) = 1 - e^{-\lambda x} \tag{3.23}$$

$$PB = 1 - \rho^{\frac{1}{\alpha n}} \tag{3.24}$$

$$\lambda = \frac{1}{\alpha n} \tag{3.25}$$

Moreover, with the aim of decreasing false positives, it has been assumed that there is no manoeuvre if the BD has a probability of 30% or less of happening. If the probability is more than 30%, a subtraction of 0.3 to this value and a division by 0.7 to the result is computed to distribute the value back in the range [0, 100]. Then, the probability that a manoeuvre has been performed is computed as shown in Equation B.3.

$$PR = \max\left\{0, \left[\left(1 - \rho^{\frac{1}{4 \cdot n}}\right) - 0.3\right] / 0.7\right\} \cdot 100 \tag{3.26}$$

3.4 Precision, recall and F-score

In this section, three metrics employed to measure the accuracy of the distances are explained. In order to simplify the comparison of distance results.

There are four basic combinations of actual data category and assigned category by the algorithm. Table 3.1 is the contingency table which arranges these categories. The rows corresponds to actual value, which is positive if there is a manoeuvre and negative otherwise. The columns corresponds to assigned value, that is positives when the algorithm detects a manoeuvre and negative otherwise. Thus, the four combinations are: true positive (the algorithm detects a real manoeuvre), true negative (the algorithm does not detect a manoeuvre in a scenario without manoeuvre), false positive (a manoeuvre is detected in a scenario without manoeuvre) and false negative (a real manoeuvre is not detected).

	Predicted positive	Predicted negative
Actual positive	True positive	False negative
Actual negative	False positive	True negative

Table 3.1 Contingency table.

Precision and recall can be computed with these values. Recall quatifies the number of positives predicted of all positives in the dataset, as expressed in Equation 3.27. Precision quantifies the number of positives predicted that actually are positives of all positives detected [29], as shown in Equation 3.28.

$$Recall = \frac{True\ \ positives}{True\ \ positives + False\ \ negatives} \tag{3.27}$$

$$Precision = \frac{True\ \ positives}{True\ \ positives + False\ \ positives} \tag{3.28}$$

F-score is a measure that balances both precision and recall in one number. The traditional F-score, named F_1, is the harmonic mean of precision and recall, as seen in Equation 3.29. There is also a more general F-score, named F_β, which uses a positive real factor β to control the weights of recall and precision (β is chosen such that recall is considered β times as important as precision). Equation 3.30 is the expression of F_β.

$$F_1 = 2 \cdot \frac{precision \cdot recall}{precision + recall} \tag{3.29}$$

$$F_\beta = (1+\beta^2) \cdot \frac{precision \cdot recall}{(\beta^2 \cdot precision) + recall} \tag{3.30}$$

In this project, both scores are computed, F_1 and F_β with $\beta = 0.5$. In order to compare distances accuracy, valuing both precision and recall equally and considering precision two times as important as recall.

4 Results

This chapter presents the different results obtained. It is structured as follows: In Section 4.1, the synthetic scenarios considered for the analyses are described. Section 4.2, which is the most important, contains the comparison of the distances. Section 4.3 contains analyses on different parameters and their impact the results. Finally, in Section 4.4, the results from real scenarios and the discussion between the three distances are shown.

4.1 Synthetic simulation scenarios

To analyze and compare the three distances, five scenarios are considered, based on Sentinel-1A, Sentinel-1B, Sentinel-2A, Sentinel-2B and Swarm-C, whose orbital elements at the initial epoch of the propagations are shown in Table 4.1. It can be noticed that the orbits have a very small eccentricity, i.e. they are almost circular. Moreover, all of them are polar orbit because they have an inclination of about 90 degrees.

Orbital element	Sentinel-1A	Sentinel-1B	Sentinel-2A	Sentinel-2B	Swarm-C
n [deg/s]	0.0608	0.0608	0.0596	0.0596	0.0644
e [-]	1.3340E-04	1.3540E-04	1.1260E-04	1.1300E-04	2.2750E-04
M [deg]	279.8708	273.7215	267.1320	265.7235	277.3101
Ω [deg]	236.9954	236.8547	305.1974	115.8571	122.0350
ω [deg]	80.2640	86.4133	92.9988	94.4088	82.8415
i [deg]	98.1828	98.1828	98.5660	98.5725	87.3481

Table 4.1 Orbital element of the considered orbits at initial epoch.

On this study, the parameters of the propagator have been kept constant for all cases (varying only the orbit from one satellite to another), which take the values presented in Table 4.2. Real values are employed to compute radar data and estimated values are used to calculate the attributables. Different real and estimated values are used to take into account that in real cases, the parameters are not perfectly known. In subsequent analyses, these values are varied to study their impact the results.

Magnitud	Real Value	Estimated value
Mass	1000 Kg	1000 Kg
C_D	2.2	2
Surface	10 m^2	9.5 m^2
Atmospheric model	Harris Priester	Harris Priester

Table 4.2 Data for the propagation.

Then, the synthetic manoeuvre set maintains a constant acceleration of 10^{-3} m/s^2 and the main parameters that are varied are the following:

- Manoeuvre type: the type of impulse can be:
  - Tangential: the impulse is tangent to the orbit.
  - Out-of-plane: the impulse is orthogonal to the orbital plane.
  - Hybrid: the impulse contains significant components in both directions (in particular, it has been modeled with the tangetial component twice as high as the other).
- Manoeuvre intensity: this parameter is regulated through the duration of the impulse. It can be high (as the largest in the data set), medium (a typical intense manoeuvre in the data set) or low (small manoeuvres that will be challenging to detect). Depending on the manoeuvre type, the intensity takes different values:
  - Tangential:

	Low	Medium	High
t [s]	5	30	120
ΔV [m/s]	5×10^{-3}	3×10^{-2}	1.2×10^{-1}

  - Out-of-plane:

	Low	Medium	High
t [s]	500	1000	2000
ΔV [m/s]	0.5	1	2

  - Hybrid:

	Low	Medium	High
t [s]	50	250	1000
ΔV [m/s]	5×10^{-2}	0.25	1

- Manoeuvre location: distance between the manoeuvre and the next radar observation: 2h, 6h or 12h.

Combining these parameters, 27 scenarios with different manoeuvres are computed. On the other hand, for scenarios without manoeuvres, from 18 to 27 scenarios of this type are considered for each satellite (this number depends on the satellite). These scenarios are computed by propagating the initial orbits for 15 or 20 days, obtaining a scenario every time the satellite cross the radar mask. Sentinel-1A and Sentinel-2B are propagated for 20 days, because they are the satellites employed in all the analyses, in order to consider more scenarios without manoeuvres in those analyses with only two satellites. Swarm-C are also propagated for 20 days because this satellite cross fewer times the mask of the radar. Finally, the other two satellites, Sentinel-1B and Sentinel-2A, are propagated for 15 days. The number of the scenarios depends on how many times the satellites cross the radar mask in the propagation time. Altogether, these are all the scenarios for the satellites.

4.2 Analysis of the distances

The results of each satellite are presented in four different tables[1]. The first one, Table B.3, contains the percentages of true negatives, false positives, true positives and false negatives. The fact of having a small number of radar plots in a segment introduces a lot of false positives, so segments with fewer than 4 radar

[1] For the sake of a better understanding, the references to the tables correspond only to the first satellite, Sentinel-1A. The tables of the rest of the satellites follows the same structure.

plots data have not been taken into account. Moreover, with the aim of reducing false positives, in the case of the MD, if the probability of manoeuvre is less than 50%, it is assumed that there is no manoeuvre. In the case of the KLD, it has been considered that there is no manoeuvre if the probability is less than 40% and, using the BD, if it is less than 5%.

The rest of tables, which are presented in Appendix A, show the results of the different distances and the probability of manoeuvre. The second table, Table A.1, contains the results of the MD. It has been computed considering only range-range rate (column 1), elevation-azimuth (column 3) and all data (column 5) (with its respective probability value in the adjacent column on the right). The third table, Table A.2, contains the results of the KLD; it has been computed considering only range-range rate (column 1) and elevation-azimuth (column 3). The computation of the KLD with all data has not been possible because, as explained in Section 3.1, the KLD is not symmetric, therefore, it does not work equally in both directions. Considering range-range rate and elevation-azimuth, the distance makes sense using the attributable as the first factor but, with all data, inconsistencies arise in both cases, using the attributable as the first factor and using it as the second one. The fourth table, Table A.3, contains the results of the BD and its coefficient. They have been computed, as the MD, considering range-range rate (the distance appeares in column 1 and the coefficient in column 2), elevation-azimuth (columns 4 and 5) and all data (columns 7 and 8).

Five different satellites are employed to see whether the orbit impacts the results. Therefore, individual results have been studied for each satellite, as well as the total percentage of manoeuvres detected and false positives, in order to obtain generic conclusions.

Table B.1 contains the summary of the results for manoeuvre detection. They are presented for the three distances and for the diverse ways of computing them.

Analyzing the obtained results, several conclusions can be drawn:

- Mahalanobis distance:
  - Using only range-range rate is more sensitive.
  - Employing only elevation-azimuth, 42% fewer manoeuvre are detected.
  - Computing the distance with all data, approximately the same pencentage of manoeuvres as using only range-range rate is obtained, but it introduces false positives.
  - All high-intensity manoeuvres are detected.
  - Medium-intensity manoeuvres are mostly detected.
  - Low-intensity manoeuvres are in general detected in the out-of-plane and the hybrid cases. Some of them are detected in the tangential case, although not the majority of them.
- Kullback-Leibler divergence:
  - Using only elevation-azimuth it always results positive, so it is invalid. On the other hand, employing only range-range rate, good results are obtained, especially avoiding false positives.
  - All high-intensity manoeuvre are detected.
  - Medium-intensity manoeuvre are detected, except for the tangential case.
  - Low-intensity manoeuvres are in general not detected in the tangential case. In the out-of-plane and hybrid case, the manoeuvres are detected in 40% of the cases.
- Bhattacharyya distance:
  - Computing the BD with range-range rate presents excellent results.
  - Using only elevation-azimuth and all data almost always detects manoeuvre, thus, both options are useless.
  - All high-intensity manoeuvre are detected.
  - Medium-intensity manoeuvre are in general detected.
  - Low-intensity manoeuvre are detected, except for the tangential case.

Common conclusion of the three distances is that the time between the manoeuvre and the next radar measurement does not seem to affect these results. This is general for all the scenarios, as well as the fact that the distances computing using only range-range rate are more sensitive, and those calculated using elevation and azimuth introduce a great number of false positives.

Comparing the results of the three distances, some conclusions can be drawn. The distance which detects more manoeuvres is the MD, with 87% of true positives. Nevertheless, the BD also detects a great number of them, 83%. Regarding false positives, the KLD and the BD are the distances which detect more scenarios without manoeuvres, 94% and 92%, respectively.

Hence, the MD is the best option for detection of manoeuvres. On the other hand, the KLD offers the greatest results avoiding false positives. However, the results of the BD are very close to these maxima in both targets. Thus, we could conclude that the best choice for the detection of manoeuvres is the BD.

	MD(R, R_r)	KLD (R,R_r)	BD (R, R_r)	MD (el, az)	KLD (el, az)	BD (el, az)	MD (All)	BD (All)
% True negatives	81%	94%	92%	79%	0%	18%	76%	0%
% False positives	19%	6%	8%	21%	100%	82%	24%	100%
% True positives	87%	66%	83%	45%	100%	70%	83%	100%
% False negatives	13%	34%	17%	55%	0%	30%	17%	0%

Table 4.3 Results of all the satellites for 247 scenarios (102 without manoeuvre and 135 with manoeuvre).

Finally, the F-score of each distance computed using range-range rate has been calculated to support this conclusion. Table B.2 presents the values of precision, recall, F_1 and F_β, with β taking the value 0.5. The F_1 is the harmonic mean of the precision and recall, and F_β with the value 0.5 weighs recall lower than precision. In view of these results, the hypothesis raised before is verified. The BD is the best distance for the detection of manoeuvres. Furthermore, after this one, the MD offers the best results whether precision and recall are equally important. However, if precision is considered more important than recall, the KLD is the best option after the BD.

	MD(R, R_r)	KLD (R,R_r)	BD (R, R_r)
Precision	0.824	0.918	0.914
Recall	0.874	0.659	0.830
F_1	0.848	0.767	0.870
F_β ($\beta = 0.5$)	0.834	0.851	0.895

Table 4.4 Precision, recall, F_1 and F_β ($\beta = 0.5$).

Sentinel-1A Scenario

The Sentinel-1A scenario with manoeuvre spans from 00:00:00 18/08/2020 to 00:00:00 22/08/2020, and the manoeuvre is placed with respect to 18:25:00 20/08/2020. On the other hand, the Sentinel-1A scenario without manoeuvre spans from 00:00:00 18/08/2020 to 00:00:00 07/09/2020, in order to simulate a greater number of segments without manoeuvre. Table B.3 presents the percentages of the results, Table A.1 contains the results from the MD, Table A.2 those from the KLD and Table A.3 shows the BD values and their probabilities.

Analyzing the obtained results for the satellite Sentinel-1A, several conclusions can be drawn:

- The three distances detect a great number of manoeuvres and hardly any false positives are obtained.
- All high-intensity manoeuvres are detected and medium-intensity manoeuvres are also in general detected.
- Low-intensity manoeuvres are detected in the out-of-plane and hybrid cases; in the tangential cases are in general not detected.

- The distance to the radar measurement does not seem to affect these results.

	MD(R, R_r)	KLD (R,R_r)	BD (R, R_r)	MD (el, az)	KLD (el, az)	BD (el, az)	MD (All)	BD (All)
% True negatives	95%	91%	100%	82%	0%	23%	82%	0%
% False positives	5%	9%	0%	18%	100%	77%	18%	100%
% True positives	93%	85%	89%	48%	100%	63%	93%	100%
% False negatives	7%	15%	11%	52%	0%	37%	7%	0%

Table 4.5 Results of satellite Sentinel-1A for 49 scenarios (22 without manoeuvre and 27 with manoeuvre).

Sentinel-1B Scenario

The Sentinel-1B scenario with manoeuvre spans from 00:00:00 18/08/2020 to 00:00:00 22/08/2020. The manoeuvre is placed with respect to 17:35:00 20/08/2020. The scenario without manoeuvre spans from 00:00:00 18/08/2020 to 00:00:00 02/09/2020. Table B.4 presents the percentages of the results, Table A.4 contains the results from the MD, those from the KLD are shown on Table A.5 and those from the BD on Table A.6.

In view of the obtained results for the satellite Sentinel-1A, several conclusions can be drawn:

- The MD and the BD detect a great number of manoeuvres, 25% more than the KLD.
- The MD and the KLD introduce more false positive than the BD.
- All high-intensity manoeuvres are detected.
- Medium-intensity manoeuvres are in general detected with all the distances, except in the tangential case with the KLD.
- Low-intensity manoeuvres are in general detected in the out-of-plane and the hybrid cases; in the tangential case some of them are detected with the MD and the BD .

	MD(R, R_r)	KLD (R,R_r)	BD (R, R_r)	MD (el, az)	KLD (el, az)	BD (el, az)	MD (All)	BD (All)
% True negatives	82%	82%	94%	82%	0%	12%	65%	0%
% False positives	18%	18%	6%	18%	100%	88%	35%	100%
% True positives	93%	70%	96%	44%	100%	74%	81%	100%
% False negatives	7%	30%	4%	56%	0%	26%	19%	0%

Table 4.6 Results of satellite Sentinel-1B for 44 scenarios (17 without manoeuvre and 27 with manoeuvre).

Sentinel-2A Scenario

The Sentinel-2A scenario with manoeuvre spans from 00:00:00 19/08/2020 to 00:00:00 23/08/2020. The manoeuvre is placed with respect to 11:10:00 21/08/2020. The scenario without manoeuvre spans from 00:00:00 19/08/2020 to 00:00:00 04/09/2020. Table B.5 presents the percentages of the results, Table A.7 contains the results from the MD, Table A.8 presents those from the KLD and Table A.9 shows the BD values and their probabilities.

Analyzing the obtained results, several conclusions can be extracted:

- The BD and the MD detect a great percentage of manoeuvres. Nevertheless, the KLD just detects 67% of them.
- Both the KLD and the BD detect correctly all the scenarios without manoeuvre.
- All high-intensity manoeuvres are detected.
- Medium-intensity manoeuvres are all detected in the out-of-plane and the hybrid cases; but in the tangential case with the KLD they are not detected.
- Low-intensity manoeuvres in the tangential case are not detected with any of the distances, and the KLD in general does not detect any low manoeuvre.

	MD(R, R_r)	KLD (R,R_r)	BD (R, R_r)	MD (el, az)	KLD (el, az)	BD (el, az)	MD (All)	BD (All)
% True negatives	89%	100%	100%	89%	0%	5%	84%	0%
% False positives	11%	0%	0%	11%	100%	95%	16%	100%
% True positives	89%	67%	89%	41%	100%	89%	89%	100%
% False negatives	11%	33%	11%	59%	0%	11%	11%	0%

Table 4.7 Results of satellite Sentinel-2A for 46 scenarios (19 without manoeuvre and 27 with manoeuvre).

Sentinel-2B Scenario

The Sentinel-2B scenario with manoeuvre spans from 00:00:00 09/02/2020 to 00:00:00 13/02/2020. The manoeuvre is placed with respect to 11:20:00 11/02/2020. The Sentinel-2B scenario without manoeuvre extents from 00:00:00 09/02/2020 to 00:00:00 29/02/2020. Table 4.8 presents the percentages of the results, Table A.10 contains the results from the MD, Table A.11 those from the KLD and Table A.12 shows the BD values and their probabilities.

Analyzing the obtained results, several conclusions can be drawn:

- In the Sentinel-2B scenario, a lower percentage of manoeuvres is obtained, and also a larger number of false positives is avoided.
- The KLD detects far fewer manoeuvres.
- In this case, the distance which offers the best results is the MD.
- High-intensity manoeuvres are in general detected.
- Medium-intensity manoeuvres in the hybrid case are detected with the three distances. In the tangential and the out-of-plane cases, they are detected with the MD and with the BD but with the KLD are in general not detected.
- Low-intensity manoeuvres are in general not detected, except for the hybrid case with the MD and the BD.

	MD(R, R_r)	KLD (R,R_r)	BD (R, R_r)	MD (el, az)	KLD (el, az)	BD (el, az)	MD (All)	BD (All)
% True negatives	92%	96%	96%	84%	0%	16%	92%	0%
% False positives	8%	4%	4%	16%	100%	84%	8%	100%
% True positives	74%	44%	63%	44%	100%	100%	70%	100%
% False negatives	26%	56%	37%	56%	0%	0%	30%	0%

Table 4.8 Results of satellite Sentinel-2B for 52 scenarios (25 without manoeuvre and 27 with manoeuvre).

Swarm-C Scenario

The Swarm-C scenario with manoeuvre spans from 00:00:00 14/07/2020 to 00:00:00 20/07/2020. The manoeuvre is placed with respect to 12:30:00 17/07/2020. The scenario without manoeuvre extents from 00:00:00 14/07/2020 to 00:00:00 03/08/2020. Table 4.9 presents the percentages of the results, Table A.13 contains the results from the MD, Table A.14 shows those from the KLD and the results from the BD are presented in Table A.15.

Analyzing the obtained results, several conclusions can be drawn:

- In Swarm-C scenario, the MD introduces a high percentage of false positives. The BD also introduces a considerable number of false positives. This is because these scenarios present a number of plots between 5 and 7, while those of the rest of satellites have around 10 plots.
- All high-intensity manoeuvre are detected.
- Medium-intensity manoeuvre are detected in the hybrid and the out-of-plane cases. In the tangential case they are detected just with the MD.
- Low–intensity manoeuvres detection success varies, with all of them being detected in the out-of-plane case and none in the tangential case.

	MD(R, R_r)	KLD (R,R_r)	BD (R, R_r)	MD (el, az)	KLD (el, az)	BD (el, az)	MD (All)	BD (All)
% True negatives	42%	100%	68%	58%	0%	32%	53%	0%
% False positives	58%	0%	32%	42%	100%	68%	47%	100%
% True positives	89%	63%	78%	48%	100%	26%	81%	100%
% False negatives	11%	37%	22%	52%	0%	74%	19%	0%

Table 4.9 Results of satellite Swarm-C for 46 scenarios (19 without manoeuvre and 27 with manoeuvre).

4.2.1 Small manoeuvres

After the previous analysis, the manoeuvre intensity has been reduced to check how small these manoeuvres can be and remain detectable for each distance. As it has been shown by the first results, the detection depends on the orbit, so it has been decided to carry out the five scenarios based on Sentinel-1A, Sentinel-1B, Sentinel-2A, Sentinel-2B and Swarm-C. Since the intensity depends on manoeuvre type, it has taken the following values for each type:

- Tangential:

	Low	Medium	High
t [s]	0.5	1	2.5
ΔV [m/s]	5×10^{-4}	10^{-3}	2.5×10^{-3}

- Out-of-plane:

	Low	Medium	High
t [s]	10	50	250
ΔV [m/s]	10^{-2}	5×10^{-2}	0.25

- Hybrid:

	Low	Medium	High
t [s]	1	5	10
ΔV [m/s]	10^{-3}	5×10^{-3}	10^{-2}

Combining these values with the locations aforementioned, 27 scenarios have been computed with different manoeuvres, all of them smaller than the manoeuvres used in the first analysis.

Tables B.8, B.9 and B.10 show the percentages of detecting manoeuvres depending on the intensity and the distance (it is shown the results for the intensities mentioned above and for the low intensity of the previous analysis). Each table presents the results of a manoeuvre type: tangential, out-of-plane and hybrid, respectively.

As it has been found that the distances computed with elevation and azimuth introduce a large number of false positives, the study is going to be focused on the results of the distances computed using only range-range rate.

Analyzing the obtained results, it can be claimed that the distance capable of detecting smaller manoeuvres is the MD, followed by the BD.

In the tangential case, the manoeuvres of 5 s, studied in Section 4.2, are undetectable with the KLD and the BD; and the MD detects only 20% of them. The results show that the MD detects also 20% of tangential manoeuvres of 1 s of duration. However, the manoeuvres detected are the three of the Swarm-C scenario, in which the MD presents 58% of false positives. Noticing also that it only detects 7% of the manoeuvres of 2.5 s, it cannot be concluded that the MD is able to detects any manoeuvre smaller than 5 s.

In the out-of-plane case, the manoeuvres of 500 s are generally detected with the three distances, with better results using the MD or the BD. The MD detects out-of-plane manoeuvers up to a duration of 250 s. Using the KLD or the BD approximately 50% of them are detected. For lower intensity this type of manoeuvre is practically undetectable.

Finally, in the hybrid case, the manoeuvres of 50 s of duration are almost all detected with the MD and the BD. If the intensity is reduced, they are no longer detectable with the BD, and the MD detects just 50% of them when its duration is 10 s.

In conclusion, it can be claimed that the tangential manoeuvres are detected when its duration is higher than 30 s with the MD and the BD. In the out-of-plane case, manoeuvres larger than 250 s are detected using the MD. In the hybrid case, all the manoeuvres higher than 50 s are detected employing the MD and the BD. In addition, 50% of the manoeuvres of 10 s are detected using the MD.

Tangent	MD(R, R_r)	KLD (R,R_r)	BD (R, R_r)	MD (el, az)	KLD (el, az)	BD (el, az)	MD (All)	BD (All)
5 s	20%	0%	0%	13%	100%	73%	7%	100%
2.5 s	7%	0%	0%	27%	100%	87%	20%	100%
1 s	20%	0%	0%	27%	100%	80%	20%	100%
0.5 s	0%	0%	0%	27%	100%	80%	7%	100%

Table 4.10 Results for tangent manoeuvre.

Out-of-plane	MD(R, R_r)	KLD (R,R_r)	BD (R, R_r)	MD (el, az)	KLD (el, az)	BD (el, az)	MD (All)	BD (All)
500 s	80%	73%	100%	20%	100%	80%	80%	100%
250 s	87%	47%	60%	33%	100%	87%	73%	100%
50 s	20%	0%	20%	27%	100%	87%	13%	100%
10 s	13%	0%	0%	27%	100%	80%	20%	100%

Table 4.11 Results for out-of-plane manoeuvre.

Hybrid	MD(R, R_r)	KLD (R,R_r)	BD (R, R_r)	MD (el, az)	KLD (el, az)	BD (el, az)	MD (All)	BD (All)
50 s	100%	40%	93%	33%	100%	80%	87%	100%
10 s	47%	0%	20%	27%	100%	87%	40%	100%
5 s	20%	0%	7%	27%	100%	80%	27%	100%
1 s	7%	0%	0%	13%	100%	80%	7%	100%

Table 4.12 Results for hybrid manoeuvre).

4.3 Analyses of the impact of different parameters

In this section, several results are presented: the analyses of the influence of propagation parameters (mass, ballistic coefficient and atmospheric model), Taylor order and the computation of the covariance matrix on manouevres detection.

To study these impacts, two scenarios are considered, based on Sentinel-1A and Sentinel-2B (the orbit impacts the results). These scenarios have been computed as explained in Section 4.1. Therefore, 27 scenarios with different manoeuvres have been calculated for each satellite.

For scenarios without manoeuvre, in the case of the Sentinel-1A, the scenario spans from 00:00:00 18/08/2020 to 00:00:00 07/09/2020, so 25 different segments without manoeuvres are computed. In the case of Sentinel-2B, the scenario spans from 00:00:00 09/02/2020 to 00:00:00 29/09/2020, obtaining 27 segments. As the scenarios with fewer plots than 4 have been eliminated, the analysis has been conducted on 101 scenarios, 47 without manoeuvre and 54 with manoeuvre.

In these analyses, only the distances computed using range-range rate have been employed, given the poor results of including elevation and azimuth.

In the first three subsections, the influence of the propagation parameters is studied. In the fourth subsection, the Taylor order, and in the last one a different method for the computation of the covariance matrix.

4.3.1 Mass

To study the impact of the satellite mass on the results, it has been considered that this parameter is well-known, so the real and the estimated values are identical. Five mass values have been taken between 1000 Kg and 3000 Kg, in intervals of 500 Kg. The distances and their probabilities for the satellite mass equal to 1000 Kg have been presented on Section 4.2 and the results for the other mass values are shown below on this section.

The tables below show the percentages of true negatives, false positives, true positives and false negatives for each value of the satellite mass. Table 4.13 presents the results using the MD, Table 4.14 the results obtained with the KLD and Table 4.15 with BD.

In view of the obtained results, it is concluded that no direct relationship can be drawn between the mass of the satellite and the performance of the algorithm. The percentages vary slightly from one mass value to another but the biggest different between two values is 9%. Taking into account that the algorithm works with statistical variables and in the generation of scenarios a random error is introduced, these differences are not relevant. Furthermore, these variations do not follow any pattern.

MD (R,Rr)	% True negatives	% False positives	% True positives	% False negatives
1000 Kg	94%	6%	83%	17%
1500 Kg	94%	6%	83%	17%
2000 Kg	85%	15%	91%	9%
2500 Kg	89%	11%	83%	17%
3000 Kg	91%	9%	85%	15%

Table 4.13 Results for the MD computed using only range-range rate.

KLD (R,Rr)	% True negatives	% False positives	% True positives	% False negatives
1000 Kg	94%	6%	65%	35%
1500 Kg	98%	2%	69%	31%
2000 Kg	96%	4%	69%	31%
2500 Kg	94%	6%	65%	35%
3000 Kg	94%	6%	65%	35%

Table 4.14 Results for the KLD computed using only range-range rate.

BD (R,Rr)	% True negatives	% False positives	% True positives	% False negatives
1000 Kg	98%	2%	76%	24%
1500 Kg	100%	0%	74%	26%
2000 Kg	96%	4%	78%	22%
2500 Kg	98%	2%	78%	22%
3000 Kg	98%	2%	80%	20%

Table 4.15 Results for the BD computed using only range-range rate.

4.3.2 Ballistic coefficient

This study analyzes the impact of the ballistic coefficient on the results. In this case, it has been considered that the estimated value has an error of 10%. Five values have been taken, from 1 to 3, with an interval of 0.5. Table 4.16 shows the estimated and the real value of the ballistic coefficient on the different cases.

Estimated value	Real value
1	1.1
1.5	1.65
2	2.2
2.5	2.75
3	3.3

Table 4.16 Ballistic coefficient values.

The tables below show the results obtained with the different distances. Table 4.17 presents the MD results, Table 4.18 the results obtained with the KLD and Table 4.19 with the BD. The percentages of true negatives, false positives, true positives and false negatives for each value of the ballistic coefficient (C_D) are contained in these tables. The distances and the probabilities for C_D equal to 2 are presented in Section 4.2, and below, in this section, the results for the rest of the values are shown.

As the mass of the satellite, the value of the ballistic coefficient does not have an impact on the results. The percentage variation from one value to another is very small. Taking into account the random error introduced on the scenarios, these small differences are irrelevant. Thus, it can be concluded that the performance of the algorithm is independent of the ballistic coefficient.

MD (R,Rr)	% True negatives	% False positives	% True positives	% False negatives
1	96%	4%	89%	11%
1.5	87%	13%	89%	11%
2	94%	6%	83%	17%
2.5	87%	13%	85%	15%
3	96%	4%	89%	11%

Table 4.17 Results for the MD computed using only range-range rate.

KLD (R,Rr)	% True negatives	% False positives	% True positives	% False negatives
1	94%	6%	67%	33%
1.5	98%	2%	69%	31%
2	94%	6%	65%	35%
2.5	89%	11%	70%	30%
3	96%	4%	70%	30%

Table 4.18 Results for the KLD computed using only range-range rate.

BD (R,Rr)	% True negatives	% False positives	% True positives	% False negatives
1	100%	0%	74%	26%
1.5	98%	2%	80%	20%
2	98%	2%	76%	24%
2.5	98%	2%	76%	24%
3	100%	0%	80%	20%

Table 4.19 Results for the BD computed using only range-range rate.

4.3.3 Atmospheric model

In the previous studies, the Harris Priester atmospheric model is used for the propagation. In this section, the results with the Marshall model and the comparison between both models is presented.

The results from both models are presented in Table 4.17, Table 4.18 and Table 4.19, using the MD, the KLD and the BD, respectively.

In view of the similar results obtained, it can be claimed that both atmospheric models work well. Moreover, the two probabilities of manoeuvre for each scenario can be compared (the probabilities computed with Marshall model are presented in this section, and those with Harris Priester model in Section 4.2). It is interesting to note that in those scenarios with manoeuvre, the probability computed with both models are usually very similar. However, false positives appear in different scenarios. This means that, when computed with the model where the false positive appears, the probability of manoeuvre occurrence is large, while using the other atmospheric model this probability is 0%. Therefore, with the aim of avoiding false positives, both results could be combined, taking the probability of 0% if one of them is 0%.

MD (R,Rr)	% True negatives	% False positives	% True positives	% False negatives
Marshall	94%	6%	87%	13%
Harris Priester	94%	6%	83%	17%

Table 4.20 Results for the MD computed using only range-range rate.

KLD (R,Rr)	% True negatives	% False positives	% True positives	% False negatives
Marshall	96%	4%	67%	33%
Harris Priester	94%	6%	65%	35%

Table 4.21 Results for the KLD computed using only range-range rate.

BD (R,Rr)	% True negatives	% False positives	% True positives	% False negatives
Marshall	98%	2%	78%	22%
Harris Priester	98%	2%	76%	24%

Table 4.22 Results for the BD computed using only range-range rate.

These three parameters, the mass, the ballistic coefficient and the atmospheric model just affect the atmospheric drag perturbation. Thus, it is not surprising that they have a similar influence.

4.3.4 Taylor order

To compute the covariance matrix Taylor differential algebra have been employed. Thus, it has been necessary to fix the order of Taylor series. In this section, the Taylor order impact on the result is studied.

On the previous analyses this order has been set at 2. The results for this value are presented in Section 4.2. In this section, the results for Taylor order 3 and 4 are shown.

The percentages of true negatives, false positives, true positives and false negatives for the three different Taylor orders are exposed on Table 4.23 (for the MD), Table 4.24 (for the KLD) and Table 4.25 (for the BD). In this analysis, the results are not the unique factor to take into account, also the computation time is an important component, since it increases considerably as the order gets higher. Applying the algorithm with Taylor order 3 takes almost three times longer than with Taylor second order, and with Taylor order 4 takes more than four times longer than with Taylor order 3.

Observing the obtained results, it is noticeable that increasing the Taylor order does not improve the results. As it can be seen on Table 4.23 and Table 4.25, the results using the MD and the BD are exactly the same for the three orders. In the case of using the KLD, there is a difference between the results with order 2 and the results with order 3 and 4 in the percentage of false positives. In particular, using Taylor order 2 decreases the percentage of false positives. Besides, Taylor order 2 means less computation time, thus this value is the best choice.

Regarding the distance and probability values, it can be noticed that the distances (and consequently the probabilities) calculated with Taylor order 3 and 4 are practically equal. These values can also be compared with the ones obtained with Taylor order 2. In the case of scenarios with manoeuvre, the distances are almost identical, and so is the probability. On the other hand, in scenarios without manoeuvre, the distances computed with Taylor order 2, and Taylor order 3 and 4 vary a little more. In general, those distances computed with Taylor order 2 are a bit smaller, and that is the reason why the percentage of false positives using the KLD is smaller employing Taylor order 2.

MD (R,Rr)	% True negatives	% False positives	% True positives	% False negatives
Taylor 2	94%	6%	83%	17%
Taylor 3	94%	6%	83%	17%
Taylor 4	94%	6%	83%	17%

Table 4.23 Results for the MD computed using only range-range rate.

KLD (R,Rr)	% True negatives	% False positives	% True positives	% False negatives
Taylor 2	94%	6%	65%	35%
Taylor 3	87%	13%	65%	35%
Taylor 4	87%	13%	65%	35%

Table 4.24 Results for the KLD computed using only range-range rate.

BD (R,Rr)	% True negatives	% False positives	% True positives	% False negatives
Taylor 2	98%	2%	76%	24%
Taylor 3	98%	2%	76%	24%
Taylor 4	98%	2%	76%	24%

Table 4.25 Results for the BD computed using only range-range rate.

4.3.5 Propagation of uncertainty

In this section, the results obtained propagating uncertainty with the two different methods are compared (Taylor differential algebra using second order and montecarlo with 50000 samples, and unscented transform). As in this analysis none of the propagation parameters change, the algorithm is applied to the same scenarios for both cases.

The results obtained with both procedures are presented in Table 4.26 (using the MD), Table 4.27 (KLD) and Table 4.28 (BD).

In view of the obtained results, it can be noticed that, using the MD, the percentages for both false and true positives, are the same for both procedures. Furthermore, in this case, unlike with the atmospheric models, false positives appear in the same scenarios for both methods.

Using the KLD the percentage varies slightly. The percentage of false positives is smaller using the Taylor method. However, using the unscented transform method, the percentage of manoeuvre detection is 5% higher than Taylor's.

In the case of the BD, the percentage of manoeuvre detection is equal with both methods. Regarding false positives, Taylor results are 2% better. However, it is important to take into account that these differences, even noticeable, are still small.

Finally, the unscented transform instead of computing the taylor coefficients and launching the montecarlo, does 13 propagations and it reduces the computation time by approximately 35%.

MD (R,Rr)	% True negatives	% False positives	% True positives	% False negatives
Taylor and Monte Carlo	94%	6%	83%	17%
UT	94%	6%	83%	17%

Table 4.26 Results for the MD computed using only range-range rate.

KLD (R,Rr)	% True negatives	% False positives	% True positives	% False negatives
Taylor and Monte Carlo	94%	6%	65%	35%
UT	91%	9%	70%	30%

Table 4.27 Results for the KLD computed using only range-range rate.

BD (R,Rr)	% True negatives	% False positives	% True positives	% False negatives
Taylor and Monte Carlo	98%	2%	76%	24%
UT	96%	4%	76%	24%

Table 4.28 Results for the BD computed using only range-range rate.

4.4 Analysis on real scenarios

In this section the analysis is conducted on real scenarios. Fifteen scenarios with different number of segments have been used. Tables A.55 to A.69 present the results of the different scenarios. It is shown the number of manoeuvres in each segment, the statistical distances computed using only range-range rate and the probability of manoeuvre occurrence. The percentages of false positives and detection manoeuvre for each distance is displayed on Table 4.29.

In view of the obtained results, several conclusions can be drawn. The KLD does not detect any manoeuvre. The values that the KLD takes in these scenarios are much lower than those that it takes in synthetic scenarios. It is important to remember that the distribution of this distance is unknown in the literature and it was computed experimentally with the synthetic data. Thus, this distribution is not working with real data.

Using the MD and the BD, the detection of manoeuvres has also decreased compared to synthetic scenarios. Using the BD, 67% of manoeuvres are detected. Using the MD, the percentage of detection is 42%, half the percentage in the synthetic scenarios. However, the MD presents fewer false positives than in synthetic scenarios.

Regarding the results of these two distances in relation to the number of plots and the propagation duration, several conclusions can be drawn. The duration of the propagation has an impact on the MD results in scenarios with manoeuvre. The percentage of false negatives increases to 77% in scenarios where the duration is more than 1 day. On the other hand, the percentage of false negatives with the BD remains around 30% even though the duration is more than 1 day. Nevertheless, the duration of the propagation impacts the results of the BD in scenarios without manoeuvre. The percentage of false positive increases to 51% in these cases. This does not affect the results of false positives of the MD.

Moreover, the number of plots impacts the percentage of false positives of the MD. Its percentage of false positives increases to 33% in scenarios with less than 10 plots. In the BD case, the percentage of false positives remains around 20% even though the number of plots is less than 10.

The combination of the results of both distances could be interesting. Since they depend differently on both the number of plots and the duration of the propagation. For instance, in case of long propagations the MD increases the number of negatives and the BD increases the number of positives. Thus, a combination of the results of both distances in this case would be interesting to be studied.

Considering only the detection of manoeuvres, the BD is the distance that offers the best result. However, with respect to false positives, the MD has the smallest percentage, hence, the best results.

	MD (R, Rr)	KLD (R, Rr)	BD (R, Rr)
% True negatives	88%	99%	78%
% False positives	12%	1%	22%
% True positives	42%	0%	67%
% False negatives	58%	100%	33%

Table 4.29 Results of 162 real segments (138 without manoeuvre and 24 with manoeuvre).

Finally, regarding the values of the F_1 and F_β, with $\beta = 0.5$, which are presented on Table B.27, conclusions about both objectives together can be drawn. The BD values are higher in both measures, F_1 and F_β. Thus, this distance is also the best choice for manoeuvres detection with real data.

	MD(R, R_r)	KLD (R,R_r)	BD (R, R_r)
Precision	0.772	0	0.754
Recall	0.417	0	0.667
F_1	0.541	-	0.708
F_β ($\beta = 0.5$)	0.659	-	0.735

Table 4.30 Precision, recall, F_1 and F_β ($\beta = 0.5$).

5 Conclusions and future works

As mentioned in Chapter 1, the interest of this project lies in the increasing population of space objects in Earth orbit. A great amount of this population is space debris, specially dangerous in Low Earth Orbits, where they travel at high speed. All the operating satellites may perform manoeuvres occasionally for diverse purposes, or change their orbits due to perturbances. This makes the satellite operation activities and the space situational awareness more difficult. These are the main reasons why methods for the detection of manoeuvres are being developed.

The project focus on the detection of manoeuvres of known objects in Low Earth Orbits using radar data. For this purpose, the project is based on the algorithm developed in [3], whose main idea is to study the correlation between the propagation of the satellite orbit and radar data of the next track. The concepts developed along the project have been those necessary to understand two things; first, the way that the algorithm operates and second, the changes that haven been implemented with the aim of trying to improve the detection of manoeuvres.

The first analyses (done to compare the distances and study the impact of the parameters on the results) have been performed with synthetic data. Then, the algorithm has been applied to real scenarios. Here, the sensitivity of the algorithm with the different distances in real cases has been analyzed.

Moreover, all the three distances behave well in synthetic scenarios. All of them result in a high value of F-score, especially the BD, which turns out to have also the highest value with real scenarios. The algorithm performance is greatly reduced in real cases. The KLD is useless in those ones because the algorithm cannot detect any manoeuvre in real cases when this metric is used.

In addition, while the orbit seems to have a great effect on the results, the propagation parameters do not seem to impact the results. The algorithm detects more or less the same percentage of manoeuvres regardless the mass or the ballistic coefficient of the satellite.

Another important aspect of the algorithm, that has been explained throughout the project, is the propagation of uncertainty. This do not impact only the results, but also the computation time of the algorithm. The Taylor order increase considerably the computation time, nevertheless, it does not increase the number of manoeuvres detected, so that choosing second order is the best option. On the other hand, to use the unscented transform instead of Taylor differential algebra (with second Taylor order) and montecarlo (with 50000 samples) reduces the computation time by 35%, without detriment on the results.

5.1 Future work

In this section, some suggestions for future works which would be interesting to continue with are presented.

The performance and effectiveness of the algorithm is not only assessed by the manoeuvres detected, but also by the number of false positives; being the last one even more important. In the project, some false positives have been eliminated by filtering with the number of radar plots, because the fact of having too few radar plots in a segment introduces a lot of false positives. Some other filters could be studied. It was mentioned in the analysis of the atmospheric model that false positives appear in different scenarios comparing one model to another. Therefore, the combination of results with both models could be studied with the aim of avoiding false positives.

As well as the combination of the atmospheric models, it would be interesting to study the combination of the results obtained with two different distances. It was seen in the analysis of real scenarios that the results of the MD and the BD depend differently on the number of plots and the duration of the propagation. Thus, the study of the results of these two distances together could lead to a reduction of false positives or increase the number of manoeuvres detected.

The distribution of the KLD has been computed experimentally because it is unknown in the literature. The fit has been done with synthetic data, but this does not work well for real data. Thus, this fit could be improved by studying the data sample and introducing more filters to exclude some data, or even using real data. In that way, the results of the algorithm with the KLD on real cases could be improved.

Finally, it is important to mention that the algorithm studied in this project just detects manoeuvres, but it does not characterize them. Thus, the satellite orbit after the manoeuvre is unknown. It would be interesting to combine this algorithm with some manoeuvre reconstruction method, in order to know the satellite orbital elements after the manoeuvre.

Appendix A
Distances and probabilities tables

This appendix shows the tables that contain the distances and their probabilities computed in the different analyses.

A.1 Analysis of the distances

In this section, as it is explained before, the different distances and the probabilities of manoeuvre of each satellite are presented in three tables [1]. The first table, Table A.1, contains the results of the MD. The second table, Table A.2, contains the results of the KLD. The third table, Table A.3, contains the results of the BD and its coefficient. The tables show the distances (and the coefficient in the BD case) computed with the different attributables and its probability, which is in the adjacent column on the right. In addition, they also present the number of plots of each segment.

A.1.1 Sentinel-1A Scenario

Scenario	MD(R,Rr)	PR	MD(el,az)	PR	MD(All)	PR	plots
Sentinel-1A No manoeuvre	1.26E-01	0%	2.35E+00	87%	2.35E+00	53%	9
Sentinel-1A No manoeuvre	1.28E+00	12%	3.79E-01	0%	1.34E+00	0%	10
Sentinel-1A No manoeuvre	6.73E-01	0%	6.57E-01	0%	9.46E-01	0%	9
Sentinel-1A No manoeuvre	1.43E+00	28%	8.35E-01	0%	1.66E+00	0%	9
Sentinel-1A No manoeuvre	1.39E+00	23%	1.05E+00	0%	1.74E+00	0%	10
Sentinel-1A No manoeuvre	1.26E-01	0%	2.85E+00	97%	2.86E+00	83%	8
Sentinel-1A No manoeuvre	1.60E+01	100%	1.59E+00	44%	1.61E+01	100%	2
Sentinel-1A No manoeuvre	4.73E-01	0%	1.21E+00	4%	1.32E+00	0%	9
Sentinel-1A No manoeuvre	8.56E-01	0%	1.90E+00	67%	2.10E+00	29%	8
Sentinel-1A No manoeuvre	1.62E+01	100%	8.54E-01	0%	1.62E+01	100%	2
Sentinel-1A No manoeuvre	8.91E-01	0%	1.29E+00	13%	1.57E+00	0%	9
Sentinel-1A No manoeuvre	1.62E+00	46%	2.09E+00	77%	2.65E+00	73%	10
Sentinel-1A No manoeuvre	1.06E+00	0%	1.18E+00	0%	1.76E+00	0%	9
Sentinel-1A No manoeuvre	1.41E-01	0%	6.60E-01	0%	6.76E-01	0%	9
Sentinel-1A No manoeuvre	8.24E-01	0%	1.51E+00	36%	1.78E+00	0%	9
Sentinel-1A No manoeuvre	7.43E-01	0%	9.02E-01	0%	1.18E+00	0%	9
Sentinel-1A No manoeuvre	1.22E+00	5%	1.52E+00	37%	2.18E+00	37%	9
Sentinel-1A No manoeuvre	1.44E-01	0%	1.06E+00	0%	1.07E+00	0%	10
Sentinel-1A No manoeuvre	2.15E-01	0%	9.92E-01	0%	1.14E+00	0%	10
Sentinel-1A No manoeuvre	4.28E-01	0%	9.90E-01	0%	1.08E+00	0%	10
Sentinel-1A No manoeuvre	8.90E-01	0%	1.68E+00	51%	1.90E+00	8%	11
Sentinel-1A No manoeuvre	6.00E-01	0%	1.43E+00	28%	1.56E+00	0%	9
Sentinel-1A No manoeuvre	1.42E+01	100%	9.66E-01	0%	1.42E+01	100%	2
Sentinel-1A No manoeuvre	6.47E-01	0%	2.11E+00	79%	2.21E+00	40%	9

[1] For the sake of a better understanding, the references to the tables correspond only to the first satellite, Sentinel-1A. The tables of the rest of the satellites follows the same order.

Scenario	MD(R,Rr)	PR	MD(el,az)	PR	MD(All)	PR	plots
Sentinel-1A No manoeuvre	2.13E+00	79%	2.20E+00	82%	3.06E+00	90%	9
Sentinel-1A Tangential Low -2	1.71E+00	54%	2.44E+00	90%	2.98E+00	87%	9
Sentinel-1A Tangential Low -6	2.60E-01	0%	4.40E-01	0%	7.17E-01	0%	9
Sentinel-1A Tangential Low -12	9.05E-01	0%	1.44E-01	0%	9.68E-01	0%	9
Sentinel-1A Tangential Medium -2	2.94E+00	97%	1.48E+00	33%	3.57E+00	97%	9
Sentinel-1A Tangential Medium -6	7.54E+00	100%	1.57E+00	42%	7.62E+00	100%	9
Sentinel-1A Tangential Medium -12	6.85E+00	100%	2.62E+00	94%	7.11E+00	100%	9
Sentinel-1A Tangential High -2	1.50E+01	100%	2.71E-01	0%	1.50E+01	100%	9
Sentinel-1A Tangential High -6	3.21E+01	100%	2.69E+00	95%	3.21E+01	100%	9
Sentinel-1A Tangential High -12	3.53E+01	100%	4.44E+00	100%	3.53E+01	100%	9
Sentinel-1A Out-of-plane Low -2	3.05E+01	100%	1.47E+00	32%	3.05E+01	100%	9
Sentinel-1A Out-of-plane Low -6	2.61E+01	100%	8.63E-01	0%	2.61E+01	100%	9
Sentinel-1A Out-of-plane Low -12	2.96E+01	100%	1.12E+00	0%	2.97E+01	100%	9
Sentinel-1A Out-of-plane Medium -2	6.46E+01	100%	1.93E+00	69%	6.46E+01	100%	9
Sentinel-1A Out-of-plane Medium -6	5.13E+01	100%	1.08E+00	0%	5.14E+01	100%	9
Sentinel-1A Out-of-plane Medium -12	5.91E+01	100%	2.57E+00	93%	5.91E+01	100%	9
Sentinel-1A Out-of-plane High -2	1.25E+02	100%	1.04E+00	0%	1.25E+02	100%	9
Sentinel-1A Out-of-plane High -6	1.01E+02	100%	1.26E+00	10%	1.01E+02	100%	9
Sentinel-1A Out-of-plane High -12	1.22E+02	100%	3.16E-01	0%	1.22E+02	100%	9
Sentinel-1A Hybrid Low -2	7.02E+00	100%	1.61E+00	45%	7.39E+00	100%	9
Sentinel-1A Hybrid Low -6	9.54E+00	100%	2.12E+00	79%	9.74E+00	100%	9
Sentinel-1A Hybrid Low -12	1.04E+01	100%	1.75E+00	57%	1.05E+01	100%	9
Sentinel-1A Hybrid Medium -2	3.75E+01	100%	1.23E+00	7%	3.75E+01	100%	9
Sentinel-1A Hybrid Medium -6	5.46E+01	100%	4.62E+00	100%	5.47E+01	100%	9
Sentinel-1A Hybrid Medium -12	8.83E+01	100%	7.27E+00	100%	8.83E+01	100%	10
Sentinel-1A Hybrid High -2	1.57E+02	100%	4.56E+00	100%	1.57E+02	100%	9
Sentinel-1A Hybrid High -6	4.35E+02	100%	1.65E+01	100%	4.35E+02	100%	9
Sentinel-1A Hybrid High -12	1.16E+03	100%	3.39E+01	100%	1.16E+03	100%	9

Table A.1 Sentinel-1A Reachability analysis and probability from MD.

Scenario	KLD(R,Rr)	PR	KLD(el,az)	PR	plots
Sentinel-1A No manoeuvre	6.72E+00	0%	8.05E+04	100%	9
Sentinel-1A No manoeuvre	7.80E+01	11%	1.02E+06	100%	10
Sentinel-1A No manoeuvre	8.85E+00	0%	2.98E+06	100%	9
Sentinel-1A No manoeuvre	1.75E+01	0%	2.74E+05	100%	9
Sentinel-1A No manoeuvre	1.78E+02	56%	3.26E+06	100%	10
Sentinel-1A No manoeuvre	2.53E+01	0%	7.48E+05	100%	8
Sentinel-1A No manoeuvre	1.28E+04	100%	1.16E+06	100%	2
Sentinel-1A No manoeuvre	5.25E+01	0%	6.52E+05	100%	9
Sentinel-1A No manoeuvre	6.09E+01	0%	3.62E+05	100%	8
Sentinel-1A No manoeuvre	5.49E+03	100%	1.57E+06	100%	2
Sentinel-1A No manoeuvre	4.40E+01	0%	4.26E+05	100%	9
Sentinel-1A No manoeuvre	6.59E+01	2%	1.38E+06	100%	10
Sentinel-1A No manoeuvre	7.54E+00	0%	2.62E+05	100%	9
Sentinel-1A No manoeuvre	2.54E+01	0%	1.10E+06	100%	9
Sentinel-1A No manoeuvre	3.88E+01	0%	4.41E+05	100%	9
Sentinel-1A No manoeuvre	3.45E+01	0%	2.42E+05	100%	9
Sentinel-1A No manoeuvre	6.53E+00	0%	1.55E+05	100%	9
Sentinel-1A No manoeuvre	1.12E+02	31%	9.76E+05	100%	10
Sentinel-1A No manoeuvre	1.04E+01	0%	8.55E+05	100%	10
Sentinel-1A No manoeuvre	1.72E+01	0%	6.12E+05	100%	10
Sentinel-1A No manoeuvre	1.15E+02	32%	2.69E+06	100%	11
Sentinel-1A No manoeuvre	2.38E+01	0%	1.27E+06	100%	9
Sentinel-1A No manoeuvre	1.90E+04	100%	7.33E+05	100%	2
Sentinel-1A No manoeuvre	2.71E+01	0%	1.41E+06	100%	9

Scenario	KLD(R,Rr)	PR	KLD(el,az)	PR	plots
Sentinel-1A No manoeuvre	2.33E+02	70%	1.41E+06	100%	9
Sentinel-1A Tangential Low -2	2.13E+01	0%	3.12E+06	100%	9
Sentinel-1A Tangential Low -6	7.58E+00	0%	4.46E+05	100%	9
Sentinel-1A Tangential Low -12	1.10E+01	0%	4.62E+05	100%	9
Sentinel-1A Tangential Medium -2	4.74E+01	0%	4.79E+05	100%	9
Sentinel-1A Tangential Medium -6	2.68E+02	76%	4.47E+05	100%	9
Sentinel-1A Tangential Medium -12	2.14E+02	66%	1.37E+06	100%	9
Sentinel-1A Tangential High -2	1.07E+03	100%	4.73E+05	100%	9
Sentinel-1A Tangential High -6	4.80E+03	100%	4.54E+05	100%	9
Sentinel-1A Tangential High -12	5.58E+03	100%	9.60E+05	100%	9
Sentinel-1A Out-of-plane Low -2	4.44E+03	100%	1.06E+06	100%	9
Sentinel-1A Out-of-plane Low -6	3.23E+03	100%	7.49E+05	100%	9
Sentinel-1A Out-of-plane Low -12	4.25E+03	100%	4.70E+05	100%	9
Sentinel-1A Out-of-plane Medium -2	1.99E+04	100%	2.11E+06	100%	9
Sentinel-1A Out-of-plane Medium -6	1.26E+04	100%	6.23E+05	100%	9
Sentinel-1A Out-of-plane Medium -12	1.65E+04	100%	3.31E+06	100%	9
Sentinel-1A Out-of-plane High -2	7.55E+04	100%	6.12E+05	100%	9
Sentinel-1A Out-of-plane High -6	4.87E+04	100%	7.68E+05	100%	9
Sentinel-1A Out-of-plane High -12	7.15E+04	100%	4.67E+05	100%	9
Sentinel-1A Hybrid Low -2	2.40E+02	71%	4.90E+05	100%	9
Sentinel-1A Hybrid Low -6	4.35E+02	91%	2.17E+06	100%	9
Sentinel-1A Hybrid Low -12	4.89E+02	94%	6.93E+05	100%	9
Sentinel-1A Hybrid Medium -2	6.69E+03	100%	6.88E+05	100%	9
Sentinel-1A Hybrid Medium -6	1.39E+04	100%	2.71E+06	100%	9
Sentinel-1A Hybrid Medium -12	4.03E+04	100%	1.30E+06	100%	10
Sentinel-1A Hybrid High -2	1.16E+05	100%	5.53E+05	100%	9
Sentinel-1A Hybrid High -6	6.55E+05	100%	4.55E+05	100%	9
Sentinel-1A Hybrid High -12	3.42E+06	100%	7.26E+05	100%	9

Table A.2 Sentinel-1A Reachability analysis and probability from KLD.

Scenario	BD(R,Rr)	ρ(R,Rr)	PR	BD(el,az)	ρ(el,az)	PR	BD(All)	ρ(All)	PR	plots
NM	2.76E+00	6.30E-02	0%	2.62E+00	7.30E-02	0%	9.78E+00	5.65E-05	23%	9
NM	2.38E+00	9.28E-02	0%	4.28E+00	1.38E-02	16%	1.02E+01	3.61E-05	25%	10
NM	2.57E+00	7.69E-02	0%	3.99E+00	1.85E-02	13%	1.14E+01	1.17E-05	30%	9
NM	2.46E+00	8.58E-02	0%	3.14E+00	4.32E-02	3%	9.75E+00	5.83E-05	23%	9
NM	2.96E+00	5.18E-02	0%	4.18E+00	1.54E-02	15%	1.10E+01	1.65E-05	29%	10
NM	2.07E+00	1.27E-01	0%	3.98E+00	1.86E-02	13%	9.91E+00	4.95E-05	23%	8
NM	2.15E+01	4.70E-10	91%	3.73E+00	2.39E-02	10%	2.92E+01	1.99E-13	79%	2
NM	2.68E+00	6.85E-02	0%	3.72E+00	2.42E-02	10%	1.05E+01	2.89E-05	26%	9
NM	2.35E+00	9.49E-02	0%	4.12E+00	1.63E-02	14%	1.02E+01	3.76E-05	25%	8
NM	2.95E+01	1.53E-13	97%	3.66E+00	2.58E-02	9%	3.78E+01	3.85E-17	88%	2
NM	2.81E+00	6.00E-02	0%	3.20E+00	4.07E-02	4%	1.03E+01	3.49E-05	25%	9
NM	2.43E+00	8.83E-02	0%	4.60E+00	1.01E-02	20%	1.07E+01	2.32E-05	27%	10
NM	2.59E+00	7.52E-02	0%	2.97E+00	5.11E-02	1%	9.97E+00	4.70E-05	24%	9
NM	2.54E+00	7.91E-02	0%	3.61E+00	2.70E-02	9%	1.03E+01	3.26E-05	25%	9
NM	2.68E+00	6.86E-02	0%	3.53E+00	2.93E-02	8%	1.02E+01	3.56E-05	25%	9
NM	2.24E+00	1.06E-01	0%	3.70E+00	2.47E-02	10%	9.80E+00	5.56E-05	23%	9
NM	2.76E+00	6.36E-02	0%	2.99E+00	5.04E-02	1%	1.03E+01	3.30E-05	25%	9
NM	2.58E+00	7.57E-02	0%	4.30E+00	1.36E-02	16%	1.06E+01	2.39E-05	27%	10
NM	2.62E+00	7.29E-02	0%	3.34E+00	3.53E-02	5%	1.06E+01	2.54E-05	27%	10
NM	2.40E+00	9.10E-02	0%	3.35E+00	3.51E-02	5%	1.00E+01	4.44E-05	24%	10
NM	2.96E+00	5.18E-02	0%	4.02E+00	1.80E-02	13%	1.10E+01	1.70E-05	29%	11
NM	2.11E+00	1.22E-01	0%	3.91E+00	2.01E-02	12%	9.94E+00	4.81E-05	24%	9
NM	2.79E+01	7.73E-13	96%	3.71E+00	2.44E-02	10%	3.57E+01	3.04E-16	86%	2
NM	2.63E+00	7.19E-02	0%	3.96E+00	1.91E-02	13%	1.07E+01	2.28E-05	27%	9
NM	3.00E+00	5.00E-02	1%	4.27E+00	1.40E-02	16%	1.11E+01	1.51E-05	29%	9
TL -2	2.89E+00	5.55E-02	0%	3.85E+00	2.12E-02	11%	1.14E+01	1.08E-05	31%	9
TL -6	2.53E+00	7.94E-02	0%	3.13E+00	4.38E-02	3%	1.04E+01	3.08E-05	26%	9
TL -12	2.63E+00	7.20E-02	0%	3.11E+00	4.45E-02	2%	1.04E+01	2.91E-05	26%	9

Scenario	BD(R,Rr)	ρ(R,Rr)	PR	BD(el,az)	ρ(el,az)	PR	BD(All)	ρ(All)	PR	plots
TM -2	3.61E+00	2.72E-02	8%	3.38E+00	3.41E-02	6%	1.19E+01	6.65E-06	33%	9
TM -6	9.63E+00	6.60E-05	59%	3.41E+00	3.30E-02	6%	1.76E+01	2.32E-08	54%	9
TM -12	8.40E+00	2.25E-04	51%	3.97E+00	1.89E-02	13%	1.67E+01	5.86E-08	51%	9
TH -2	3.06E+01	5.02E-14	97%	3.12E+00	4.43E-02	2%	3.85E+01	1.90E-17	88%	9
TH -6	1.31E+02	1.36E-57	100%	4.01E+00	1.82E-02	13%	1.39E+02	5.57E-61	100%	9
TH -12	1.58E+02	1.93E-69	100%	5.57E+00	3.80E-03	29%	1.66E+02	6.56E-73	100%	9
OL -2	1.19E+02	2.38E-52	100%	3.38E+00	3.41E-02	6%	1.27E+02	7.59E-56	100%	9
OL -6	8.75E+01	9.66E-39	100%	3.20E+00	4.08E-02	3%	9.55E+01	3.50E-42	100%	9
OL -12	1.12E+02	1.91E-49	100%	3.27E+00	3.81E-02	4%	1.20E+02	5.64E-53	100%	9
OM -2	5.24E+02	3.50E-228	100%	3.57E+00	2.81E-02	8%	5.32E+02	8.78E-232	100%	9
OM -6	3.32E+02	6.78E-145	100%	3.25E+00	3.87E-02	4%	3.40E+02	1.93E-148	100%	9
OM -12	4.39E+02	3.50E-191	100%	3.93E+00	1.96E-02	12%	4.47E+02	6.59E-195	100%	9
OH -2	1.95E+03	0.00E+00	100%	3.25E+00	3.89E-02	4%	1.96E+03	0.00E+00	100%	9
OH -6	1.29E+03	0.00E+00	100%	3.30E+00	3.68E-02	5%	1.30E+03	0.00E+00	100%	9
OH -12	1.87E+03	0.00E+00	100%	3.12E+00	4.41E-02	2%	1.88E+03	0.00E+00	100%	9
HL -2	8.69E+00	1.69E-04	53%	3.43E+00	3.24E-02	6%	1.72E+01	3.56E-08	52%	9
HL -6	1.39E+01	9.11E-07	76%	3.67E+00	2.54E-02	9%	2.22E+01	2.35E-10	66%	9
HL -12	1.62E+01	9.43E-08	82%	3.49E+00	3.06E-02	7%	2.40E+01	3.62E-11	70%	9
HM -2	1.78E+02	4.97E-78	100%	3.30E+00	3.69E-02	5%	1.86E+02	1.83E-81	100%	9
HM -6	3.76E+02	6.96E-164	100%	5.77E+00	3.11E-03	31%	3.84E+02	1.24E-167	100%	9
HM -12	9.76E+02	0.00E+00	100%	9.78E+00	5.63E-05	59%	9.85E+02	0.00E+00	100%	10
HH -2	3.09E+03	0.00E+00	100%	5.71E+00	3.33E-03	31%	3.10E+03	0.00E+00	100%	9
HH -6	2.36E+04	0.00E+00	100%	3.69E+01	9.09E-17	99%	2.36E+04	0.00E+00	100%	9
HH -12	1.68E+05	0.00E+00	100%	1.47E+02	1.78E-64	100%	1.68E+05	0.00E+00	100%	9

Table A.3 Sentinel-1A Reachability analysis and probability from BD [2].

A.1.2 Sentinel-1B Scenario

Scenario	MD(R,Rr)	PR	MD(el,az)	PR	MD(All)	PR	plots
Sentinel-1B No manoeuvre	2.52E-01	0%	2.98E+00	98%	3.02E+00	88%	9
Sentinel-1B No manoeuvre	1.47E-01	0%	1.29E+00	13%	1.29E+00	0%	9
Sentinel-1B No manoeuvre	1.38E+01	100%	4.54E-01	0%	1.39E+01	100%	2
Sentinel-1B No manoeuvre	2.00E+00	73%	1.78E+00	59%	2.73E+00	77%	9
Sentinel-1B No manoeuvre	1.49E+00	34%	3.10E+00	98%	3.44E+00	96%	11
Sentinel-1B No manoeuvre	4.55E-02	0%	1.69E+00	52%	1.75E+00	0%	9
Sentinel-1B No manoeuvre	4.60E-01	0%	6.11E-01	0%	7.86E-01	0%	9
Sentinel-1B No manoeuvre	3.67E-01	0%	1.44E+00	29%	1.49E+00	0%	10
Sentinel-1B No manoeuvre	2.64E+00	94%	1.69E+00	52%	3.13E+00	91%	8
Sentinel-1B No manoeuvre	4.80E-01	0%	5.45E-01	0%	8.44E-01	0%	9
Sentinel-1B No manoeuvre	6.32E-01	0%	9.60E-01	0%	1.15E+00	0%	10
Sentinel-1B No manoeuvre	9.84E-01	0%	1.16E+00	0%	1.52E+00	0%	10
Sentinel-1B No manoeuvre	3.36E-01	0%	1.03E+00	0%	1.14E+00	0%	10
Sentinel-1B No manoeuvre	2.09E+00	77%	1.59E+00	43%	2.62E+00	72%	10
Sentinel-1B No manoeuvre	1.17E+00	0%	2.92E-01	0%	1.20E+00	0%	8
Sentinel-1B No manoeuvre	1.27E+01	100%	1.65E+00	49%	1.28E+01	100%	2
Sentinel-1B No manoeuvre	5.38E-01	0%	1.19E+00	1%	1.33E+00	0%	9
Sentinel-1B No manoeuvre	1.25E-01	0%	1.52E-01	0%	1.92E-01	0%	8
Sentinel-1B No manoeuvre	1.55E+01	100%	7.07E-01	0%	1.55E+01	100%	2
Sentinel-1B No manoeuvre	6.93E-01	0%	2.22E+00	83%	2.51E+00	64%	9
Sentinel-1B Tangential Low -2	1.66E+00	50%	9.30E-01	0%	1.97E+00	15%	11
Sentinel-1B Tangential Low -6	1.86E+00	65%	4.02E-01	0%	1.93E+00	11%	11
Sentinel-1B Tangential Low -12	1.01E+00	0%	4.07E-01	0%	1.05E+00	0%	11
Sentinel-1B Tangential Medium -2	2.46E+00	90%	9.36E-01	0%	2.62E+00	71%	11
Sentinel-1B Tangential Medium -6	1.45E+00	30%	1.74E+00	56%	2.10E+00	29%	11
Sentinel-1B Tangential Medium -12	2.47E+00	90%	1.40E+00	25%	3.00E+00	88%	10
Sentinel-1B Tangential High -2	1.20E+01	100%	2.63E+00	94%	1.23E+01	100%	11
Sentinel-1B Tangential High -6	6.68E+00	100%	2.64E+00	94%	6.76E+00	100%	10

[2] NM: No manoeuvre, TL: Tangential Low, TM: Tangential Medium, TH: Tangential High, OL: Out-of-plane Low, OM: Out-of-plane Medium, OH: Out-of-plane High, HL: Hybrid Low, HM: Hybrid Medium, HH: Hybrid High

Scenario	MD(R,Rr)	PR	MD(el,az)	PR	MD(All)	PR	plots
Sentinel-1B Tangential High -12	1.47E+01	100%	3.77E+00	100%	1.47E+01	100%	10
Sentinel-1B Out-of-plane Low -2	1.30E+01	100%	1.38E+00	23%	1.31E+01	100%	11
Sentinel-1B Out-of-plane Low -6	1.10E+01	100%	7.31E-01	0%	1.10E+01	100%	11
Sentinel-1B Out-of-plane Low -12	1.21E+01	100%	5.17E-01	0%	1.21E+01	100%	11
Sentinel-1B Out-of-plane Medium -2	2.72E+01	100%	1.16E+00	0%	2.72E+01	100%	11
Sentinel-1B Out-of-plane Medium -6	2.22E+01	100%	9.43E-01	0%	2.22E+01	100%	11
Sentinel-1B Out-of-plane Medium -12	2.67E+01	100%	2.35E+00	87%	2.69E+01	100%	11
Sentinel-1B Out-of-plane High -2	5.32E+01	100%	7.52E-01	0%	5.32E+01	100%	11
Sentinel-1B Out-of-plane High -6	4.21E+01	100%	8.04E-01	0%	4.21E+01	100%	11
Sentinel-1B Out-of-plane High -12	5.16E+01	100%	6.18E-01	0%	5.16E+01	100%	11
Sentinel-1B Hybrid Low -2	5.17E+00	100%	1.76E+00	58%	5.45E+00	100%	11
Sentinel-1B Hybrid Low -6	1.75E+00	57%	1.47E+00	32%	2.11E+00	30%	11
Sentinel-1B Hybrid Low -12	3.89E+00	100%	1.58E+00	42%	3.95E+00	99%	10
Sentinel-1B Hybrid Medium -2	2.42E+01	100%	1.73E+00	55%	2.42E+01	100%	10
Sentinel-1B Hybrid Medium -6	1.20E+01	100%	2.94E+00	97%	1.21E+01	100%	10
Sentinel-1B Hybrid Medium -12	4.65E+01	100%	6.95E+00	100%	4.66E+01	100%	11
Sentinel-1B Hybrid High -2	1.09E+02	100%	2.96E+00	98%	1.09E+02	100%	10
Sentinel-1B Hybrid High -6	1.10E+02	100%	1.24E+01	100%	1.10E+02	100%	11
Sentinel-1B Hybrid High -12	5.76E+02	100%	2.98E+01	100%	5.76E+02	100%	10

Table A.4 Sentinel-1B Reachability analysis and probability from MD.

Scenario	KLD(R,Rr)	PR	KLD(el,az)	PR	plots
Sentinel-1B No manoeuvre	1.59E+01	0%	9.80E+05	100%	9
Sentinel-1B No manoeuvre	3.58E+01	0%	6.51E+05	100%	9
Sentinel-1B No manoeuvre	4.67E+03	100%	1.46E+06	100%	2
Sentinel-1B No manoeuvre	6.11E+01	0%	5.16E+05	100%	9
Sentinel-1B No manoeuvre	1.66E+02	53%	1.13E+07	100%	11
Sentinel-1B No manoeuvre	7.30E+00	0%	7.14E+05	100%	9
Sentinel-1B No manoeuvre	2.39E+01	0%	4.12E+05	100%	9
Sentinel-1B No manoeuvre	6.09E+01	0%	2.17E+06	100%	10
Sentinel-1B No manoeuvre	2.77E+02	77%	3.91E+05	100%	8
Sentinel-1B No manoeuvre	6.08E+00	0%	3.00E+04	100%	9
Sentinel-1B No manoeuvre	8.16E+01	13%	1.20E+06	100%	10
Sentinel-1B No manoeuvre	1.67E+01	0%	1.33E+06	100%	10
Sentinel-1B No manoeuvre	1.63E+01	0%	3.27E+05	100%	10
Sentinel-1B No manoeuvre	3.93E+02	89%	3.09E+06	100%	10
Sentinel-1B No manoeuvre	5.86E+01	0%	6.06E+05	100%	8
Sentinel-1B No manoeuvre	1.51E+04	100%	1.71E+06	100%	2
Sentinel-1B No manoeuvre	2.81E+01	0%	4.29E+05	100%	9
Sentinel-1B No manoeuvre	4.86E+01	0%	2.90E+05	100%	8
Sentinel-1B No manoeuvre	6.57E+03	100%	1.70E+06	100%	2
Sentinel-1B No manoeuvre	1.59E+01	0%	1.66E+05	100%	9
Sentinel-1B Tangential Low -2	6.65E+01	2%	6.84E+05	100%	11
Sentinel-1B Tangential Low -6	7.71E+01	10%	6.83E+05	100%	11
Sentinel-1B Tangential Low -12	3.50E+01	0%	6.77E+05	100%	11
Sentinel-1B Tangential Medium -2	1.18E+02	34%	6.64E+05	100%	11
Sentinel-1B Tangential Medium -6	4.14E+01	0%	1.17E+06	100%	11
Sentinel-1B Tangential Medium -12	5.00E+01	0%	2.10E+06	100%	10
Sentinel-1B Tangential High -2	2.48E+03	100%	8.86E+05	100%	11
Sentinel-1B Tangential High -6	5.82E+02	96%	7.49E+05	100%	10
Sentinel-1B Tangential High -12	2.56E+03	100%	9.10E+05	100%	10
Sentinel-1B Out-of-plane Low -2	2.90E+03	100%	8.59E+05	100%	11
Sentinel-1B Out-of-plane Low -6	2.03E+03	100%	8.88E+05	100%	11
Sentinel-1B Out-of-plane Low -12	2.56E+03	100%	6.89E+05	100%	11
Sentinel-1B Out-of-plane Medium -2	1.28E+04	100%	7.36E+05	100%	11

Scenario	KLD(R,Rr)	PR	KLD(el,az)	PR	plots
Sentinel-1B Out-of-plane Medium -6	8.45E+03	100%	1.15E+06	100%	11
Sentinel-1B Out-of-plane Medium -12	1.20E+04	100%	8.59E+05	100%	11
Sentinel-1B Out-of-plane High -2	4.86E+04	100%	1.06E+06	100%	11
Sentinel-1B Out-of-plane High -6	3.01E+04	100%	7.07E+05	100%	11
Sentinel-1B Out-of-plane High -12	4.53E+04	100%	9.10E+05	100%	11
Sentinel-1B Hybrid Low -2	4.69E+02	93%	7.19E+05	100%	11
Sentinel-1B Hybrid Low -6	4.27E+01	0%	1.54E+06	100%	11
Sentinel-1B Hybrid Low -12	1.11E+02	30%	1.06E+06	100%	10
Sentinel-1B Hybrid Medium -2	1.03E+04	100%	2.02E+06	100%	10
Sentinel-1B Hybrid Medium -6	1.77E+03	100%	1.43E+06	100%	10
Sentinel-1B Hybrid Medium -12	2.56E+04	100%	1.00E+06	100%	11
Sentinel-1B Hybrid High -2	2.06E+05	100%	7.31E+05	100%	10
Sentinel-1B Hybrid High -6	1.50E+05	100%	1.61E+06	100%	11
Sentinel-1B Hybrid High -12	3.44E+06	100%	1.77E+06	100%	10

Table A.5 Sentinel-1B Reachability analysis and probability from KLD.

Scenario	BD(R,Rr)	ρ(R,Rr)	PR	BD(el,az)	ρ(el,az)	PR	BD(All)	ρ(All)	PR	plots
NM	2.40E+00	9.10E-02	0%	4.51E+00	1.10E-02	19%	1.11E+01	1.58E-05	29%	9
NM	2.20E+00	1.11E-01	0%	4.04E+00	1.76E-02	14%	9.89E+00	5.05E-05	23%	9
NM	2.68E+01	2.32E-12	96%	3.48E+00	3.07E-02	7%	3.48E+01	7.37E-16	85%	2
NM	2.97E+00	5.14E-02	0%	3.37E+00	3.43E-02	6%	1.05E+01	2.81E-05	26%	9
NM	2.60E+00	7.45E-02	0%	5.56E+00	3.85E-03	29%	1.17E+01	8.28E-06	32%	11
NM	2.58E+00	7.60E-02	0%	3.24E+00	3.91E-02	4%	1.03E+01	3.38E-05	25%	9
NM	2.54E+00	7.86E-02	0%	3.35E+00	3.52E-02	5%	1.00E+01	4.44E-05	24%	9
NM	2.75E+00	6.37E-02	0%	3.97E+00	1.89E-02	13%	1.07E+01	2.32E-05	27%	10
NM	3.08E+00	4.59E-02	2%	4.08E+00	1.70E-02	14%	1.10E+01	1.68E-05	29%	8
NM	2.75E+00	6.41E-02	0%	2.43E+00	8.78E-02	0%	9.69E+00	6.19E-05	22%	9
NM	2.45E+00	8.60E-02	0%	4.23E+00	1.45E-02	16%	1.04E+01	3.17E-05	26%	10
NM	2.76E+00	6.35E-02	0%	3.37E+00	3.44E-02	6%	1.08E+01	2.02E-05	28%	10
NM	2.39E+00	9.16E-02	0%	3.34E+00	3.55E-02	5%	9.95E+00	4.78E-05	24%	10
NM	3.40E+00	3.34E-02	9%	4.12E+00	1.62E-02	15%	1.15E+01	1.05E-05	31%	10
NM	2.27E+00	1.04E-01	0%	3.84E+00	2.14E-02	11%	1.00E+01	4.54E-05	24%	8
NM	2.30E+01	1.05E-10	93%	3.94E+00	1.94E-02	12%	3.09E+01	3.64E-14	81%	2
NM	2.60E+00	7.44E-02	0%	3.59E+00	2.75E-02	8%	1.03E+01	3.43E-05	25%	9
NM	2.39E+00	9.17E-02	0%	3.79E+00	2.27E-02	11%	9.97E+00	4.66E-05	24%	8
NM	3.29E+01	5.18E-15	98%	3.53E+00	2.93E-02	8%	4.10E+01	1.61E-18	90%	2
NM	2.47E+00	8.44E-02	0%	3.62E+00	2.68E-02	9%	1.05E+01	2.85E-05	26%	9
TL -2	3.38E+00	3.40E-02	6%	3.38E+00	3.39E-02	6%	1.10E+01	1.63E-05	29%	11
TL -6	3.47E+00	3.12E-02	7%	3.29E+00	3.72E-02	5%	1.10E+01	1.66E-05	29%	11
TL -12	3.16E+00	4.22E-02	3%	3.30E+00	3.71E-02	5%	1.07E+01	2.30E-05	27%	11
TM -2	3.79E+00	2.26E-02	11%	3.38E+00	3.41E-02	6%	1.14E+01	1.12E-05	31%	11
TM -6	3.30E+00	3.70E-02	5%	3.65E+00	2.60E-02	9%	1.11E+01	1.53E-05	29%	11
TM -12	3.78E+00	2.28E-02	11%	3.54E+00	2.90E-02	8%	1.17E+01	8.26E-06	32%	10
TH -2	2.11E+01	6.55E-10	91%	4.14E+00	1.59E-02	15%	2.93E+01	1.88E-13	79%	11
TH -6	8.59E+00	1.86E-04	53%	4.17E+00	1.55E-02	15%	1.63E+01	8.41E-08	50%	10
TH -12	3.01E+01	8.61E-14	97%	5.07E+00	6.27E-03	25%	3.77E+01	4.30E-17	88%	10
OL -2	2.42E+01	2.97E-11	94%	3.51E+00	2.98E-02	7%	3.21E+01	1.16E-14	82%	11
OL -6	1.81E+01	1.43E-08	86%	3.34E+00	3.55E-02	5%	2.56E+01	7.45E-12	73%	11
OL -12	2.13E+01	5.38E-10	91%	3.31E+00	3.64E-02	5%	2.89E+01	2.78E-13	78%	11
OM -2	9.55E+01	3.22E-42	100%	3.45E+00	3.19E-02	7%	1.03E+02	1.54E-45	100%	11
OM -6	6.46E+01	9.16E-29	100%	3.39E+00	3.38E-02	6%	7.22E+01	4.59E-32	99%	11
OM -12	9.24E+01	7.25E-41	100%	3.97E+00	1.90E-02	13%	1.01E+02	1.40E-44	100%	11
OH -2	3.56E+02	2.06E-155	100%	3.35E+00	3.51E-02	5%	3.64E+02	1.01E-158	100%	11
OH -6	2.25E+02	2.56E-98	100%	3.35E+00	3.49E-02	5%	2.32E+02	1.13E-101	100%	11
OH -12	3.36E+02	1.50E-146	100%	3.32E+00	3.61E-02	5%	3.43E+02	7.47E-150	100%	11
HL -2	6.38E+00	1.70E-03	36%	3.66E+00	2.57E-02	9%	1.43E+01	6.42E-07	42%	11
HL -6	3.42E+00	3.26E-02	6%	3.55E+00	2.88E-02	8%	1.11E+01	1.51E-05	29%	11
HL -12	4.91E+00	7.40E-03	23%	3.60E+00	2.72E-02	8%	1.25E+01	3.64E-06	35%	10
HM -2	7.61E+01	8.77E-34	100%	3.67E+00	2.55E-02	9%	8.39E+01	3.62E-37	99%	10
HM -6	2.11E+01	6.93E-10	91%	4.37E+00	1.26E-02	17%	2.88E+01	3.10E-13	78%	10
HM -12	2.74E+02	1.40E-119	100%	9.25E+00	9.61E-05	56%	2.82E+02	5.28E-123	100%	11
HH -2	1.50E+03	0.00E+00	100%	4.38E+00	1.25E-02	17%	1.50E+03	0.00E+00	100%	10
HH -6	1.53E+03	0.00E+00	100%	2.25E+01	1.75E-10	92%	1.54E+03	0.00E+00	100%	11

Scenario	BD(R,Rr)	ρ(R,Rr)	PR	BD(el,az)	ρ(el,az)	PR	BD(All)	ρ(All)	PR	plots
HH -12	4.15E+04	0.00E+00	100%	1.14E+02	3.08E-50	100%	4.15E+04	0.00E+00	100%	10

Table A.6 Sentinel-1B Reachability analysis and probability from BD.

A.1.3 Sentinel-2A Scenario

Scenario	MD(R,Rr)	PR	MD(el,az)	PR	MD(All)	PR	plots
Sentinel-2A No manoeuvre	1.10E+00	0%	1.34E+00	18%	1.80E+00	0%	12
Sentinel-2A No manoeuvre	7.06E-01	0%	1.02E+00	0%	1.25E+00	0%	13
Sentinel-2A No manoeuvre	4.80E-01	0%	5.01E-01	0%	7.06E-01	0%	10
Sentinel-2A No manoeuvre	1.05E+00	0%	4.75E-01	0%	1.15E+00	0%	10
Sentinel-2A No manoeuvre	8.78E-01	0%	1.56E+00	41%	1.79E+00	0%	5
Sentinel-2A No manoeuvre	1.33E+01	100%	1.03E+00	0%	1.33E+01	100%	3
Sentinel-2A No manoeuvre	1.49E+00	34%	1.37E+00	22%	2.03E+00	22%	10
Sentinel-2A No manoeuvre	1.59E+00	44%	2.36E+00	88%	2.86E+00	83%	10
Sentinel-2A No manoeuvre	1.97E-01	0%	1.78E+00	59%	1.82E+00	0%	12
Sentinel-2A No manoeuvre	5.83E-01	0%	1.37E+00	22%	1.49E+00	0%	12
Sentinel-2A No manoeuvre	1.24E+00	8%	5.47E-01	0%	1.36E+00	0%	11
Sentinel-2A No manoeuvre	1.64E+00	48%	1.27E+00	10%	2.08E+00	27%	11
Sentinel-2A No manoeuvre	1.61E+00	45%	1.11E+00	0%	1.95E+00	14%	10
Sentinel-2A No manoeuvre	6.44E-01	0%	1.95E+00	70%	2.06E+00	25%	10
Sentinel-2A No manoeuvre	6.75E-01	0%	1.40E+00	25%	1.72E+00	0%	12
Sentinel-2A No manoeuvre	4.18E-02	0%	1.60E+00	44%	1.60E+00	0%	12
Sentinel-2A No manoeuvre	7.93E-01	0%	2.52E-01	0%	8.32E-01	0%	10
Sentinel-2A No manoeuvre	6.49E-01	0%	2.69E+00	95%	2.79E+00	80%	10
Sentinel-2A No manoeuvre	1.68E+00	51%	1.51E+00	36%	2.26E+00	45%	5
Sentinel-2A No manoeuvre	1.49E+01	100%	5.71E-01	0%	1.49E+01	100%	3
Sentinel-2A No manoeuvre	2.43E+00	90%	1.00E+00	0%	2.63E+00	72%	10
Sentinel-2A Tangential Low -2	1.03E+00	0%	1.03E+00	0%	1.45E+00	0%	10
Sentinel-2A Tangential Low -6	5.72E-01	0%	9.34E-01	0%	1.15E+00	0%	10
Sentinel-2A Tangential Low -12	9.93E-01	0%	1.10E+00	0%	1.37E+00	0%	10
Sentinel-2A Tangential Medium -2	3.93E+00	100%	2.29E+00	86%	4.55E+00	100%	10
Sentinel-2A Tangential Medium -6	3.65E+00	100%	2.12E+00	79%	3.94E+00	99%	10
Sentinel-2A Tangential Medium -12	6.08E+00	100%	8.31E-01	0%	6.13E+00	100%	9
Sentinel-2A Tangential High -2	1.81E+01	100%	1.12E+00	0%	1.81E+01	100%	10
Sentinel-2A Tangential High -6	1.83E+01	100%	4.40E+00	100%	1.84E+01	100%	9
Sentinel-2A Tangential High -12	2.43E+01	100%	3.70E+00	100%	2.43E+01	100%	10
Sentinel-2A Out-of-plane Low -2	6.38E+00	100%	1.29E+00	13%	6.52E+00	100%	10
Sentinel-2A Out-of-plane Low -6	8.59E+00	100%	1.44E+00	29%	8.72E+00	100%	10
Sentinel-2A Out-of-plane Low -12	5.70E+00	100%	8.42E-01	0%	5.77E+00	100%	10
Sentinel-2A Out-of-plane Medium -2	1.22E+01	100%	1.40E+00	25%	1.23E+01	100%	10
Sentinel-2A Out-of-plane Medium -6	1.23E+01	100%	9.33E-01	0%	1.24E+01	100%	10
Sentinel-2A Out-of-plane Medium -12	1.30E+01	100%	1.22E+00	5%	1.31E+01	100%	10
Sentinel-2A Out-of-plane High -2	2.82E+01	100%	1.27E+00	11%	2.82E+01	100%	10
Sentinel-2A Out-of-plane High -6	2.39E+01	100%	1.61E+00	45%	2.39E+01	100%	10
Sentinel-2A Out-of-plane High -12	2.85E+01	100%	1.05E+00	0%	2.86E+01	100%	10
Sentinel-2A Hybrid Low -2	7.16E+00	100%	1.33E+00	17%	7.30E+00	100%	10
Sentinel-2A Hybrid Low -6	6.04E+00	100%	1.04E+00	0%	6.04E+00	100%	9
Sentinel-2A Hybrid Low -12	8.99E+00	100%	1.89E+00	66%	8.99E+00	100%	9
Sentinel-2A Hybrid Medium -2	3.71E+01	100%	2.05E+00	75%	3.71E+01	100%	9
Sentinel-2A Hybrid Medium -6	3.42E+01	100%	4.40E+00	100%	3.42E+01	100%	10
Sentinel-2A Hybrid Medium -12	5.02E+01	100%	9.37E+00	100%	5.02E+01	100%	10
Sentinel-2A Hybrid High -2	1.29E+02	100%	3.40E+00	99%	1.29E+02	100%	10
Sentinel-2A Hybrid High -6	2.10E+02	100%	1.83E+01	100%	2.10E+02	100%	10
Sentinel-2A Hybrid High -12	4.01E+02	100%	3.19E+01	100%	4.01E+02	100%	10

Table A.7 Sentinel-2A Reachability analysis and probability from MD.

Scenario	KLD(R,Rr)	PR	KLD(el,az)	PR	plots
Sentinel-2A No manoeuvre	1.16E+01	0%	1.58E+06	100%	12
Sentinel-2A No manoeuvre	1.02E+01	0%	1.99E+06	100%	13
Sentinel-2A No manoeuvre	5.92E+00	0%	1.72E+05	100%	10
Sentinel-2A No manoeuvre	9.35E+01	21%	2.04E+05	100%	10
Sentinel-2A No manoeuvre	2.45E+01	0%	1.32E+06	100%	5
Sentinel-2A No manoeuvre	1.19E+04	100%	3.41E+07	100%	3
Sentinel-2A No manoeuvre	1.27E+01	0%	8.38E+05	100%	10
Sentinel-2A No manoeuvre	8.26E+01	14%	1.76E+06	100%	10
Sentinel-2A No manoeuvre	4.80E+00	0%	5.93E+05	100%	12
Sentinel-2A No manoeuvre	9.08E+01	19%	1.44E+06	100%	12
Sentinel-2A No manoeuvre	1.15E+01	0%	4.69E+05	100%	11
Sentinel-2A No manoeuvre	3.72E+01	0%	2.32E+06	100%	11
Sentinel-2A No manoeuvre	1.34E+01	0%	5.28E+05	100%	10
Sentinel-2A No manoeuvre	9.81E+01	23%	1.45E+06	100%	10
Sentinel-2A No manoeuvre	8.07E+00	0%	6.23E+05	100%	12
Sentinel-2A No manoeuvre	7.71E+00	0%	5.61E+06	100%	12
Sentinel-2A No manoeuvre	7.09E+00	0%	1.96E+05	100%	10
Sentinel-2A No manoeuvre	5.19E+01	0%	1.66E+05	100%	10
Sentinel-2A No manoeuvre	3.80E+01	0%	1.89E+06	100%	5
Sentinel-2A No manoeuvre	4.29E+03	100%	8.93E+06	100%	3
Sentinel-2A No manoeuvre	2.62E+01	0%	4.60E+05	100%	10
Sentinel-2A Tangential Low -2	8.47E+00	0%	3.21E+05	100%	10
Sentinel-2A Tangential Low -6	5.53E+00	0%	2.78E+05	100%	10
Sentinel-2A Tangential Low -12	5.69E+00	0%	2.31E+05	100%	10
Sentinel-2A Tangential Medium -2	5.17E+01	0%	1.06E+06	100%	10
Sentinel-2A Tangential Medium -6	2.03E+01	0%	1.83E+05	100%	10
Sentinel-2A Tangential Medium -12	2.37E+01	0%	1.57E+05	100%	9
Sentinel-2A Tangential High -2	9.92E+02	100%	1.70E+05	100%	10
Sentinel-2A Tangential High -6	5.69E+02	96%	1.38E+05	100%	9
Sentinel-2A Tangential High -12	3.29E+02	83%	5.52E+05	100%	10
Sentinel-2A Out-of-plane Low -2	1.31E+02	40%	4.42E+05	100%	10
Sentinel-2A Out-of-plane Low -6	2.33E+02	70%	3.35E+05	100%	10
Sentinel-2A Out-of-plane Low -12	1.06E+02	27%	1.83E+05	100%	10
Sentinel-2A Out-of-plane Medium -2	4.68E+02	93%	2.80E+05	100%	10
Sentinel-2A Out-of-plane Medium -6	4.77E+02	93%	2.26E+05	100%	10
Sentinel-2A Out-of-plane Medium -12	5.21E+02	95%	3.63E+05	100%	10
Sentinel-2A Out-of-plane High -2	2.48E+03	100%	3.94E+05	100%	10
Sentinel-2A Out-of-plane High -6	1.75E+03	100%	5.89E+05	100%	10
Sentinel-2A Out-of-plane High -12	2.52E+03	100%	1.68E+05	100%	10
Sentinel-2A Hybrid Low -2	1.61E+02	51%	3.97E+05	100%	10
Sentinel-2A Hybrid Low -6	5.43E+01	0%	1.45E+05	100%	9
Sentinel-2A Hybrid Low -12	4.59E+01	0%	1.38E+05	100%	9
Sentinel-2A Hybrid Medium -2	3.73E+03	100%	1.44E+05	100%	9
Sentinel-2A Hybrid Medium -6	2.72E+03	100%	1.90E+05	100%	10
Sentinel-2A Hybrid Medium -12	3.30E+03	100%	3.35E+05	100%	10
Sentinel-2A Hybrid High -2	6.43E+04	100%	8.57E+05	100%	10
Sentinel-2A Hybrid High -6	1.83E+05	100%	8.67E+05	100%	10
Sentinel-2A Hybrid High -12	8.27E+05	100%	2.50E+06	100%	10

Table A.8 Sentinel-2A Reachability analysis and probability from KLD.

Scenario	BD(R,Rr)	ρ(R,Rr)	PR	BD(el,az)	ρ(el,az)	PR	BD(All)	ρ(All)	PR	plots
NM	2.89E+00	5.54E-02	0%	3.52E+00	2.96E-02	7%	1.07E+01	2.27E-05	27%	12
NM	1.90E+00	1.50E-01	0%	4.09E+00	1.67E-02	14%	9.95E+00	4.79E-05	24%	13

Scenario	BD(R,Rr)	ρ(R,Rr)	PR	BD(el,az)	ρ(el,az)	PR	BD(All)	ρ(All)	PR	plots
NM	2.05E+00	1.29E-01	0%	3.31E+00	3.67E-02	5%	9.72E+00	6.02E-05	22%	10
NM	2.67E+00	6.90E-02	0%	3.66E+00	2.58E-02	9%	1.01E+01	4.27E-05	24%	10
NM	2.33E+00	9.70E-02	0%	4.25E+00	1.43E-02	16%	1.08E+01	2.09E-05	28%	5
NM	2.49E+01	1.54E-11	94%	4.59E+00	1.01E-02	20%	3.32E+01	3.73E-15	83%	3
NM	2.34E+00	9.64E-02	0%	3.77E+00	2.31E-02	10%	1.03E+01	3.28E-05	25%	10
NM	2.64E+00	7.13E-02	0%	4.37E+00	1.26E-02	17%	1.09E+01	1.93E-05	28%	10
NM	1.84E+00	1.59E-01	0%	3.71E+00	2.45E-02	10%	9.82E+00	5.44E-05	23%	12
NM	2.71E+00	6.64E-02	0%	4.09E+00	1.67E-02	14%	1.03E+01	3.29E-05	25%	12
NM	2.88E+00	5.62E-02	0%	3.14E+00	4.34E-02	3%	1.04E+01	3.12E-05	26%	11
NM	2.34E+00	9.65E-02	0%	4.01E+00	1.80E-02	13%	1.03E+01	3.49E-05	25%	11
NM	2.26E+00	1.05E-01	0%	3.47E+00	3.10E-02	7%	9.98E+00	4.61E-05	24%	10
NM	2.70E+00	6.71E-02	0%	4.22E+00	1.47E-02	16%	1.05E+01	2.76E-05	26%	10
NM	2.73E+00	6.55E-02	0%	3.49E+00	3.06E-02	7%	1.07E+01	2.36E-05	27%	12
NM	1.84E+00	1.59E-01	0%	4.35E+00	1.29E-02	17%	1.02E+01	3.89E-05	25%	12
NM	2.08E+00	1.25E-01	0%	3.35E+00	3.49E-02	5%	9.76E+00	5.75E-05	23%	10
NM	2.51E+00	8.15E-02	0%	4.50E+00	1.12E-02	19%	1.07E+01	2.21E-05	27%	10
NM	2.46E+00	8.57E-02	0%	4.26E+00	1.42E-02	16%	1.08E+01	1.98E-05	28%	5
NM	3.03E+01	6.99E-14	97%	4.27E+00	1.40E-02	16%	3.89E+01	1.22E-17	89%	3
NM	2.81E+00	6.01E-02	0%	3.74E+00	2.38E-02	10%	1.08E+01	2.14E-05	28%	10
TL -2	2.15E+00	1.17E-01	0%	3.41E+00	3.31E-02	6%	9.92E+00	4.91E-05	23%	10
TL -6	2.06E+00	1.28E-01	0%	3.38E+00	3.40E-02	6%	9.82E+00	5.41E-05	23%	10
TL -12	2.14E+00	1.18E-01	0%	3.42E+00	3.26E-02	6%	9.89E+00	5.06E-05	23%	10
TM -2	3.94E+00	1.94E-02	12%	3.93E+00	1.96E-02	12%	1.23E+01	4.78E-06	34%	10
TM -6	3.68E+00	2.52E-02	9%	3.84E+00	2.16E-02	11%	1.16E+01	9.22E-06	31%	10
TM -12	6.65E+00	1.29E-03	39%	3.28E+00	3.78E-02	4%	1.43E+01	6.23E-07	43%	9
TH -2	4.30E+01	2.18E-19	99%	3.43E+00	3.24E-02	6%	5.06E+01	1.01E-22	95%	10
TH -6	4.40E+01	7.46E-20	100%	5.61E+00	3.66E-03	30%	5.19E+01	2.87E-23	95%	9
TH -12	7.56E+01	1.42E-33	100%	5.07E+00	6.31E-03	24%	8.38E+01	4.12E-37	99%	10
OL -2	7.11E+00	8.16E-04	42%	3.48E+00	3.08E-02	7%	1.50E+01	3.17E-07	45%	10
OL -6	1.13E+01	1.30E-05	67%	3.53E+00	2.94E-02	8%	1.92E+01	4.75E-09	58%	10
OL -12	6.08E+00	2.29E-03	34%	3.36E+00	3.48E-02	5%	1.38E+01	9.90E-07	41%	10
OM -2	2.06E+01	1.15E-09	90%	3.52E+00	2.97E-02	7%	2.85E+01	4.13E-13	77%	10
OM -6	2.10E+01	7.77E-10	91%	3.38E+00	3.40E-02	6%	2.87E+01	3.27E-13	78%	10
OM -12	2.31E+01	9.01E-11	93%	3.46E+00	3.16E-02	7%	3.09E+01	3.64E-14	81%	10
OH -2	1.01E+02	1.02E-44	100%	3.48E+00	3.10E-02	7%	1.09E+02	4.09E-48	100%	10
OH -6	7.33E+01	1.50E-32	100%	3.60E+00	2.75E-02	8%	8.12E+01	5.21E-36	99%	10
OH -12	1.04E+02	9.29E-46	100%	3.41E+00	3.30E-02	6%	1.12E+02	3.58E-49	100%	10
HL -2	8.42E+00	2.21E-04	51%	3.49E+00	3.04E-02	7%	1.63E+01	8.13E-08	50%	10
HL -6	6.59E+00	1.38E-03	38%	3.32E+00	3.62E-02	5%	1.42E+01	7.10E-07	42%	9
HL -12	1.21E+01	5.42E-06	70%	3.63E+00	2.64E-02	9%	1.97E+01	2.81E-09	60%	9
HM -2	1.74E+02	2.96E-76	100%	3.72E+00	2.43E-02	10%	1.82E+02	1.41E-79	100%	9
HM -6	1.49E+02	2.70E-65	100%	5.77E+00	3.13E-03	31%	1.56E+02	1.19E-68	100%	10
HM -12	3.17E+02	1.74E-138	100%	1.43E+01	6.02E-07	78%	3.25E+02	6.37E-142	100%	10
HH -2	2.09E+03	0.00E+00	100%	4.79E+00	8.28E-03	22%	2.10E+03	0.00E+00	100%	10
HH -6	5.52E+03	0.00E+00	100%	4.52E+01	2.33E-20	100%	5.52E+03	0.00E+00	100%	10
HH -12	2.01E+04	0.00E+00	100%	1.31E+02	2.01E-57	100%	2.01E+04	0.00E+00	100%	10

Table A.9 Sentinel-2A Reachability analysis and probability from BD.

A.1.4 Sentinel-2B Scenario

Scenario	MD(R,Rr)	PR	MD(el,az)	PR	MD(All)	PR	plots
Sentinel-2B No manoeuvre	7.04E-01	0%	8.85E-01	0%	1.14E+00	0%	5
Sentinel-2B No manoeuvre	1.46E+01	100%	4.12E-01	0%	1.46E+01	100%	3
Sentinel-2B No manoeuvre	7.21E-01	0%	1.50E+00	35%	1.69E+00	0%	10
Sentinel-2B No manoeuvre	7.86E-01	0%	1.06E+00	0%	1.32E+00	0%	10
Sentinel-2B No manoeuvre	4.48E-01	0%	1.21E+00	3%	1.32E+00	0%	12
Sentinel-2B No manoeuvre	2.24E+00	84%	1.24E+00	7%	2.56E+00	68%	11
Sentinel-2B No manoeuvre	1.06E+00	0%	1.08E+00	0%	1.57E+00	0%	10
Sentinel-2B No manoeuvre	1.10E-01	0%	1.75E+00	57%	1.76E+00	0%	11
Sentinel-2B No manoeuvre	6.00E-02	0%	9.40E-01	0%	1.00E+00	0%	11
Sentinel-2B No manoeuvre	6.63E-01	0%	8.76E-01	0%	1.10E+00	0%	11
Sentinel-2B No manoeuvre	5.27E-01	0%	7.05E-01	0%	9.62E-01	0%	12
Sentinel-2B No manoeuvre	1.12E+00	0%	1.07E+00	0%	1.56E+00	0%	12
Sentinel-2B No manoeuvre	7.50E-01	0%	1.03E+00	0%	1.29E+00	0%	9

Scenario	MD(R,Rr)	PR	MD(el,az)	PR	MD(All)	PR	plots
Sentinel-2B No manoeuvre	6.86E-01	0%	1.34E+00	19%	1.51E+00	0%	10
Sentinel-2B No manoeuvre	3.53E-01	0%	2.23E+00	83%	2.29E+00	47%	5
Sentinel-2B No manoeuvre	1.42E+01	100%	6.61E-01	0%	1.42E+01	100%	3
Sentinel-2B No manoeuvre	2.19E-01	0%	1.01E+00	0%	1.03E+00	0%	10
Sentinel-2B No manoeuvre	9.62E-01	0%	1.67E+00	50%	1.94E+00	12%	10
Sentinel-2B No manoeuvre	3.40E-01	0%	9.76E-01	0%	1.09E+00	0%	12
Sentinel-2B No manoeuvre	6.07E-01	0%	1.82E+00	62%	1.92E+00	10%	11
Sentinel-2B No manoeuvre	1.93E+00	69%	7.33E-01	0%	2.18E+00	38%	10
Sentinel-2B No manoeuvre	1.23E+00	6%	1.66E+00	50%	2.08E+00	27%	11
Sentinel-2B No manoeuvre	4.45E-01	0%	1.20E+00	3%	1.35E+00	0%	11
Sentinel-2B No manoeuvre	1.43E+00	28%	1.57E+00	42%	2.13E+00	32%	10
Sentinel-2B No manoeuvre	9.47E-01	0%	1.15E+00	0%	1.82E+00	0%	12
Sentinel-2B No manoeuvre	4.17E-01	0%	8.43E-01	0%	9.43E-01	0%	12
Sentinel-2B No manoeuvre	1.38E+00	23%	1.79E+00	60%	2.35E+00	53%	10
Sentinel-2B Tangential Low -2	1.20E+00	3%	1.11E+00	0%	1.65E+00	0%	10
Sentinel-2B Tangential Low -6	6.34E-01	0%	4.28E-01	0%	7.30E-01	0%	10
Sentinel-2B Tangential Low -12	8.13E-01	0%	9.15E-01	0%	1.34E+00	0%	10
Sentinel-2B Tangential Medium -2	1.73E+00	55%	1.22E+00	5%	2.18E+00	37%	10
Sentinel-2B Tangential Medium -6	4.23E+00	100%	1.34E+00	19%	4.45E+00	100%	10
Sentinel-2B Tangential Medium -12	4.53E+00	100%	1.23E+00	6%	4.58E+00	100%	10
Sentinel-2B Tangential High -2	6.01E+00	100%	6.82E-01	0%	6.07E+00	100%	10
Sentinel-2B Tangential High -6	2.06E+01	100%	1.81E+00	61%	2.06E+01	100%	10
Sentinel-2B Tangential High -12	1.63E+01	100%	4.33E+00	100%	1.64E+01	100%	10
Sentinel-2B Out-of-plane Low -2	7.65E-01	0%	2.84E-01	0%	8.28E-01	0%	10
Sentinel-2B Out-of-plane Low -6	1.07E+00	0%	1.32E+00	17%	1.70E+00	0%	10
Sentinel-2B Out-of-plane Low -12	1.00E+00	0%	6.12E-01	0%	1.17E+00	0%	10
Sentinel-2B Out-of-plane Medium -2	2.09E+00	78%	1.12E+00	0%	2.37E+00	54%	10
Sentinel-2B Out-of-plane Medium -6	6.23E-01	0%	2.07E-01	0%	6.50E-01	0%	10
Sentinel-2B Out-of-plane Medium -12	3.12E+00	98%	2.14E+00	80%	3.78E+00	99%	10
Sentinel-2B Out-of-plane High -2	7.53E+00	100%	2.69E+00	95%	7.99E+00	100%	10
Sentinel-2B Out-of-plane High -6	2.13E+00	79%	1.95E+00	70%	2.92E+00	85%	10
Sentinel-2B Out-of-plane High -12	6.52E+00	100%	3.17E+00	99%	7.32E+00	100%	10
Sentinel-2B Hybrid Low -2	2.92E+00	97%	9.54E-01	0%	3.07E+00	90%	10
Sentinel-2B Hybrid Low -6	5.51E+00	100%	1.03E+00	0%	5.77E+00	100%	10
Sentinel-2B Hybrid Low -12	6.94E+00	100%	3.71E+00	100%	7.30E+00	100%	10
Sentinel-2B Hybrid Medium -2	1.35E+01	100%	1.11E+00	0%	1.35E+01	100%	10
Sentinel-2B Hybrid Medium -6	4.18E+01	100%	3.46E+00	100%	4.18E+01	100%	10
Sentinel-2B Hybrid Medium -12	2.95E+01	100%	6.98E+00	100%	2.95E+01	100%	10
Sentinel-2B Hybrid High -2	5.69E+01	100%	4.43E+00	100%	5.69E+01	100%	10
Sentinel-2B Hybrid High -6	2.37E+02	100%	1.38E+01	100%	2.37E+02	100%	10
Sentinel-2B Hybrid High -12	3.21E+02	100%	2.68E+01	100%	3.21E+02	100%	10

Table A.10 Sentinel-2B Reachability analysis and probability from MD.

Scenario	KLD(R,Rr)	PR	KLD(el,az)	PR	plots
Sentinel-2B No manoeuvre	1.64E+01	0%	6.51E+06	100%	5
Sentinel-2B No manoeuvre	6.21E+03	100%	5.14E+06	100%	3
Sentinel-2B No manoeuvre	1.24E+01	0%	7.84E+05	100%	10
Sentinel-2B No manoeuvre	2.87E+01	0%	5.12E+06	100%	10
Sentinel-2B No manoeuvre	5.76E+00	0%	2.07E+06	100%	12
Sentinel-2B No manoeuvre	2.53E+02	73%	5.08E+06	100%	11
Sentinel-2B No manoeuvre	1.03E+01	0%	1.63E+05	100%	10
Sentinel-2B No manoeuvre	1.55E+01	0%	1.61E+07	100%	11
Sentinel-2B No manoeuvre	5.70E+00	0%	1.27E+06	100%	11
Sentinel-2B No manoeuvre	4.08E+01	0%	2.09E+06	100%	11
Sentinel-2B No manoeuvre	8.18E+00	0%	1.95E+05	100%	12
Sentinel-2B No manoeuvre	2.36E+01	0%	3.39E+06	100%	12

Scenario	KLD(R,Rr)	PR	KLD(el,az)	PR	plots
Sentinel-2B No manoeuvre	8.50E+00	0%	8.54E+05	100%	9
Sentinel-2B No manoeuvre	3.86E+01	0%	4.68E+06	100%	10
Sentinel-2B No manoeuvre	1.21E+01	0%	4.96E+06	100%	5
Sentinel-2B No manoeuvre	6.77E+03	100%	1.12E+07	100%	3
Sentinel-2B No manoeuvre	9.56E+00	0%	5.94E+05	100%	10
Sentinel-2B No manoeuvre	3.83E+01	0%	6.15E+06	100%	10
Sentinel-2B No manoeuvre	5.45E+00	0%	1.36E+06	100%	12
Sentinel-2B No manoeuvre	5.65E+01	0%	1.10E+07	100%	11
Sentinel-2B No manoeuvre	1.68E+01	0%	6.68E+04	100%	10
Sentinel-2B No manoeuvre	4.10E+01	0%	4.38E+06	100%	11
Sentinel-2B No manoeuvre	6.55E+00	0%	1.53E+06	100%	11
Sentinel-2B No manoeuvre	1.07E+02	28%	8.76E+06	100%	10
Sentinel-2B No manoeuvre	9.82E+00	0%	1.49E+05	100%	12
Sentinel-2B No manoeuvre	1.76E+01	0%	3.41E+06	100%	12
Sentinel-2B No manoeuvre	1.68E+01	0%	4.78E+05	100%	10
Sentinel-2B Tangential Low -2	1.86E+01	0%	7.77E+05	100%	10
Sentinel-2B Tangential Low -6	1.11E+01	0%	3.91E+05	100%	10
Sentinel-2B Tangential Low -12	1.07E+01	0%	5.29E+05	100%	10
Sentinel-2B Tangential Medium -2	2.75E+01	0%	7.36E+05	100%	10
Sentinel-2B Tangential Medium -6	1.05E+02	27%	1.06E+06	100%	10
Sentinel-2B Tangential Medium -12	4.73E+01	0%	5.53E+05	100%	10
Sentinel-2B Tangential High -2	2.29E+02	69%	5.59E+05	100%	10
Sentinel-2B Tangential High -6	2.53E+03	100%	3.83E+05	100%	10
Sentinel-2B Tangential High -12	2.29E+02	69%	6.58E+05	100%	10
Sentinel-2B Out-of-plane Low -2	1.29E+01	0%	3.88E+05	100%	10
Sentinel-2B Out-of-plane Low -6	1.66E+01	0%	1.04E+06	100%	10
Sentinel-2B Out-of-plane Low -12	1.56E+01	0%	5.27E+05	100%	10
Sentinel-2B Out-of-plane Medium -2	3.79E+01	0%	8.59E+05	100%	10
Sentinel-2B Out-of-plane Medium -6	1.15E+01	0%	3.82E+05	100%	10
Sentinel-2B Out-of-plane Medium -12	7.49E+01	9%	2.01E+06	100%	10
Sentinel-2B Out-of-plane High -2	3.92E+02	89%	2.27E+06	100%	10
Sentinel-2B Out-of-plane High -6	3.92E+01	0%	1.36E+06	100%	10
Sentinel-2B Out-of-plane High -12	2.92E+02	79%	6.51E+05	100%	10
Sentinel-2B Hybrid Low -2	6.31E+01	0%	7.30E+05	100%	10
Sentinel-2B Hybrid Low -6	1.62E+02	51%	5.42E+05	100%	10
Sentinel-2B Hybrid Low -12	1.15E+02	32%	4.10E+05	100%	10
Sentinel-2B Hybrid Medium -2	1.16E+03	100%	4.76E+05	100%	10
Sentinel-2B Hybrid Medium -6	1.04E+04	100%	1.85E+06	100%	10
Sentinel-2B Hybrid Medium -12	5.84E+02	96%	4.80E+05	100%	10
Sentinel-2B Hybrid High -2	2.05E+04	100%	2.56E+06	100%	10
Sentinel-2B Hybrid High -6	4.53E+05	100%	5.65E+05	100%	10
Sentinel-2B Hybrid High -12	9.69E+05	100%	1.22E+07	100%	10

Table A.11 Sentinel-2B Reachability analysis and probability from KLD.

Scenario	BD(R,Rr)	ρ(R,Rr)	PR	BD(el,az)	ρ(el,az)	PR	BD(All)	ρ(All)	PR	plots
NM	2.28E+00	1.02E-01	0%	4.47E+00	1.14E-02	18%	1.08E+01	2.06E-05	28%	5
NM	2.97E+01	1.22E-13	97%	3.98E+00	1.87E-02	13%	3.76E+01	4.77E-17	88%	3
NM	2.53E+00	7.97E-02	0%	3.67E+00	2.55E-02	9%	1.03E+01	3.36E-05	25%	10
NM	2.33E+00	9.70E-02	0%	4.29E+00	1.37E-02	16%	1.04E+01	3.13E-05	26%	10
NM	2.11E+00	1.21E-01	0%	3.74E+00	2.37E-02	10%	1.01E+01	4.28E-05	24%	12
NM	3.20E+00	4.07E-02	4%	4.36E+00	1.28E-02	17%	1.14E+01	1.17E-05	30%	11
NM	3.03E+00	4.82E-02	1%	2.80E+00	6.07E-02	0%	1.03E+01	3.49E-05	25%	10
NM	2.15E+00	1.16E-01	0%	4.57E+00	1.04E-02	19%	1.05E+01	2.65E-05	26%	11
NM	2.19E+00	1.12E-01	0%	3.60E+00	2.74E-02	8%	9.74E+00	5.88E-05	23%	11
NM	2.52E+00	8.08E-02	0%	4.19E+00	1.51E-02	15%	1.05E+01	2.84E-05	26%	11

Scenario	BD(R,Rr)	ρ(R,Rr)	PR	BD(el,az)	ρ(el,az)	PR	BD(All)	ρ(All)	PR	plots
NM	2.98E+00	5.10E-02	1%	2.88E+00	5.64E-02	0%	1.02E+01	3.82E-05	25%	12
NM	2.08E+00	1.25E-01	0%	4.34E+00	1.30E-02	17%	1.03E+01	3.35E-05	25%	12
NM	2.39E+00	9.17E-02	0%	3.43E+00	3.23E-02	6%	9.99E+00	4.59E-05	24%	9
NM	2.47E+00	8.43E-02	0%	4.40E+00	1.23E-02	18%	1.06E+01	2.59E-05	27%	10
NM	2.39E+00	9.18E-02	0%	4.80E+00	8.23E-03	22%	1.14E+01	1.09E-05	31%	5
NM	2.80E+01	6.70E-13	96%	4.29E+00	1.38E-02	16%	3.66E+01	1.29E-16	87%	3
NM	2.49E+00	8.31E-02	0%	3.44E+00	3.21E-02	6%	1.00E+01	4.42E-05	24%	10
NM	2.39E+00	9.19E-02	0%	4.49E+00	1.12E-02	19%	1.06E+01	2.44E-05	27%	10
NM	2.10E+00	1.23E-01	0%	3.69E+00	2.50E-02	9%	9.91E+00	4.95E-05	23%	12
NM	2.59E+00	7.47E-02	0%	4.67E+00	9.38E-03	20%	1.09E+01	1.78E-05	28%	11
NM	3.36E+00	3.49E-02	5%	2.67E+00	6.91E-02	0%	1.06E+01	2.60E-05	27%	10
NM	2.33E+00	9.70E-02	0%	4.49E+00	1.13E-02	19%	1.07E+01	2.32E-05	27%	11
NM	2.24E+00	1.06E-01	0%	3.64E+00	2.63E-02	9%	9.81E+00	5.49E-05	23%	11
NM	2.75E+00	6.39E-02	0%	4.56E+00	1.05E-02	19%	1.09E+01	1.76E-05	28%	10
NM	3.06E+00	4.67E-02	2%	2.94E+00	5.27E-02	0%	1.05E+01	2.73E-05	26%	12
NM	2.05E+00	1.29E-01	0%	4.29E+00	1.38E-02	16%	1.02E+01	3.65E-05	25%	12
NM	2.61E+00	7.39E-02	0%	3.72E+00	2.43E-02	10%	1.06E+01	2.59E-05	27%	10
TL -2	2.65E+00	7.07E-02	0%	3.54E+00	2.89E-02	8%	1.03E+01	3.43E-05	25%	10
TL -6	2.52E+00	8.07E-02	0%	3.41E+00	3.29E-02	6%	1.00E+01	4.51E-05	24%	10
TL -12	2.55E+00	7.84E-02	0%	3.50E+00	3.02E-02	7%	1.02E+01	3.83E-05	25%	10
TM -2	2.84E+00	5.87E-02	0%	3.58E+00	2.79E-02	8%	1.05E+01	2.65E-05	26%	10
TM -6	4.70E+00	9.10E-03	21%	3.61E+00	2.69E-02	9%	1.24E+01	4.07E-06	35%	10
TM -12	5.03E+00	6.55E-03	24%	3.58E+00	2.79E-02	8%	1.26E+01	3.51E-06	36%	10
TH -2	6.98E+00	9.29E-04	41%	3.45E+00	3.18E-02	7%	1.45E+01	4.81E-07	44%	10
TH -6	5.55E+01	8.23E-25	100%	3.80E+00	2.24E-02	11%	6.29E+01	4.64E-28	98%	10
TH -12	3.58E+01	2.74E-16	99%	5.74E+00	3.22E-03	31%	4.34E+01	1.41E-19	92%	10
OL -2	2.54E+00	7.87E-02	0%	3.40E+00	3.33E-02	6%	1.00E+01	4.40E-05	24%	10
OL -6	2.61E+00	7.36E-02	0%	3.61E+00	2.71E-02	9%	1.03E+01	3.36E-05	25%	10
OL -12	2.59E+00	7.52E-02	0%	3.44E+00	3.21E-02	6%	1.01E+01	4.05E-05	24%	10
OM -2	3.01E+00	4.94E-02	1%	3.55E+00	2.87E-02	8%	1.06E+01	2.38E-05	27%	10
OM -6	2.51E+00	8.10E-02	0%	3.40E+00	3.35E-02	6%	1.00E+01	4.55E-05	24%	10
OM -12	3.68E+00	2.51E-02	9%	3.96E+00	1.91E-02	13%	1.17E+01	8.05E-06	32%	10
OH -2	9.55E+00	7.12E-05	58%	4.30E+00	1.36E-02	16%	1.79E+01	1.64E-08	55%	10
OH -6	3.03E+00	4.83E-02	1%	3.87E+00	2.09E-02	12%	1.10E+01	1.65E-05	29%	10
OH -12	7.77E+00	4.21E-04	47%	4.65E+00	9.55E-03	20%	1.66E+01	5.89E-08	51%	10
HL -2	3.53E+00	2.92E-02	8%	3.50E+00	3.01E-02	7%	1.11E+01	1.48E-05	29%	10
HL -6	6.26E+00	1.91E-03	35%	3.52E+00	2.95E-02	7%	1.41E+01	7.47E-07	42%	10
HL -12	8.49E+00	2.05E-04	52%	5.11E+00	6.05E-03	25%	1.66E+01	6.08E-08	51%	10
HM -2	2.53E+01	1.08E-11	95%	3.55E+00	2.89E-02	8%	3.28E+01	5.95E-15	83%	10
HM -6	2.21E+02	1.30E-96	100%	4.89E+00	7.52E-03	23%	2.29E+02	4.17E-100	100%	10
HM -12	1.11E+02	4.92E-49	100%	9.56E+00	7.03E-05	58%	1.19E+02	2.60E-52	100%	10
HH -2	4.07E+02	2.20E-177	100%	5.84E+00	2.90E-03	32%	4.15E+02	6.15E-181	100%	10
HH -6	6.99E+03	0.00E+00	100%	2.74E+01	1.32E-12	96%	7.00E+03	0.00E+00	100%	10
HH -12	1.29E+04	0.00E+00	100%	9.34E+01	2.65E-41	100%	1.29E+04	0.00E+00	100%	10

Table A.12 Sentinel-2B Reachability analysis and probability from BD.

A.1.5 Swarm-C Scenario

Scenario	MD(R,Rr)	PR	MD(el,az)	PR	MD(All)	PR	plots
Swarm-C No manoeuvre	7.03E-01	0%	6.64E-01	0%	9.66E-01	0%	6
Swarm-C No manoeuvre	3.65E+00	100%	1.52E+00	37%	3.90E+00	99%	5
Swarm-C No manoeuvre	2.39E+00	88%	2.34E+00	87%	2.61E+00	71%	7
Swarm-C No manoeuvre	5.12E-01	0%	1.52E-01	0%	5.96E-01	0%	6
Swarm-C No manoeuvre	1.55E+00	40%	1.03E+00	0%	2.00E+00	19%	7
Swarm-C No manoeuvre	1.62E+00	46%	1.86E+00	65%	1.94E+00	12%	4
Swarm-C No manoeuvre	2.12E+00	79%	1.54E+00	38%	2.70E+00	76%	5
Swarm-C No manoeuvre	1.26E+00	10%	1.67E+00	50%	2.03E+00	22%	7
Swarm-C No manoeuvre	7.59E+00	100%	2.05E+00	75%	8.06E+00	100%	5
Swarm-C No manoeuvre	1.79E+00	60%	1.52E-01	0%	1.84E+00	1%	5
Swarm-C No manoeuvre	2.47E+00	90%	2.36E+00	88%	2.62E+00	72%	6
Swarm-C No manoeuvre	4.95E-01	0%	7.29E-01	0%	7.55E-01	0%	6
Swarm-C No manoeuvre	5.66E+00	100%	4.21E+00	100%	5.78E+00	100%	6
Swarm-C No manoeuvre	1.61E+00	45%	4.36E-01	0%	1.67E+00	0%	6
Swarm-C No manoeuvre	2.60E+00	93%	2.61E+00	93%	2.97E+00	87%	4

Scenario	MD(R,Rr)	PR	MD(el,az)	PR	MD(All)	PR	plots
Swarm-C No manoeuvre	1.75E+00	57%	1.23E+00	6%	2.10E+00	29%	5
Swarm-C No manoeuvre	2.00E+00	73%	1.42E+00	27%	2.36E+00	54%	6
Swarm-C No manoeuvre	2.04E+00	75%	2.60E+00	93%	2.92E+00	85%	7
Swarm-C No manoeuvre	1.51E+00	36%	1.29E+00	14%	2.16E+00	35%	6
Swarm-C Tangential Low -2	1.63E+00	47%	1.56E+00	41%	2.12E+00	31%	7
Swarm-C Tangential Low -6	1.18E+00	0%	1.76E+00	58%	1.97E+00	15%	7
Swarm-C Tangential Low -12	1.20E+00	3%	1.06E+00	0%	1.87E+00	5%	7
Swarm-C Tangential Medium -2	3.23E+00	99%	1.78E+00	59%	3.67E+00	98%	7
Swarm-C Tangential Medium -6	1.91E+00	68%	1.64E+00	48%	2.80E+00	80%	7
Swarm-C Tangential Medium -12	2.17E+00	81%	5.66E-01	0%	2.30E+00	48%	7
Swarm-C Tangential High -2	1.93E+01	100%	7.22E-01	0%	1.93E+01	100%	7
Swarm-C Tangential High -6	6.71E+00	100%	1.73E+00	55%	6.92E+00	100%	7
Swarm-C Tangential High -12	3.25E+01	100%	4.96E+00	100%	3.25E+01	100%	7
Swarm-C Out-of-plane Low -2	2.88E+01	100%	1.36E+00	21%	2.88E+01	100%	7
Swarm-C Out-of-plane Low -6	2.00E+01	100%	2.05E+00	75%	2.01E+01	100%	7
Swarm-C Out-of-plane Low -12	2.75E+01	100%	1.82E+00	62%	2.75E+01	100%	7
Swarm-C Out-of-plane Medium -2	5.76E+01	100%	1.14E+00	0%	5.76E+01	100%	7
Swarm-C Out-of-plane Medium -6	4.19E+01	100%	1.87E+00	65%	4.19E+01	100%	7
Swarm-C Out-of-plane Medium -12	5.75E+01	100%	1.48E+00	33%	5.75E+01	100%	7
Swarm-C Out-of-plane High -2	1.16E+02	100%	9.00E-01	0%	1.16E+02	100%	7
Swarm-C Out-of-plane High -6	8.77E+01	100%	1.68E+00	52%	8.77E+01	100%	7
Swarm-C Out-of-plane High -12	9.06E+01	100%	9.90E-01	0%	9.06E+01	100%	6
Swarm-C Hybrid Low -2	5.76E+00	100%	3.90E-01	0%	5.82E+00	100%	7
Swarm-C Hybrid Low -6	1.70E+00	52%	5.24E-01	0%	1.90E+00	8%	7
Swarm-C Hybrid Low -12	6.87E+00	100%	7.20E-01	0%	6.95E+00	100%	7
Swarm-C Hybrid Medium -2	3.24E+01	100%	4.25E-01	0%	3.24E+01	100%	7
Swarm-C Hybrid Medium -6	2.34E+01	100%	5.69E+00	100%	2.34E+01	100%	7
Swarm-C Hybrid Medium -12	9.73E+01	100%	8.90E+00	100%	9.73E+01	100%	6
Swarm-C Hybrid High -2	1.49E+02	100%	5.06E+00	100%	1.49E+02	100%	7
Swarm-C Hybrid High -6	3.95E+02	100%	2.04E+01	100%	3.95E+02	100%	7
Swarm-C Hybrid High -12	1.80E+03	100%	4.19E+01	100%	1.80E+03	100%	7

Table A.13 Swarm-C Reachability analysis and probability from MD.

Scenario	KLD(R,Rr)	PR	KLD(el,az)	PR	plots
Swarm-C No manoeuvre	3.13E+00	0%	4.94E+05	100%	6
Swarm-C No manoeuvre	1.04E+02	26%	1.03E+06	100%	5
Swarm-C No manoeuvre	9.06E+00	0%	2.43E+04	100%	7
Swarm-C No manoeuvre	6.08E+00	0%	2.47E+05	100%	6
Swarm-C No manoeuvre	1.68E+01	0%	1.13E+06	100%	7
Swarm-C No manoeuvre	6.73E+00	0%	1.03E+05	100%	4
Swarm-C No manoeuvre	3.67E+01	0%	9.29E+05	100%	5
Swarm-C No manoeuvre	1.04E+01	0%	1.46E+06	100%	7
Swarm-C No manoeuvre	7.82E+01	11%	2.32E+05	100%	5
Swarm-C No manoeuvre	1.97E+01	0%	8.24E+05	100%	5
Swarm-C No manoeuvre	9.30E+00	0%	6.52E+03	100%	6
Swarm-C No manoeuvre	5.60E+00	0%	4.51E+05	100%	6
Swarm-C No manoeuvre	3.46E+01	0%	2.13E+05	100%	6
Swarm-C No manoeuvre	2.36E+01	0%	2.44E+05	100%	6
Swarm-C No manoeuvre	9.81E+00	0%	6.33E+04	100%	4
Swarm-C No manoeuvre	1.12E+01	0%	6.11E+05	100%	5
Swarm-C No manoeuvre	3.99E+01	0%	1.60E+06	100%	6
Swarm-C No manoeuvre	8.02E+00	0%	5.85E+04	100%	7
Swarm-C No manoeuvre	2.20E+01	0%	2.12E+05	100%	6
Swarm-C Tangential Low -2	9.59E+00	0%	6.17E+05	100%	7
Swarm-C Tangential Low -6	7.08E+00	0%	2.31E+05	100%	7
Swarm-C Tangential Low -12	7.81E+00	0%	4.78E+05	100%	7

Scenario	KLD(R,Rr)	PR	KLD(el,az)	PR	plots
Swarm-C Tangential Medium -2	2.76E+01	0%	2.97E+05	100%	7
Swarm-C Tangential Medium -6	1.33E+01	0%	4.43E+05	100%	7
Swarm-C Tangential Medium -12	1.40E+01	0%	2.81E+05	100%	7
Swarm-C Tangential High -2	8.17E+02	99%	3.32E+05	100%	7
Swarm-C Tangential High -6	8.49E+01	15%	5.23E+05	100%	7
Swarm-C Tangential High -12	2.22E+03	100%	3.87E+05	100%	7
Swarm-C Out-of-plane Low -2	1.80E+03	100%	2.24E+05	100%	7
Swarm-C Out-of-plane Low -6	8.58E+02	99%	6.36E+05	100%	7
Swarm-C Out-of-plane Low -12	1.70E+03	100%	4.11E+05	100%	7
Swarm-C Out-of-plane Medium -2	7.27E+03	100%	3.50E+05	100%	7
Swarm-C Out-of-plane Medium -6	3.84E+03	100%	5.21E+05	100%	7
Swarm-C Out-of-plane Medium -12	7.15E+03	100%	2.51E+05	100%	7
Swarm-C Out-of-plane High -2	2.92E+04	100%	3.79E+05	100%	7
Swarm-C Out-of-plane High -6	1.68E+04	100%	4.15E+05	100%	7
Swarm-C Out-of-plane High -12	2.62E+04	100%	3.15E+05	100%	6
Swarm-C Hybrid Low -2	7.62E+01	10%	2.45E+05	100%	7
Swarm-C Hybrid Low -6	1.12E+01	0%	2.78E+05	100%	7
Swarm-C Hybrid Low -12	1.01E+02	25%	2.37E+05	100%	7
Swarm-C Hybrid Medium -2	2.31E+03	100%	2.49E+05	100%	7
Swarm-C Hybrid Medium -6	1.11E+03	100%	4.44E+05	100%	7
Swarm-C Hybrid Medium -12	2.06E+04	100%	4.90E+05	100%	6
Swarm-C Hybrid High -2	4.74E+04	100%	2.24E+05	100%	7
Swarm-C Hybrid High -6	2.40E+05	100%	1.85E+06	100%	7
Swarm-C Hybrid High -12	3.54E+06	100%	3.19E+06	100%	7

Table A.14 Swarm-C Reachability analysis and probability from KLD.

Scenario	BD(R,Rr)	ρ(R,Rr)	PR	BD(el,az)	ρ(el,az)	PR	BD(All)	ρ(All)	PR	plots
NM	8.64E-01	4.21E-01	0%	4.29E+00	1.37E-02	16%	8.78E+00	1.53E-04	17%	6
NM	3.68E+00	2.52E-02	9%	3.94E+00	1.95E-02	12%	1.19E+01	7.03E-06	33%	5
NM	3.60E+00	2.73E-02	8%	2.98E+00	5.10E-02	1%	1.08E+01	1.98E-05	28%	7
NM	2.30E+00	1.00E-01	0%	3.10E+00	4.49E-02	2%	9.57E+00	6.96E-05	22%	6
NM	2.25E+00	1.06E-01	0%	3.84E+00	2.15E-02	11%	1.08E+01	2.12E-05	28%	7
NM	2.91E+00	5.47E-02	0%	3.03E+00	4.81E-02	1%	9.97E+00	4.69E-05	24%	4
NM	2.64E+00	7.11E-02	0%	3.89E+00	2.04E-02	12%	1.07E+01	2.27E-05	27%	5
NM	2.43E+00	8.85E-02	0%	3.65E+00	2.59E-02	9%	1.05E+01	2.86E-05	26%	7
NM	9.59E+00	6.84E-05	58%	3.18E+00	4.18E-02	3%	1.78E+01	1.85E-08	54%	5
NM	2.36E+00	9.40E-02	0%	3.75E+00	2.35E-02	10%	1.05E+01	2.82E-05	26%	5
NM	3.66E+00	2.57E-02	9%	2.81E+00	6.04E-02	0%	1.08E+01	2.09E-05	28%	6
NM	2.21E+00	1.09E-01	0%	3.26E+00	3.84E-02	4%	9.54E+00	7.22E-05	21%	6
NM	6.49E+00	1.52E-03	37%	5.12E+00	5.98E-03	25%	1.41E+01	7.29E-07	42%	6
NM	2.47E+00	8.47E-02	0%	3.42E+00	3.27E-02	6%	1.01E+01	4.13E-05	24%	6
NM	3.65E+00	2.60E-02	9%	3.30E+00	3.71E-02	5%	1.11E+01	1.47E-05	29%	4
NM	2.51E+00	8.09E-02	0%	3.43E+00	3.23E-02	6%	1.01E+01	4.12E-05	24%	5
NM	2.50E+00	8.20E-02	0%	4.06E+00	1.73E-02	14%	1.12E+01	1.30E-05	30%	6
NM	3.09E+00	4.54E-02	2%	3.36E+00	3.47E-02	6%	1.05E+01	2.76E-05	26%	7
NM	2.45E+00	8.63E-02	0%	3.59E+00	2.75E-02	8%	1.02E+01	3.64E-05	25%	6
TL -2	2.76E+00	6.32E-02	0%	3.21E+00	4.03E-02	4%	1.04E+01	3.15E-05	26%	7
TL -6	2.60E+00	7.43E-02	0%	3.29E+00	3.73E-02	5%	1.03E+01	3.41E-05	25%	7
TL -12	2.61E+00	7.37E-02	0%	3.06E+00	4.70E-02	2%	1.02E+01	3.56E-05	25%	7
TM -2	3.73E+00	2.39E-02	10%	3.31E+00	3.65E-02	5%	1.15E+01	1.03E-05	31%	7
TM -6	2.88E+00	5.59E-02	0%	3.24E+00	3.90E-02	4%	1.08E+01	2.08E-05	28%	7
TM -12	3.02E+00	4.88E-02	1%	2.95E+00	5.22E-02	0%	1.05E+01	2.85E-05	26%	7
TH -2	4.88E+01	6.47E-22	100%	2.97E+00	5.11E-02	1%	5.62E+01	3.81E-25	96%	7
TH -6	8.05E+00	3.19E-04	49%	3.28E+00	3.77E-02	4%	1.58E+01	1.39E-07	48%	7
TH -12	1.35E+02	3.78E-59	100%	5.98E+00	2.53E-03	33%	1.42E+02	2.14E-62	100%	7
OL -2	1.06E+02	8.03E-47	100%	3.14E+00	4.33E-02	3%	1.14E+02	4.81E-50	100%	7
OL -6	5.23E+01	1.97E-23	100%	3.43E+00	3.25E-02	6%	6.01E+01	7.98E-27	97%	7
OL -12	9.69E+01	8.04E-43	100%	3.33E+00	3.57E-02	5%	1.05E+02	3.52E-46	100%	7
OM -2	4.17E+02	9.56E-182	100%	3.07E+00	4.63E-02	2%	4.24E+02	5.47E-185	100%	7
OM -6	2.22E+02	5.69E-97	100%	3.34E+00	3.53E-02	5%	2.29E+02	2.36E-100	100%	7

Scenario	BD(R,Rr)	ρ(R,Rr)	PR	BD(el,az)	ρ(el,az)	PR	BD(All)	ρ(All)	PR	plots
OM -12	4.15E+02	5.39E-181	100%	3.18E+00	4.15E-02	3%	4.23E+02	2.50E-184	100%	7
OH -2	1.69E+03	0.00E+00	100%	3.01E+00	4.93E-02	1%	1.69E+03	0.00E+00	100%	7
OH -6	9.63E+02	0.00E+00	100%	3.26E+00	3.82E-02	4%	9.71E+02	0.00E+00	100%	7
OH -12	1.03E+03	0.00E+00	100%	3.13E+00	4.39E-02	3%	1.04E+03	0.00E+00	100%	6
HL -2	6.57E+00	1.40E-03	38%	2.92E+00	5.38E-02	0%	1.40E+01	8.00E-07	42%	7
HL -6	2.79E+00	6.16E-02	0%	2.94E+00	5.28E-02	0%	1.03E+01	3.51E-05	25%	7
HL -12	8.34E+00	2.40E-04	51%	2.97E+00	5.11E-02	1%	1.59E+01	1.31E-07	48%	7
HM -2	1.34E+02	7.26E-59	100%	2.93E+00	5.32E-02	0%	1.41E+02	4.04E-62	100%	7
HM -6	7.06E+01	2.19E-31	100%	6.96E+00	9.52E-04	41%	7.83E+01	1.02E-34	99%	7
HM -12	1.19E+03	0.00E+00	100%	1.28E+01	2.65E-06	73%	1.19E+03	0.00E+00	100%	6
HH -2	2.76E+03	0.00E+00	100%	6.11E+00	2.23E-03	34%	2.77E+03	0.00E+00	100%	7
HH -6	1.95E+04	0.00E+00	100%	5.46E+01	1.89E-24	100%	1.95E+04	0.00E+00	100%	7
HH -12	4.03E+05	0.00E+00	100%	2.22E+02	3.01E-97	100%	4.03E+05	0.00E+00	100%	7

Table A.15 Swarm-C Reachability analysis and probability from BD.

A.2 Small manoeuvres

In this section, the distances and the probabilities are presented in tables with the same structure as those of the previous section, except for the last column. Scenarios without manoeuvres are not necessary in this analysis, so the tables does not present the number of plots of each segment.

Sentinel-1A Scenario

Scenario	MD(R,Rr)	PR	MD(el,az)	PR	MD(All)	PR
Sentinel-1A Tangential Low -2	9.22E-02	0%	1.83E+00	62%	1.84E+00	1%
Sentinel-1A Tangential Low -6	1.65E-01	0%	1.19E+00	1%	1.22E+00	0%
Sentinel-1A Tangential Low -12	1.24E+00	7%	1.87E+00	65%	2.24E+00	43%
Sentinel-1A Tangential Medium -2	2.07E-01	0%	6.95E-01	0%	7.10E-01	0%
Sentinel-1A Tangential Medium -6	1.08E+00	0%	1.69E+00	52%	2.00E+00	18%
Sentinel-1A Tangential Medium -12	8.21E-01	0%	1.84E+00	63%	2.01E+00	20%
Sentinel-1A Tangential High -2	1.80E+00	60%	3.31E+00	99%	3.72E+00	98%
Sentinel-1A Tangential High -6	1.32E+00	17%	8.42E-01	0%	1.50E+00	0%
Sentinel-1A Tangential High -12	1.22E+00	4%	5.24E-01	0%	1.36E+00	0%
Sentinel-1A Out-of-plane Low -2	1.37E-01	0%	6.22E-01	0%	6.61E-01	0%
Sentinel-1A Out-of-plane Low -6	1.03E+00	0%	8.50E-01	0%	1.34E+00	0%
Sentinel-1A Out-of-plane Low -12	1.00E+00	0%	5.65E-01	0%	1.15E+00	0%
Sentinel-1A Out-of-plane Medium -2	2.12E-01	0%	1.74E+00	56%	1.74E+00	0%
Sentinel-1A Out-of-plane Medium -6	6.13E-01	0%	1.42E+00	27%	1.54E+00	0%
Sentinel-1A Out-of-plane Medium -12	1.85E-01	0%	2.28E+00	85%	2.30E+00	48%
Sentinel-1A Out-of-plane High -2	1.66E+00	50%	6.23E-01	0%	1.79E+00	0%
Sentinel-1A Out-of-plane High -6	2.47E+00	91%	6.17E-01	0%	2.55E+00	67%
Sentinel-1A Out-of-plane High -12	2.00E+00	73%	2.11E+00	78%	2.91E+00	85%
Sentinel-1A Hybrid Low -2	1.19E+00	2%	3.58E-01	0%	1.24E+00	0%
Sentinel-1A Hybrid Low -6	1.25E+00	9%	3.81E-01	0%	1.30E+00	0%
Sentinel-1A Hybrid Low -12	4.83E-01	0%	1.07E+00	0%	1.20E+00	0%
Sentinel-1A Hybrid Medium -2	1.61E+00	46%	1.07E+00	0%	1.96E+00	14%
Sentinel-1A Hybrid Medium -6	1.47E+00	32%	1.63E+00	47%	2.03E+00	22%
Sentinel-1A Hybrid Medium -12	2.57E+00	93%	1.48E+00	33%	2.80E+00	81%
Sentinel-1A Hybrid High -2	2.55E+00	92%	9.29E-01	0%	2.84E+00	82%
Sentinel-1A Hybrid High -6	3.17E+00	99%	3.21E+00	99%	4.69E+00	100%
Sentinel-1A Hybrid High -12	4.31E+00	100%	1.45E+00	30%	4.43E+00	100%

Table A.16 Sentinel-1A Reachability analysis and probability from MD for small manoeuvres.

Scenario	KLD(R,Rr)	PR	KLD(el,az)	PR
Sentinel-1A Tangential Low -2	2.51E+01	0%	8.98E+05	100%
Sentinel-1A Tangential Low -6	2.55E+01	0%	4.00E+05	100%
Sentinel-1A Tangential Low -12	6.14E+01	0%	1.13E+06	100%
Sentinel-1A Tangential Medium -2	2.54E+01	0%	2.61E+05	100%
Sentinel-1A Tangential Medium -6	5.12E+01	0%	2.60E+05	100%
Sentinel-1A Tangential Medium -12	3.79E+01	0%	1.11E+06	100%
Sentinel-1A Tangential High -2	9.35E+01	21%	9.78E+05	100%
Sentinel-1A Tangential High -6	5.29E+01	0%	2.57E+05	100%
Sentinel-1A Tangential High -12	3.26E+01	0%	3.24E+05	100%
Sentinel-1A Out-of-plane Low -2	2.49E+01	0%	3.00E+05	100%
Sentinel-1A Out-of-plane Low -6	5.02E+01	0%	4.39E+05	100%
Sentinel-1A Out-of-plane Low -12	4.91E+01	0%	3.29E+05	100%
Sentinel-1A Out-of-plane Medium -2	2.56E+01	0%	9.76E+05	100%
Sentinel-1A Out-of-plane Medium -6	3.35E+01	0%	7.45E+05	100%
Sentinel-1A Out-of-plane Medium -12	2.50E+01	0%	1.48E+06	100%
Sentinel-1A Out-of-plane High -2	8.83E+01	17%	2.59E+05	100%
Sentinel-1A Out-of-plane High -6	1.69E+02	54%	3.19E+05	100%
Sentinel-1A Out-of-plane High -12	1.19E+02	34%	1.30E+06	100%
Sentinel-1A Hybrid Low -2	5.80E+01	0%	2.58E+05	100%
Sentinel-1A Hybrid Low -6	6.16E+01	0%	2.61E+05	100%
Sentinel-1A Hybrid Low -12	2.85E+01	0%	5.01E+05	100%
Sentinel-1A Hybrid Medium -2	5.49E+01	0%	5.51E+05	100%
Sentinel-1A Hybrid Medium -6	2.71E+01	0%	2.84E+05	100%
Sentinel-1A Hybrid Medium -12	8.45E+01	15%	2.67E+05	100%
Sentinel-1A Hybrid High -2	3.73E+01	0%	4.10E+05	100%
Sentinel-1A Hybrid High -6	4.89E+01	0%	2.61E+06	100%
Sentinel-1A Hybrid High -12	4.67E+01	0%	4.97E+05	100%

Table A.17 Sentinel-1A Reachability analysis and probability from KLD for small manoeuvres.

Scenario	BD(R,Rr)	ρ(R,Rr)	PR	BD(el,az)	ρ(el,az)	PR	BD(All)	ρ(All)	PR
TL -2	2.53E+00	7.94E-02	0%	3.87E+00	2.09E-02	12%	1.04E+01	2.93E-05	26%
TL -6	2.53E+00	7.93E-02	0%	3.63E+00	2.66E-02	9%	1.02E+01	3.71E-05	25%
TL -12	2.73E+00	6.55E-02	0%	3.89E+00	2.05E-02	12%	1.06E+01	2.38E-05	27%
TM -2	2.54E+00	7.89E-02	0%	3.51E+00	2.99E-02	7%	1.01E+01	4.19E-05	24%
TM -6	2.68E+00	6.89E-02	0%	3.81E+00	2.22E-02	11%	1.05E+01	2.72E-05	26%
TM -12	2.61E+00	7.32E-02	0%	3.87E+00	2.08E-02	12%	1.05E+01	2.70E-05	26%
TH -2	2.94E+00	5.30E-02	0%	4.82E+00	8.05E-03	22%	1.17E+01	7.91E-06	32%
TH -6	2.75E+00	6.38E-02	0%	3.53E+00	2.92E-02	8%	1.03E+01	3.37E-05	25%
TH -12	2.72E+00	6.59E-02	0%	3.48E+00	3.07E-02	7%	1.03E+01	3.54E-05	25%
OL -2	2.54E+00	7.92E-02	0%	3.50E+00	3.03E-02	7%	1.01E+01	4.23E-05	24%
OL -6	2.67E+00	6.94E-02	0%	3.54E+00	2.91E-02	8%	1.02E+01	3.56E-05	25%
OL -12	2.66E+00	6.99E-02	0%	3.49E+00	3.04E-02	7%	1.02E+01	3.77E-05	25%
OM -2	2.54E+00	7.89E-02	0%	3.83E+00	2.18E-02	11%	1.04E+01	3.06E-05	26%
OM -6	2.58E+00	7.59E-02	0%	3.70E+00	2.47E-02	10%	1.03E+01	3.33E-05	25%
OM -12	2.53E+00	7.93E-02	0%	4.10E+00	1.66E-02	14%	1.07E+01	2.31E-05	27%
OH -2	2.87E+00	5.64E-02	0%	3.49E+00	3.04E-02	7%	1.04E+01	3.00E-05	26%
OH -6	3.30E+00	3.71E-02	5%	3.49E+00	3.04E-02	7%	1.08E+01	1.99E-05	28%
OH -12	3.03E+00	4.82E-02	1%	4.00E+00	1.83E-02	13%	1.11E+01	1.55E-05	29%
HL -2	2.71E+00	6.66E-02	0%	3.47E+00	3.12E-02	7%	1.02E+01	3.69E-05	25%
HL -6	2.73E+00	6.53E-02	0%	3.47E+00	3.12E-02	7%	1.02E+01	3.62E-05	25%
HL -12	2.57E+00	7.69E-02	0%	3.59E+00	2.76E-02	8%	1.02E+01	3.73E-05	25%
HM -2	2.86E+00	5.73E-02	0%	3.59E+00	2.76E-02	8%	1.05E+01	2.76E-05	26%
HM -6	2.81E+00	6.04E-02	0%	3.78E+00	2.27E-02	11%	1.05E+01	2.67E-05	26%
HM -12	3.36E+00	3.48E-02	5%	3.72E+00	2.41E-02	10%	1.10E+01	1.67E-05	29%
HH -2	3.34E+00	3.54E-02	5%	3.55E+00	2.86E-02	8%	1.10E+01	1.65E-05	29%

Scenario	BD(R,Rr)	ρ(R,Rr)	PR	BD(el,az)	ρ(el,az)	PR	BD(All)	ρ(All)	PR
HH -6	3.79E+00	2.26E-02	11%	4.73E+00	8.79E-03	21%	1.28E+01	2.86E-06	36%
HH -12	4.86E+00	7.77E-03	22%	3.71E+00	2.44E-02	10%	1.25E+01	3.86E-06	35%

Table A.18 Sentinel-1A Reachability analysis and probability from BD for small manoeuvres.

Sentinel-1B Scenario

Scenario	MD(R,Rr)	PR	MD(el,az)	PR	MD(All)	PR
Sentinel-1B Tangential Low -2	7.90E-01	0%	5.48E-01	0%	9.83E-01	0%
Sentinel-1B Tangential Low -6	7.44E-01	0%	1.11E+00	0%	1.36E+00	0%
Sentinel-1B Tangential Low -12	4.72E-01	0%	1.90E+00	67%	1.97E+00	15%
Sentinel-1B Tangential Medium -2	5.34E-01	0%	7.63E-01	0%	1.03E+00	0%
Sentinel-1B Tangential Medium -6	1.20E+00	2%	1.85E+00	64%	2.41E+00	58%
Sentinel-1B Tangential Medium -12	6.69E-01	0%	4.23E-01	0%	8.10E-01	0%
Sentinel-1B Tangential High -2	6.59E-02	0%	8.28E-01	0%	9.04E-01	0%
Sentinel-1B Tangential High -6	2.64E-01	0%	1.82E+00	61%	1.93E+00	11%
Sentinel-1B Tangential High -12	6.20E-01	0%	8.49E-01	0%	1.05E+00	0%
Sentinel-1B Out-of-plane Low -2	5.10E-01	0%	6.43E-01	0%	8.84E-01	0%
Sentinel-1B Out-of-plane Low -6	8.59E-02	0%	1.45E+00	30%	1.62E+00	0%
Sentinel-1B Out-of-plane Low -12	7.20E-01	0%	2.24E+00	84%	2.50E+00	64%
Sentinel-1B Out-of-plane Medium -2	2.13E+00	79%	3.64E-01	0%	2.17E+00	37%
Sentinel-1B Out-of-plane Medium -6	2.24E+00	84%	5.17E-01	0%	2.30E+00	48%
Sentinel-1B Out-of-plane Medium -12	9.86E-01	0%	6.64E-01	0%	1.23E+00	0%
Sentinel-1B Out-of-plane High -2	6.40E+00	100%	1.96E+00	71%	6.75E+00	100%
Sentinel-1B Out-of-plane High -6	5.40E+00	100%	9.54E-01	0%	5.48E+00	100%
Sentinel-1B Out-of-plane High -12	6.43E+00	100%	1.14E+00	0%	6.53E+00	100%
Sentinel-1B Hybrid Low -2	4.55E-01	0%	2.56E+00	92%	2.61E+00	71%
Sentinel-1B Hybrid Low -6	7.66E-01	0%	1.23E+00	6%	1.54E+00	0%
Sentinel-1B Hybrid Low -12	9.92E-02	0%	7.75E-01	0%	7.87E-01	0%
Sentinel-1B Hybrid Medium -2	3.12E-02	0%	1.03E+00	0%	1.16E+00	0%
Sentinel-1B Hybrid Medium -6	1.84E-01	0%	2.15E+00	80%	2.36E+00	54%
Sentinel-1B Hybrid Medium -12	5.21E-01	0%	1.97E+00	71%	2.05E+00	24%
Sentinel-1B Hybrid High -2	1.11E+00	0%	1.33E+00	17%	1.76E+00	0%
Sentinel-1B Hybrid High -6	4.38E-01	0%	2.51E+00	91%	2.56E+00	68%
Sentinel-1B Hybrid High -12	6.07E-01	0%	2.22E+00	83%	2.25E+00	44%

Table A.19 Sentinel-1B Reachability analysis and probability from MD for small manoeuvres.

Scenario	KLD(R,Rr)	PR	KLD(el,az)	PR
Sentinel-1B Tangential Low -2	2.97E+01	0%	7.24E+05	100%
Sentinel-1B Tangential Low -6	2.86E+01	0%	1.38E+06	100%
Sentinel-1B Tangential Low -12	2.32E+01	0%	3.01E+06	100%
Sentinel-1B Tangential Medium -2	2.44E+01	0%	7.00E+05	100%
Sentinel-1B Tangential Medium -6	4.37E+01	0%	7.32E+05	100%
Sentinel-1B Tangential Medium -12	2.74E+01	0%	6.93E+05	100%
Sentinel-1B Tangential High -2	1.93E+01	0%	8.47E+05	100%
Sentinel-1B Tangential High -6	2.06E+01	0%	2.14E+06	100%
Sentinel-1B Tangential High -12	2.61E+01	0%	1.01E+06	100%
Sentinel-1B Out-of-plane Low -2	2.37E+01	0%	7.46E+05	100%
Sentinel-1B Out-of-plane Low -6	1.93E+01	0%	6.78E+05	100%
Sentinel-1B Out-of-plane Low -12	2.85E+01	0%	2.56E+06	100%
Sentinel-1B Out-of-plane Medium -2	9.53E+01	22%	6.75E+05	100%

Scenario	KLD(R,Rr)	PR	KLD(el,az)	PR
Sentinel-1B Out-of-plane Medium -6	1.05E+02	27%	7.98E+05	100%
Sentinel-1B Out-of-plane Medium -12	3.63E+01	0%	6.90E+05	100%
Sentinel-1B Out-of-plane High -2	7.07E+02	98%	1.94E+06	100%
Sentinel-1B Out-of-plane High -6	5.14E+02	95%	1.13E+06	100%
Sentinel-1B Out-of-plane High -12	7.16E+02	98%	1.39E+06	100%
Sentinel-1B Hybrid Low -2	2.26E+01	0%	4.90E+06	100%
Sentinel-1B Hybrid Low -6	2.97E+01	0%	1.03E+06	100%
Sentinel-1B Hybrid Low -12	1.96E+01	0%	1.07E+06	100%
Sentinel-1B Hybrid Medium -2	1.94E+01	0%	6.73E+05	100%
Sentinel-1B Hybrid Medium -6	1.93E+01	0%	9.43E+05	100%
Sentinel-1B Hybrid Medium -12	2.24E+01	0%	2.25E+06	100%
Sentinel-1B Hybrid High -2	3.97E+01	0%	1.72E+06	100%
Sentinel-1B Hybrid High -6	2.19E+01	0%	4.05E+06	100%
Sentinel-1B Hybrid High -12	2.00E+01	0%	1.58E+06	100%

Table A.20 Sentinel-1B Reachability analysis and probability from KLD for small manoeuvres.

Scenario	BD(R,Rr)	ρ(R,Rr)	PR	BD(el,az)	ρ(el,az)	PR	BD(All)	ρ(All)	PR
TL -2	3.11E+00	4.45E-02	2%	3.31E+00	3.66E-02	5%	1.07E+01	2.35E-05	27%
TL -6	3.10E+00	4.49E-02	2%	3.43E+00	3.25E-02	6%	1.08E+01	2.10E-05	28%
TL -12	3.06E+00	4.68E-02	2%	3.73E+00	2.41E-02	10%	1.10E+01	1.63E-05	29%
TM -2	3.07E+00	4.63E-02	2%	3.35E+00	3.51E-02	5%	1.07E+01	2.31E-05	27%
TM -6	3.21E+00	4.02E-02	4%	3.70E+00	2.47E-02	10%	1.13E+01	1.28E-05	30%
TM -12	3.10E+00	4.52E-02	2%	3.30E+00	3.69E-02	5%	1.06E+01	2.43E-05	27%
TH -2	3.04E+00	4.81E-02	1%	3.36E+00	3.49E-02	5%	1.06E+01	2.40E-05	27%
TH -6	3.05E+00	4.76E-02	1%	3.69E+00	2.51E-02	9%	1.10E+01	1.66E-05	29%
TH -12	3.09E+00	4.56E-02	2%	3.37E+00	3.44E-02	6%	1.07E+01	2.29E-05	27%
OL -2	3.07E+00	4.66E-02	2%	3.32E+00	3.60E-02	5%	1.06E+01	2.40E-05	27%
OL -6	3.04E+00	4.80E-02	1%	3.53E+00	2.92E-02	8%	1.09E+01	1.91E-05	28%
OL -12	3.10E+00	4.50E-02	2%	3.91E+00	2.01E-02	12%	1.13E+01	1.21E-05	30%
OM -2	3.60E+00	2.73E-02	8%	3.29E+00	3.73E-02	5%	1.11E+01	1.47E-05	29%
OM -6	3.66E+00	2.57E-02	9%	3.31E+00	3.66E-02	5%	1.12E+01	1.37E-05	30%
OM -12	3.16E+00	4.24E-02	3%	3.33E+00	3.57E-02	5%	1.07E+01	2.18E-05	27%
OH -2	8.16E+00	2.85E-04	50%	3.75E+00	2.35E-02	10%	1.62E+01	8.90E-08	49%
OH -6	6.68E+00	1.26E-03	39%	3.39E+00	3.38E-02	6%	1.43E+01	6.17E-07	43%
OH -12	8.20E+00	2.75E-04	50%	3.43E+00	3.23E-02	6%	1.59E+01	1.29E-07	48%
HL -2	3.06E+00	4.69E-02	2%	4.09E+00	1.67E-02	14%	1.14E+01	1.13E-05	30%
HL -6	3.11E+00	4.45E-02	2%	3.46E+00	3.13E-02	7%	1.08E+01	1.96E-05	28%
HL -12	3.04E+00	4.79E-02	1%	3.35E+00	3.51E-02	5%	1.06E+01	2.44E-05	27%
HM -2	3.03E+00	4.81E-02	1%	3.41E+00	3.31E-02	6%	1.07E+01	2.24E-05	27%
HM -6	3.04E+00	4.81E-02	1%	3.84E+00	2.14E-02	11%	1.12E+01	1.32E-05	30%
HM -12	3.07E+00	4.66E-02	2%	3.76E+00	2.33E-02	10%	1.11E+01	1.57E-05	29%
HH -2	3.19E+00	4.13E-02	3%	3.49E+00	3.04E-02	7%	1.09E+01	1.80E-05	28%
HH -6	3.06E+00	4.68E-02	2%	4.06E+00	1.72E-02	14%	1.14E+01	1.16E-05	30%
HH -12	3.09E+00	4.57E-02	2%	3.89E+00	2.04E-02	12%	1.12E+01	1.40E-05	30%

Table A.21 Sentinel-1B Reachability analysis and probability from BD for small manoeuvres.

Sentinel-2A Scenario

Scenario	MD(R,Rr)	PR	MD(el,az)	PR	MD(All)	PR
Sentinel-2A Tangential Low -2	1.26E+00	0%	2.62E+00	100%	2.95E+00	100%
Sentinel-2A Tangential Low -6	9.33E-01	0%	4.32E-01	0%	1.03E+00	0%
Sentinel-2A Tangential Low -12	9.36E-01	0%	6.94E-01	0%	1.19E+00	0%

Scenario	MD(R,Rr)	PR	MD(el,az)	PR	MD(All)	PR
Sentinel-2A Tangential Medium -2	7.10E-01	0%	5.79E-01	0%	9.16E-01	0%
Sentinel-2A Tangential Medium -6	1.02E+00	0%	1.26E+00	0%	1.63E+00	0%
Sentinel-2A Tangential Medium -12	7.27E-01	0%	1.12E+00	0%	1.38E+00	0%
Sentinel-2A Tangential High -2	1.22E+00	0%	6.69E-01	0%	1.40E+00	0%
Sentinel-2A Tangential High -6	6.62E-01	0%	1.62E+00	0%	1.73E+00	0%
Sentinel-2A Tangential High -12	5.79E-01	0%	1.33E-01	0%	5.89E-01	0%
Sentinel-2A Out-of-plane Low -2	8.77E-02	0%	2.69E+00	100%	2.70E+00	100%
Sentinel-2A Out-of-plane Low -6	7.83E-01	0%	6.98E-01	0%	1.05E+00	0%
Sentinel-2A Out-of-plane Low -12	1.15E+00	0%	1.27E+00	0%	1.71E+00	0%
Sentinel-2A Out-of-plane Medium -2	2.38E-01	0%	7.14E-01	0%	7.71E-01	0%
Sentinel-2A Out-of-plane Medium -6	6.50E-01	0%	5.33E-01	0%	8.41E-01	0%
Sentinel-2A Out-of-plane Medium -12	4.17E-01	0%	1.34E+00	0%	1.43E+00	0%
Sentinel-2A Out-of-plane High -2	3.83E+00	100%	2.71E+00	100%	4.70E+00	100%
Sentinel-2A Out-of-plane High -6	2.67E+00	100%	1.20E+00	0%	2.93E+00	100%
Sentinel-2A Out-of-plane High -12	4.34E+00	100%	1.72E+00	100%	4.67E+00	100%
Sentinel-2A Hybrid Low -2	1.15E+00	0%	1.63E+00	0%	2.01E+00	0%
Sentinel-2A Hybrid Low -6	6.49E-01	0%	1.39E+00	0%	1.53E+00	0%
Sentinel-2A Hybrid Low -12	1.73E+00	100%	1.27E+00	0%	2.14E+00	0%
Sentinel-2A Hybrid Medium -2	1.43E+00	0%	8.31E-01	0%	1.65E+00	0%
Sentinel-2A Hybrid Medium -6	1.69E+00	100%	5.83E-01	0%	1.78E+00	0%
Sentinel-2A Hybrid Medium -12	1.58E+00	0%	3.41E-01	0%	1.60E+00	0%
Sentinel-2A Hybrid High -2	1.58E+00	0%	1.50E+00	0%	2.17E+00	0%
Sentinel-2A Hybrid High -6	1.28E+00	0%	4.40E-01	0%	1.44E+00	0%
Sentinel-2A Hybrid High -12	1.98E+00	100%	6.32E-01	0%	2.00E+00	0%

Table A.22 Sentinel-2A Reachability analysis and probability from MD for small manoeuvres.

Scenario	KLD(R,Rr)	PR	KLD(el,az)	PR
Sentinel-2A Tangential Low -2	9.98E+00	0%	3.48E+05	100%
Sentinel-2A Tangential Low -6	7.89E+00	0%	1.85E+05	100%
Sentinel-2A Tangential Low -12	7.94E+00	0%	1.69E+05	100%
Sentinel-2A Tangential Medium -2	6.79E+00	0%	2.09E+05	100%
Sentinel-2A Tangential Medium -6	8.39E+00	0%	4.07E+05	100%
Sentinel-2A Tangential Medium -12	6.74E+00	0%	2.38E+05	100%
Sentinel-2A Tangential High -2	9.82E+00	0%	1.70E+05	100%
Sentinel-2A Tangential High -6	6.39E+00	0%	1.74E+05	100%
Sentinel-2A Tangential High -12	5.59E+00	0%	1.71E+05	100%
Sentinel-2A Out-of-plane Low -2	5.22E+00	0%	1.23E+06	100%
Sentinel-2A Out-of-plane Low -6	7.11E+00	0%	2.20E+05	100%
Sentinel-2A Out-of-plane Low -12	9.32E+00	0%	4.10E+05	100%
Sentinel-2A Out-of-plane Medium -2	5.36E+00	0%	1.93E+05	100%
Sentinel-2A Out-of-plane Medium -6	6.48E+00	0%	1.97E+05	100%
Sentinel-2A Out-of-plane Medium -12	5.75E+00	0%	2.83E+05	100%
Sentinel-2A Out-of-plane High -2	5.06E+01	0%	7.40E+05	100%
Sentinel-2A Out-of-plane High -6	2.72E+01	0%	3.91E+05	100%
Sentinel-2A Out-of-plane High -12	6.38E+01	0%	6.05E+05	100%
Sentinel-2A Hybrid Low -2	9.27E+00	0%	2.99E+05	100%
Sentinel-2A Hybrid Low -6	6.45E+00	0%	4.61E+05	100%
Sentinel-2A Hybrid Low -12	1.44E+01	0%	3.62E+05	100%
Sentinel-2A Hybrid Medium -2	1.15E+01	0%	2.82E+05	100%
Sentinel-2A Hybrid Medium -6	1.35E+01	0%	2.11E+05	100%
Sentinel-2A Hybrid Medium -12	1.10E+01	0%	1.78E+05	100%
Sentinel-2A Hybrid High -2	1.28E+01	0%	1.75E+05	100%
Sentinel-2A Hybrid High -6	7.93E+00	0%	1.71E+05	100%

Scenario	KLD(R,Rr)	PR	KLD(el,az)	PR
Sentinel-2A Hybrid High -12	9.12E+00	0%	1.68E+05	100%

Table A.23 Sentinel-2A Reachability analysis and probability from KLD for small manoeuvres.

Scenario	BD(R,Rr)	ρ(R,Rr)	PR	BD(el,az)	ρ(el,az)	PR	BD(All)	ρ(All)	PR
TL -2	2.21E+00	1.10E-01	0%	4.13E+00	1.61E-02	17%	1.07E+01	2.16E-05	30%
TL -6	2.13E+00	1.19E-01	0%	3.29E+00	3.71E-02	7%	9.80E+00	5.56E-05	25%
TL -12	2.13E+00	1.19E-01	0%	3.33E+00	3.57E-02	8%	9.83E+00	5.37E-05	25%
TM -2	2.08E+00	1.25E-01	0%	3.32E+00	3.62E-02	8%	9.76E+00	5.76E-05	25%
TM -6	2.15E+00	1.17E-01	0%	3.47E+00	3.12E-02	9%	9.99E+00	4.58E-05	26%
TM -12	2.08E+00	1.25E-01	0%	3.43E+00	3.25E-02	9%	9.89E+00	5.05E-05	25%
TH -2	2.21E+00	1.10E-01	0%	3.33E+00	3.59E-02	8%	9.91E+00	4.99E-05	26%
TH -6	2.07E+00	1.26E-01	0%	3.60E+00	2.74E-02	11%	1.00E+01	4.39E-05	26%
TH -12	2.06E+00	1.27E-01	0%	3.27E+00	3.78E-02	7%	9.70E+00	6.10E-05	25%
OL -2	2.02E+00	1.33E-01	0%	4.17E+00	1.54E-02	17%	1.06E+01	2.57E-05	29%
OL -6	2.10E+00	1.23E-01	0%	3.33E+00	3.58E-02	8%	9.80E+00	5.53E-05	25%
OL -12	2.18E+00	1.13E-01	0%	3.47E+00	3.10E-02	10%	1.00E+01	4.44E-05	26%
OM -2	2.03E+00	1.32E-01	0%	3.33E+00	3.57E-02	8%	9.74E+00	5.91E-05	25%
OM -6	2.07E+00	1.26E-01	0%	3.31E+00	3.66E-02	8%	9.74E+00	5.86E-05	25%
OM -12	2.04E+00	1.30E-01	0%	3.49E+00	3.04E-02	10%	9.92E+00	4.94E-05	26%
OH -2	3.86E+00	2.12E-02	14%	4.19E+00	1.52E-02	18%	1.24E+01	4.03E-06	37%
OH -6	2.91E+00	5.46E-02	3%	3.45E+00	3.16E-02	9%	1.07E+01	2.20E-05	29%
OH -12	4.37E+00	1.26E-02	20%	3.64E+00	2.62E-02	12%	1.24E+01	4.20E-06	37%
HL -2	2.18E+00	1.13E-01	0%	3.60E+00	2.73E-02	11%	1.02E+01	3.86E-05	27%
HL -6	2.07E+00	1.26E-01	0%	3.51E+00	2.98E-02	10%	9.95E+00	4.76E-05	26%
HL -12	2.39E+00	9.13E-02	0%	3.47E+00	3.12E-02	9%	1.02E+01	3.59E-05	27%
HM -2	2.27E+00	1.03E-01	0%	3.36E+00	3.48E-02	8%	1.00E+01	4.54E-05	26%
HM -6	2.38E+00	9.29E-02	0%	3.31E+00	3.64E-02	8%	1.01E+01	4.30E-05	26%
HM -12	2.33E+00	9.71E-02	0%	3.29E+00	3.74E-02	7%	9.98E+00	4.62E-05	26%
HH -2	2.33E+00	9.75E-02	0%	3.55E+00	2.87E-02	10%	1.02E+01	3.54E-05	27%
HH -6	2.22E+00	1.08E-01	0%	3.29E+00	3.72E-02	7%	9.92E+00	4.94E-05	26%
HH -12	2.51E+00	8.14E-02	0%	3.32E+00	3.61E-02	8%	1.02E+01	3.87E-05	27%

Table A.24 Sentinel-2A Reachability analysis and probability from BD for small manoeuvres.

Sentinel-2B Scenario

Scenario	MD(R,Rr)	PR	MD(el,az)	PR	MD(All)	PR
Sentinel-2B Tangential Low -2	9.38E-01	0%	7.95E-01	0%	1.23E+00	0%
Sentinel-2B Tangential Low -6	8.67E-02	0%	1.37E+00	22%	1.41E+00	0%
Sentinel-2B Tangential Low -12	2.06E-01	0%	9.26E-01	0%	9.59E-01	0%
Sentinel-2B Tangential Medium -2	1.34E+00	18%	9.12E-01	0%	1.62E+00	0%
Sentinel-2B Tangential Medium -6	1.17E+00	0%	2.20E+00	82%	2.49E+00	63%
Sentinel-2B Tangential Medium -12	2.26E-01	0%	1.48E+00	33%	1.49E+00	0%
Sentinel-2B Tangential High -2	1.26E-01	0%	4.66E-01	0%	4.82E-01	0%
Sentinel-2B Tangential High -6	2.10E-01	0%	5.68E-01	0%	6.41E-01	0%
Sentinel-2B Tangential High -12	6.80E-01	0%	1.47E+00	32%	1.58E+00	0%
Sentinel-2B Out-of-plane Low -2	2.38E-01	0%	2.06E+00	76%	2.12E+00	31%
Sentinel-2B Out-of-plane Low -6	1.03E+00	0%	1.86E+00	64%	2.13E+00	33%
Sentinel-2B Out-of-plane Low -12	2.08E-01	0%	3.82E-01	0%	4.41E-01	0%
Sentinel-2B Out-of-plane Medium -2	8.87E-01	0%	1.70E+00	53%	1.92E+00	10%
Sentinel-2B Out-of-plane Medium -6	1.12E+00	0%	1.07E+00	0%	1.56E+00	0%
Sentinel-2B Out-of-plane Medium -12	1.15E-01	0%	7.58E-01	0%	7.89E-01	0%
Sentinel-2B Out-of-plane High -2	1.61E+00	45%	1.18E+00	1%	2.00E+00	19%

Scenario	MD(R,Rr)	PR	MD(el,az)	PR	MD(All)	PR
Sentinel-2B Out-of-plane High -6	6.73E-01	0%	1.36E+00	21%	1.54E+00	0%
Sentinel-2B Out-of-plane High -12	1.66E+00	50%	7.82E-01	0%	1.84E+00	1%
Sentinel-2B Hybrid Low -2	1.33E+00	17%	1.07E+00	0%	1.71E+00	0%
Sentinel-2B Hybrid Low -6	1.13E+00	0%	1.31E+00	15%	1.74E+00	0%
Sentinel-2B Hybrid Low -12	9.27E-01	0%	2.05E+00	76%	2.25E+00	44%
Sentinel-2B Hybrid Medium -2	8.79E-01	0%	2.58E+00	93%	2.82E+00	81%
Sentinel-2B Hybrid Medium -6	6.69E-01	0%	8.16E-01	0%	1.13E+00	0%
Sentinel-2B Hybrid Medium -12	1.94E+00	70%	2.20E+00	82%	2.88E+00	84%
Sentinel-2B Hybrid High -2	6.15E-01	0%	1.22E+00	5%	1.36E+00	0%
Sentinel-2B Hybrid High -6	1.34E+00	18%	1.10E+00	0%	1.69E+00	0%
Sentinel-2B Hybrid High -12	1.95E+00	70%	7.24E-01	0%	2.00E+00	19%

Table A.25 Sentinel-2B Reachability analysis and probability from MD for small manoeuvres.

Scenario	KLD(R,Rr)	PR	KLD(el,az)	PR
Sentinel-2B Tangential Low -2	1.49E+01	0%	5.62E+05	100%
Sentinel-2B Tangential Low -6	8.94E+00	0%	3.89E+05	100%
Sentinel-2B Tangential Low -12	9.21E+00	0%	6.56E+05	100%
Sentinel-2B Tangential Medium -2	2.09E+01	0%	6.44E+05	100%
Sentinel-2B Tangential Medium -6	1.84E+01	0%	2.20E+06	100%
Sentinel-2B Tangential Medium -12	9.15E+00	0%	1.15E+06	100%
Sentinel-2B Tangential High -2	9.06E+00	0%	4.35E+05	100%
Sentinel-2B Tangential High -6	9.05E+00	0%	4.59E+05	100%
Sentinel-2B Tangential High -12	1.15E+01	0%	3.88E+05	100%
Sentinel-2B Out-of-plane Low -2	9.34E+00	0%	1.06E+06	100%
Sentinel-2B Out-of-plane Low -6	1.63E+01	0%	1.51E+06	100%
Sentinel-2B Out-of-plane Low -12	9.19E+00	0%	4.07E+05	100%
Sentinel-2B Out-of-plane Medium -2	1.43E+01	0%	1.41E+06	100%
Sentinel-2B Out-of-plane Medium -6	1.73E+01	0%	5.10E+05	100%
Sentinel-2B Out-of-plane Medium -12	9.10E+00	0%	3.92E+05	100%
Sentinel-2B Out-of-plane High -2	2.64E+01	0%	9.08E+05	100%
Sentinel-2B Out-of-plane High -6	1.20E+01	0%	7.11E+05	100%
Sentinel-2B Out-of-plane High -12	2.74E+01	0%	4.96E+05	100%
Sentinel-2B Hybrid Low -2	2.10E+01	0%	7.80E+05	100%
Sentinel-2B Hybrid Low -6	1.76E+01	0%	5.32E+05	100%
Sentinel-2B Hybrid Low -12	1.46E+01	0%	1.76E+06	100%
Sentinel-2B Hybrid Medium -2	1.41E+01	0%	5.38E+05	100%
Sentinel-2B Hybrid Medium -6	1.14E+01	0%	4.18E+05	100%
Sentinel-2B Hybrid Medium -12	3.25E+01	0%	4.01E+05	100%
Sentinel-2B Hybrid High -2	1.14E+01	0%	6.61E+05	100%
Sentinel-2B Hybrid High -6	1.88E+01	0%	6.96E+05	100%
Sentinel-2B Hybrid High -12	2.57E+01	0%	3.96E+05	100%

Table A.26 Sentinel-2B Reachability analysis and probability from KLD for small manoeuvres.

Scenario	BD(R,Rr)	ρ(R,Rr)	PR	BD(el,az)	ρ(el,az)	PR	BD(All)	ρ(All)	PR
TL -2	2.57E+00	7.64E-02	0%	3.47E+00	3.10E-02	7%	1.01E+01	4.00E-05	24%
TL -6	2.47E+00	8.49E-02	0%	3.62E+00	2.67E-02	9%	1.02E+01	3.75E-05	25%
TL -12	2.47E+00	8.48E-02	0%	3.50E+00	3.02E-02	7%	1.01E+01	4.28E-05	24%
TM -2	2.69E+00	6.82E-02	0%	3.50E+00	3.03E-02	7%	1.03E+01	3.46E-05	25%
TM -6	2.64E+00	7.13E-02	0%	4.00E+00	1.84E-02	13%	1.07E+01	2.21E-05	27%
TM -12	2.47E+00	8.45E-02	0%	3.66E+00	2.57E-02	9%	1.02E+01	3.66E-05	25%

Scenario	BD(R,Rr)	ρ(R,Rr)	PR	BD(el,az)	ρ(el,az)	PR	BD(All)	ρ(All)	PR
TM -2	2.47E+00	8.48E-02	0%	3.42E+00	3.27E-02	6%	9.98E+00	4.64E-05	24%
TH -6	2.47E+00	8.46E-02	0%	3.43E+00	3.23E-02	6%	1.00E+01	4.56E-05	24%
TH -12	2.53E+00	7.98E-02	0%	3.66E+00	2.57E-02	9%	1.03E+01	3.52E-05	25%
OL -2	2.47E+00	8.45E-02	0%	3.92E+00	1.97E-02	12%	1.05E+01	2.74E-05	26%
OL -6	2.60E+00	7.42E-02	0%	3.82E+00	2.18E-02	11%	1.05E+01	2.70E-05	26%
OL -12	2.47E+00	8.44E-02	0%	3.41E+00	3.31E-02	6%	9.97E+00	4.70E-05	24%
OM -2	2.56E+00	7.70E-02	0%	3.75E+00	2.35E-02	10%	1.04E+01	3.04E-05	26%
OM -6	2.62E+00	7.29E-02	0%	3.54E+00	2.91E-02	8%	1.02E+01	3.56E-05	25%
OM -12	2.47E+00	8.47E-02	0%	3.47E+00	3.13E-02	7%	1.00E+01	4.44E-05	24%
OH -2	2.79E+00	6.15E-02	0%	3.57E+00	2.82E-02	8%	1.04E+01	2.91E-05	26%
OH -6	2.52E+00	8.02E-02	0%	3.62E+00	2.68E-02	9%	1.02E+01	3.60E-05	25%
OH -12	2.81E+00	6.02E-02	0%	3.46E+00	3.13E-02	7%	1.04E+01	3.15E-05	26%
HL -2	2.69E+00	6.82E-02	0%	3.54E+00	2.91E-02	8%	1.03E+01	3.34E-05	25%
HL -6	2.62E+00	7.25E-02	0%	3.61E+00	2.71E-02	9%	1.03E+01	3.28E-05	25%
HL -12	2.57E+00	7.63E-02	0%	3.91E+00	2.00E-02	12%	1.06E+01	2.55E-05	27%
HM -2	2.56E+00	7.73E-02	0%	4.22E+00	1.46E-02	16%	1.09E+01	1.78E-05	28%
HM -6	2.52E+00	8.06E-02	0%	3.47E+00	3.11E-02	7%	1.01E+01	4.13E-05	24%
HM -12	2.94E+00	5.30E-02	0%	4.00E+00	1.83E-02	13%	1.10E+01	1.70E-05	29%
HH -2	2.51E+00	8.11E-02	0%	3.57E+00	2.81E-02	8%	1.02E+01	3.84E-05	25%
HH -6	2.69E+00	6.80E-02	0%	3.55E+00	2.89E-02	8%	1.03E+01	3.36E-05	25%
HH -12	2.94E+00	5.28E-02	0%	3.46E+00	3.16E-02	7%	1.04E+01	2.92E-05	26%

Table A.27 Sentinel-2B Reachability analysis and probability from BD for small manoeuvres.

Swarm-C Scenario

Scenario	MD(R,Rr)	PR	MD(el,az)	PR	MD(All)	PR
Swarm-C Tangential Low -2	1.15E+00	0%	8.62E-01	0%	1.17E+00	0%
Swarm-C Tangential Low -6	1.12E+00	0%	8.79E-01	0%	1.36E+00	0%
Swarm-C Tangential Low -12	1.05E+00	0%	1.51E+00	36%	1.88E+00	6%
Swarm-C Tangential Medium -2	1.78E+00	59%	1.06E-01	0%	1.96E+00	14%
Swarm-C Tangential Medium -6	2.10E+00	78%	1.58E+00	43%	2.48E+00	62%
Swarm-C Tangential Medium -12	1.83E+00	63%	1.60E+00	45%	2.23E+00	42%
Swarm-C Tangential High -2	1.07E+00	0%	2.31E+00	86%	2.33E+00	51%
Swarm-C Tangential High -6	1.00E+00	0%	1.88E+00	66%	1.91E+00	9%
Swarm-C Tangential High -12	1.38E+00	22%	1.50E+00	35%	2.61E+00	71%
Swarm-C Out-of-plane Low -2	1.90E+00	67%	1.24E+00	8%	2.22E+00	41%
Swarm-C Out-of-plane Low -6	1.43E+00	28%	1.09E+00	0%	1.84E+00	0%
Swarm-C Out-of-plane Low -12	1.88E+00	66%	1.09E+00	0%	3.02E+00	88%
Swarm-C Out-of-plane Medium -2	3.12E+00	98%	2.19E+00	82%	3.66E+00	98%
Swarm-C Out-of-plane Medium -6	1.40E+00	25%	1.55E+00	39%	1.81E+00	0%
Swarm-C Out-of-plane Medium -12	1.33E+00	18%	8.97E-01	0%	2.43E+00	59%
Swarm-C Out-of-plane High -2	1.50E+01	100%	1.84E+00	63%	1.50E+01	100%
Swarm-C Out-of-plane High -6	9.90E+00	100%	1.09E+00	0%	1.01E+01	100%
Swarm-C Out-of-plane High -12	1.23E+01	100%	1.43E+00	28%	1.24E+01	100%
Swarm-C Hybrid Low -2	1.05E+00	0%	8.56E-01	0%	1.17E+00	0%
Swarm-C Hybrid Low -6	1.25E+00	8%	5.82E-01	0%	1.35E+00	0%
Swarm-C Hybrid Low -12	1.63E+00	47%	1.27E+00	10%	1.83E+00	0%
Swarm-C Hybrid Medium -2	1.02E+00	0%	9.13E-01	0%	1.09E+00	0%
Swarm-C Hybrid Medium -6	1.01E+00	0%	8.16E-01	0%	1.09E+00	0%
Swarm-C Hybrid Medium -12	1.10E+00	0%	6.69E-01	0%	1.51E+00	0%
Swarm-C Hybrid High -2	1.85E+00	64%	2.04E+00	75%	2.59E+00	70%
Swarm-C Hybrid High -6	1.78E+00	59%	1.28E+00	12%	2.65E+00	73%
Swarm-C Hybrid High -12	4.76E-01	0%	6.53E-01	0%	1.34E+00	0%

Table A.28 Swarm-C Reachability analysis and probability from MD for small manoeuvres.

Scenario	KLD(R,Rr)	PR	KLD(el,az)	PR
Swarm-C Tangential Low -2	6.44E+00	0%	2.29E+05	100%
Swarm-C Tangential Low -6	6.37E+00	0%	3.37E+05	100%
Swarm-C Tangential Low -12	6.07E+00	0%	7.17E+05	100%
Swarm-C Tangential Medium -2	1.06E+01	0%	2.23E+05	100%
Swarm-C Tangential Medium -6	1.33E+01	0%	5.59E+05	100%
Swarm-C Tangential Medium -12	1.12E+01	0%	3.79E+05	100%
Swarm-C Tangential High -2	6.15E+00	0%	9.77E+05	100%
Swarm-C Tangential High -6	6.05E+00	0%	4.04E+05	100%
Swarm-C Tangential High -12	8.17E+00	0%	6.04E+05	100%
Swarm-C Out-of-plane Low -2	1.14E+01	0%	5.10E+05	100%
Swarm-C Out-of-plane Low -6	8.09E+00	0%	4.74E+05	100%
Swarm-C Out-of-plane Low -12	1.14E+01	0%	2.69E+05	100%
Swarm-C Out-of-plane Medium -2	2.47E+01	0%	5.01E+05	100%
Swarm-C Out-of-plane Medium -6	7.91E+00	0%	2.22E+05	100%
Swarm-C Out-of-plane Medium -12	7.53E+00	0%	2.75E+05	100%
Swarm-C Out-of-plane High -2	4.90E+02	94%	5.78E+05	100%
Swarm-C Out-of-plane High -6	2.16E+02	66%	4.44E+05	100%
Swarm-C Out-of-plane High -12	3.33E+02	84%	2.25E+05	100%
Swarm-C Hybrid Low -2	6.05E+00	0%	2.87E+05	100%
Swarm-C Hybrid Low -6	7.07E+00	0%	2.52E+05	100%
Swarm-C Hybrid Low -12	9.63E+00	0%	2.98E+05	100%
Swarm-C Hybrid Medium -2	6.00E+00	0%	2.49E+05	100%
Swarm-C Hybrid Medium -6	6.29E+00	0%	2.52E+05	100%
Swarm-C Hybrid Medium -12	7.16E+00	0%	3.18E+05	100%
Swarm-C Hybrid High -2	1.14E+01	0%	5.34E+05	100%
Swarm-C Hybrid High -6	1.14E+01	0%	4.69E+05	100%
Swarm-C Hybrid High -12	5.64E+00	0%	2.33E+05	100%

Table A.29 Swarm-C Reachability analysis and probability from KLD for small manoeuvres.

Scenario	BD(R,Rr)	ρ(R,Rr)	PR	BD(el,az)	ρ(el,az)	PR	BD(All)	ρ(All)	PR
TL -2	2.59E+00	7.47E-02	0%	3.01E+00	4.95E-02	1%	9.98E+00	4.65E-05	24%
TL -6	2.58E+00	7.54E-02	0%	3.00E+00	4.97E-02	1%	1.00E+01	4.38E-05	24%
TL -12	2.57E+00	7.69E-02	0%	3.20E+00	4.09E-02	3%	1.02E+01	3.55E-05	25%
TM -2	2.83E+00	5.93E-02	0%	2.91E+00	5.46E-02	0%	1.03E+01	3.42E-05	25%
TM -6	2.98E+00	5.07E-02	1%	3.22E+00	4.01E-02	4%	1.06E+01	2.57E-05	27%
TM -12	2.85E+00	5.79E-02	0%	3.23E+00	3.95E-02	4%	1.04E+01	2.98E-05	26%
TH -2	2.57E+00	7.65E-02	0%	3.57E+00	2.81E-02	8%	1.05E+01	2.81E-05	26%
TH -6	2.55E+00	7.79E-02	0%	3.35E+00	3.49E-02	5%	1.03E+01	3.51E-05	25%
TH -12	2.66E+00	6.98E-02	0%	3.18E+00	4.15E-02	3%	1.07E+01	2.36E-05	27%
OL -2	2.88E+00	5.62E-02	0%	3.10E+00	4.49E-02	2%	1.04E+01	2.98E-05	26%
OL -6	2.68E+00	6.83E-02	0%	3.06E+00	4.68E-02	2%	1.02E+01	3.62E-05	25%
OL -12	2.87E+00	5.65E-02	0%	3.06E+00	4.71E-02	2%	1.09E+01	1.77E-05	28%
OM -2	3.65E+00	2.61E-02	9%	3.51E+00	2.99E-02	7%	1.15E+01	1.03E-05	31%
OM -6	2.67E+00	6.91E-02	0%	3.20E+00	4.07E-02	4%	1.02E+01	3.66E-05	25%
OM -12	2.65E+00	7.07E-02	0%	3.01E+00	4.95E-02	1%	1.05E+01	2.64E-05	26%
OH -2	3.05E+01	5.84E-14	97%	3.33E+00	3.58E-02	5%	3.81E+01	2.82E-17	88%
OH -6	1.47E+01	4.22E-07	79%	3.05E+00	4.72E-02	2%	2.24E+01	1.80E-10	66%
OH -12	2.14E+01	4.90E-10	91%	3.16E+00	4.23E-02	3%	2.90E+01	2.65E-13	78%
HL -2	2.57E+00	7.68E-02	0%	3.00E+00	4.97E-02	1%	9.97E+00	4.67E-05	24%
HL -6	2.63E+00	7.24E-02	0%	2.95E+00	5.24E-02	0%	1.00E+01	4.40E-05	24%
HL -12	2.76E+00	6.33E-02	0%	3.11E+00	4.44E-02	2%	1.02E+01	3.61E-05	25%
HM -2	2.56E+00	7.74E-02	0%	3.01E+00	4.91E-02	1%	9.95E+00	4.75E-05	24%
HM -6	2.56E+00	7.75E-02	0%	2.99E+00	5.04E-02	1%	9.95E+00	4.75E-05	24%
HM -12	2.58E+00	7.58E-02	0%	2.96E+00	5.18E-02	0%	1.01E+01	4.18E-05	24%
HH -2	2.86E+00	5.75E-02	0%	3.44E+00	3.22E-02	6%	1.06E+01	2.38E-05	27%

Scenario	BD(R,Rr)	ρ(R,Rr)	PR	BD(el,az)	ρ(el,az)	PR	BD(All)	ρ(All)	PR
HH -6	2.83E+00	5.93E-02	0%	3.11E+00	4.47E-02	2%	1.07E+01	2.30E-05	27%
HH -12	2.46E+00	8.57E-02	0%	2.96E+00	5.17E-02	0%	1.00E+01	4.42E-05	24%

Table A.30 Swarm-C Reachability analysis and probability from BD for small manoeuvres.

A.3 Analyses of the impact of different parameters

In this section, the distances and the probabilies obtained in the analyses of the different parameters are presented. In Section A.3.1, the tables of the mass analysis are shown. The values of the ballistic coefficient analysis are presented in Section A.3.2. In Section A.3.3, the distances and the probabilities obtained with the Marshall model are shown. Finally, in Sections A.3.4 and A.3.5, the tables of the Taylor order analysis and the computation methods of the covariance matrix analysis are presented.

In these analyses, only the distances computed using range-range rate have been employed. Thus, the distances and the probabilities of each satellite are presented in a single table. The MD appears in column 1, the KLD in column 3 and the BD and its coefficients in columns 5 and 6 respectively (with its respective probability value in the adjacent column on the right). It also contains a column with the number of plots of the segment.

These analyses are performed considering two scenarios, based on Sentinel-1A and Sentinel-2B. Then, for each case two tables are presented, one for each satellite.

A.3.1 Mass

Mass = 1500 Kg

Sentinel-1A

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-1A No manoeuvre	1.18E+00	0%	8.38E+00	0%	2.88E+00	5.63E-02	0%	9
Sentinel-1A No manoeuvre	1.81E-01	0%	6.04E+01	0%	2.34E+00	9.60E-02	0%	10
Sentinel-1A No manoeuvre	3.32E-01	0%	8.05E+00	0%	2.55E+00	7.83E-02	0%	9
Sentinel-1A No manoeuvre	1.77E+00	59%	5.58E+01	0%	2.82E+00	5.98E-02	0%	9
Sentinel-1A No manoeuvre	2.07E-01	0%	8.17E+01	13%	2.81E+00	6.00E-02	0%	10
Sentinel-1A No manoeuvre	1.29E-01	0%	1.83E+01	0%	1.98E+00	1.38E-01	0%	9
Sentinel-1A No manoeuvre	1.37E+01	100%	1.57E+04	100%	2.62E+01	4.29E-12	95%	2
Sentinel-1A No manoeuvre	6.69E-01	0%	3.34E+01	0%	2.58E+00	7.61E-02	0%	9
Sentinel-1A No manoeuvre	2.29E-01	0%	3.68E+01	0%	2.25E+00	1.05E-01	0%	9
Sentinel-1A No manoeuvre	1.50E+01	100%	6.01E+03	100%	3.08E+01	4.11E-14	97%	2
Sentinel-1A No manoeuvre	1.06E+00	0%	2.50E+01	0%	2.60E+00	7.44E-02	0%	9
Sentinel-1A No manoeuvre	1.28E+00	11%	1.20E+02	35%	2.56E+00	7.75E-02	0%	11
Sentinel-1A No manoeuvre	2.48E-01	0%	8.80E+00	0%	2.61E+00	7.32E-02	0%	10
Sentinel-1A No manoeuvre	5.50E-01	0%	2.47E+01	0%	2.50E+00	8.21E-02	0%	8
Sentinel-1A No manoeuvre	1.22E+00	5%	1.18E+02	33%	2.93E+00	5.36E-02	0%	9
Sentinel-1A No manoeuvre	2.54E+00	92%	2.55E+02	74%	3.05E+00	4.75E-02	2%	8
Sentinel-1A No manoeuvre	1.15E-01	0%	5.80E+00	0%	2.69E+00	6.80E-02	0%	9
Sentinel-1A No manoeuvre	4.23E-01	0%	6.39E+01	0%	2.46E+00	8.56E-02	0%	10
Sentinel-1A No manoeuvre	9.35E-01	0%	1.57E+01	0%	2.68E+00	6.84E-02	0%	9
Sentinel-1A No manoeuvre	3.49E-02	0%	1.58E+01	0%	2.41E+00	8.99E-02	0%	10
Sentinel-1A No manoeuvre	2.04E-01	0%	6.73E+01	3%	2.88E+00	5.63E-02	0%	10
Sentinel-1A No manoeuvre	9.95E-01	0%	3.35E+01	0%	2.18E+00	1.14E-01	0%	9
Sentinel-1A No manoeuvre	1.40E+01	100%	1.78E+04	100%	2.72E+01	1.51E-12	96%	2
Sentinel-1A No manoeuvre	2.28E-01	0%	2.00E+01	0%	2.58E+00	7.57E-02	0%	9
Sentinel-1A No manoeuvre	9.49E-02	0%	4.45E+01	0%	2.45E+00	8.61E-02	0%	9
Sentinel-1A Tangential Low -2	7.36E-01	0%	1.00E+01	0%	2.60E+00	7.45E-02	0%	9
Sentinel-1A Tangential Low -6	5.07E-01	0%	8.36E+00	0%	2.56E+00	7.73E-02	0%	9
Sentinel-1A Tangential Low -12	2.29E+00	85%	3.21E+01	0%	3.18E+00	4.14E-02	3%	9
Sentinel-1A Tangential Medium -2	4.20E+00	100%	9.00E+01	19%	4.74E+00	8.75E-03	21%	9
Sentinel-1A Tangential Medium -6	6.37E+00	100%	1.92E+02	60%	7.60E+00	5.01E-04	46%	9
Sentinel-1A Tangential Medium -12	6.38E+00	100%	1.84E+02	58%	7.62E+00	4.89E-04	46%	9
Sentinel-1A Tangential High -2	1.47E+01	100%	1.03E+03	100%	2.95E+01	1.48E-13	97%	9

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-1A Tangential High -6	3.18E+01	100%	4.74E+03	100%	1.29E+02	1.32E-56	100%	9
Sentinel-1A Tangential High -12	3.78E+01	100%	6.49E+03	100%	1.81E+02	1.52E-79	100%	9
Sentinel-1A Out-of-plane Low -2	3.00E+01	100%	4.33E+03	100%	1.15E+02	8.03E-51	100%	9
Sentinel-1A Out-of-plane Low -6	2.79E+01	100%	3.72E+03	100%	9.99E+01	4.06E-44	100%	9
Sentinel-1A Out-of-plane Low -12	3.07E+01	100%	4.59E+03	100%	1.20E+02	5.75E-53	100%	9
Sentinel-1A Out-of-plane Medium -2	6.15E+01	100%	1.82E+04	100%	4.76E+02	2.05E-207	100%	9
Sentinel-1A Out-of-plane Medium -6	5.37E+01	100%	1.39E+04	100%	3.62E+02	3.92E-158	100%	9
Sentinel-1A Out-of-plane Medium -12	5.90E+01	100%	1.66E+04	100%	4.38E+02	5.97E-191	100%	9
Sentinel-1A Out-of-plane High -2	1.26E+02	100%	7.74E+04	100%	1.99E+03	0.00E+00	100%	9
Sentinel-1A Out-of-plane High -6	1.01E+02	100%	4.86E+04	100%	1.28E+03	0.00E+00	100%	9
Sentinel-1A Out-of-plane High -12	1.21E+02	100%	7.08E+04	100%	1.84E+03	0.00E+00	100%	9
Sentinel-1A Hybrid Low -2	8.10E+00	100%	3.20E+02	82%	1.07E+01	2.18E-05	64%	9
Sentinel-1A Hybrid Low -6	7.61E+00	100%	2.75E+02	77%	9.78E+00	5.68E-05	59%	9
Sentinel-1A Hybrid Low -12	1.16E+01	100%	6.16E+02	97%	1.95E+01	3.44E-09	89%	9
Sentinel-1A Hybrid Medium -2	3.94E+01	100%	7.44E+03	100%	1.97E+02	4.41E-86	100%	9
Sentinel-1A Hybrid Medium -6	5.66E+01	100%	1.50E+04	100%	4.02E+02	1.95E-175	100%	9
Sentinel-1A Hybrid Medium -12	8.89E+01	100%	4.11E+04	100%	9.90E+02	0.00E+00	100%	10
Sentinel-1A Hybrid High -2	1.58E+02	100%	1.18E+05	100%	3.12E+03	0.00E+00	100%	9
Sentinel-1A Hybrid High -6	4.34E+02	100%	6.58E+05	100%	2.35E+04	0.00E+00	100%	9
Sentinel-1A Hybrid High -12	1.16E+03	100%	3.44E+06	100%	1.68E+05	0.00E+00	100%	9

Table A.31 Sentinel-1A Reachability analysis and probability from the three distances computed using range-range rate.

Sentinel-2B

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-2B No manoeuvre	3.05E-01	0%	1.24E+01	0%	2.23E+00	1.07E-01	0%	5
Sentinel-2B No manoeuvre	1.34E+01	100%	4.97E+03	100%	2.54E+01	9.08E-12	95%	3
Sentinel-2B No manoeuvre	5.29E-02	0%	9.02E+00	0%	2.47E+00	8.47E-02	0%	10
Sentinel-2B No manoeuvre	2.80E-01	0%	1.97E+01	0%	2.27E+00	1.03E-01	0%	10
Sentinel-2B No manoeuvre	8.73E-02	0%	5.20E+00	0%	2.08E+00	1.25E-01	0%	12
Sentinel-2B No manoeuvre	1.19E+00	2%	1.03E+02	26%	2.75E+00	6.36E-02	0%	11
Sentinel-2B No manoeuvre	1.10E+00	0%	1.03E+01	0%	3.03E+00	4.81E-02	1%	10
Sentinel-2B No manoeuvre	1.22E+00	5%	3.76E+01	0%	2.35E+00	9.56E-02	0%	11
Sentinel-2B No manoeuvre	3.24E-01	0%	5.99E+00	0%	2.19E+00	1.12E-01	0%	11
Sentinel-2B No manoeuvre	2.48E-01	0%	3.06E+01	0%	2.48E+00	8.38E-02	0%	11
Sentinel-2B No manoeuvre	8.83E-01	0%	9.79E+00	0%	3.03E+00	4.81E-02	1%	12
Sentinel-2B No manoeuvre	2.81E-01	0%	1.21E+01	0%	1.94E+00	1.43E-01	0%	12
Sentinel-2B No manoeuvre	1.41E+00	26%	1.88E+01	0%	2.66E+00	7.03E-02	0%	10
Sentinel-2B No manoeuvre	7.76E-01	0%	4.26E+01	0%	2.50E+00	8.21E-02	0%	9
Sentinel-2B No manoeuvre	6.94E-01	0%	1.50E+01	0%	2.42E+00	8.93E-02	0%	5
Sentinel-2B No manoeuvre	1.36E+01	100%	6.42E+03	100%	2.60E+01	5.19E-12	95%	3
Sentinel-2B No manoeuvre	4.41E-01	0%	1.23E+01	0%	2.59E+00	7.53E-02	0%	10
Sentinel-2B No manoeuvre	1.05E-01	0%	2.18E+01	0%	2.30E+00	1.00E-01	0%	10
Sentinel-2B No manoeuvre	2.00E+00	73%	1.55E+01	0%	2.56E+00	7.74E-02	0%	12
Sentinel-2B No manoeuvre	1.42E+00	27%	1.01E+02	25%	2.75E+00	6.40E-02	0%	12
Sentinel-2B No manoeuvre	1.07E+00	0%	9.31E+00	0%	3.03E+00	4.82E-02	1%	11
Sentinel-2B No manoeuvre	9.23E-01	0%	3.39E+01	0%	2.26E+00	1.04E-01	0%	11
Sentinel-2B No manoeuvre	1.47E+00	32%	1.54E+01	0%	2.53E+00	7.99E-02	0%	11
Sentinel-2B No manoeuvre	1.29E+00	13%	7.79E+01	11%	2.66E+00	6.99E-02	0%	10
Sentinel-2B No manoeuvre	3.75E-01	0%	7.29E+00	0%	2.94E+00	5.28E-02	0%	13
Sentinel-2B No manoeuvre	3.39E-01	0%	1.43E+01	0%	1.96E+00	1.41E-01	0%	12
Sentinel-2B No manoeuvre	6.19E-01	0%	1.03E+01	0%	2.48E+00	8.39E-02	0%	10
Sentinel-2B Tangential Low -2	1.01E-01	0%	9.02E+00	0%	2.47E+00	8.49E-02	0%	10
Sentinel-2B Tangential Low -6	5.30E-01	0%	1.00E+01	0%	2.50E+00	8.22E-02	0%	10
Sentinel-2B Tangential Low -12	1.18E+00	0%	1.53E+01	0%	2.64E+00	7.16E-02	0%	10
Sentinel-2B Tangential Medium -2	4.99E-01	0%	9.17E+00	0%	2.50E+00	8.21E-02	0%	10
Sentinel-2B Tangential Medium -6	4.71E+00	100%	1.34E+02	41%	5.24E+00	5.32E-03	26%	10
Sentinel-2B Tangential Medium -12	4.68E+00	100%	5.68E+01	0%	5.20E+00	5.52E-03	26%	10
Sentinel-2B Tangential High -2	7.04E+00	100%	3.16E+02	82%	8.66E+00	1.74E-04	53%	10
Sentinel-2B Tangential High -6	1.83E+01	100%	1.90E+03	100%	4.45E+01	4.56E-20	100%	10
Sentinel-2B Tangential High -12	1.64E+01	100%	2.47E+02	72%	3.61E+01	2.13E-16	99%	10
Sentinel-2B Out-of-plane Low -2	2.02E+00	74%	3.66E+01	0%	2.98E+00	5.09E-02	1%	10
Sentinel-2B Out-of-plane Low -6	1.15E+00	0%	1.77E+01	0%	2.63E+00	7.22E-02	0%	10
Sentinel-2B Out-of-plane Low -12	1.55E+00	39%	2.47E+01	0%	2.76E+00	6.34E-02	0%	10
Sentinel-2B Out-of-plane Medium -2	5.66E+00	100%	2.22E+02	67%	6.47E+00	1.55E-03	37%	10
Sentinel-2B Out-of-plane Medium -6	2.39E+00	88%	4.77E+01	0%	3.18E+00	4.17E-02	3%	10

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-2B Out-of-plane Medium -12	2.30E+00	86%	4.43E+01	0%	3.13E+00	4.38E-02	3%	10
Sentinel-2B Out-of-plane High -2	6.97E+00	100%	3.36E+02	84%	8.54E+00	1.95E-04	52%	10
Sentinel-2B Out-of-plane High -6	1.85E+00	64%	3.16E+01	0%	2.89E+00	5.56E-02	0%	10
Sentinel-2B Out-of-plane High -12	6.57E+00	100%	3.00E+02	80%	7.86E+00	3.85E-04	48%	10
Sentinel-2B Hybrid Low -2	1.14E+00	0%	1.43E+01	0%	2.63E+00	7.22E-02	0%	10
Sentinel-2B Hybrid Low -6	7.27E+00	100%	3.11E+02	82%	9.07E+00	1.15E-04	55%	10
Sentinel-2B Hybrid Low -12	6.67E+00	100%	8.63E+01	16%	8.02E+00	3.29E-04	49%	10
Sentinel-2B Hybrid Medium -2	1.34E+01	100%	1.15E+03	100%	2.50E+01	1.36E-11	95%	10
Sentinel-2B Hybrid Medium -6	4.13E+01	100%	1.02E+04	100%	2.16E+02	1.70E-94	100%	10
Sentinel-2B Hybrid Medium -12	2.96E+01	100%	6.36E+02	97%	1.12E+02	1.67E-49	100%	10
Sentinel-2B Hybrid High -2	5.54E+01	100%	1.93E+04	100%	3.86E+02	1.41E-168	100%	10
Sentinel-2B Hybrid High -6	2.35E+02	100%	4.45E+05	100%	6.92E+03	0.00E+00	100%	10
Sentinel-2B Hybrid High -12	3.19E+02	100%	9.51E+05	100%	1.27E+04	0.00E+00	100%	10

Table A.32 Sentinel-2B Reachability analysis and probability from the three distances computed using range-range rate.

Mass = 2000 Kg

Sentinel-1A

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-1A No manoeuvre	1.70E+00	53%	1.11E+01	0%	3.07E+00	4.66E-02	2%	9
Sentinel-1A No manoeuvre	2.45E-01	0%	6.13E+01	0%	2.35E+00	9.58E-02	0%	10
Sentinel-1A No manoeuvre	3.84E-01	0%	8.25E+00	0%	2.55E+00	7.80E-02	0%	9
Sentinel-1A No manoeuvre	6.49E-01	0%	2.03E+01	0%	2.48E+00	8.40E-02	0%	9
Sentinel-1A No manoeuvre	3.95E-01	0%	8.22E+01	14%	2.82E+00	5.96E-02	0%	10
Sentinel-1A No manoeuvre	3.17E-01	0%	1.93E+01	0%	1.99E+00	1.37E-01	0%	9
Sentinel-1A No manoeuvre	1.51E+01	100%	1.89E+04	100%	3.12E+01	2.77E-14	98%	2
Sentinel-1A No manoeuvre	4.81E-01	0%	2.60E+01	0%	2.54E+00	7.86E-02	0%	9
Sentinel-1A No manoeuvre	7.79E-01	0%	5.71E+01	0%	2.33E+00	9.71E-02	0%	9
Sentinel-1A No manoeuvre	1.45E+01	100%	5.81E+03	100%	2.92E+01	2.12E-13	97%	2
Sentinel-1A No manoeuvre	5.48E-01	0%	1.53E+01	0%	2.48E+00	8.40E-02	0%	9
Sentinel-1A No manoeuvre	1.56E+00	41%	1.61E+02	51%	2.67E+00	6.91E-02	0%	11
Sentinel-1A No manoeuvre	1.43E+00	28%	2.14E+01	0%	2.89E+00	5.58E-02	0%	10
Sentinel-1A No manoeuvre	1.23E+00	6%	6.09E+01	0%	2.73E+00	6.55E-02	0%	8
Sentinel-1A No manoeuvre	1.66E+00	50%	1.67E+02	53%	3.07E+00	4.66E-02	2%	9
Sentinel-1A No manoeuvre	1.48E+00	33%	1.16E+02	33%	2.55E+00	7.83E-02	0%	8
Sentinel-1A No manoeuvre	5.60E-01	0%	6.18E+00	0%	2.75E+00	6.41E-02	0%	9
Sentinel-1A No manoeuvre	9.14E-01	0%	1.07E+02	28%	2.57E+00	7.64E-02	0%	10
Sentinel-1A No manoeuvre	5.33E-01	0%	1.24E+01	0%	2.66E+00	7.00E-02	0%	9
Sentinel-1A No manoeuvre	1.52E+00	37%	4.35E+01	0%	2.64E+00	7.15E-02	0%	10
Sentinel-1A No manoeuvre	4.19E-01	0%	8.48E+01	15%	2.93E+00	5.35E-02	0%	10
Sentinel-1A No manoeuvre	8.63E-01	0%	3.34E+01	0%	2.21E+00	1.10E-01	0%	9
Sentinel-1A No manoeuvre	1.46E+01	100%	2.12E+04	100%	2.95E+01	1.55E-13	97%	2
Sentinel-1A No manoeuvre	3.69E-01	0%	1.80E+01	0%	2.54E+00	7.92E-02	0%	9
Sentinel-1A No manoeuvre	9.52E-01	0%	7.38E+01	8%	2.51E+00	8.10E-02	0%	9
Sentinel-1A Tangential Low -2	3.69E-01	0%	8.07E+00	0%	2.55E+00	7.80E-02	0%	9
Sentinel-1A Tangential Low -6	1.69E+00	52%	2.08E+01	0%	2.89E+00	5.56E-02	0%	9
Sentinel-1A Tangential Low -12	2.39E+00	88%	3.49E+01	0%	3.25E+00	3.89E-02	4%	9
Sentinel-1A Tangential Medium -2	5.80E+00	100%	1.72E+02	54%	6.74E+00	1.18E-03	39%	9
Sentinel-1A Tangential Medium -6	7.91E+00	100%	2.97E+02	80%	1.04E+01	3.18E-05	62%	9
Sentinel-1A Tangential Medium -12	6.81E+00	100%	2.11E+02	65%	8.32E+00	2.43E-04	51%	9
Sentinel-1A Tangential High -2	1.56E+01	100%	1.17E+03	100%	3.30E+01	4.86E-15	98%	9
Sentinel-1A Tangential High -6	3.00E+01	100%	4.24E+03	100%	1.15E+02	1.48E-50	100%	9
Sentinel-1A Tangential High -12	3.69E+01	100%	6.21E+03	100%	1.73E+02	1.17E-75	100%	9
Sentinel-1A Out-of-plane Low -2	3.19E+01	100%	4.94E+03	100%	1.30E+02	3.90E-57	100%	9
Sentinel-1A Out-of-plane Low -6	2.68E+01	100%	3.46E+03	100%	9.26E+01	6.14E-41	100%	9
Sentinel-1A Out-of-plane Low -12	2.98E+01	100%	4.31E+03	100%	1.13E+02	5.64E-50	100%	9
Sentinel-1A Out-of-plane Medium -2	6.35E+01	100%	1.94E+04	100%	5.07E+02	5.42E-221	100%	9
Sentinel-1A Out-of-plane Medium -6	5.23E+01	100%	1.31E+04	100%	3.44E+02	4.02E-150	100%	9
Sentinel-1A Out-of-plane Medium -12	5.80E+01	100%	1.64E+04	100%	4.24E+02	1.05E-184	100%	9
Sentinel-1A Out-of-plane High -2	1.24E+02	100%	7.42E+04	100%	1.93E+03	0.00E+00	100%	9
Sentinel-1A Out-of-plane High -6	1.00E+02	100%	4.83E+04	100%	1.26E+03	0.00E+00	100%	9
Sentinel-1A Out-of-plane High -12	1.22E+02	100%	7.08E+04	100%	1.85E+03	0.00E+00	100%	9
Sentinel-1A Hybrid Low -2	6.20E+00	100%	1.89E+02	59%	7.34E+00	6.50E-04	44%	9

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-1A Hybrid Low -6	9.10E+00	100%	3.90E+02	89%	1.29E+01	2.53E-06	73%	9
Sentinel-1A Hybrid Low -12	1.13E+01	100%	5.80E+02	96%	1.84E+01	1.07E-08	87%	9
Sentinel-1A Hybrid Medium -2	3.87E+01	100%	7.20E+03	100%	1.90E+02	3.27E-83	100%	9
Sentinel-1A Hybrid Medium -6	5.60E+01	100%	1.47E+04	100%	3.94E+02	7.46E-172	100%	9
Sentinel-1A Hybrid Medium -12	8.98E+01	100%	4.19E+04	100%	1.01E+03	0.00E+00	100%	10
Sentinel-1A Hybrid High -2	1.57E+02	100%	1.16E+05	100%	3.07E+03	0.00E+00	100%	9
Sentinel-1A Hybrid High -6	4.31E+02	100%	6.52E+05	100%	2.33E+04	0.00E+00	100%	9
Sentinel-1A Hybrid High -12	1.16E+03	100%	3.44E+06	100%	1.67E+05	0.00E+00	100%	9

Table A.33 Sentinel-1A Reachability analysis and probability from the three distances computed using range-range rate.

Sentinel-2B

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-2B No manoeuvre	3.09E-01	0%	1.23E+01	0%	2.23E+00	1.08E-01	0%	5
Sentinel-2B No manoeuvre	1.40E+01	100%	5.56E+03	100%	2.76E+01	1.03E-12	96%	3
Sentinel-2B No manoeuvre	1.23E-01	0%	9.02E+00	0%	2.47E+00	8.49E-02	0%	10
Sentinel-2B No manoeuvre	1.89E-01	0%	1.89E+01	0%	2.26E+00	1.04E-01	0%	10
Sentinel-2B No manoeuvre	6.69E-01	0%	6.44E+00	0%	2.14E+00	1.18E-01	0%	12
Sentinel-2B No manoeuvre	5.89E-02	0%	4.31E+01	0%	2.58E+00	7.56E-02	0%	11
Sentinel-2B No manoeuvre	8.82E-01	0%	9.10E+00	0%	2.98E+00	5.08E-02	1%	10
Sentinel-2B No manoeuvre	1.67E+00	50%	5.74E+01	0%	2.51E+00	8.11E-02	0%	11
Sentinel-2B No manoeuvre	6.87E-01	0%	7.13E+00	0%	2.23E+00	1.07E-01	0%	11
Sentinel-2B No manoeuvre	5.78E-01	0%	3.85E+01	0%	2.51E+00	8.10E-02	0%	11
Sentinel-2B No manoeuvre	1.16E+00	0%	1.16E+01	0%	3.10E+00	4.50E-02	2%	12
Sentinel-2B No manoeuvre	1.26E+00	9%	2.85E+01	0%	2.15E+00	1.17E-01	0%	12
Sentinel-2B No manoeuvre	2.90E-01	0%	8.22E+00	0%	2.41E+00	8.96E-02	0%	10
Sentinel-2B No manoeuvre	1.61E+00	45%	9.69E+01	23%	2.76E+00	6.35E-02	0%	9
Sentinel-2B No manoeuvre	1.25E-01	0%	1.07E+01	0%	2.36E+00	9.46E-02	0%	5
Sentinel-2B No manoeuvre	1.23E+01	100%	5.38E+03	100%	2.18E+01	3.33E-10	92%	3
Sentinel-2B No manoeuvre	2.81E-01	0%	1.11E+01	0%	2.56E+00	7.70E-02	0%	10
Sentinel-2B No manoeuvre	1.78E+00	59%	9.03E+01	19%	2.70E+00	6.69E-02	0%	10
Sentinel-2B No manoeuvre	7.17E-01	0%	6.26E+00	0%	2.11E+00	1.21E-01	0%	12
Sentinel-2B No manoeuvre	8.62E-01	0%	6.00E+01	0%	2.60E+00	7.44E-02	0%	12
Sentinel-2B No manoeuvre	2.03E+00	75%	1.60E+01	0%	3.39E+00	3.36E-02	6%	11
Sentinel-2B No manoeuvre	1.85E+00	64%	8.44E+01	15%	2.60E+00	7.43E-02	0%	11
Sentinel-2B No manoeuvre	1.58E+00	43%	1.63E+01	0%	2.55E+00	7.83E-02	0%	11
Sentinel-2B No manoeuvre	1.33E-01	0%	3.28E+01	0%	2.45E+00	8.60E-02	0%	10
Sentinel-2B No manoeuvre	1.96E+00	71%	1.76E+01	0%	3.39E+00	3.37E-02	6%	13
Sentinel-2B No manoeuvre	9.32E-01	0%	2.47E+01	0%	2.08E+00	1.25E-01	0%	12
Sentinel-2B No manoeuvre	6.08E-01	0%	9.74E+00	0%	2.45E+00	8.64E-02	0%	10
Sentinel-2B Tangential Low -2	8.55E-01	0%	1.37E+01	0%	2.55E+00	7.78E-02	0%	10
Sentinel-2B Tangential Low -6	8.23E-01	0%	1.28E+01	0%	2.55E+00	7.81E-02	0%	10
Sentinel-2B Tangential Low -12	1.36E+00	21%	1.84E+01	0%	2.70E+00	6.74E-02	0%	10
Sentinel-2B Tangential Medium -2	2.03E+00	75%	3.51E+01	0%	2.98E+00	5.07E-02	1%	10
Sentinel-2B Tangential Medium -6	4.33E+00	100%	1.11E+02	30%	4.81E+00	8.19E-03	22%	10
Sentinel-2B Tangential Medium -12	4.55E+00	100%	4.73E+01	0%	5.06E+00	6.37E-03	24%	10
Sentinel-2B Tangential High -2	6.58E+00	100%	2.77E+02	77%	7.87E+00	3.80E-04	48%	10
Sentinel-2B Tangential High -6	2.18E+01	100%	2.84E+03	100%	6.19E+01	1.38E-27	100%	10
Sentinel-2B Tangential High -12	1.64E+01	100%	2.47E+02	72%	3.59E+01	2.49E-16	99%	10
Sentinel-2B Out-of-plane Low -2	1.67E+00	50%	2.76E+01	0%	2.81E+00	6.00E-02	0%	10
Sentinel-2B Out-of-plane Low -6	9.31E-01	0%	1.49E+01	0%	2.58E+00	7.61E-02	0%	10
Sentinel-2B Out-of-plane Low -12	3.37E+00	99%	8.46E+01	15%	3.89E+00	2.05E-02	12%	10
Sentinel-2B Out-of-plane Medium -2	2.95E+00	97%	6.72E+01	3%	3.55E+00	2.87E-02	8%	10
Sentinel-2B Out-of-plane Medium -6	2.13E+00	79%	3.92E+01	0%	3.03E+00	4.82E-02	1%	10
Sentinel-2B Out-of-plane Medium -12	1.88E+00	66%	3.26E+01	0%	2.91E+00	5.47E-02	0%	10
Sentinel-2B Out-of-plane High -2	8.02E+00	100%	4.41E+02	92%	1.05E+01	2.73E-05	63%	10
Sentinel-2B Out-of-plane High -6	3.05E+00	98%	7.13E+01	6%	3.63E+00	2.66E-02	9%	10
Sentinel-2B Out-of-plane High -12	7.77E+00	100%	4.16E+02	90%	1.00E+01	4.46E-05	61%	10
Sentinel-2B Hybrid Low -2	2.48E+00	91%	4.68E+01	0%	3.24E+00	3.93E-02	4%	10
Sentinel-2B Hybrid Low -6	6.40E+00	100%	2.28E+02	68%	7.58E+00	5.09E-04	46%	10
Sentinel-2B Hybrid Low -12	8.04E+00	100%	2.24E+02	68%	1.06E+01	2.61E-05	63%	10
Sentinel-2B Hybrid Medium -2	1.26E+01	100%	9.84E+02	100%	2.23E+01	2.17E-10	92%	10
Sentinel-2B Hybrid Medium -6	4.19E+01	100%	1.06E+04	100%	2.22E+02	5.11E-97	100%	10
Sentinel-2B Hybrid Medium -12	2.94E+01	100%	4.76E+02	93%	1.10E+02	1.07E-48	100%	10
Sentinel-2B Hybrid High -2	5.73E+01	100%	2.07E+04	100%	4.12E+02	9.26E-180	100%	10

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-2B Hybrid High -6	2.36E+02	100%	4.56E+05	100%	6.99E+03	0.00E+00	100%	10
Sentinel-2B Hybrid High -12	3.22E+02	100%	9.71E+05	100%	1.29E+04	0.00E+00	100%	10

Table A.34 Sentinel-2B Reachability analysis and probability from the three distances computed using range-range rate.

Mass = 2500 Kg

Sentinel-1A

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-1A No manoeuvre	1.04E+00	0%	7.82E+00	0%	2.84E+00	5.84E-02	0%	9
Sentinel-1A No manoeuvre	1.90E-01	0%	5.97E+01	0%	2.35E+00	9.57E-02	0%	10
Sentinel-1A No manoeuvre	1.75E-01	0%	7.52E+00	0%	2.54E+00	7.92E-02	0%	9
Sentinel-1A No manoeuvre	1.48E+00	33%	4.34E+01	0%	2.69E+00	6.76E-02	0%	9
Sentinel-1A No manoeuvre	1.01E+00	0%	1.47E+02	46%	2.93E+00	5.32E-02	0%	10
Sentinel-1A No manoeuvre	2.88E+00	97%	1.70E+02	54%	3.02E+00	4.89E-02	1%	9
Sentinel-1A No manoeuvre	1.35E+01	100%	1.49E+04	100%	2.55E+01	8.48E-12	95%	2
Sentinel-1A No manoeuvre	5.71E-01	0%	2.62E+01	0%	2.55E+00	7.79E-02	0%	9
Sentinel-1A No manoeuvre	3.44E-01	0%	3.97E+01	0%	2.28E+00	1.02E-01	0%	9
Sentinel-1A No manoeuvre	1.64E+01	100%	7.43E+03	100%	3.64E+01	1.62E-16	99%	2
Sentinel-1A No manoeuvre	7.86E-01	0%	1.84E+01	0%	2.51E+00	8.15E-02	0%	9
Sentinel-1A No manoeuvre	2.61E-01	0%	5.00E+01	0%	2.38E+00	9.21E-02	0%	11
Sentinel-1A No manoeuvre	1.99E-01	0%	8.99E+00	0%	2.64E+00	7.11E-02	0%	10
Sentinel-1A No manoeuvre	1.15E+00	0%	5.48E+01	0%	2.69E+00	6.81E-02	0%	8
Sentinel-1A No manoeuvre	1.03E+00	0%	7.20E+01	7%	2.83E+00	5.88E-02	0%	9
Sentinel-1A No manoeuvre	5.97E-01	0%	5.12E+01	0%	2.34E+00	9.67E-02	0%	8
Sentinel-1A No manoeuvre	9.25E-01	0%	6.88E+00	0%	2.80E+00	6.08E-02	0%	9
Sentinel-1A No manoeuvre	1.21E+00	4%	1.51E+02	47%	2.67E+00	6.92E-02	0%	10
Sentinel-1A No manoeuvre	1.68E+00	52%	2.38E+01	0%	2.89E+00	5.55E-02	0%	9
Sentinel-1A No manoeuvre	1.67E-01	0%	1.83E+01	0%	2.47E+00	8.46E-02	0%	10
Sentinel-1A No manoeuvre	4.60E-01	0%	7.95E+01	12%	2.91E+00	5.44E-02	0%	10
Sentinel-1A No manoeuvre	1.19E+00	2%	5.01E+01	0%	2.33E+00	9.77E-02	0%	9
Sentinel-1A No manoeuvre	1.53E+01	100%	2.16E+04	100%	3.18E+01	1.53E-14	98%	2
Sentinel-1A No manoeuvre	2.48E+00	91%	1.26E+02	37%	3.33E+00	3.59E-02	5%	9
Sentinel-1A No manoeuvre	2.36E-01	0%	4.50E+01	0%	2.45E+00	8.62E-02	0%	9
Sentinel-1A Tangential Low -2	1.23E+00	7%	1.47E+01	0%	2.73E+00	6.55E-02	0%	9
Sentinel-1A Tangential Low -6	5.35E-01	0%	8.36E+00	0%	2.57E+00	7.67E-02	0%	9
Sentinel-1A Tangential Low -12	1.05E+00	0%	1.17E+01	0%	2.67E+00	6.92E-02	0%	9
Sentinel-1A Tangential Medium -2	3.77E+00	100%	7.49E+01	9%	4.31E+00	1.34E-02	17%	9
Sentinel-1A Tangential Medium -6	8.46E+00	100%	3.45E+02	85%	1.15E+01	1.04E-05	68%	9
Sentinel-1A Tangential Medium -12	7.02E+00	100%	2.25E+02	68%	8.69E+00	1.69E-04	53%	9
Sentinel-1A Tangential High -2	1.41E+01	100%	9.47E+02	100%	2.75E+01	1.16E-12	96%	9
Sentinel-1A Tangential High -6	3.09E+01	100%	4.56E+03	100%	1.22E+02	1.70E-53	100%	9
Sentinel-1A Tangential High -12	3.52E+01	100%	5.55E+03	100%	1.57E+02	6.00E-69	100%	9
Sentinel-1A Out-of-plane Low -2	3.20E+01	100%	4.93E+03	100%	1.30E+02	3.01E-57	100%	9
Sentinel-1A Out-of-plane Low -6	2.75E+01	100%	3.68E+03	100%	9.73E+01	5.41E-43	100%	9
Sentinel-1A Out-of-plane Low -12	2.99E+01	100%	4.37E+03	100%	1.15E+02	1.62E-50	100%	9
Sentinel-1A Out-of-plane Medium -2	6.41E+01	100%	1.96E+04	100%	5.17E+02	3.36E-225	100%	9
Sentinel-1A Out-of-plane Medium -6	5.23E+01	100%	1.32E+04	100%	3.44E+02	2.80E-150	100%	9
Sentinel-1A Out-of-plane Medium -12	5.97E+01	100%	1.70E+04	100%	4.49E+02	1.64E-195	100%	9
Sentinel-1A Out-of-plane High -2	1.26E+02	100%	7.59E+04	100%	1.98E+03	0.00E+00	100%	9
Sentinel-1A Out-of-plane High -6	9.92E+01	100%	4.73E+04	100%	1.23E+03	0.00E+00	100%	9
Sentinel-1A Out-of-plane High -12	1.22E+02	100%	7.14E+04	100%	1.86E+03	0.00E+00	100%	9
Sentinel-1A Hybrid Low -2	8.37E+00	100%	3.42E+02	85%	1.13E+01	1.24E-05	67%	9
Sentinel-1A Hybrid Low -6	1.10E+01	100%	5.98E+02	97%	1.78E+01	1.89E-08	86%	9
Sentinel-1A Hybrid Low -12	1.17E+01	100%	6.18E+02	97%	1.98E+01	2.61E-09	89%	9
Sentinel-1A Hybrid Medium -2	3.73E+01	100%	6.74E+03	100%	1.76E+02	2.86E-77	100%	9
Sentinel-1A Hybrid Medium -6	5.56E+01	100%	1.47E+04	100%	3.89E+02	1.21E-169	100%	9
Sentinel-1A Hybrid Medium -12	8.80E+01	100%	4.02E+04	100%	9.70E+02	0.00E+00	100%	10
Sentinel-1A Hybrid High -2	1.57E+02	100%	1.19E+05	100%	3.08E+03	0.00E+00	100%	9
Sentinel-1A Hybrid High -6	4.33E+02	100%	6.77E+05	100%	2.35E+04	0.00E+00	100%	9
Sentinel-1A Hybrid High -12	1.16E+03	100%	3.46E+06	100%	1.67E+05	0.00E+00	100%	9

Table A.35 Sentinel-1A Reachability analysis and probability from the three distances computed using range-range rate.

Sentinel-2B

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-2B No manoeuvre	2.45E+00	90%	7.21E+01	7%	2.97E+00	5.12E-02	1%	5
Sentinel-2B No manoeuvre	1.50E+01	100%	6.32E+03	100%	3.09E+01	3.71E-14	97%	3
Sentinel-2B No manoeuvre	3.93E-01	0%	1.01E+01	0%	2.49E+00	8.33E-02	0%	10
Sentinel-2B No manoeuvre	1.09E+00	0%	3.86E+01	0%	2.41E+00	9.01E-02	0%	10
Sentinel-2B No manoeuvre	1.01E+00	0%	8.10E+00	0%	2.21E+00	1.10E-01	0%	12
Sentinel-2B No manoeuvre	6.59E-01	0%	6.15E+01	0%	2.63E+00	7.18E-02	0%	11
Sentinel-2B No manoeuvre	7.63E-01	0%	8.51E+00	0%	2.96E+00	5.20E-02	0%	10
Sentinel-2B No manoeuvre	1.15E+00	0%	3.55E+01	0%	2.33E+00	9.75E-02	0%	11
Sentinel-2B No manoeuvre	1.56E+00	41%	1.36E+01	0%	2.48E+00	8.35E-02	0%	11
Sentinel-2B No manoeuvre	2.81E-01	0%	3.10E+01	0%	2.48E+00	8.38E-02	0%	11
Sentinel-2B No manoeuvre	1.72E-01	0%	7.22E+00	0%	2.93E+00	5.32E-02	0%	12
Sentinel-2B No manoeuvre	2.66E-01	0%	1.23E+01	0%	1.96E+00	1.41E-01	0%	12
Sentinel-2B No manoeuvre	1.56E+00	41%	2.10E+01	0%	2.70E+00	6.70E-02	0%	10
Sentinel-2B No manoeuvre	5.40E-01	0%	2.40E+01	0%	2.36E+00	9.45E-02	0%	9
Sentinel-2B No manoeuvre	1.46E-01	0%	1.07E+01	0%	2.35E+00	9.52E-02	0%	5
Sentinel-2B No manoeuvre	1.18E+01	100%	4.96E+03	100%	2.01E+01	1.79E-09	90%	3
Sentinel-2B No manoeuvre	4.56E-01	0%	1.20E+01	0%	2.58E+00	7.61E-02	0%	10
Sentinel-2B No manoeuvre	2.02E+00	74%	1.12E+02	31%	2.83E+00	5.91E-02	0%	10
Sentinel-2B No manoeuvre	1.08E+00	0%	7.85E+00	0%	2.19E+00	1.12E-01	0%	12
Sentinel-2B No manoeuvre	3.05E-01	0%	3.88E+01	0%	2.52E+00	8.01E-02	0%	12
Sentinel-2B No manoeuvre	3.65E-01	0%	6.70E+00	0%	2.89E+00	5.57E-02	0%	11
Sentinel-2B No manoeuvre	5.54E-01	0%	1.93E+01	0%	2.13E+00	1.19E-01	0%	11
Sentinel-2B No manoeuvre	4.77E-01	0%	7.09E+00	0%	2.29E+00	1.01E-01	0%	11
Sentinel-2B No manoeuvre	6.36E-01	0%	4.60E+01	0%	2.51E+00	8.12E-02	0%	10
Sentinel-2B No manoeuvre	6.13E-01	0%	7.79E+00	0%	2.97E+00	5.14E-02	0%	13
Sentinel-2B No manoeuvre	9.59E-02	0%	1.43E+01	0%	1.99E+00	1.36E-01	0%	12
Sentinel-2B No manoeuvre	3.56E-01	0%	8.23E+00	0%	2.40E+00	9.03E-02	0%	10
Sentinel-2B Tangential Low -2	1.68E+00	52%	2.80E+01	0%	2.82E+00	5.98E-02	0%	10
Sentinel-2B Tangential Low -6	4.67E-01	0%	9.51E+00	0%	2.49E+00	8.30E-02	0%	10
Sentinel-2B Tangential Low -12	6.97E-01	0%	9.30E+00	0%	2.52E+00	8.01E-02	0%	10
Sentinel-2B Tangential Medium -2	2.27E+00	85%	4.26E+01	0%	3.11E+00	4.44E-02	2%	10
Sentinel-2B Tangential Medium -6	4.45E+00	100%	1.18E+02	34%	4.94E+00	7.13E-03	23%	10
Sentinel-2B Tangential Medium -12	4.51E+00	100%	4.53E+01	0%	5.00E+00	6.72E-03	24%	10
Sentinel-2B Tangential High -2	6.57E+00	100%	2.74E+02	77%	7.86E+00	3.86E-04	48%	10
Sentinel-2B Tangential High -6	2.02E+01	100%	2.35E+03	100%	5.34E+01	6.64E-24	100%	10
Sentinel-2B Tangential High -12	1.65E+01	100%	2.59E+02	74%	3.64E+01	1.62E-16	99%	10
Sentinel-2B Out-of-plane Low -2	1.41E+00	26%	2.22E+01	0%	2.71E+00	6.64E-02	0%	10
Sentinel-2B Out-of-plane Low -6	1.41E+00	26%	2.26E+01	0%	2.72E+00	6.61E-02	0%	10
Sentinel-2B Out-of-plane Low -12	9.17E-01	0%	1.45E+01	0%	2.57E+00	7.67E-02	0%	10
Sentinel-2B Out-of-plane Medium -2	3.26E+00	99%	8.15E+01	13%	3.80E+00	2.25E-02	11%	10
Sentinel-2B Out-of-plane Medium -6	8.13E-01	0%	1.34E+01	0%	2.54E+00	7.85E-02	0%	10
Sentinel-2B Out-of-plane Medium -12	2.73E+00	95%	5.91E+01	0%	3.39E+00	3.36E-02	6%	10
Sentinel-2B Out-of-plane High -2	7.66E+00	100%	4.04E+02	90%	9.81E+00	5.51E-05	60%	10
Sentinel-2B Out-of-plane High -6	1.93E+00	69%	3.40E+01	0%	2.93E+00	5.34E-02	0%	10
Sentinel-2B Out-of-plane High -12	5.69E+00	100%	2.26E+02	68%	6.52E+00	1.48E-03	38%	10
Sentinel-2B Hybrid Low -2	3.62E+00	100%	9.33E+01	21%	4.10E+00	1.66E-02	14%	10
Sentinel-2B Hybrid Low -6	7.96E+00	100%	3.82E+02	88%	1.04E+01	3.10E-05	62%	10
Sentinel-2B Hybrid Low -12	6.34E+00	100%	5.71E+01	0%	7.49E+00	5.59E-04	45%	10
Sentinel-2B Hybrid Medium -2	1.42E+01	100%	1.28E+03	100%	2.78E+01	8.12E-13	96%	10
Sentinel-2B Hybrid Medium -6	4.27E+01	100%	1.10E+04	100%	2.30E+02	1.49E-100	100%	10
Sentinel-2B Hybrid Medium -12	2.94E+01	100%	5.25E+02	95%	1.11E+02	9.72E-49	100%	10
Sentinel-2B Hybrid High -2	5.58E+01	100%	1.94E+04	100%	3.91E+02	1.16E-170	100%	10
Sentinel-2B Hybrid High -6	2.37E+02	100%	4.51E+05	100%	7.00E+03	0.00E+00	100%	10
Sentinel-2B Hybrid High -12	3.21E+02	100%	9.78E+05	100%	1.29E+04	0.00E+00	100%	10

Table A.36 Sentinel-2B Reachability analysis and probability from the three distances computed using range-range rate.

Mass = 3000 Kg

Sentinel-1A

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-1A No manoeuvre	8.43E-01	0%	7.09E+00	0%	2.79E+00	6.14E-02	0%	9
Sentinel-1A No manoeuvre	1.13E+00	0%	1.32E+02	40%	2.50E+00	8.21E-02	0%	10

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-1A No manoeuvre	2.26E-01	0%	7.60E+00	0%	2.54E+00	7.91E-02	0%	9
Sentinel-1A No manoeuvre	4.37E-01	0%	1.71E+01	0%	2.45E+00	8.65E-02	0%	9
Sentinel-1A No manoeuvre	1.34E+00	19%	1.98E+02	62%	3.02E+00	4.86E-02	1%	10
Sentinel-1A No manoeuvre	1.45E+00	30%	5.59E+01	0%	2.25E+00	1.06E-01	0%	9
Sentinel-1A No manoeuvre	1.54E+01	100%	1.95E+04	100%	3.24E+01	8.87E-15	98%	2
Sentinel-1A No manoeuvre	7.99E-01	0%	3.22E+01	0%	2.59E+00	7.52E-02	0%	9
Sentinel-1A No manoeuvre	3.55E-01	0%	3.98E+01	0%	2.28E+00	1.02E-01	0%	9
Sentinel-1A No manoeuvre	1.56E+01	100%	6.86E+03	100%	3.34E+01	3.10E-15	98%	2
Sentinel-1A No manoeuvre	2.56E-01	0%	1.24E+01	0%	2.43E+00	8.79E-02	0%	9
Sentinel-1A No manoeuvre	8.35E-01	0%	8.03E+01	12%	2.46E+00	8.51E-02	0%	11
Sentinel-1A No manoeuvre	1.48E+00	33%	2.31E+01	0%	2.93E+00	5.35E-02	0%	10
Sentinel-1A No manoeuvre	3.96E-01	0%	2.71E+01	0%	2.53E+00	7.97E-02	0%	8
Sentinel-1A No manoeuvre	8.40E-01	0%	5.47E+01	0%	2.77E+00	6.25E-02	0%	9
Sentinel-1A No manoeuvre	6.08E-01	0%	3.67E+01	0%	2.25E+00	1.05E-01	0%	8
Sentinel-1A No manoeuvre	2.46E-01	0%	5.68E+00	0%	2.69E+00	6.78E-02	0%	9
Sentinel-1A No manoeuvre	6.29E-01	0%	5.70E+01	0%	2.43E+00	8.76E-02	0%	10
Sentinel-1A No manoeuvre	2.74E-01	0%	9.21E+00	0%	2.54E+00	7.90E-02	0%	9
Sentinel-1A No manoeuvre	1.42E-01	0%	1.72E+01	0%	2.45E+00	8.67E-02	0%	10
Sentinel-1A No manoeuvre	1.60E+00	44%	2.26E+02	68%	3.20E+00	4.06E-02	4%	10
Sentinel-1A No manoeuvre	1.29E+00	12%	6.04E+01	0%	2.35E+00	9.56E-02	0%	9
Sentinel-1A No manoeuvre	1.51E+01	100%	2.06E+04	100%	3.12E+01	2.84E-14	98%	2
Sentinel-1A No manoeuvre	6.86E-01	0%	2.32E+01	0%	2.59E+00	7.48E-02	0%	9
Sentinel-1A No manoeuvre	8.60E-01	0%	8.42E+01	15%	2.54E+00	7.91E-02	0%	9
Sentinel-1A Tangential Low -2	1.10E+00	0%	1.33E+01	0%	2.69E+00	6.81E-02	0%	9
Sentinel-1A Tangential Low -6	1.17E+00	0%	1.38E+01	0%	2.71E+00	6.67E-02	0%	9
Sentinel-1A Tangential Low -12	8.51E-01	0%	9.92E+00	0%	2.62E+00	7.25E-02	0%	9
Sentinel-1A Tangential Medium -2	3.42E+00	99%	6.38E+01	0%	4.00E+00	1.84E-02	13%	9
Sentinel-1A Tangential Medium -6	6.24E+00	100%	1.88E+02	59%	7.41E+00	6.06E-04	45%	9
Sentinel-1A Tangential Medium -12	5.58E+00	100%	1.35E+02	41%	6.42E+00	1.62E-03	37%	9
Sentinel-1A Tangential High -2	1.64E+01	100%	1.31E+03	100%	3.60E+01	2.36E-16	99%	9
Sentinel-1A Tangential High -6	3.10E+01	100%	4.54E+03	100%	1.23E+02	4.03E-54	100%	9
Sentinel-1A Tangential High -12	3.65E+01	100%	6.08E+03	100%	1.69E+02	4.06E-74	100%	9
Sentinel-1A Out-of-plane Low -2	3.10E+01	100%	4.69E+03	100%	1.23E+02	4.38E-54	100%	9
Sentinel-1A Out-of-plane Low -6	2.72E+01	100%	3.58E+03	100%	9.47E+01	7.49E-42	100%	9
Sentinel-1A Out-of-plane Low -12	3.03E+01	100%	4.42E+03	100%	1.18E+02	9.03E-52	100%	9
Sentinel-1A Out-of-plane Medium -2	6.39E+01	100%	2.00E+04	100%	5.14E+02	8.33E-224	100%	9
Sentinel-1A Out-of-plane Medium -6	5.10E+01	100%	1.25E+04	100%	3.28E+02	3.46E-143	100%	9
Sentinel-1A Out-of-plane Medium -12	6.01E+01	100%	1.76E+04	100%	4.55E+02	3.27E-198	100%	9
Sentinel-1A Out-of-plane High -2	1.24E+02	100%	7.36E+04	100%	1.92E+03	0.00E+00	100%	9
Sentinel-1A Out-of-plane High -6	9.97E+01	100%	4.81E+04	100%	1.25E+03	0.00E+00	100%	9
Sentinel-1A Out-of-plane High -12	1.20E+02	100%	7.07E+04	100%	1.80E+03	0.00E+00	100%	9
Sentinel-1A Hybrid Low -2	7.46E+00	100%	2.76E+02	77%	9.49E+00	7.54E-05	58%	9
Sentinel-1A Hybrid Low -6	1.14E+01	100%	6.11E+02	97%	1.87E+01	7.88E-09	87%	9
Sentinel-1A Hybrid Low -12	1.09E+01	100%	5.34E+02	95%	1.74E+01	2.77E-08	85%	9
Sentinel-1A Hybrid Medium -2	3.77E+01	100%	6.77E+03	100%	1.80E+02	5.43E-79	100%	9
Sentinel-1A Hybrid Medium -6	5.70E+01	100%	1.54E+04	100%	4.09E+02	2.47E-178	100%	9
Sentinel-1A Hybrid Medium -12	8.79E+01	100%	4.07E+04	100%	9.69E+02	0.00E+00	100%	10
Sentinel-1A Hybrid High -2	1.56E+02	100%	1.17E+05	100%	3.06E+03	0.00E+00	100%	9
Sentinel-1A Hybrid High -6	4.35E+02	100%	6.74E+05	100%	2.36E+04	0.00E+00	100%	9
Sentinel-1A Hybrid High -12	1.16E+03	100%	3.47E+06	100%	1.68E+05	0.00E+00	100%	9

Table A.37 Sentinel-1A Reachability analysis and probability from the three distances computed using range-range rate.

Sentinel-2B

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-2B No manoeuvre	1.91E-01	0%	1.18E+01	0%	2.22E+00	1.08E-01	0%	5
Sentinel-2B No manoeuvre	1.38E+01	100%	5.46E+03	100%	2.67E+01	2.47E-12	96%	3
Sentinel-2B No manoeuvre	4.10E-01	0%	9.95E+00	0%	2.48E+00	8.36E-02	0%	10
Sentinel-2B No manoeuvre	3.87E-01	0%	2.08E+01	0%	2.28E+00	1.02E-01	0%	10
Sentinel-2B No manoeuvre	5.06E-01	0%	5.85E+00	0%	2.11E+00	1.22E-01	0%	12
Sentinel-2B No manoeuvre	1.09E-01	0%	4.35E+01	0%	2.58E+00	7.55E-02	0%	11
Sentinel-2B No manoeuvre	9.63E-02	0%	6.82E+00	0%	2.88E+00	5.59E-02	0%	10
Sentinel-2B No manoeuvre	1.28E+00	12%	4.07E+01	0%	2.34E+00	9.67E-02	0%	11
Sentinel-2B No manoeuvre	1.84E+00	63%	1.63E+01	0%	2.59E+00	7.48E-02	0%	11
Sentinel-2B No manoeuvre	7.89E-01	0%	4.70E+01	0%	2.55E+00	7.79E-02	0%	11
Sentinel-2B No manoeuvre	7.34E-01	0%	8.81E+00	0%	2.99E+00	5.01E-02	1%	12

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-2B No manoeuvre	8.67E-01	0%	1.98E+01	0%	2.05E+00	1.29E-01	0%	12
Sentinel-2B No manoeuvre	5.85E-01	0%	9.54E+00	0%	2.44E+00	8.71E-02	0%	10
Sentinel-2B No manoeuvre	1.51E+00	36%	5.97E+01	0%	2.61E+00	7.35E-02	0%	9
Sentinel-2B No manoeuvre	7.69E-01	0%	1.55E+01	0%	2.42E+00	8.88E-02	0%	5
Sentinel-2B No manoeuvre	1.25E+01	100%	5.53E+03	100%	2.24E+01	1.80E-10	92%	3
Sentinel-2B No manoeuvre	5.19E-01	0%	1.24E+01	0%	2.58E+00	7.61E-02	0%	10
Sentinel-2B No manoeuvre	2.06E+00	76%	1.14E+02	32%	2.85E+00	5.81E-02	0%	10
Sentinel-2B No manoeuvre	7.47E-01	0%	6.24E+00	0%	2.10E+00	1.22E-01	0%	12
Sentinel-2B No manoeuvre	1.41E+00	25%	1.05E+02	27%	2.76E+00	6.34E-02	0%	12
Sentinel-2B No manoeuvre	1.10E+00	0%	9.16E+00	0%	3.02E+00	4.90E-02	1%	11
Sentinel-2B No manoeuvre	5.59E-01	0%	1.95E+01	0%	2.13E+00	1.18E-01	0%	11
Sentinel-2B No manoeuvre	6.94E-01	0%	8.04E+00	0%	2.32E+00	9.85E-02	0%	11
Sentinel-2B No manoeuvre	8.49E-01	0%	5.69E+01	0%	2.55E+00	7.77E-02	0%	10
Sentinel-2B No manoeuvre	1.93E+00	69%	1.91E+01	0%	3.43E+00	3.24E-02	6%	13
Sentinel-2B No manoeuvre	8.05E-01	0%	2.31E+01	0%	2.08E+00	1.25E-01	0%	12
Sentinel-2B No manoeuvre	1.81E+00	61%	2.46E+01	0%	2.79E+00	6.14E-02	0%	10
Sentinel-2B Tangential Low -2	6.74E-01	0%	1.18E+01	0%	2.52E+00	8.06E-02	0%	10
Sentinel-2B Tangential Low -6	1.17E+00	0%	1.73E+01	0%	2.63E+00	7.18E-02	0%	10
Sentinel-2B Tangential Low -12	1.72E+00	55%	2.59E+01	0%	2.84E+00	5.86E-02	0%	10
Sentinel-2B Tangential Medium -2	1.33E+00	17%	1.91E+01	0%	2.69E+00	6.81E-02	0%	10
Sentinel-2B Tangential Medium -6	5.29E+00	100%	1.72E+02	54%	5.96E+00	2.57E-03	33%	10
Sentinel-2B Tangential Medium -12	4.74E+00	100%	5.83E+01	0%	5.28E+00	5.11E-03	27%	10
Sentinel-2B Tangential High -2	5.89E+00	100%	2.17E+02	66%	6.80E+00	1.11E-03	40%	10
Sentinel-2B Tangential High -6	2.22E+01	100%	2.95E+03	100%	6.43E+01	1.18E-28	100%	10
Sentinel-2B Tangential High -12	1.64E+01	100%	2.56E+02	74%	3.60E+01	2.21E-16	99%	10
Sentinel-2B Out-of-plane Low -2	2.46E+00	90%	4.95E+01	0%	3.22E+00	3.98E-02	4%	10
Sentinel-2B Out-of-plane Low -6	9.26E-01	0%	1.45E+01	0%	2.57E+00	7.68E-02	0%	10
Sentinel-2B Out-of-plane Low -12	1.92E+00	68%	3.38E+01	0%	2.93E+00	5.36E-02	0%	10
Sentinel-2B Out-of-plane Medium -2	3.35E+00	99%	8.46E+01	15%	3.87E+00	2.08E-02	12%	10
Sentinel-2B Out-of-plane Medium -6	2.85E+00	97%	6.33E+01	0%	3.48E+00	3.09E-02	7%	10
Sentinel-2B Out-of-plane Medium -12	3.20E+00	99%	7.76E+01	10%	3.75E+00	2.36E-02	10%	10
Sentinel-2B Out-of-plane High -2	6.63E+00	100%	3.02E+02	80%	7.95E+00	3.51E-04	48%	10
Sentinel-2B Out-of-plane High -6	3.50E+00	100%	9.12E+01	19%	4.00E+00	1.84E-02	13%	10
Sentinel-2B Out-of-plane High -12	4.11E+00	100%	1.22E+02	36%	4.58E+00	1.02E-02	20%	10
Sentinel-2B Hybrid Low -2	1.01E+00	0%	1.21E+01	0%	2.59E+00	7.49E-02	0%	10
Sentinel-2B Hybrid Low -6	8.33E+00	100%	4.20E+02	91%	1.11E+01	1.47E-05	66%	10
Sentinel-2B Hybrid Low -12	6.29E+00	100%	4.95E+01	0%	7.41E+00	6.07E-04	45%	10
Sentinel-2B Hybrid Medium -2	1.45E+01	100%	1.33E+03	100%	2.86E+01	3.81E-13	97%	10
Sentinel-2B Hybrid Medium -6	4.35E+01	100%	1.15E+04	100%	2.39E+02	2.54E-104	100%	10
Sentinel-2B Hybrid Medium -12	2.96E+01	100%	6.73E+02	98%	1.12E+02	1.83E-49	100%	10
Sentinel-2B Hybrid High -2	5.85E+01	100%	2.18E+04	100%	4.31E+02	9.03E-188	100%	10
Sentinel-2B Hybrid High -6	2.37E+02	100%	4.58E+05	100%	7.02E+03	0.00E+00	100%	10
Sentinel-2B Hybrid High -12	3.21E+02	100%	9.77E+05	100%	1.29E+04	0.00E+00	100%	10

Table A.38 Sentinel-2B Reachability analysis and probability from the three distances computed using range-range rate.

A.3.2 Ballistic coefficient

C_D = 1

Sentinel-1A

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-1A No manoeuvre	7.12E-01	0%	6.76E+00	0%	2.77E+00	6.28E-02	0%	9
Sentinel-1A No manoeuvre	1.13E+00	0%	1.36E+02	42%	2.50E+00	8.21E-02	0%	10
Sentinel-1A No manoeuvre	1.70E-01	0%	7.68E+00	0%	2.54E+00	7.89E-02	0%	9
Sentinel-1A No manoeuvre	3.14E-01	0%	1.58E+01	0%	2.43E+00	8.77E-02	0%	9
Sentinel-1A No manoeuvre	2.31E-01	0%	8.43E+01	15%	2.81E+00	6.01E-02	0%	10
Sentinel-1A No manoeuvre	1.20E-01	0%	1.85E+01	0%	1.98E+00	1.38E-01	0%	9
Sentinel-1A No manoeuvre	1.60E+01	100%	2.13E+04	100%	3.49E+01	6.99E-16	99%	2
Sentinel-1A No manoeuvre	9.55E-01	0%	4.39E+01	0%	2.63E+00	7.24E-02	0%	9
Sentinel-1A No manoeuvre	1.65E-01	0%	3.69E+01	0%	2.26E+00	1.04E-01	0%	9
Sentinel-1A No manoeuvre	1.54E+01	100%	6.50E+03	100%	3.24E+01	8.15E-15	98%	2
Sentinel-1A No manoeuvre	4.54E-01	0%	1.45E+01	0%	2.47E+00	8.47E-02	0%	9
Sentinel-1A No manoeuvre	1.59E+00	44%	1.67E+02	53%	2.68E+00	6.83E-02	0%	11
Sentinel-1A No manoeuvre	7.93E-01	0%	1.26E+01	0%	2.71E+00	6.67E-02	0%	10
Sentinel-1A No manoeuvre	1.95E-01	0%	2.61E+01	0%	2.54E+00	7.88E-02	0%	8

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-1A No manoeuvre	1.02E+00	0%	9.16E+01	20%	2.85E+00	5.81E-02	0%	9
Sentinel-1A No manoeuvre	6.12E-01	0%	5.04E+01	0%	2.32E+00	9.86E-02	0%	8
Sentinel-1A No manoeuvre	7.78E-01	0%	6.64E+00	0%	2.78E+00	6.20E-02	0%	9
Sentinel-1A No manoeuvre	7.35E-02	0%	5.91E+01	0%	2.47E+00	8.45E-02	0%	10
Sentinel-1A No manoeuvre	1.14E+00	0%	2.07E+01	0%	2.79E+00	6.16E-02	0%	9
Sentinel-1A No manoeuvre	5.81E-02	0%	1.41E+01	0%	2.35E+00	9.56E-02	0%	10
Sentinel-1A No manoeuvre	8.92E-01	0%	1.39E+02	43%	3.01E+00	4.94E-02	1%	10
Sentinel-1A No manoeuvre	1.13E-01	0%	1.99E+01	0%	2.12E+00	1.21E-01	0%	9
Sentinel-1A No manoeuvre	1.44E+01	100%	2.08E+04	100%	2.87E+01	3.51E-13	97%	2
Sentinel-1A No manoeuvre	1.78E+00	59%	6.57E+01	2%	2.91E+00	5.45E-02	0%	9
Sentinel-1A No manoeuvre	5.91E-01	0%	5.34E+01	0%	2.45E+00	8.62E-02	0%	9
Sentinel-1A Tangential Low -2	6.52E-01	0%	9.53E+00	0%	2.59E+00	7.53E-02	0%	9
Sentinel-1A Tangential Low -6	3.70E-01	0%	8.01E+00	0%	2.55E+00	7.82E-02	0%	9
Sentinel-1A Tangential Low -12	2.19E+00	82%	2.98E+01	0%	3.13E+00	4.38E-02	3%	9
Sentinel-1A Tangential Medium -2	4.78E+00	100%	1.16E+02	33%	5.39E+00	4.58E-03	28%	9
Sentinel-1A Tangential Medium -6	4.36E+00	100%	9.25E+01	20%	4.91E+00	7.37E-03	23%	9
Sentinel-1A Tangential Medium -12	6.85E+00	100%	2.17E+02	66%	8.40E+00	2.24E-04	51%	9
Sentinel-1A Tangential High -2	1.59E+01	100%	1.21E+03	100%	3.42E+01	1.46E-15	98%	9
Sentinel-1A Tangential High -6	2.88E+01	100%	3.89E+03	100%	1.06E+02	7.03E-47	100%	9
Sentinel-1A Tangential High -12	3.47E+01	100%	5.44E+03	100%	1.53E+02	2.66E-67	100%	9
Sentinel-1A Out-of-plane Low -2	3.17E+01	100%	4.84E+03	100%	1.28E+02	1.85E-56	100%	9
Sentinel-1A Out-of-plane Low -6	2.57E+01	100%	3.16E+03	100%	8.51E+01	1.06E-37	100%	9
Sentinel-1A Out-of-plane Low -12	2.70E+01	100%	3.59E+03	100%	9.37E+01	1.95E-41	100%	9
Sentinel-1A Out-of-plane Medium -2	6.41E+01	100%	2.03E+04	100%	5.16E+02	9.53E-225	100%	9
Sentinel-1A Out-of-plane Medium -6	5.21E+01	100%	1.31E+04	100%	3.42E+02	2.75E-149	100%	9
Sentinel-1A Out-of-plane Medium -12	5.89E+01	100%	1.68E+04	100%	4.36E+02	5.68E-190	100%	9
Sentinel-1A Out-of-plane High -2	1.23E+02	100%	7.25E+04	100%	1.90E+03	0.00E+00	100%	9
Sentinel-1A Out-of-plane High -6	1.00E+02	100%	4.83E+04	100%	1.26E+03	0.00E+00	100%	9
Sentinel-1A Out-of-plane High -12	1.21E+02	100%	6.98E+04	100%	1.85E+03	0.00E+00	100%	9
Sentinel-1A Hybrid Low -2	6.83E+00	100%	2.34E+02	70%	8.36E+00	2.34E-04	51%	9
Sentinel-1A Hybrid Low -6	1.02E+01	100%	4.96E+02	94%	1.55E+01	1.91E-07	81%	9
Sentinel-1A Hybrid Low -12	1.22E+01	100%	6.74E+02	98%	2.10E+01	7.36E-10	91%	9
Sentinel-1A Hybrid Medium -2	3.74E+01	100%	6.88E+03	100%	1.78E+02	6.92E-78	100%	9
Sentinel-1A Hybrid Medium -6	5.49E+01	100%	1.42E+04	100%	3.79E+02	1.68E-165	100%	9
Sentinel-1A Hybrid Medium -12	8.79E+01	100%	4.00E+04	100%	9.67E+02	0.00E+00	100%	10
Sentinel-1A Hybrid High -2	1.56E+02	100%	1.17E+05	100%	3.04E+03	0.00E+00	100%	9
Sentinel-1A Hybrid High -6	4.32E+02	100%	6.69E+05	100%	2.33E+04	0.00E+00	100%	9
Sentinel-1A Hybrid High -12	1.16E+03	100%	3.49E+06	100%	1.67E+05	0.00E+00	100%	9

Table A.39 Sentinel-1A Reachability analysis and probability from the three distances computed using range-range rate.

Sentinel-2B

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-2B No manoeuvre	1.31E+00	16%	2.90E+01	0%	2.44E+00	8.75E-02	0%	5
Sentinel-2B No manoeuvre	1.39E+01	100%	5.30E+03	100%	2.69E+01	2.00E-12	96%	3
Sentinel-2B No manoeuvre	1.46E+00	31%	2.33E+01	0%	2.73E+00	6.51E-02	0%	10
Sentinel-2B No manoeuvre	1.60E+00	45%	6.31E+01	0%	2.58E+00	7.55E-02	0%	10
Sentinel-2B No manoeuvre	1.01E+00	0%	8.05E+00	0%	2.20E+00	1.10E-01	0%	12
Sentinel-2B No manoeuvre	4.67E-02	0%	4.26E+01	0%	2.58E+00	7.60E-02	0%	11
Sentinel-2B No manoeuvre	1.07E+00	0%	1.03E+01	0%	3.03E+00	4.83E-02	1%	10
Sentinel-2B No manoeuvre	1.53E+00	38%	5.05E+01	0%	2.46E+00	8.58E-02	0%	11
Sentinel-2B No manoeuvre	1.42E+00	27%	1.22E+01	0%	2.43E+00	8.79E-02	0%	11
Sentinel-2B No manoeuvre	2.33E-01	0%	3.11E+01	0%	2.49E+00	8.33E-02	0%	11
Sentinel-2B No manoeuvre	4.05E-01	0%	7.62E+00	0%	2.95E+00	5.23E-02	0%	12
Sentinel-2B No manoeuvre	6.86E-01	0%	1.64E+01	0%	2.00E+00	1.35E-01	0%	12
Sentinel-2B No manoeuvre	6.47E-01	0%	1.00E+01	0%	2.45E+00	8.61E-02	0%	10
Sentinel-2B No manoeuvre	1.25E+00	8%	6.95E+01	5%	2.63E+00	7.24E-02	0%	9
Sentinel-2B No manoeuvre	3.73E-01	0%	1.18E+01	0%	2.37E+00	9.34E-02	0%	5
Sentinel-2B No manoeuvre	1.41E+01	100%	6.96E+03	100%	2.76E+01	9.84E-13	96%	3
Sentinel-2B No manoeuvre	5.61E-01	0%	1.30E+01	0%	2.59E+00	7.50E-02	0%	10
Sentinel-2B No manoeuvre	5.56E-01	0%	2.85E+01	0%	2.34E+00	9.61E-02	0%	10
Sentinel-2B No manoeuvre	2.49E+00	91%	2.09E+01	0%	2.82E+00	5.96E-02	0%	12
Sentinel-2B No manoeuvre	1.02E-01	0%	3.52E+01	0%	2.51E+00	8.12E-02	0%	12
Sentinel-2B No manoeuvre	9.67E-02	0%	6.46E+00	0%	2.88E+00	5.63E-02	0%	11
Sentinel-2B No manoeuvre	1.40E+00	25%	5.59E+01	0%	2.41E+00	8.96E-02	0%	11
Sentinel-2B No manoeuvre	1.54E+00	39%	1.58E+01	0%	2.53E+00	7.95E-02	0%	11

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-2B No manoeuvre	8.91E-01	0%	5.75E+01	0%	2.55E+00	7.80E-02	0%	10
Sentinel-2B No manoeuvre	6.34E-01	0%	7.88E+00	0%	2.96E+00	5.19E-02	0%	13
Sentinel-2B No manoeuvre	5.83E-01	0%	1.81E+01	0%	2.02E+00	1.33E-01	0%	12
Sentinel-2B No manoeuvre	2.31E-01	0%	8.06E+00	0%	2.41E+00	9.01E-02	0%	10
Sentinel-2B Tangential Low -2	3.18E-01	0%	9.56E+00	0%	2.48E+00	8.41E-02	0%	10
Sentinel-2B Tangential Low -6	1.68E+00	51%	2.73E+01	0%	2.82E+00	5.98E-02	0%	10
Sentinel-2B Tangential Low -12	2.07E+00	76%	3.46E+01	0%	3.00E+00	5.00E-02	1%	10
Sentinel-2B Tangential Medium -2	2.31E+00	86%	4.36E+01	0%	3.13E+00	4.37E-02	3%	10
Sentinel-2B Tangential Medium -6	6.35E+00	100%	2.60E+02	74%	7.51E+00	5.45E-04	45%	10
Sentinel-2B Tangential Medium -12	6.65E+00	100%	2.07E+02	64%	7.99E+00	3.40E-04	49%	10
Sentinel-2B Tangential High -2	7.17E+00	100%	3.28E+02	83%	8.89E+00	1.38E-04	54%	10
Sentinel-2B Tangential High -6	2.02E+01	100%	2.42E+03	100%	5.37E+01	4.84E-24	100%	10
Sentinel-2B Tangential High -12	1.62E+01	100%	1.94E+02	61%	3.52E+01	4.94E-16	99%	10
Sentinel-2B Out-of-plane Low -2	1.93E+00	69%	3.42E+01	0%	2.93E+00	5.33E-02	0%	10
Sentinel-2B Out-of-plane Low -6	9.58E-01	0%	1.50E+01	0%	2.58E+00	7.60E-02	0%	10
Sentinel-2B Out-of-plane Low -12	1.76E+00	57%	2.96E+01	0%	2.85E+00	5.79E-02	0%	10
Sentinel-2B Out-of-plane Medium -2	2.21E+00	82%	4.17E+01	0%	3.08E+00	4.62E-02	2%	10
Sentinel-2B Out-of-plane Medium -6	1.92E+00	69%	3.37E+01	0%	2.93E+00	5.35E-02	0%	10
Sentinel-2B Out-of-plane Medium -12	1.27E+00	11%	1.96E+01	0%	2.66E+00	6.97E-02	0%	10
Sentinel-2B Out-of-plane High -2	6.74E+00	100%	3.14E+02	82%	8.14E+00	2.91E-04	50%	10
Sentinel-2B Out-of-plane High -6	1.48E+00	33%	2.33E+01	0%	2.74E+00	6.48E-02	0%	10
Sentinel-2B Out-of-plane High -12	5.45E+00	100%	2.07E+02	64%	6.17E+00	2.09E-03	35%	10
Sentinel-2B Hybrid Low -2	3.14E+00	99%	7.14E+01	6%	3.70E+00	2.48E-02	10%	10
Sentinel-2B Hybrid Low -6	7.40E+00	100%	3.27E+02	83%	9.31E+00	9.08E-05	57%	10
Sentinel-2B Hybrid Low -12	6.67E+00	100%	8.82E+01	17%	8.02E+00	3.28E-04	49%	10
Sentinel-2B Hybrid Medium -2	1.29E+01	100%	1.03E+03	100%	2.32E+01	8.75E-11	93%	10
Sentinel-2B Hybrid Medium -6	4.16E+01	100%	1.05E+04	100%	2.19E+02	6.57E-96	100%	10
Sentinel-2B Hybrid Medium -12	2.93E+01	100%	5.61E+02	96%	1.10E+02	1.39E-48	100%	10
Sentinel-2B Hybrid High -2	5.61E+01	100%	1.99E+04	100%	3.96E+02	8.50E-173	100%	10
Sentinel-2B Hybrid High -6	2.36E+02	100%	4.47E+05	100%	6.99E+03	0.00E+00	100%	10
Sentinel-2B Hybrid High -12	3.21E+02	100%	9.63E+05	100%	1.29E+04	0.00E+00	100%	10

Table A.40 Sentinel-2B Reachability analysis and probability from the three distances computed using range-range rate.

C_D = 1.5

Sentinel-1A

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-1A No manoeuvre	1.25E+00	8%	8.70E+00	0%	2.90E+00	5.50E-02	0%	9
Sentinel-1A No manoeuvre	2.99E-01	0%	6.45E+01	1%	2.35E+00	9.55E-02	0%	10
Sentinel-1A No manoeuvre	2.69E-01	0%	7.90E+00	0%	2.54E+00	7.89E-02	0%	9
Sentinel-1A No manoeuvre	6.07E-01	0%	1.98E+01	0%	2.47E+00	8.42E-02	0%	9
Sentinel-1A No manoeuvre	1.20E-01	0%	8.14E+01	13%	2.81E+00	6.04E-02	0%	10
Sentinel-1A No manoeuvre	5.30E-01	0%	2.27E+01	0%	2.00E+00	1.35E-01	0%	9
Sentinel-1A No manoeuvre	1.49E+01	100%	1.86E+04	100%	3.04E+01	6.08E-14	97%	2
Sentinel-1A No manoeuvre	4.30E-01	0%	2.84E+01	0%	2.55E+00	7.83E-02	0%	9
Sentinel-1A No manoeuvre	8.20E-01	0%	5.87E+01	0%	2.33E+00	9.76E-02	0%	9
Sentinel-1A No manoeuvre	1.52E+01	100%	6.19E+03	100%	3.18E+01	1.54E-14	98%	2
Sentinel-1A No manoeuvre	1.22E+00	5%	2.91E+01	0%	2.65E+00	7.08E-02	0%	9
Sentinel-1A No manoeuvre	3.93E-01	0%	5.18E+01	0%	2.37E+00	9.37E-02	0%	11
Sentinel-1A No manoeuvre	9.91E-01	0%	1.41E+01	0%	2.72E+00	6.57E-02	0%	10
Sentinel-1A No manoeuvre	3.13E-01	0%	2.13E+01	0%	2.49E+00	8.32E-02	0%	8
Sentinel-1A No manoeuvre	5.66E-01	0%	6.51E+01	1%	2.79E+00	6.12E-02	0%	9
Sentinel-1A No manoeuvre	6.49E-01	0%	4.48E+01	0%	2.31E+00	9.90E-02	0%	8
Sentinel-1A No manoeuvre	7.65E-01	0%	6.96E+00	0%	2.77E+00	6.24E-02	0%	9
Sentinel-1A No manoeuvre	2.39E+00	89%	2.94E+02	79%	3.12E+00	4.41E-02	2%	10
Sentinel-1A No manoeuvre	8.24E-01	0%	1.35E+01	0%	2.63E+00	7.20E-02	0%	9
Sentinel-1A No manoeuvre	1.74E+00	56%	6.37E+01	0%	2.82E+00	5.97E-02	0%	10
Sentinel-1A No manoeuvre	7.02E-01	0%	1.08E+02	29%	2.93E+00	5.31E-02	0%	10
Sentinel-1A No manoeuvre	2.15E-01	0%	2.25E+01	0%	2.16E+00	1.16E-01	0%	9
Sentinel-1A No manoeuvre	1.56E+01	100%	2.28E+04	100%	3.31E+01	4.30E-15	98%	2
Sentinel-1A No manoeuvre	4.37E-01	0%	2.59E+01	0%	2.61E+00	7.38E-02	0%	9
Sentinel-1A No manoeuvre	2.37E-01	0%	4.26E+01	0%	2.42E+00	8.91E-02	0%	9
Sentinel-1A Tangential Low -2	6.29E-01	0%	9.36E+00	0%	2.58E+00	7.57E-02	0%	9
Sentinel-1A Tangential Low -6	2.72E+00	95%	4.27E+01	0%	3.45E+00	3.17E-02	7%	9
Sentinel-1A Tangential Low -12	4.20E-01	0%	7.94E+00	0%	2.55E+00	7.79E-02	0%	9

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-1A Tangential Medium -2	5.21E+00	100%	1.35E+02	41%	5.91E+00	2.70E-03	32%	9
Sentinel-1A Tangential Medium -6	7.74E+00	100%	2.90E+02	79%	1.00E+01	4.47E-05	61%	9
Sentinel-1A Tangential Medium -12	6.53E+00	100%	1.91E+02	60%	7.85E+00	3.89E-04	48%	9
Sentinel-1A Tangential High -2	1.54E+01	100%	1.15E+03	100%	3.23E+01	9.14E-15	98%	9
Sentinel-1A Tangential High -6	2.96E+01	100%	4.03E+03	100%	1.12E+02	2.08E-49	100%	9
Sentinel-1A Tangential High -12	3.64E+01	100%	6.04E+03	100%	1.68E+02	1.26E-73	100%	9
Sentinel-1A Out-of-plane Low -2	3.18E+01	100%	4.81E+03	100%	1.29E+02	8.95E-57	100%	9
Sentinel-1A Out-of-plane Low -6	2.70E+01	100%	3.47E+03	100%	9.40E+01	1.52E-41	100%	9
Sentinel-1A Out-of-plane Low -12	2.96E+01	100%	4.15E+03	100%	1.12E+02	1.71E-49	100%	9
Sentinel-1A Out-of-plane Medium -2	6.35E+01	100%	1.93E+04	100%	5.07E+02	9.94E-221	100%	9
Sentinel-1A Out-of-plane Medium -6	5.25E+01	100%	1.30E+04	100%	3.47E+02	2.77E-151	100%	9
Sentinel-1A Out-of-plane Medium -12	5.80E+01	100%	1.61E+04	100%	4.23E+02	2.10E-184	100%	9
Sentinel-1A Out-of-plane High -2	1.24E+02	100%	7.43E+04	100%	1.94E+03	0.00E+00	100%	9
Sentinel-1A Out-of-plane High -6	1.00E+02	100%	4.82E+04	100%	1.26E+03	0.00E+00	100%	9
Sentinel-1A Out-of-plane High -12	1.22E+02	100%	6.98E+04	100%	1.85E+03	0.00E+00	100%	9
Sentinel-1A Hybrid Low -2	6.06E+00	100%	1.84E+02	58%	7.12E+00	8.06E-04	42%	9
Sentinel-1A Hybrid Low -6	8.88E+00	100%	3.67E+02	87%	1.24E+01	4.16E-06	71%	9
Sentinel-1A Hybrid Low -12	1.09E+01	100%	5.43E+02	96%	1.74E+01	2.66E-08	85%	9
Sentinel-1A Hybrid Medium -2	3.85E+01	100%	6.96E+03	100%	1.88E+02	3.01E-82	100%	9
Sentinel-1A Hybrid Medium -6	5.54E+01	100%	1.42E+04	100%	3.86E+02	1.58E-168	100%	9
Sentinel-1A Hybrid Medium -12	8.91E+01	100%	4.10E+04	100%	9.95E+02	0.00E+00	100%	10
Sentinel-1A Hybrid High -2	1.56E+02	100%	1.15E+05	100%	3.06E+03	0.00E+00	100%	9
Sentinel-1A Hybrid High -6	4.31E+02	100%	6.64E+05	100%	2.32E+04	0.00E+00	100%	9
Sentinel-1A Hybrid High -12	1.16E+03	100%	3.49E+06	100%	1.68E+05	0.00E+00	100%	9

Table A.41 Sentinel-1A Reachability analysis and probability from the three distances computed using range-range rate.

Sentinel-2B

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-2B No manoeuvre	3.60E-01	0%	1.28E+01	0%	2.24E+00	1.06E-01	0%	5
Sentinel-2B No manoeuvre	1.29E+01	100%	4.74E+03	100%	2.37E+01	5.05E-11	94%	3
Sentinel-2B No manoeuvre	1.49E+00	34%	2.37E+01	0%	2.74E+00	6.47E-02	0%	10
Sentinel-2B No manoeuvre	1.90E+00	67%	8.09E+01	13%	2.71E+00	6.65E-02	0%	10
Sentinel-2B No manoeuvre	5.87E-01	0%	6.15E+00	0%	2.12E+00	1.20E-01	0%	12
Sentinel-2B No manoeuvre	4.34E-01	0%	5.06E+01	0%	2.60E+00	7.42E-02	0%	11
Sentinel-2B No manoeuvre	1.91E-02	0%	6.84E+00	0%	2.89E+00	5.57E-02	0%	10
Sentinel-2B No manoeuvre	2.29E-01	0%	1.65E+01	0%	2.17E+00	1.14E-01	0%	11
Sentinel-2B No manoeuvre	7.10E-01	0%	7.33E+00	0%	2.25E+00	1.06E-01	0%	11
Sentinel-2B No manoeuvre	1.18E+00	0%	6.79E+01	3%	2.64E+00	7.13E-02	0%	11
Sentinel-2B No manoeuvre	8.23E-01	0%	9.46E+00	0%	3.02E+00	4.87E-02	1%	12
Sentinel-2B No manoeuvre	1.06E+00	0%	2.28E+01	0%	2.07E+00	1.26E-01	0%	12
Sentinel-2B No manoeuvre	1.99E-01	0%	8.06E+00	0%	2.41E+00	8.96E-02	0%	10
Sentinel-2B No manoeuvre	1.02E+00	0%	5.38E+01	0%	2.55E+00	7.80E-02	0%	9
Sentinel-2B No manoeuvre	7.88E-01	0%	1.65E+01	0%	2.45E+00	8.67E-02	0%	5
Sentinel-2B No manoeuvre	1.38E+01	100%	6.45E+03	100%	2.65E+01	3.22E-12	95%	3
Sentinel-2B No manoeuvre	5.80E-01	0%	1.10E+01	0%	2.54E+00	7.92E-02	0%	10
Sentinel-2B No manoeuvre	3.57E-01	0%	2.36E+01	0%	2.30E+00	9.99E-02	0%	10
Sentinel-2B No manoeuvre	2.25E+00	84%	1.86E+01	0%	2.70E+00	6.74E-02	0%	12
Sentinel-2B No manoeuvre	4.08E-01	0%	3.88E+01	0%	2.51E+00	8.12E-02	0%	12
Sentinel-2B No manoeuvre	2.79E+00	96%	2.58E+01	0%	3.87E+00	2.09E-02	12%	11
Sentinel-2B No manoeuvre	2.11E-01	0%	1.90E+01	0%	2.15E+00	1.17E-01	0%	11
Sentinel-2B No manoeuvre	6.55E-01	0%	8.45E+00	0%	2.32E+00	9.82E-02	0%	11
Sentinel-2B No manoeuvre	9.68E-01	0%	5.52E+01	0%	2.56E+00	7.76E-02	0%	10
Sentinel-2B No manoeuvre	1.38E+00	22%	1.25E+01	0%	3.17E+00	4.21E-02	3%	13
Sentinel-2B No manoeuvre	2.07E+00	77%	6.33E+01	0%	2.47E+00	8.49E-02	0%	12
Sentinel-2B No manoeuvre	1.08E+00	0%	1.53E+01	0%	2.59E+00	7.51E-02	0%	10
Sentinel-2B Tangential Low -2	8.43E-01	0%	1.37E+01	0%	2.55E+00	7.79E-02	0%	10
Sentinel-2B Tangential Low -6	8.20E-01	0%	1.28E+01	0%	2.55E+00	7.82E-02	0%	10
Sentinel-2B Tangential Low -12	1.36E+00	20%	1.85E+01	0%	2.70E+00	6.75E-02	0%	10
Sentinel-2B Tangential Medium -2	2.02E+00	74%	3.52E+01	0%	2.98E+00	5.09E-02	1%	10
Sentinel-2B Tangential Medium -6	4.32E+00	100%	1.12E+02	31%	4.80E+00	8.26E-03	22%	10
Sentinel-2B Tangential Medium -12	4.54E+00	100%	4.77E+01	0%	5.04E+00	6.50E-03	24%	10
Sentinel-2B Tangential High -2	6.55E+00	100%	2.68E+02	76%	7.83E+00	3.97E-04	48%	10
Sentinel-2B Tangential High -6	2.18E+01	100%	2.86E+03	100%	6.17E+01	1.64E-27	100%	10
Sentinel-2B Tangential High -12	1.63E+01	100%	2.49E+02	73%	3.57E+01	3.16E-16	99%	10
Sentinel-2B Out-of-plane Low -2	1.67E+00	50%	2.75E+01	0%	2.81E+00	6.00E-02	0%	10

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-2B Out-of-plane Low -6	9.26E-01	0%	1.47E+01	0%	2.57E+00	7.63E-02	0%	10
Sentinel-2B Out-of-plane Low -12	3.37E+00	99%	8.51E+01	16%	3.89E+00	2.05E-02	12%	10
Sentinel-2B Out-of-plane Medium -2	2.93E+00	97%	6.60E+01	2%	3.53E+00	2.92E-02	8%	10
Sentinel-2B Out-of-plane Medium -6	2.14E+00	80%	3.98E+01	0%	3.04E+00	4.81E-02	1%	10
Sentinel-2B Out-of-plane Medium -12	1.88E+00	66%	3.25E+01	0%	2.91E+00	5.46E-02	0%	10
Sentinel-2B Out-of-plane High -2	8.01E+00	100%	4.44E+02	92%	1.05E+01	2.79E-05	63%	10
Sentinel-2B Out-of-plane High -6	3.05E+00	98%	7.09E+01	6%	3.62E+00	2.68E-02	9%	10
Sentinel-2B Out-of-plane High -12	7.77E+00	100%	4.18E+02	90%	1.00E+01	4.51E-05	61%	10
Sentinel-2B Hybrid Low -2	2.47E+00	91%	4.65E+01	0%	3.23E+00	3.96E-02	4%	10
Sentinel-2B Hybrid Low -6	6.40E+00	100%	2.33E+02	69%	7.58E+00	5.09E-04	46%	10
Sentinel-2B Hybrid Low -12	8.03E+00	100%	2.22E+02	67%	1.05E+01	2.67E-05	63%	10
Sentinel-2B Hybrid Medium -2	1.26E+01	100%	9.81E+02	100%	2.22E+01	2.32E-10	92%	10
Sentinel-2B Hybrid Medium -6	4.18E+01	100%	1.04E+04	100%	2.21E+02	1.30E-96	100%	10
Sentinel-2B Hybrid Medium -12	2.93E+01	100%	4.70E+02	93%	1.10E+02	2.67E-48	100%	10
Sentinel-2B Hybrid High -2	5.72E+01	100%	2.06E+04	100%	4.12E+02	1.09E-179	100%	10
Sentinel-2B Hybrid High -6	2.36E+02	100%	4.55E+05	100%	6.98E+03	0.00E+00	100%	10
Sentinel-2B Hybrid High -12	3.21E+02	100%	9.72E+05	100%	1.29E+04	0.00E+00	100%	10

Table A.42 Sentinel-2B Reachability analysis and probability from the three distances computed using range-range rate.

C_D = 2.5

Sentinel-1A

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-1A No manoeuvre	1.45E+00	30%	9.72E+00	0%	2.97E+00	5.14E-02	0%	9
Sentinel-1A No manoeuvre	1.42E+00	27%	1.78E+02	56%	2.59E+00	7.49E-02	0%	10
Sentinel-1A No manoeuvre	1.71E+00	54%	2.11E+01	0%	2.89E+00	5.56E-02	0%	9
Sentinel-1A No manoeuvre	6.27E-01	0%	2.22E+01	0%	2.46E+00	8.58E-02	0%	9
Sentinel-1A No manoeuvre	4.40E-01	0%	9.78E+01	23%	2.84E+00	5.81E-02	0%	10
Sentinel-1A No manoeuvre	5.18E-01	0%	3.14E+01	0%	2.09E+00	1.24E-01	0%	9
Sentinel-1A No manoeuvre	1.45E+01	100%	1.81E+04	100%	2.92E+01	2.09E-13	97%	2
Sentinel-1A No manoeuvre	6.17E-01	0%	3.44E+01	0%	2.59E+00	7.47E-02	0%	9
Sentinel-1A No manoeuvre	9.07E-02	0%	4.64E+01	0%	2.31E+00	9.93E-02	0%	9
Sentinel-1A No manoeuvre	1.89E+01	100%	6.28E+03	100%	4.77E+01	1.99E-21	100%	2
Sentinel-1A No manoeuvre	1.29E+00	13%	3.88E+01	0%	2.70E+00	6.69E-02	0%	9
Sentinel-1A No manoeuvre	1.10E+00	0%	1.23E+02	36%	2.54E+00	7.86E-02	0%	11
Sentinel-1A No manoeuvre	1.56E+00	41%	6.41E+01	1%	2.29E+00	1.02E-01	0%	10
Sentinel-1A No manoeuvre	5.29E-01	0%	2.97E+01	0%	2.54E+00	7.88E-02	0%	8
Sentinel-1A No manoeuvre	4.13E-01	0%	4.44E+01	0%	2.73E+00	6.55E-02	0%	9
Sentinel-1A No manoeuvre	7.55E-01	0%	5.74E+01	0%	2.34E+00	9.63E-02	0%	8
Sentinel-1A No manoeuvre	6.73E-01	0%	6.59E+00	0%	2.75E+00	6.42E-02	0%	9
Sentinel-1A No manoeuvre	1.68E+00	52%	1.71E+02	54%	2.76E+00	6.33E-02	0%	10
Sentinel-1A No manoeuvre	6.25E-01	0%	1.13E+01	0%	2.58E+00	7.56E-02	0%	9
Sentinel-1A No manoeuvre	9.14E-01	0%	3.13E+01	0%	2.57E+00	7.67E-02	0%	10
Sentinel-1A No manoeuvre	1.72E+00	54%	3.12E+02	82%	3.28E+00	3.77E-02	4%	10
Sentinel-1A No manoeuvre	3.19E-01	0%	2.14E+01	0%	2.12E+00	1.21E-01	0%	9
Sentinel-1A No manoeuvre	1.26E+00	10%	4.60E+01	0%	2.76E+00	6.34E-02	0%	2
Sentinel-1A No manoeuvre	2.50E-01	0%	4.59E+01	0%	2.44E+00	8.68E-02	0%	9
Sentinel-1A No manoeuvre	3.57E-02	0%	7.43E+00	0%	2.52E+00	8.02E-02	0%	9
Sentinel-1A Tangential Low -2	4.05E-01	0%	8.05E+00	0%	2.54E+00	7.87E-02	0%	9
Sentinel-1A Tangential Low -6	2.35E+00	87%	3.32E+01	0%	3.22E+00	4.01E-02	4%	9
Sentinel-1A Tangential Low -12	4.13E+00	100%	8.79E+01	17%	4.66E+00	9.50E-03	20%	9
Sentinel-1A Tangential Medium -2	8.10E+00	100%	3.09E+02	81%	1.07E+01	2.20E-05	64%	9
Sentinel-1A Tangential Medium -6	7.08E+00	100%	2.29E+02	69%	8.80E+00	1.51E-04	54%	9
Sentinel-1A Tangential Medium -12	1.40E+01	100%	9.28E+02	100%	2.69E+01	2.04E-12	96%	9
Sentinel-1A Tangential High -2	3.06E+01	100%	4.34E+03	100%	1.20E+02	1.24E-52	100%	9
Sentinel-1A Tangential High -6	3.47E+01	100%	5.36E+03	100%	1.53E+02	2.41E-67	100%	9
Sentinel-1A Tangential High -12	3.13E+01	100%	4.76E+03	100%	1.25E+02	3.72E-55	100%	9
Sentinel-1A Out-of-plane Low -2	2.58E+01	100%	3.17E+03	100%	8.56E+01	6.80E-38	100%	9
Sentinel-1A Out-of-plane Low -6	2.81E+01	100%	3.69E+03	100%	1.01E+02	1.16E-44	100%	9
Sentinel-1A Out-of-plane Low -12	6.36E+01	100%	1.93E+04	100%	5.08E+02	1.72E-221	100%	9
Sentinel-1A Out-of-plane Medium -2	5.28E+01	100%	1.33E+04	100%	3.51E+02	3.84E-153	100%	9
Sentinel-1A Out-of-plane Medium -6	5.82E+01	100%	1.61E+04	100%	4.25E+02	2.16E-185	100%	9
Sentinel-1A Out-of-plane Medium -12	1.25E+02	100%	7.33E+04	100%	1.95E+03	0.00E+00	100%	9
Sentinel-1A Out-of-plane High -2	1.01E+02	100%	4.89E+04	100%	1.29E+03	0.00E+00	100%	9
Sentinel-1A Out-of-plane High -6	1.21E+02	100%	6.78E+04	100%	1.83E+03	0.00E+00	100%	9

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-1A Out-of-plane High -12	6.94E+00	100%	2.33E+02	69%	8.55E+00	1.94E-04	52%	9
Sentinel-1A Hybrid Low -2	9.22E+00	100%	4.00E+02	89%	1.31E+01	1.95E-06	74%	9
Sentinel-1A Hybrid Low -6	1.18E+01	100%	6.27E+02	97%	2.01E+01	1.95E-09	89%	9
Sentinel-1A Hybrid Low -12	3.94E+01	100%	7.35E+03	100%	1.96E+02	5.68E-86	100%	9
Sentinel-1A Hybrid Medium -2	5.77E+01	100%	1.55E+04	100%	4.18E+02	2.95E-182	100%	9
Sentinel-1A Hybrid Medium -6	8.69E+01	100%	3.86E+04	100%	9.46E+02	0.00E+00	100%	9
Sentinel-1A Hybrid Medium -12	1.58E+02	100%	1.20E+05	100%	3.12E+03	0.00E+00	100%	10
Sentinel-1A Hybrid High -2	4.34E+02	100%	6.68E+05	100%	2.36E+04	0.00E+00	100%	9
Sentinel-1A Hybrid High -6	1.16E+03	100%	3.41E+06	100%	1.69E+05	0.00E+00	100%	9
Sentinel-1A Hybrid High -12	1.16E+03	100%	3.49E+06	100%	1.68E+05	0.00E+00	100%	9

Table A.43 Sentinel-1A Reachability analysis and probability from the three distances computed using range-range rate.

Sentinel-2B

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-2B No manoeuvre	2.03E+00	75%	5.29E+01	0%	2.74E+00	6.48E-02	0%	5
Sentinel-2B No manoeuvre	1.34E+01	100%	5.02E+03	100%	2.54E+01	9.45E-12	95%	3
Sentinel-2B No manoeuvre	1.50E+00	35%	2.42E+01	0%	2.75E+00	6.41E-02	0%	10
Sentinel-2B No manoeuvre	6.11E-01	0%	2.51E+01	0%	2.31E+00	9.92E-02	0%	10
Sentinel-2B No manoeuvre	7.05E-01	0%	6.57E+00	0%	2.14E+00	1.17E-01	0%	12
Sentinel-2B No manoeuvre	2.50E+00	91%	3.07E+02	81%	3.36E+00	3.48E-02	5%	11
Sentinel-2B No manoeuvre	2.51E-01	0%	7.05E+00	0%	2.90E+00	5.51E-02	0%	10
Sentinel-2B No manoeuvre	1.85E-01	0%	1.60E+01	0%	2.16E+00	1.16E-01	0%	11
Sentinel-2B No manoeuvre	3.95E-01	0%	6.24E+00	0%	2.21E+00	1.10E-01	0%	11
Sentinel-2B No manoeuvre	1.57E-01	0%	2.88E+01	0%	2.46E+00	8.54E-02	0%	11
Sentinel-2B No manoeuvre	1.01E-01	0%	7.27E+00	0%	2.95E+00	5.25E-02	0%	12
Sentinel-2B No manoeuvre	2.38E-01	0%	1.13E+01	0%	1.92E+00	1.46E-01	0%	12
Sentinel-2B No manoeuvre	4.23E-01	0%	7.07E+00	0%	2.35E+00	9.55E-02	0%	10
Sentinel-2B No manoeuvre	1.36E+00	21%	7.23E+01	7%	2.64E+00	7.16E-02	0%	9
Sentinel-2B No manoeuvre	5.10E-01	0%	1.35E+01	0%	2.41E+00	8.94E-02	0%	5
Sentinel-2B No manoeuvre	1.27E+01	100%	6.36E+03	100%	2.32E+01	8.73E-11	93%	3
Sentinel-2B No manoeuvre	2.34E-01	0%	9.78E+00	0%	2.50E+00	8.18E-02	0%	10
Sentinel-2B No manoeuvre	5.72E-01	0%	2.56E+01	0%	2.30E+00	1.01E-01	0%	10
Sentinel-2B No manoeuvre	2.94E-01	0%	5.53E+00	0%	2.12E+00	1.20E-01	0%	12
Sentinel-2B No manoeuvre	3.95E-01	0%	4.59E+01	0%	2.55E+00	7.78E-02	0%	12
Sentinel-2B No manoeuvre	5.94E-01	0%	7.08E+00	0%	2.90E+00	5.52E-02	0%	11
Sentinel-2B No manoeuvre	1.53E-01	0%	1.62E+01	0%	2.12E+00	1.20E-01	0%	11
Sentinel-2B No manoeuvre	4.26E-01	0%	6.79E+00	0%	2.27E+00	1.03E-01	0%	11
Sentinel-2B No manoeuvre	1.74E+00	56%	1.33E+02	40%	2.85E+00	5.78E-02	0%	10
Sentinel-2B No manoeuvre	5.09E-01	0%	7.46E+00	0%	2.94E+00	5.30E-02	0%	13
Sentinel-2B No manoeuvre	1.71E-01	0%	1.41E+01	0%	1.98E+00	1.38E-01	0%	12
Sentinel-2B No manoeuvre	7.42E-01	0%	1.09E+01	0%	2.48E+00	8.39E-02	0%	10
Sentinel-2B Tangential Low -2	7.99E-01	0%	1.32E+01	0%	2.54E+00	7.86E-02	0%	10
Sentinel-2B Tangential Low -6	1.46E+00	32%	2.28E+01	0%	2.73E+00	6.50E-02	0%	10
Sentinel-2B Tangential Low -12	9.08E-01	0%	1.18E+01	0%	2.57E+00	7.67E-02	0%	10
Sentinel-2B Tangential Medium -2	2.20E+00	82%	4.00E+01	0%	3.07E+00	4.65E-02	2%	10
Sentinel-2B Tangential Medium -6	4.86E+00	100%	1.46E+02	46%	5.42E+00	4.45E-03	28%	10
Sentinel-2B Tangential Medium -12	5.76E+00	100%	1.33E+02	40%	6.61E+00	1.34E-03	38%	10
Sentinel-2B Tangential High -2	4.71E+00	100%	1.35E+02	41%	5.24E+00	5.31E-03	26%	10
Sentinel-2B Tangential High -6	2.07E+01	100%	2.51E+03	100%	5.58E+01	6.01E-25	100%	10
Sentinel-2B Tangential High -12	1.66E+01	100%	3.08E+02	81%	3.67E+01	1.13E-16	99%	10
Sentinel-2B Out-of-plane Low -2	2.44E+00	90%	4.96E+01	0%	3.21E+00	4.02E-02	4%	10
Sentinel-2B Out-of-plane Low -6	4.12E-01	0%	1.01E+01	0%	2.49E+00	8.30E-02	0%	10
Sentinel-2B Out-of-plane Low -12	2.50E+00	91%	5.15E+01	0%	3.25E+00	3.88E-02	4%	10
Sentinel-2B Out-of-plane Medium -2	1.46E+00	31%	2.33E+01	0%	2.73E+00	6.49E-02	0%	10
Sentinel-2B Out-of-plane Medium -6	1.50E+00	35%	2.38E+01	0%	2.74E+00	6.43E-02	0%	10
Sentinel-2B Out-of-plane Medium -12	1.73E+00	55%	2.89E+01	0%	2.84E+00	5.86E-02	0%	10
Sentinel-2B Out-of-plane High -2	9.74E+00	100%	6.46E+02	98%	1.43E+01	6.08E-07	78%	10
Sentinel-2B Out-of-plane High -6	2.84E+00	96%	6.31E+01	0%	3.47E+00	3.10E-02	7%	10
Sentinel-2B Out-of-plane High -12	6.48E+00	100%	2.90E+02	79%	7.71E+00	4.49E-04	47%	10
Sentinel-2B Hybrid Low -2	3.05E+00	98%	6.80E+01	4%	3.63E+00	2.66E-02	9%	10
Sentinel-2B Hybrid Low -6	7.18E+00	100%	3.04E+02	81%	8.90E+00	1.36E-04	54%	10
Sentinel-2B Hybrid Low -12	7.68E+00	100%	1.86E+02	59%	9.84E+00	5.34E-05	60%	10
Sentinel-2B Hybrid Medium -2	1.20E+01	100%	8.95E+02	99%	2.04E+01	1.32E-09	90%	10
Sentinel-2B Hybrid Medium -6	4.13E+01	100%	1.03E+04	100%	2.15E+02	3.41E-94	100%	10
Sentinel-2B Hybrid Medium -12	2.98E+01	100%	6.78E+02	98%	1.14E+02	3.63E-50	100%	10

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-2B Hybrid High -2	5.78E+01	100%	2.13E+04	100%	4.20E+02	5.19E-183	100%	10
Sentinel-2B Hybrid High -6	2.36E+02	100%	4.53E+05	100%	6.97E+03	0.00E+00	100%	10
Sentinel-2B Hybrid High -12	3.20E+02	100%	9.77E+05	100%	1.28E+04	0.00E+00	100%	10

Table A.44 Sentinel-2B Reachability analysis and probability from the three distances computed using range-range rate.

$C_D = 3$

Sentinel-1A

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-1A No manoeuvre	3.35E-01	0%	6.03E+00	0%	2.72E+00	6.59E-02	0%	9
Sentinel-1A No manoeuvre	1.04E+00	0%	1.23E+02	36%	2.47E+00	8.45E-02	0%	10
Sentinel-1A No manoeuvre	7.12E-02	0%	9.63E+00	0%	2.64E+00	7.16E-02	0%	9
Sentinel-1A No manoeuvre	3.38E-01	0%	1.82E+01	0%	2.42E+00	8.85E-02	0%	9
Sentinel-1A No manoeuvre	6.18E-01	0%	1.12E+02	31%	2.87E+00	5.67E-02	0%	10
Sentinel-1A No manoeuvre	4.94E-01	0%	2.85E+01	0%	2.11E+00	1.21E-01	0%	9
Sentinel-1A No manoeuvre	1.26E+01	100%	1.37E+04	100%	2.25E+01	1.73E-10	92%	2
Sentinel-1A No manoeuvre	4.09E-01	0%	3.11E+01	0%	2.55E+00	7.78E-02	0%	9
Sentinel-1A No manoeuvre	1.11E+00	0%	9.33E+01	21%	2.47E+00	8.45E-02	0%	9
Sentinel-1A No manoeuvre	1.62E+01	100%	4.51E+03	100%	3.56E+01	3.47E-16	99%	2
Sentinel-1A No manoeuvre	3.46E-01	0%	1.24E+01	0%	2.41E+00	8.96E-02	0%	9
Sentinel-1A No manoeuvre	9.92E-01	0%	9.99E+01	24%	2.51E+00	8.10E-02	0%	11
Sentinel-1A No manoeuvre	1.99E-01	0%	1.80E+01	0%	1.95E+00	1.42E-01	0%	10
Sentinel-1A No manoeuvre	3.70E-01	0%	2.84E+01	0%	2.56E+00	7.73E-02	0%	8
Sentinel-1A No manoeuvre	1.12E+00	0%	1.09E+02	29%	2.90E+00	5.49E-02	0%	9
Sentinel-1A No manoeuvre	3.90E-01	0%	3.59E+01	0%	2.27E+00	1.03E-01	0%	8
Sentinel-1A No manoeuvre	8.76E-01	0%	6.85E+00	0%	2.78E+00	6.22E-02	0%	9
Sentinel-1A No manoeuvre	8.61E-01	0%	1.06E+02	27%	2.56E+00	7.70E-02	0%	10
Sentinel-1A No manoeuvre	1.03E-01	0%	7.97E+00	0%	2.51E+00	8.16E-02	0%	9
Sentinel-1A No manoeuvre	1.47E-01	0%	1.59E+01	0%	2.40E+00	9.03E-02	0%	10
Sentinel-1A No manoeuvre	1.10E+00	0%	1.63E+02	52%	3.03E+00	4.84E-02	1%	10
Sentinel-1A No manoeuvre	2.02E-01	0%	2.22E+01	0%	2.15E+00	1.16E-01	0%	9
Sentinel-1A No manoeuvre	1.57E+01	100%	2.51E+04	100%	3.37E+01	2.26E-15	98%	2
Sentinel-1A No manoeuvre	7.90E-01	0%	2.79E+01	0%	2.62E+00	7.30E-02	0%	9
Sentinel-1A No manoeuvre	2.36E-01	0%	5.04E+01	0%	2.43E+00	8.77E-02	0%	9
Sentinel-1A Tangential Low -2	2.19E+00	82%	4.33E+01	0%	3.24E+00	3.93E-02	4%	9
Sentinel-1A Tangential Low -6	8.30E-01	0%	1.42E+01	0%	2.72E+00	6.59E-02	0%	9
Sentinel-1A Tangential Low -12	3.09E-01	0%	9.69E+00	0%	2.65E+00	7.07E-02	0%	9
Sentinel-1A Tangential Medium -2	4.54E+00	100%	1.54E+02	48%	5.21E+00	5.48E-03	26%	9
Sentinel-1A Tangential Medium -6	8.27E+00	100%	3.27E+02	83%	1.11E+01	1.56E-05	66%	9
Sentinel-1A Tangential Medium -12	6.66E+00	100%	2.02E+02	63%	8.08E+00	3.11E-04	49%	9
Sentinel-1A Tangential High -2	1.69E+01	100%	1.32E+03	100%	3.81E+01	2.78E-17	99%	9
Sentinel-1A Tangential High -6	3.18E+01	100%	4.63E+03	100%	1.29E+02	8.25E-57	100%	9
Sentinel-1A Tangential High -12	3.39E+01	100%	5.20E+03	100%	1.46E+02	2.89E-64	100%	9
Sentinel-1A Out-of-plane Low -2	2.52E+01	100%	4.55E+03	100%	8.23E+01	1.78E-36	100%	9
Sentinel-1A Out-of-plane Low -6	2.13E+01	100%	3.22E+03	100%	5.96E+01	1.34E-26	100%	9
Sentinel-1A Out-of-plane Low -12	2.36E+01	100%	3.97E+03	100%	7.21E+01	4.79E-32	100%	9
Sentinel-1A Out-of-plane Medium -2	5.32E+01	100%	2.00E+04	100%	3.56E+02	2.17E-155	100%	9
Sentinel-1A Out-of-plane Medium -6	4.14E+01	100%	1.18E+04	100%	2.17E+02	8.76E-95	100%	9
Sentinel-1A Out-of-plane Medium -12	4.76E+01	100%	1.64E+04	100%	2.86E+02	5.29E-125	100%	9
Sentinel-1A Out-of-plane High -2	1.02E+02	100%	7.32E+04	100%	1.30E+03	0.00E+00	100%	9
Sentinel-1A Out-of-plane High -6	8.19E+01	100%	4.67E+04	100%	8.40E+02	0.00E+00	100%	9
Sentinel-1A Out-of-plane High -12	9.90E+01	100%	6.75E+04	100%	1.23E+03	0.00E+00	100%	9
Sentinel-1A Hybrid Low -2	4.86E+00	100%	1.70E+02	54%	5.59E+00	3.74E-03	30%	9
Sentinel-1A Hybrid Low -6	9.26E+00	100%	3.97E+02	89%	1.32E+01	1.79E-06	74%	9
Sentinel-1A Hybrid Low -12	1.11E+01	100%	5.43E+02	96%	1.79E+01	1.68E-08	86%	9
Sentinel-1A Hybrid Medium -2	3.70E+01	100%	6.29E+03	100%	1.73E+02	5.25E-76	100%	9
Sentinel-1A Hybrid Medium -6	5.56E+01	100%	1.41E+04	100%	3.89E+02	1.22E-169	100%	9
Sentinel-1A Hybrid Medium -12	9.25E+01	100%	3.87E+04	100%	1.07E+03	0.00E+00	100%	10
Sentinel-1A Hybrid High -2	1.60E+02	100%	1.20E+05	100%	3.21E+03	0.00E+00	100%	9
Sentinel-1A Hybrid High -6	4.35E+02	100%	6.54E+05	100%	2.36E+04	0.00E+00	100%	9
Sentinel-1A Hybrid High -12	1.17E+03	100%	3.44E+06	100%	1.70E+05	0.00E+00	100%	9

Table A.45 Sentinel-1A Reachability analysis and probability from the three distances computed using range-range rate.

Sentinel-2B

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-2B No manoeuvre	1.37E-01	0%	1.16E+01	0%	2.23E+00	1.08E-01	0%	5
Sentinel-2B No manoeuvre	1.25E+01	100%	4.30E+03	100%	2.25E+01	1.72E-10	92%	3
Sentinel-2B No manoeuvre	1.69E-01	0%	9.15E+00	0%	2.47E+00	8.48E-02	0%	10
Sentinel-2B No manoeuvre	1.79E+00	60%	7.45E+01	8%	2.66E+00	6.97E-02	0%	10
Sentinel-2B No manoeuvre	5.83E-01	0%	6.05E+00	0%	2.08E+00	1.25E-01	0%	12
Sentinel-2B No manoeuvre	8.03E-01	0%	6.91E+01	4%	2.65E+00	7.04E-02	0%	11
Sentinel-2B No manoeuvre	2.91E-01	0%	7.09E+00	0%	2.90E+00	5.49E-02	0%	10
Sentinel-2B No manoeuvre	4.16E-01	0%	1.79E+01	0%	2.17E+00	1.14E-01	0%	11
Sentinel-2B No manoeuvre	1.39E+00	24%	1.23E+01	0%	2.44E+00	8.74E-02	0%	11
Sentinel-2B No manoeuvre	1.38E+00	23%	7.97E+01	12%	2.69E+00	6.79E-02	0%	11
Sentinel-2B No manoeuvre	5.41E-01	0%	8.28E+00	0%	2.99E+00	5.05E-02	1%	12
Sentinel-2B No manoeuvre	1.65E-01	0%	1.11E+01	0%	1.96E+00	1.41E-01	0%	12
Sentinel-2B No manoeuvre	7.50E-01	0%	9.50E+00	0%	2.40E+00	9.08E-02	0%	10
Sentinel-2B No manoeuvre	2.23E+00	83%	1.45E+02	45%	3.01E+00	4.92E-02	1%	9
Sentinel-2B No manoeuvre	2.50E-01	0%	1.19E+01	0%	2.40E+00	9.07E-02	0%	5
Sentinel-2B No manoeuvre	1.59E+01	100%	9.49E+03	100%	3.44E+01	1.12E-15	98%	3
Sentinel-2B No manoeuvre	4.44E-01	0%	1.11E+01	0%	2.54E+00	7.93E-02	0%	10
Sentinel-2B No manoeuvre	4.83E-01	0%	2.29E+01	0%	2.27E+00	1.04E-01	0%	10
Sentinel-2B No manoeuvre	3.69E-01	0%	5.66E+00	0%	2.09E+00	1.24E-01	0%	12
Sentinel-2B No manoeuvre	3.48E-01	0%	4.12E+01	0%	2.55E+00	7.82E-02	0%	12
Sentinel-2B No manoeuvre	7.19E-01	0%	7.58E+00	0%	2.93E+00	5.34E-02	0%	11
Sentinel-2B No manoeuvre	6.52E-01	0%	2.10E+01	0%	2.14E+00	1.17E-01	0%	11
Sentinel-2B No manoeuvre	7.84E-01	0%	8.73E+00	0%	2.31E+00	9.90E-02	0%	11
Sentinel-2B No manoeuvre	1.54E+00	39%	9.85E+01	24%	2.76E+00	6.36E-02	0%	10
Sentinel-2B No manoeuvre	3.34E-02	0%	6.87E+00	0%	2.92E+00	5.37E-02	0%	13
Sentinel-2B No manoeuvre	6.90E-01	0%	1.82E+01	0%	2.00E+00	1.36E-01	0%	12
Sentinel-2B No manoeuvre	8.73E-02	0%	8.36E+00	0%	2.45E+00	8.64E-02	0%	10
Sentinel-2B Tangential Low -2	1.51E+00	36%	2.43E+01	0%	2.75E+00	6.40E-02	0%	10
Sentinel-2B Tangential Low -6	6.62E-01	0%	1.12E+01	0%	2.52E+00	8.05E-02	0%	10
Sentinel-2B Tangential Low -12	2.11E+00	78%	3.62E+01	0%	3.02E+00	4.88E-02	1%	10
Sentinel-2B Tangential Medium -2	1.51E+00	36%	2.29E+01	0%	2.75E+00	6.37E-02	0%	10
Sentinel-2B Tangential Medium -6	3.95E+00	100%	9.10E+01	19%	4.41E+00	1.21E-02	18%	10
Sentinel-2B Tangential Medium -12	4.52E+00	100%	4.82E+01	0%	5.02E+00	6.60E-03	24%	10
Sentinel-2B Tangential High -2	8.27E+00	100%	4.50E+02	92%	1.10E+01	1.64E-05	66%	10
Sentinel-2B Tangential High -6	2.09E+01	100%	2.59E+03	100%	5.68E+01	2.06E-25	100%	10
Sentinel-2B Tangential High -12	1.65E+01	100%	2.95E+02	79%	3.66E+01	1.22E-16	99%	10
Sentinel-2B Out-of-plane Low -2	2.28E+00	85%	4.43E+01	0%	3.12E+00	4.43E-02	2%	10
Sentinel-2B Out-of-plane Low -6	1.69E+00	52%	2.84E+01	0%	2.82E+00	5.94E-02	0%	10
Sentinel-2B Out-of-plane Low -12	8.65E-01	0%	1.40E+01	0%	2.56E+00	7.74E-02	0%	10
Sentinel-2B Out-of-plane Medium -2	3.03E+00	98%	7.14E+01	6%	3.62E+00	2.69E-02	9%	10
Sentinel-2B Out-of-plane Medium -6	2.01E+00	74%	3.63E+01	0%	2.97E+00	5.11E-02	1%	10
Sentinel-2B Out-of-plane Medium -12	4.70E+00	100%	1.58E+02	50%	5.23E+00	5.37E-03	26%	10
Sentinel-2B Out-of-plane High -2	6.94E+00	100%	3.35E+02	84%	8.48E+00	2.07E-04	52%	10
Sentinel-2B Out-of-plane High -6	3.20E+00	99%	7.85E+01	11%	3.75E+00	2.35E-02	10%	10
Sentinel-2B Out-of-plane High -12	5.62E+00	100%	2.23E+02	67%	6.42E+00	1.63E-03	37%	10
Sentinel-2B Hybrid Low -2	3.04E+00	98%	6.82E+01	4%	3.62E+00	2.67E-02	9%	10
Sentinel-2B Hybrid Low -6	6.95E+00	100%	2.85E+02	78%	8.51E+00	2.01E-04	52%	10
Sentinel-2B Hybrid Low -12	7.19E+00	100%	1.39E+02	43%	8.92E+00	1.33E-04	55%	10
Sentinel-2B Hybrid Medium -2	1.40E+01	100%	1.25E+03	100%	2.70E+01	1.93E-12	96%	10
Sentinel-2B Hybrid Medium -6	4.23E+01	100%	1.09E+04	100%	2.26E+02	7.23E-99	100%	10
Sentinel-2B Hybrid Medium -12	2.95E+01	100%	5.16E+02	95%	1.11E+02	3.93E-49	100%	10
Sentinel-2B Hybrid High -2	5.78E+01	100%	2.13E+04	100%	4.21E+02	2.07E-183	100%	10
Sentinel-2B Hybrid High -6	2.35E+02	100%	4.48E+05	100%	6.90E+03	0.00E+00	100%	10
Sentinel-2B Hybrid High -12	3.18E+02	100%	9.54E+05	100%	1.26E+04	0.00E+00	100%	10

Table A.46 Sentinel-2B Reachability analysis and probability from the three distances computed using range-range rate.

A.3.3 Atmospheric model

Marshall

Sentinel-1A

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-1A No manoeuvre	4.27E-01	0%	6.16E+00	0%	2.73E+00	6.55E-02	0%	9
Sentinel-1A No manoeuvre	7.77E-01	0%	9.59E+01	22%	2.42E+00	8.92E-02	0%	10
Sentinel-1A No manoeuvre	7.39E-01	0%	1.03E+01	0%	2.61E+00	7.37E-02	0%	9
Sentinel-1A No manoeuvre	3.94E-01	0%	1.63E+01	0%	2.43E+00	8.77E-02	0%	9
Sentinel-1A No manoeuvre	5.68E-01	0%	9.95E+01	24%	2.85E+00	5.76E-02	0%	10
Sentinel-1A No manoeuvre	8.24E-01	0%	3.14E+01	0%	2.08E+00	1.25E-01	0%	9
Sentinel-1A No manoeuvre	1.51E+01	100%	1.84E+04	100%	3.13E+01	2.62E-14	98%	2
Sentinel-1A No manoeuvre	3.03E-01	0%	2.45E+01	0%	2.51E+00	8.17E-02	0%	9
Sentinel-1A No manoeuvre	1.60E-01	0%	3.89E+01	0%	2.28E+00	1.02E-01	0%	9
Sentinel-1A No manoeuvre	1.66E+01	100%	8.00E+03	100%	3.73E+01	6.15E-17	99%	2
Sentinel-1A No manoeuvre	1.90E-01	0%	1.18E+01	0%	2.41E+00	9.02E-02	0%	9
Sentinel-1A No manoeuvre	7.48E-01	0%	7.95E+01	12%	2.47E+00	8.47E-02	0%	11
Sentinel-1A No manoeuvre	1.42E+00	27%	1.67E+01	0%	2.82E+00	5.94E-02	0%	10
Sentinel-1A No manoeuvre	9.72E-01	0%	4.03E+01	0%	2.63E+00	7.20E-02	0%	8
Sentinel-1A No manoeuvre	1.34E+00	18%	1.41E+02	44%	2.99E+00	5.03E-02	1%	9
Sentinel-1A No manoeuvre	1.28E+00	12%	8.14E+01	13%	2.46E+00	8.57E-02	0%	8
Sentinel-1A No manoeuvre	2.66E-01	0%	5.84E+00	0%	2.69E+00	6.76E-02	0%	9
Sentinel-1A No manoeuvre	9.54E-01	0%	1.07E+02	28%	2.57E+00	7.67E-02	0%	10
Sentinel-1A No manoeuvre	4.96E-01	0%	1.23E+01	0%	2.65E+00	7.08E-02	0%	9
Sentinel-1A No manoeuvre	1.21E+00	4%	3.25E+01	0%	2.53E+00	7.99E-02	0%	10
Sentinel-1A No manoeuvre	1.12E+00	0%	1.67E+02	53%	3.05E+00	4.74E-02	2%	10
Sentinel-1A No manoeuvre	3.74E-01	0%	2.34E+01	0%	2.16E+00	1.15E-01	0%	9
Sentinel-1A No manoeuvre	1.49E+01	100%	2.10E+04	100%	3.04E+01	6.25E-14	97%	2
Sentinel-1A No manoeuvre	7.52E-02	0%	1.89E+01	0%	2.55E+00	7.82E-02	0%	9
Sentinel-1A No manoeuvre	3.27E-01	0%	5.31E+01	0%	2.43E+00	8.79E-02	0%	9
Sentinel-1A Tangential Low -2	1.75E+00	57%	2.24E+01	0%	2.92E+00	5.39E-02	0%	9
Sentinel-1A Tangential Low -6	2.98E-01	0%	7.78E+00	0%	2.55E+00	7.83E-02	0%	9
Sentinel-1A Tangential Low -12	9.24E-01	0%	1.11E+01	0%	2.64E+00	7.13E-02	0%	9
Sentinel-1A Tangential Medium -2	4.07E+00	100%	8.68E+01	17%	4.60E+00	1.00E-02	20%	9
Sentinel-1A Tangential Medium -6	7.00E+00	100%	2.37E+02	70%	8.65E+00	1.75E-04	53%	9
Sentinel-1A Tangential Medium -12	6.85E+00	100%	2.19E+02	67%	8.40E+00	2.24E-04	51%	9
Sentinel-1A Tangential High -2	1.49E+01	100%	1.07E+03	100%	3.03E+01	6.90E-14	97%	9
Sentinel-1A Tangential High -6	3.18E+01	100%	4.82E+03	100%	1.29E+02	6.84E-57	100%	9
Sentinel-1A Tangential High -12	3.51E+01	100%	5.61E+03	100%	1.57E+02	1.00E-68	100%	9
Sentinel-1A Out-of-plane Low -2	3.02E+01	100%	4.42E+03	100%	1.16E+02	2.76E-51	100%	9
Sentinel-1A Out-of-plane Low -6	2.58E+01	100%	3.21E+03	100%	8.55E+01	7.66E-38	100%	9
Sentinel-1A Out-of-plane Low -12	2.94E+01	100%	4.28E+03	100%	1.10E+02	1.32E-48	100%	9
Sentinel-1A Out-of-plane Medium -2	6.40E+01	100%	2.04E+04	100%	5.15E+02	1.96E-224	100%	9
Sentinel-1A Out-of-plane Medium -6	5.15E+01	100%	1.29E+04	100%	3.34E+02	1.15E-145	100%	9
Sentinel-1A Out-of-plane Medium -12	5.88E+01	100%	1.69E+04	100%	4.34E+02	2.13E-189	100%	9
Sentinel-1A Out-of-plane High -2	1.24E+02	100%	7.36E+04	100%	1.91E+03	0.00E+00	100%	9
Sentinel-1A Out-of-plane High -6	1.01E+02	100%	4.90E+04	100%	1.27E+03	0.00E+00	100%	9
Sentinel-1A Out-of-plane High -12	1.20E+02	100%	6.91E+04	100%	1.81E+03	0.00E+00	100%	9
Sentinel-1A Hybrid Low -2	6.38E+00	100%	2.04E+02	63%	7.62E+00	4.90E-04	46%	9
Sentinel-1A Hybrid Low -6	9.49E+00	100%	4.34E+02	91%	1.38E+01	1.02E-06	76%	9
Sentinel-1A Hybrid Low -12	1.04E+01	100%	4.98E+02	94%	1.62E+01	9.68E-08	82%	9
Sentinel-1A Hybrid Medium -2	3.83E+01	100%	7.14E+03	100%	1.86E+02	1.94E-81	100%	9
Sentinel-1A Hybrid Medium -6	5.49E+01	100%	1.45E+04	100%	3.80E+02	1.11E-165	100%	9
Sentinel-1A Hybrid Medium -12	8.59E+01	100%	3.89E+04	100%	9.24E+02	0.00E+00	100%	10
Sentinel-1A Hybrid High -2	1.56E+02	100%	1.17E+05	100%	3.05E+03	0.00E+00	100%	9
Sentinel-1A Hybrid High -6	4.30E+02	100%	6.63E+05	100%	2.31E+04	0.00E+00	100%	9
Sentinel-1A Hybrid High -12	1.15E+03	100%	3.47E+06	100%	1.65E+05	0.00E+00	100%	9

Table A.47 Sentinel-1A Reachability analysis and probability from the three distances computed using range-range rate.

Sentinel-2B

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-2B No manoeuvre	1.40E+00	25%	3.11E+01	0%	2.47E+00	8.49E-02	0%	5
Sentinel-2B No manoeuvre	1.27E+01	100%	4.55E+03	100%	2.33E+01	7.82E-11	93%	3

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-2B No manoeuvre	1.28E-01	0%	9.08E+00	0%	2.47E+00	8.50E-02	0%	10
Sentinel-2B No manoeuvre	2.72E-01	0%	1.97E+01	0%	2.27E+00	1.03E-01	0%	10
Sentinel-2B No manoeuvre	9.97E-02	0%	5.19E+00	0%	2.08E+00	1.25E-01	0%	12
Sentinel-2B No manoeuvre	5.55E-02	0%	4.35E+01	0%	2.59E+00	7.54E-02	0%	11
Sentinel-2B No manoeuvre	5.31E-01	0%	7.54E+00	0%	2.91E+00	5.42E-02	0%	10
Sentinel-2B No manoeuvre	5.63E-01	0%	2.11E+01	0%	2.18E+00	1.13E-01	0%	11
Sentinel-2B No manoeuvre	2.02E+00	74%	2.37E+01	0%	2.76E+00	6.32E-02	0%	11
Sentinel-2B No manoeuvre	9.39E-02	0%	3.00E+01	0%	2.48E+00	8.36E-02	0%	11
Sentinel-2B No manoeuvre	2.04E+00	75%	2.02E+01	0%	3.44E+00	3.19E-02	7%	12
Sentinel-2B No manoeuvre	1.65E-01	0%	1.20E+01	0%	1.96E+00	1.41E-01	0%	12
Sentinel-2B No manoeuvre	4.60E-01	0%	8.73E+00	0%	2.42E+00	8.93E-02	0%	10
Sentinel-2B No manoeuvre	8.32E-01	0%	3.22E+01	0%	2.42E+00	8.88E-02	0%	9
Sentinel-2B No manoeuvre	3.51E-02	0%	1.02E+01	0%	2.34E+00	9.62E-02	0%	5
Sentinel-2B No manoeuvre	1.24E+01	100%	5.68E+03	100%	2.22E+01	2.29E-10	92%	3
Sentinel-2B No manoeuvre	2.04E+00	75%	4.25E+01	0%	3.05E+00	4.74E-02	2%	10
Sentinel-2B No manoeuvre	5.11E-01	0%	1.95E+01	0%	2.25E+00	1.06E-01	0%	10
Sentinel-2B No manoeuvre	6.22E-01	0%	6.50E+00	0%	2.13E+00	1.18E-01	0%	12
Sentinel-2B No manoeuvre	7.63E-01	0%	5.79E+01	0%	2.60E+00	7.44E-02	0%	12
Sentinel-2B No manoeuvre	1.59E+00	43%	1.19E+01	0%	3.17E+00	4.21E-02	3%	11
Sentinel-2B No manoeuvre	2.73E-01	0%	1.72E+01	0%	2.13E+00	1.19E-01	0%	11
Sentinel-2B No manoeuvre	4.08E-01	0%	6.56E+00	0%	2.25E+00	1.05E-01	0%	11
Sentinel-2B No manoeuvre	5.15E-01	0%	4.49E+01	0%	2.52E+00	8.05E-02	0%	10
Sentinel-2B No manoeuvre	5.00E-01	0%	7.81E+00	0%	2.97E+00	5.12E-02	1%	13
Sentinel-2B No manoeuvre	6.71E-01	0%	1.70E+01	0%	1.96E+00	1.41E-01	0%	12
Sentinel-2B No manoeuvre	1.10E+00	0%	1.57E+01	0%	2.60E+00	7.43E-02	0%	10
Sentinel-2B Tangential Low -2	2.38E-01	0%	9.28E+00	0%	2.47E+00	8.42E-02	0%	10
Sentinel-2B Tangential Low -6	4.03E-01	0%	9.31E+00	0%	2.48E+00	8.37E-02	0%	10
Sentinel-2B Tangential Low -12	9.71E-01	0%	1.25E+01	0%	2.58E+00	7.58E-02	0%	10
Sentinel-2B Tangential Medium -2	1.61E+00	46%	2.51E+01	0%	2.79E+00	6.16E-02	0%	10
Sentinel-2B Tangential Medium -6	3.48E+00	100%	6.73E+01	3%	3.98E+00	1.87E-02	13%	10
Sentinel-2B Tangential Medium -12	4.14E+00	100%	2.42E+01	0%	4.60E+00	1.00E-02	20%	10
Sentinel-2B Tangential High -2	8.56E+00	100%	4.77E+02	93%	1.16E+01	8.99E-06	68%	10
Sentinel-2B Tangential High -6	1.98E+01	100%	2.28E+03	100%	5.16E+01	3.86E-23	100%	10
Sentinel-2B Tangential High -12	1.63E+01	100%	2.36E+02	70%	3.57E+01	2.99E-16	99%	10
Sentinel-2B Out-of-plane Low -2	2.00E+00	73%	3.58E+01	0%	2.96E+00	5.16E-02	0%	10
Sentinel-2B Out-of-plane Low -6	1.74E+00	56%	2.90E+01	0%	2.84E+00	5.84E-02	0%	10
Sentinel-2B Out-of-plane Low -12	1.76E+00	58%	2.99E+01	0%	2.85E+00	5.77E-02	0%	10
Sentinel-2B Out-of-plane Medium -2	5.20E+00	100%	1.88E+02	59%	5.84E+00	2.90E-03	32%	10
Sentinel-2B Out-of-plane Medium -6	1.15E+00	0%	1.77E+01	0%	2.63E+00	7.22E-02	0%	10
Sentinel-2B Out-of-plane Medium -12	3.79E+00	100%	1.05E+02	27%	4.26E+00	1.42E-02	16%	10
Sentinel-2B Out-of-plane High -2	7.56E+00	100%	3.88E+02	89%	9.60E+00	6.79E-05	58%	10
Sentinel-2B Out-of-plane High -6	3.13E+00	99%	7.44E+01	8%	3.69E+00	2.50E-02	10%	10
Sentinel-2B Out-of-plane High -12	4.80E+00	100%	1.62E+02	51%	5.35E+00	4.76E-03	27%	10
Sentinel-2B Hybrid Low -2	2.11E+00	79%	3.55E+01	0%	3.02E+00	4.86E-02	1%	10
Sentinel-2B Hybrid Low -6	7.57E+00	100%	3.39E+02	84%	9.63E+00	6.55E-05	59%	10
Sentinel-2B Hybrid Low -12	6.32E+00	100%	5.98E+01	0%	7.46E+00	5.74E-04	45%	10
Sentinel-2B Hybrid Medium -2	1.29E+01	100%	1.04E+03	100%	2.33E+01	7.79E-11	93%	10
Sentinel-2B Hybrid Medium -6	4.28E+01	100%	1.11E+04	100%	2.31E+02	3.61E-101	100%	10
Sentinel-2B Hybrid Medium -12	2.95E+01	100%	5.97E+02	97%	1.11E+02	5.55E-49	100%	10
Sentinel-2B Hybrid High -2	5.81E+01	100%	2.13E+04	100%	4.25E+02	2.63E-185	100%	10
Sentinel-2B Hybrid High -6	2.36E+02	100%	4.54E+05	100%	6.95E+03	0.00E+00	100%	10
Sentinel-2B Hybrid High -12	3.20E+02	100%	9.59E+05	100%	1.28E+04	0.00E+00	100%	10

Table A.48 Sentinel-2B Reachability analysis and probability from the three distances computed using range-range rate.

A.3.4 Taylor order

Order 3

Sentinel-1A

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-1A No manoeuvre	1.26E-01	0%	5.86E+00	0%	2.71E+00	6.68E-02	0%	9
Sentinel-1A No manoeuvre	1.28E+00	12%	1.57E+02	50%	2.54E+00	7.85E-02	0%	10
Sentinel-1A No manoeuvre	6.73E-01	0%	9.67E+00	0%	2.59E+00	7.52E-02	0%	9
Sentinel-1A No manoeuvre	1.43E+00	28%	4.17E+01	0%	2.68E+00	6.83E-02	0%	9
Sentinel-1A No manoeuvre	1.39E+00	23%	2.38E+02	71%	3.05E+00	4.72E-02	2%	10

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-1A No manoeuvre	1.26E-01	0%	2.53E+01	0%	2.07E+00	1.27E-01	0%	9
Sentinel-1A No manoeuvre	1.60E+01	100%	2.19E+04	100%	3.48E+01	7.36E-16	98%	2
Sentinel-1A No manoeuvre	4.73E-01	0%	2.97E+01	0%	2.56E+00	7.72E-02	0%	9
Sentinel-1A No manoeuvre	8.56E-01	0%	8.18E+01	13%	2.41E+00	8.98E-02	0%	9
Sentinel-1A No manoeuvre	1.62E+01	100%	6.71E+03	100%	3.55E+01	3.98E-16	99%	2
Sentinel-1A No manoeuvre	8.91E-01	0%	2.29E+01	0%	2.59E+00	7.51E-02	0%	9
Sentinel-1A No manoeuvre	1.62E+00	46%	2.07E+02	64%	2.73E+00	6.49E-02	0%	11
Sentinel-1A No manoeuvre	1.06E+00	0%	1.28E+01	0%	2.73E+00	6.53E-02	0%	10
Sentinel-1A No manoeuvre	1.41E-01	0%	2.16E+01	0%	2.51E+00	8.10E-02	0%	8
Sentinel-1A No manoeuvre	8.24E-01	0%	5.83E+01	0%	2.75E+00	6.39E-02	0%	9
Sentinel-1A No manoeuvre	7.43E-01	0%	4.41E+01	0%	2.28E+00	1.02E-01	0%	8
Sentinel-1A No manoeuvre	1.22E+00	5%	8.10E+00	0%	2.88E+00	5.63E-02	0%	9
Sentinel-1A No manoeuvre	1.44E-01	0%	6.10E+01	0%	2.47E+00	8.42E-02	0%	10
Sentinel-1A No manoeuvre	2.15E-01	0%	1.04E+01	0%	2.62E+00	7.29E-02	0%	9
Sentinel-1A No manoeuvre	4.28E-01	0%	1.72E+01	0%	2.40E+00	9.10E-02	0%	10
Sentinel-1A No manoeuvre	8.90E-01	0%	1.15E+02	32%	2.96E+00	5.18E-02	0%	10
Sentinel-1A No manoeuvre	6.00E-01	0%	2.38E+01	0%	2.11E+00	1.22E-01	0%	9
Sentinel-1A No manoeuvre	1.42E+01	100%	1.90E+04	100%	2.79E+01	7.73E-13	96%	2
Sentinel-1A No manoeuvre	6.47E-01	0%	2.71E+01	0%	2.63E+00	7.19E-02	0%	9
Sentinel-1A No manoeuvre	2.13E+00	79%	2.33E+02	70%	3.00E+00	5.00E-02	1%	9
Sentinel-1A Tangential Low -2	1.71E+00	54%	2.13E+01	0%	2.89E+00	5.54E-02	0%	9
Sentinel-1A Tangential Low -6	2.53E-01	0%	7.59E+00	0%	2.53E+00	7.94E-02	0%	9
Sentinel-1A Tangential Low -12	9.01E-01	0%	1.08E+01	0%	2.63E+00	7.23E-02	0%	9
Sentinel-1A Tangential Medium -2	2.95E+00	97%	4.87E+01	0%	3.61E+00	2.70E-02	9%	9
Sentinel-1A Tangential Medium -6	7.54E+00	100%	2.71E+02	76%	9.63E+00	6.58E-05	59%	9
Sentinel-1A Tangential Medium -12	6.84E+00	100%	2.09E+02	64%	8.38E+00	2.30E-04	51%	9
Sentinel-1A Tangential High -2	1.50E+01	100%	1.08E+03	100%	3.07E+01	4.79E-14	97%	9
Sentinel-1A Tangential High -6	3.20E+01	100%	4.76E+03	100%	1.31E+02	1.43E-57	100%	9
Sentinel-1A Tangential High -12	3.53E+01	100%	5.52E+03	100%	1.58E+02	2.37E-69	100%	9
Sentinel-1A Out-of-plane Low -2	3.05E+01	100%	4.44E+03	100%	1.19E+02	2.43E-52	100%	9
Sentinel-1A Out-of-plane Low -6	2.61E+01	100%	3.24E+03	100%	8.76E+01	9.02E-39	100%	9
Sentinel-1A Out-of-plane Low -12	2.96E+01	100%	4.20E+03	100%	1.12E+02	2.21E-49	100%	9
Sentinel-1A Out-of-plane Medium -2	6.45E+01	100%	1.97E+04	100%	5.23E+02	6.25E-228	100%	9
Sentinel-1A Out-of-plane Medium -6	5.13E+01	100%	1.25E+04	100%	3.32E+02	9.05E-145	100%	9
Sentinel-1A Out-of-plane Medium -12	5.90E+01	100%	1.64E+04	100%	4.38E+02	6.30E-191	100%	9
Sentinel-1A Out-of-plane High -2	1.25E+02	100%	7.42E+04	100%	1.95E+03	0.00E+00	100%	9
Sentinel-1A Out-of-plane High -6	1.01E+02	100%	4.82E+04	100%	1.29E+03	0.00E+00	100%	9
Sentinel-1A Out-of-plane High -12	1.22E+02	100%	7.00E+04	100%	1.86E+03	0.00E+00	100%	9
Sentinel-1A Hybrid Low -2	7.02E+00	100%	2.42E+02	71%	8.69E+00	1.69E-04	53%	9
Sentinel-1A Hybrid Low -6	9.54E+00	100%	4.28E+02	91%	1.39E+01	9.22E-07	76%	9
Sentinel-1A Hybrid Low -12	1.05E+01	100%	4.87E+02	94%	1.62E+01	9.13E-08	83%	9
Sentinel-1A Hybrid Medium -2	3.75E+01	100%	6.64E+03	100%	1.78E+02	5.34E-78	100%	9
Sentinel-1A Hybrid Medium -6	5.46E+01	100%	1.37E+04	100%	3.76E+02	7.02E-164	100%	9
Sentinel-1A Hybrid Medium -12	8.83E+01	100%	3.98E+04	100%	9.77E+02	0.00E+00	100%	10
Sentinel-1A Hybrid High -2	1.57E+02	100%	1.19E+05	100%	3.10E+03	0.00E+00	100%	9
Sentinel-1A Hybrid High -6	4.35E+02	100%	6.61E+05	100%	2.36E+04	0.00E+00	100%	9
Sentinel-1A Hybrid High -12	1.16E+03	100%	3.54E+06	100%	1.70E+05	0.00E+00	100%	9

Table A.49 Sentinel-1A Reachability analysis and probability from the three distances computed using range-range rate.

Sentinel-2B

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-2B No manoeuvre	1.27E+00	11%	2.76E+01	0%	2.42E+00	8.87E-02	0%	5
Sentinel-2B No manoeuvre	1.45E+01	100%	5.89E+03	100%	2.91E+01	2.27E-13	97%	3
Sentinel-2B No manoeuvre	3.35E-01	0%	9.75E+00	0%	2.48E+00	8.36E-02	0%	10
Sentinel-2B No manoeuvre	9.54E-01	0%	3.42E+01	0%	2.38E+00	9.28E-02	0%	10
Sentinel-2B No manoeuvre	5.97E-01	0%	6.21E+00	0%	2.13E+00	1.19E-01	0%	12
Sentinel-2B No manoeuvre	1.76E+00	58%	1.74E+02	55%	2.97E+00	5.15E-02	0%	11
Sentinel-2B No manoeuvre	2.44E-01	0%	7.00E+00	0%	2.90E+00	5.53E-02	0%	10
Sentinel-2B No manoeuvre	1.92E-01	0%	1.62E+01	0%	2.16E+00	1.15E-01	0%	11
Sentinel-2B No manoeuvre	1.04E+00	0%	9.23E+00	0%	2.32E+00	9.84E-02	0%	11
Sentinel-2B No manoeuvre	1.02E-01	0%	2.90E+01	0%	2.47E+00	8.48E-02	0%	11
Sentinel-2B No manoeuvre	4.58E-01	0%	7.96E+00	0%	2.97E+00	5.13E-02	1%	12
Sentinel-2B No manoeuvre	3.43E-01	0%	1.22E+01	0%	1.94E+00	1.44E-01	0%	12
Sentinel-2B No manoeuvre	2.94E-01	0%	6.66E+00	0%	2.33E+00	9.72E-02	0%	9
Sentinel-2B No manoeuvre	1.95E-01	0%	2.72E+01	0%	2.42E+00	8.92E-02	0%	10

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-2B No manoeuvre	4.22E-01	0%	1.25E+01	0%	2.39E+00	9.13E-02	0%	5
Sentinel-2B No manoeuvre	1.38E+01	100%	6.42E+03	100%	2.67E+01	2.58E-12	96%	3
Sentinel-2B No manoeuvre	9.09E-01	0%	1.49E+01	0%	2.59E+00	7.53E-02	0%	10
Sentinel-2B No manoeuvre	3.57E-01	0%	2.27E+01	0%	2.29E+00	1.02E-01	0%	10
Sentinel-2B No manoeuvre	4.11E-01	0%	5.65E+00	0%	2.11E+00	1.21E-01	0%	12
Sentinel-2B No manoeuvre	1.65E+00	49%	1.51E+02	47%	2.88E+00	5.60E-02	0%	11
Sentinel-2B No manoeuvre	2.74E+00	95%	2.65E+01	0%	3.82E+00	2.18E-02	11%	10
Sentinel-2B No manoeuvre	1.21E+00	4%	4.03E+01	0%	2.33E+00	9.73E-02	0%	11
Sentinel-2B No manoeuvre	3.56E-01	0%	6.35E+00	0%	2.24E+00	1.07E-01	0%	11
Sentinel-2B No manoeuvre	2.87E-01	0%	3.84E+01	0%	2.50E+00	8.17E-02	0%	10
Sentinel-2B No manoeuvre	1.14E+00	0%	1.11E+01	0%	3.11E+00	4.45E-02	2%	12
Sentinel-2B No manoeuvre	2.64E-01	0%	1.60E+01	0%	2.04E+00	1.31E-01	0%	12
Sentinel-2B No manoeuvre	9.83E-01	0%	1.22E+01	0%	2.49E+00	8.31E-02	0%	10
Sentinel-2B Tangential Low -2	1.20E+00	2%	1.86E+01	0%	2.64E+00	7.12E-02	0%	10
Sentinel-2B Tangential Low -6	6.37E-01	0%	1.10E+01	0%	2.51E+00	8.09E-02	0%	10
Sentinel-2B Tangential Low -12	8.04E-01	0%	1.07E+01	0%	2.55E+00	7.84E-02	0%	10
Sentinel-2B Tangential Medium -2	1.72E+00	55%	2.73E+01	0%	2.84E+00	5.87E-02	0%	10
Sentinel-2B Tangential Medium -6	4.24E+00	100%	1.08E+02	29%	4.71E+00	8.97E-03	21%	10
Sentinel-2B Tangential Medium -12	4.53E+00	100%	4.73E+01	0%	5.02E+00	6.58E-03	24%	10
Sentinel-2B Tangential High -2	6.02E+00	100%	2.29E+02	69%	6.99E+00	9.21E-04	41%	10
Sentinel-2B Tangential High -6	2.06E+01	100%	2.48E+03	100%	5.53E+01	9.63E-25	100%	10
Sentinel-2B Tangential High -12	1.63E+01	100%	2.32E+02	69%	3.56E+01	3.55E-16	99%	10
Sentinel-2B Out-of-plane Low -2	7.66E-01	0%	1.29E+01	0%	2.54E+00	7.91E-02	0%	10
Sentinel-2B Out-of-plane Low -6	1.07E+00	0%	1.66E+01	0%	2.61E+00	7.37E-02	0%	10
Sentinel-2B Out-of-plane Low -12	9.99E-01	0%	1.55E+01	0%	2.59E+00	7.52E-02	0%	10
Sentinel-2B Out-of-plane Medium -2	2.09E+00	78%	3.80E+01	0%	3.01E+00	4.92E-02	1%	10
Sentinel-2B Out-of-plane Medium -6	6.21E-01	0%	1.15E+01	0%	2.51E+00	8.10E-02	0%	10
Sentinel-2B Out-of-plane Medium -12	3.12E+00	98%	7.46E+01	8%	3.69E+00	2.51E-02	9%	10
Sentinel-2B Out-of-plane High -2	7.53E+00	100%	3.88E+02	89%	9.55E+00	7.11E-05	58%	10
Sentinel-2B Out-of-plane High -6	2.13E+00	79%	3.93E+01	0%	3.03E+00	4.83E-02	1%	10
Sentinel-2B Out-of-plane High -12	6.52E+00	100%	2.94E+02	79%	7.78E+00	4.17E-04	47%	10
Sentinel-2B Hybrid Low -2	2.92E+00	97%	6.31E+01	0%	3.53E+00	2.94E-02	8%	10
Sentinel-2B Hybrid Low -6	5.51E+00	100%	1.59E+02	50%	6.26E+00	1.91E-03	35%	10
Sentinel-2B Hybrid Low -12	6.92E+00	100%	1.16E+02	33%	8.46E+00	2.12E-04	52%	10
Sentinel-2B Hybrid Medium -2	1.35E+01	100%	1.16E+03	100%	2.52E+01	1.09E-11	95%	10
Sentinel-2B Hybrid Medium -6	4.18E+01	100%	1.06E+04	100%	2.21E+02	1.02E-96	100%	10
Sentinel-2B Hybrid Medium -12	2.96E+01	100%	5.84E+02	96%	1.12E+02	2.23E-49	100%	10
Sentinel-2B Hybrid High -2	5.69E+01	100%	2.03E+04	100%	4.07E+02	2.78E-177	100%	10
Sentinel-2B Hybrid High -6	2.37E+02	100%	4.58E+05	100%	7.01E+03	0.00E+00	100%	10
Sentinel-2B Hybrid High -12	3.21E+02	100%	9.68E+05	100%	1.29E+04	0.00E+00	100%	10

Table A.50 Sentinel-2B Reachability analysis and probability from the three distances computed using range-range rate.

Order 4

Sentinel-1A

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-1A No manoeuvre	1.24E-01	0%	5.86E+00	0%	2.71E+00	6.67E-02	0%	9
Sentinel-1A No manoeuvre	1.28E+00	12%	1.57E+02	49%	2.54E+00	7.87E-02	0%	10
Sentinel-1A No manoeuvre	6.70E-01	0%	9.70E+00	0%	2.58E+00	7.54E-02	0%	9
Sentinel-1A No manoeuvre	1.43E+00	28%	4.24E+01	0%	2.69E+00	6.82E-02	0%	9
Sentinel-1A No manoeuvre	1.39E+00	23%	2.38E+02	71%	3.05E+00	4.74E-02	2%	10
Sentinel-1A No manoeuvre	1.26E-01	0%	2.49E+01	0%	2.06E+00	1.27E-01	0%	9
Sentinel-1A No manoeuvre	1.60E+01	100%	2.19E+04	100%	3.48E+01	7.36E-16	98%	2
Sentinel-1A No manoeuvre	4.71E-01	0%	2.98E+01	0%	2.56E+00	7.72E-02	0%	9
Sentinel-1A No manoeuvre	8.56E-01	0%	8.26E+01	14%	2.41E+00	8.97E-02	0%	9
Sentinel-1A No manoeuvre	1.62E+01	100%	6.74E+03	100%	3.55E+01	3.97E-16	99%	2
Sentinel-1A No manoeuvre	8.91E-01	0%	2.26E+01	0%	2.59E+00	7.54E-02	0%	9
Sentinel-1A No manoeuvre	1.62E+00	46%	2.06E+02	64%	2.74E+00	6.49E-02	0%	11
Sentinel-1A No manoeuvre	1.06E+00	0%	1.30E+01	0%	2.73E+00	6.51E-02	0%	10
Sentinel-1A No manoeuvre	1.43E-01	0%	2.13E+01	0%	2.51E+00	8.10E-02	0%	8
Sentinel-1A No manoeuvre	8.26E-01	0%	5.88E+01	0%	2.75E+00	6.36E-02	0%	9
Sentinel-1A No manoeuvre	7.42E-01	0%	4.42E+01	0%	2.29E+00	1.02E-01	0%	8
Sentinel-1A No manoeuvre	1.23E+00	6%	8.14E+00	0%	2.88E+00	5.61E-02	0%	9
Sentinel-1A No manoeuvre	1.44E-01	0%	6.06E+01	0%	2.47E+00	8.44E-02	0%	10
Sentinel-1A No manoeuvre	2.14E-01	0%	1.03E+01	0%	2.62E+00	7.30E-02	0%	9

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-1A No manoeuvre	4.28E-01	0%	1.73E+01	0%	2.40E+00	9.08E-02	0%	10
Sentinel-1A No manoeuvre	8.89E-01	0%	1.15E+02	32%	2.96E+00	5.20E-02	0%	10
Sentinel-1A No manoeuvre	6.01E-01	0%	2.37E+01	0%	2.11E+00	1.22E-01	0%	9
Sentinel-1A No manoeuvre	1.42E+01	100%	1.87E+04	100%	2.79E+01	7.77E-13	96%	2
Sentinel-1A No manoeuvre	6.47E-01	0%	2.74E+01	0%	2.64E+00	7.16E-02	0%	9
Sentinel-1A No manoeuvre	2.13E+00	79%	2.29E+02	69%	2.99E+00	5.04E-02	1%	9
Sentinel-1A Tangential Low -2	1.71E+00	54%	2.13E+01	0%	2.89E+00	5.54E-02	0%	9
Sentinel-1A Tangential Low -6	2.56E-01	0%	7.63E+00	0%	2.53E+00	7.93E-02	0%	9
Sentinel-1A Tangential Low -12	9.06E-01	0%	1.09E+01	0%	2.63E+00	7.23E-02	0%	9
Sentinel-1A Tangential Medium -2	2.94E+00	97%	4.80E+01	0%	3.61E+00	2.71E-02	9%	9
Sentinel-1A Tangential Medium -6	7.54E+00	100%	2.71E+02	76%	9.64E+00	6.50E-05	59%	9
Sentinel-1A Tangential Medium -12	6.85E+00	100%	2.16E+02	66%	8.40E+00	2.24E-04	51%	9
Sentinel-1A Tangential High -2	1.50E+01	100%	1.06E+03	100%	3.06E+01	4.99E-14	97%	9
Sentinel-1A Tangential High -6	3.21E+01	100%	4.79E+03	100%	1.31E+02	1.34E-57	100%	9
Sentinel-1A Tangential High -12	3.53E+01	100%	5.56E+03	100%	1.58E+02	2.13E-69	100%	9
Sentinel-1A Out-of-plane Low -2	3.05E+01	100%	4.42E+03	100%	1.19E+02	2.54E-52	100%	9
Sentinel-1A Out-of-plane Low -6	2.61E+01	100%	3.22E+03	100%	8.75E+01	9.79E-39	100%	9
Sentinel-1A Out-of-plane Low -12	2.96E+01	100%	4.27E+03	100%	1.12E+02	1.76E-49	100%	9
Sentinel-1A Out-of-plane Medium -2	6.47E+01	100%	2.04E+04	100%	5.25E+02	9.25E-229	100%	9
Sentinel-1A Out-of-plane Medium -6	5.13E+01	100%	1.26E+04	100%	3.32E+02	7.31E-145	100%	9
Sentinel-1A Out-of-plane Medium -12	5.91E+01	100%	1.67E+04	100%	4.39E+02	1.94E-191	100%	9
Sentinel-1A Out-of-plane High -2	1.25E+02	100%	7.33E+04	100%	1.94E+03	0.00E+00	100%	9
Sentinel-1A Out-of-plane High -6	1.01E+02	100%	4.88E+04	100%	1.29E+03	0.00E+00	100%	9
Sentinel-1A Out-of-plane High -12	1.22E+02	100%	7.05E+04	100%	1.87E+03	0.00E+00	100%	9
Sentinel-1A Hybrid Low -2	7.02E+00	100%	2.45E+02	72%	8.69E+00	1.68E-04	53%	9
Sentinel-1A Hybrid Low -6	9.55E+00	100%	4.40E+02	92%	1.39E+01	8.95E-07	76%	9
Sentinel-1A Hybrid Low -12	1.05E+01	100%	4.90E+02	94%	1.62E+01	8.97E-08	83%	9
Sentinel-1A Hybrid Medium -2	3.75E+01	100%	6.69E+03	100%	1.78E+02	4.95E-78	100%	9
Sentinel-1A Hybrid Medium -6	5.47E+01	100%	1.40E+04	100%	3.76E+02	4.78E-164	100%	9
Sentinel-1A Hybrid Medium -12	8.83E+01	100%	3.99E+04	100%	9.78E+02	0.00E+00	100%	10
Sentinel-1A Hybrid High -2	1.57E+02	100%	1.18E+05	100%	3.10E+03	0.00E+00	100%	9
Sentinel-1A Hybrid High -6	4.35E+02	100%	6.64E+05	100%	2.36E+04	0.00E+00	100%	9
Sentinel-1A Hybrid High -12	1.16E+03	100%	3.41E+06	100%	1.68E+05	0.00E+00	100%	9

Table A.51 Sentinel-1A Reachability analysis and probability from the three distances computed using range-range rate.

Sentinel-2B

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-2B No manoeuvre	1.27E+00	11%	2.76E+01	0%	2.42E+00	8.87E-02	0%	5
Sentinel-2B No manoeuvre	1.45E+01	100%	5.89E+03	100%	2.91E+01	2.27E-13	97%	3
Sentinel-2B No manoeuvre	3.35E-01	0%	9.75E+00	0%	2.48E+00	8.36E-02	0%	10
Sentinel-2B No manoeuvre	9.54E-01	0%	3.42E+01	0%	2.38E+00	9.28E-02	0%	10
Sentinel-2B No manoeuvre	5.97E-01	0%	6.21E+00	0%	2.13E+00	1.19E-01	0%	12
Sentinel-2B No manoeuvre	1.76E+00	58%	1.74E+02	55%	2.97E+00	5.15E-02	0%	11
Sentinel-2B No manoeuvre	2.44E-01	0%	7.00E+00	0%	2.90E+00	5.53E-02	0%	10
Sentinel-2B No manoeuvre	1.92E-01	0%	1.62E+01	0%	2.16E+00	1.15E-01	0%	11
Sentinel-2B No manoeuvre	1.04E+00	0%	9.23E+00	0%	2.32E+00	9.84E-02	0%	11
Sentinel-2B No manoeuvre	1.02E-01	0%	2.90E+01	0%	2.47E+00	8.48E-02	0%	11
Sentinel-2B No manoeuvre	4.58E-01	0%	7.96E+00	0%	2.97E+00	5.13E-02	1%	12
Sentinel-2B No manoeuvre	3.43E-01	0%	1.22E+01	0%	1.94E+00	1.44E-01	0%	12
Sentinel-2B No manoeuvre	2.94E-01	0%	6.66E+00	0%	2.33E+00	9.72E-02	0%	9
Sentinel-2B No manoeuvre	1.95E-01	0%	2.72E+01	0%	2.42E+00	8.92E-02	0%	10
Sentinel-2B No manoeuvre	4.22E-01	0%	1.25E+01	0%	2.39E+00	9.13E-02	0%	5
Sentinel-2B No manoeuvre	1.38E+01	100%	6.42E+03	100%	2.67E+01	2.58E-12	96%	3
Sentinel-2B No manoeuvre	9.09E-01	0%	1.49E+01	0%	2.59E+00	7.53E-02	0%	10
Sentinel-2B No manoeuvre	3.57E-01	0%	2.27E+01	0%	2.29E+00	1.02E-01	0%	10
Sentinel-2B No manoeuvre	4.11E-01	0%	5.65E+00	0%	2.11E+00	1.21E-01	0%	12
Sentinel-2B No manoeuvre	1.65E+00	49%	1.51E+02	47%	2.88E+00	5.60E-02	0%	11
Sentinel-2B No manoeuvre	2.74E+00	95%	2.65E+01	0%	3.82E+00	2.18E-02	11%	10
Sentinel-2B No manoeuvre	1.21E+00	4%	4.03E+01	0%	2.33E+00	9.73E-02	0%	11
Sentinel-2B No manoeuvre	3.56E-01	0%	6.35E+00	0%	2.24E+00	1.07E-01	0%	11
Sentinel-2B No manoeuvre	2.87E-01	0%	3.84E+01	0%	2.50E+00	8.17E-02	0%	10
Sentinel-2B No manoeuvre	1.14E+00	0%	1.11E+01	0%	3.11E+00	4.45E-02	2%	12
Sentinel-2B No manoeuvre	2.64E-01	0%	1.60E+01	0%	2.04E+00	1.31E-01	0%	12
Sentinel-2B No manoeuvre	9.83E-01	0%	1.22E+01	0%	2.49E+00	8.31E-02	0%	10
Sentinel-2B Tangential Low -2	1.19E+00	2%	1.87E+01	0%	2.65E+00	7.09E-02	0%	10

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-2B Tangential Low -6	6.32E-01	0%	1.10E+01	0%	2.51E+00	8.11E-02	0%	10
Sentinel-2B Tangential Low -12	8.04E-01	0%	1.07E+01	0%	2.55E+00	7.84E-02	0%	10
Sentinel-2B Tangential Medium -2	1.73E+00	55%	2.74E+01	0%	2.84E+00	5.87E-02	0%	10
Sentinel-2B Tangential Medium -6	4.23E+00	100%	1.07E+02	28%	4.71E+00	9.01E-03	21%	10
Sentinel-2B Tangential Medium -12	4.52E+00	100%	4.77E+01	0%	5.02E+00	6.63E-03	24%	10
Sentinel-2B Tangential High -2	6.01E+00	100%	2.27E+02	68%	6.98E+00	9.32E-04	41%	10
Sentinel-2B Tangential High -6	2.06E+01	100%	2.48E+03	100%	5.53E+01	9.74E-25	100%	10
Sentinel-2B Tangential High -12	1.62E+01	100%	2.27E+02	68%	3.51E+01	5.81E-16	99%	10
Sentinel-2B Out-of-plane Low -2	7.62E-01	0%	1.29E+01	0%	2.54E+00	7.88E-02	0%	10
Sentinel-2B Out-of-plane Low -6	1.07E+00	0%	1.65E+01	0%	2.60E+00	7.39E-02	0%	10
Sentinel-2B Out-of-plane Low -12	9.98E-01	0%	1.55E+01	0%	2.59E+00	7.52E-02	0%	10
Sentinel-2B Out-of-plane Medium -2	2.10E+00	78%	3.85E+01	0%	3.01E+00	4.91E-02	1%	10
Sentinel-2B Out-of-plane Medium -6	6.23E-01	0%	1.15E+01	0%	2.51E+00	8.09E-02	0%	10
Sentinel-2B Out-of-plane Medium -12	3.12E+00	98%	7.44E+01	8%	3.69E+00	2.51E-02	9%	10
Sentinel-2B Out-of-plane High -2	7.53E+00	100%	3.88E+02	88%	9.55E+00	7.15E-05	58%	10
Sentinel-2B Out-of-plane High -6	2.13E+00	79%	3.92E+01	0%	3.03E+00	4.82E-02	1%	10
Sentinel-2B Out-of-plane High -12	6.52E+00	100%	2.95E+02	79%	7.79E+00	4.16E-04	47%	10
Sentinel-2B Hybrid Low -2	2.92E+00	97%	6.29E+01	0%	3.53E+00	2.93E-02	8%	10
Sentinel-2B Hybrid Low -6	5.51E+00	100%	1.62E+02	51%	6.26E+00	1.92E-03	35%	10
Sentinel-2B Hybrid Low -12	6.96E+00	100%	1.16E+02	33%	8.53E+00	1.98E-04	52%	10
Sentinel-2B Hybrid Medium -2	1.35E+01	100%	1.14E+03	100%	2.52E+01	1.13E-11	95%	10
Sentinel-2B Hybrid Medium -6	4.18E+01	100%	1.06E+04	100%	2.20E+02	1.94E-96	100%	10
Sentinel-2B Hybrid Medium -12	2.95E+01	100%	5.84E+02	96%	1.12E+02	3.26E-49	100%	10
Sentinel-2B Hybrid High -2	5.69E+01	100%	2.04E+04	100%	4.07E+02	2.54E-177	100%	10
Sentinel-2B Hybrid High -6	2.37E+02	100%	4.59E+05	100%	7.00E+03	0.00E+00	100%	10
Sentinel-2B Hybrid High -12	3.21E+02	100%	9.70E+05	100%	1.29E+04	0.00E+00	100%	10

Table A.52 Sentinel-2B Reachability analysis and probability from the three distances computed using range-range rate.

A.3.5 Propagation of uncertainty

Unscented transform

Sentinel-1A

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-1A No manoeuvre	4.10E-01	0%	5.86E+00	0%	2.71E+00	6.67E-02	0%	9
Sentinel-1A No manoeuvre	1.26E+00	10%	1.57E+02	49%	2.54E+00	7.87E-02	0%	10
Sentinel-1A No manoeuvre	5.61E-01	0%	9.70E+00	0%	2.58E+00	7.54E-02	0%	9
Sentinel-1A No manoeuvre	1.38E+00	23%	4.24E+01	0%	2.69E+00	6.82E-02	0%	9
Sentinel-1A No manoeuvre	1.37E+00	22%	2.38E+02	71%	3.05E+00	4.74E-02	2%	10
Sentinel-1A No manoeuvre	1.33E-01	0%	2.49E+01	0%	2.06E+00	1.27E-01	0%	8
Sentinel-1A No manoeuvre	1.59E+01	100%	2.19E+04	100%	3.48E+01	7.36E-16	98%	2
Sentinel-1A No manoeuvre	4.75E-01	0%	2.98E+01	0%	2.56E+00	7.72E-02	0%	9
Sentinel-1A No manoeuvre	8.31E-01	0%	8.26E+01	14%	2.41E+00	8.97E-02	0%	8
Sentinel-1A No manoeuvre	1.61E+01	100%	6.74E+03	100%	3.55E+01	3.97E-16	99%	2
Sentinel-1A No manoeuvre	8.75E-01	0%	2.26E+01	0%	2.59E+00	7.54E-02	0%	9
Sentinel-1A No manoeuvre	1.59E+00	43%	2.06E+02	64%	2.74E+00	6.49E-02	0%	10
Sentinel-1A No manoeuvre	9.41E-01	0%	1.30E+01	0%	2.73E+00	6.51E-02	0%	9
Sentinel-1A No manoeuvre	1.28E-01	0%	2.13E+01	0%	2.51E+00	8.10E-02	0%	9
Sentinel-1A No manoeuvre	8.41E-01	0%	5.88E+01	0%	2.75E+00	6.36E-02	0%	9
Sentinel-1A No manoeuvre	7.33E-01	0%	4.42E+01	0%	2.29E+00	1.02E-01	0%	9
Sentinel-1A No manoeuvre	1.12E+00	0%	8.14E+00	0%	2.88E+00	5.61E-02	0%	9
Sentinel-1A No manoeuvre	1.45E-01	0%	6.06E+01	0%	2.47E+00	8.44E-02	0%	10
Sentinel-1A No manoeuvre	3.01E-01	0%	1.03E+01	0%	2.62E+00	7.30E-02	0%	10
Sentinel-1A No manoeuvre	4.45E-01	0%	1.73E+01	0%	2.40E+00	9.08E-02	0%	10
Sentinel-1A No manoeuvre	8.84E-01	0%	1.15E+02	32%	2.96E+00	5.20E-02	0%	11
Sentinel-1A No manoeuvre	5.63E-01	0%	2.37E+01	0%	2.11E+00	1.22E-01	0%	9
Sentinel-1A No manoeuvre	1.41E+01	100%	1.87E+04	100%	2.79E+01	7.77E-13	96%	2
Sentinel-1A No manoeuvre	6.54E-01	0%	2.74E+01	0%	2.64E+00	7.16E-02	0%	9
Sentinel-1A No manoeuvre	2.05E+00	76%	2.29E+02	69%	2.99E+00	5.04E-02	1%	9
Sentinel-1A Tangential Low -2	1.78E+00	59%	2.13E+01	0%	2.89E+00	5.54E-02	0%	9
Sentinel-1A Tangential Low -6	3.26E-01	0%	7.63E+00	0%	2.53E+00	7.93E-02	0%	9
Sentinel-1A Tangential Low -12	9.32E-01	0%	1.09E+01	0%	2.63E+00	7.23E-02	0%	9
Sentinel-1A Tangential Medium -2	2.92E+00	97%	4.80E+01	0%	3.61E+00	2.71E-02	9%	9
Sentinel-1A Tangential Medium -6	7.25E+00	100%	2.71E+02	76%	9.64E+00	6.50E-05	59%	9
Sentinel-1A Tangential Medium -12	6.51E+00	100%	2.16E+02	66%	8.40E+00	2.24E-04	51%	9

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-1A Tangential High -2	1.45E+01	100%	1.06E+03	100%	3.06E+01	4.99E-14	97%	9
Sentinel-1A Tangential High -6	5.81E+01	100%	4.79E+03	100%	1.31E+02	1.34E-57	100%	9
Sentinel-1A Tangential High -12	3.33E+01	100%	5.56E+03	100%	1.58E+02	2.13E-69	100%	9
Sentinel-1A Out-of-plane Low -2	3.02E+01	100%	4.42E+03	100%	1.19E+02	2.54E-52	100%	9
Sentinel-1A Out-of-plane Low -6	2.56E+01	100%	3.22E+03	100%	8.75E+01	9.79E-39	100%	9
Sentinel-1A Out-of-plane Low -12	2.92E+01	100%	4.27E+03	100%	1.12E+02	1.76E-49	100%	9
Sentinel-1A Out-of-plane Medium -2	6.37E+01	100%	2.04E+04	100%	5.25E+02	9.25E-229	100%	9
Sentinel-1A Out-of-plane Medium -6	5.05E+01	100%	1.26E+04	100%	3.32E+02	7.31E-145	100%	9
Sentinel-1A Out-of-plane Medium -12	5.83E+01	100%	1.67E+04	100%	4.39E+02	1.94E-191	100%	9
Sentinel-1A Out-of-plane High -2	1.23E+02	100%	7.33E+04	100%	1.94E+03	0.00E+00	100%	9
Sentinel-1A Out-of-plane High -6	9.99E+01	100%	4.88E+04	100%	1.29E+03	0.00E+00	100%	9
Sentinel-1A Out-of-plane High -12	1.20E+02	100%	7.05E+04	100%	1.87E+03	0.00E+00	100%	9
Sentinel-1A Hybrid Low -2	6.89E+00	100%	2.45E+02	72%	8.69E+00	1.68E-04	53%	9
Sentinel-1A Hybrid Low -6	9.10E+00	100%	4.40E+02	92%	1.39E+01	8.95E-07	76%	9
Sentinel-1A Hybrid Low -12	9.89E+00	100%	4.90E+02	94%	1.62E+01	8.97E-08	83%	9
Sentinel-1A Hybrid Medium -2	3.64E+01	100%	6.69E+03	100%	1.78E+02	4.95E-78	100%	9
Sentinel-1A Hybrid Medium -6	5.19E+01	100%	1.40E+04	100%	3.76E+02	4.78E-164	100%	9
Sentinel-1A Hybrid Medium -12	8.38E+01	100%	3.99E+04	100%	9.78E+02	0.00E+00	100%	10
Sentinel-1A Hybrid High -2	1.53E+02	100%	1.18E+05	100%	3.10E+03	0.00E+00	100%	9
Sentinel-1A Hybrid High -6	4.16E+02	100%	6.64E+05	100%	2.36E+04	0.00E+00	100%	9
Sentinel-1A Hybrid High -12	1.11E+03	100%	3.41E+06	100%	1.68E+05	0.00E+00	100%	9

Table A.53 Sentinel-1A Reachability analysis and probability from the three distances computed using range-range rate.

Sentinel-2B

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-2B No manoeuvre	1.28E+00	12%	3.13E+01	0%	2.09E+00	1.24E-01	0%	5
Sentinel-2B No manoeuvre	1.46E+01	100%	8.47E+03	100%	2.92E+01	2.12E-13	97%	3
Sentinel-2B No manoeuvre	3.22E-01	0%	1.68E+01	0%	2.28E+00	1.03E-01	0%	10
Sentinel-2B No manoeuvre	9.36E-01	0%	1.57E+01	0%	2.20E+00	1.11E-01	0%	10
Sentinel-2B No manoeuvre	6.02E-01	0%	8.93E+00	0%	1.91E+00	1.48E-01	0%	12
Sentinel-2B No manoeuvre	1.76E+00	58%	1.46E+02	45%	2.94E+00	5.30E-02	0%	11
Sentinel-2B No manoeuvre	4.72E-01	0%	2.28E+01	0%	2.94E+00	5.26E-02	0%	10
Sentinel-2B No manoeuvre	1.89E-01	0%	6.97E+00	0%	1.96E+00	1.41E-01	0%	11
Sentinel-2B No manoeuvre	1.05E+00	0%	1.55E+01	0%	2.13E+00	1.19E-01	0%	11
Sentinel-2B No manoeuvre	1.01E-01	0%	1.94E+01	0%	2.39E+00	9.19E-02	0%	11
Sentinel-2B No manoeuvre	6.82E-01	0%	2.98E+01	0%	3.04E+00	4.79E-02	1%	12
Sentinel-2B No manoeuvre	3.22E-01	0%	5.06E+00	0%	1.73E+00	1.78E-01	0%	12
Sentinel-2B No manoeuvre	2.73E-01	0%	9.83E+00	0%	2.14E+00	1.18E-01	0%	9
Sentinel-2B No manoeuvre	1.93E-01	0%	1.45E+01	0%	2.29E+00	1.01E-01	0%	10
Sentinel-2B No manoeuvre	4.45E-01	0%	2.29E+01	0%	2.22E+00	1.09E-01	0%	5
Sentinel-2B No manoeuvre	1.35E+01	100%	1.68E+03	100%	2.54E+01	9.26E-12	95%	3
Sentinel-2B No manoeuvre	9.03E-01	0%	2.67E+01	0%	2.41E+00	9.01E-02	0%	10
Sentinel-2B No manoeuvre	3.48E-01	0%	1.01E+01	0%	2.12E+00	1.21E-01	0%	10
Sentinel-2B No manoeuvre	3.99E-01	0%	7.84E+00	0%	1.92E+00	1.46E-01	0%	12
Sentinel-2B No manoeuvre	1.65E+00	48%	1.19E+02	34%	2.87E+00	5.68E-02	0%	11
Sentinel-2B No manoeuvre	2.78E+00	96%	1.47E+02	46%	3.93E+00	1.97E-02	12%	10
Sentinel-2B No manoeuvre	1.17E+00	0%	1.39E+01	0%	2.12E+00	1.20E-01	0%	11
Sentinel-2B No manoeuvre	4.13E-01	0%	9.68E+00	0%	2.07E+00	1.26E-01	0%	11
Sentinel-2B No manoeuvre	2.85E-01	0%	2.42E+01	0%	2.44E+00	8.69E-02	0%	10
Sentinel-2B No manoeuvre	1.43E+00	28%	6.10E+01	0%	3.30E+00	3.70E-02	5%	12
Sentinel-2B No manoeuvre	2.53E-01	0%	5.71E+00	0%	1.81E+00	1.63E-01	0%	12
Sentinel-2B No manoeuvre	1.05E+00	0%	2.25E+01	0%	2.35E+00	9.55E-02	0%	10
Sentinel-2B Tangential Low -2	1.30E+00	14%	3.89E+01	0%	2.48E+00	8.41E-02	0%	10
Sentinel-2B Tangential Low -6	9.83E-01	0%	2.29E+01	0%	2.39E+00	9.21E-02	0%	10
Sentinel-2B Tangential Low -12	1.41E+00	26%	1.68E+01	0%	2.51E+00	8.11E-02	0%	10
Sentinel-2B Tangential Medium -2	2.19E+00	82%	6.84E+01	4%	2.87E+00	5.70E-02	0%	10
Sentinel-2B Tangential Medium -6	6.21E+00	100%	3.33E+02	84%	7.08E+00	8.43E-04	42%	10
Sentinel-2B Tangential Medium -12	8.52E+00	100%	5.59E+01	0%	1.13E+01	1.18E-05	67%	10
Sentinel-2B Tangential High -2	7.85E+00	100%	6.50E+02	98%	9.97E+00	4.68E-05	60%	10
Sentinel-2B Tangential High -6	2.79E+01	100%	7.43E+03	100%	9.93E+01	7.72E-44	100%	10
Sentinel-2B Tangential High -12	3.39E+01	100%	6.78E+02	98%	1.46E+02	5.62E-64	100%	10
Sentinel-2B Out-of-plane Low -2	8.53E-01	0%	2.53E+01	0%	2.36E+00	9.48E-02	0%	10
Sentinel-2B Out-of-plane Low -6	1.10E+00	0%	3.25E+01	0%	2.42E+00	8.93E-02	0%	10
Sentinel-2B Out-of-plane Low -12	9.78E-01	0%	2.88E+01	0%	2.38E+00	9.22E-02	0%	10
Sentinel-2B Out-of-plane Medium -2	2.07E+00	76%	7.48E+01	9%	2.80E+00	6.08E-02	0%	10

Scenario	MD(R,Rr)	PR	KLD(R,Rr)	PR	BD(R,Rr)	ρ(R,Rr)	PR	plots
Sentinel-2B Out-of-plane Medium -6	6.51E-01	0%	2.07E+01	0%	2.32E+00	9.85E-02	0%	10
Sentinel-2B Out-of-plane Medium -12	3.11E+00	98%	1.53E+02	48%	3.48E+00	3.09E-02	7%	10
Sentinel-2B Out-of-plane High -2	7.55E+00	100%	8.24E+02	99%	9.40E+00	8.29E-05	57%	10
Sentinel-2B Out-of-plane High -6	2.15E+00	80%	7.92E+01	12%	2.84E+00	5.82E-02	0%	10
Sentinel-2B Out-of-plane High -12	6.54E+00	100%	6.21E+02	97%	7.61E+00	4.95E-04	46%	10
Sentinel-2B Hybrid Low -2	3.56E+00	100%	1.63E+02	52%	3.85E+00	2.13E-02	11%	10
Sentinel-2B Hybrid Low -6	8.58E+00	100%	5.45E+02	96%	1.15E+01	1.05E-05	67%	10
Sentinel-2B Hybrid Low -12	1.27E+01	100%	1.19E+02	34%	2.25E+01	1.71E-10	92%	10
Sentinel-2B Hybrid Medium -2	1.67E+01	100%	3.16E+03	100%	3.72E+01	6.67E-17	99%	10
Sentinel-2B Hybrid Medium -6	5.50E+01	100%	3.05E+04	100%	3.80E+02	9.71E-166	100%	10
Sentinel-2B Hybrid Medium -12	6.40E+01	100%	5.84E+03	100%	5.15E+02	2.16E-224	100%	10
Sentinel-2B Hybrid High -2	6.95E+01	100%	5.54E+04	100%	6.05E+02	1.41E-263	100%	10
Sentinel-2B Hybrid High -6	2.79E+02	100%	1.17E+06	100%	9.75E+03	0.00E+00	100%	10
Sentinel-2B Hybrid High -12	4.14E+02	100%	2.67E+06	100%	2.14E+04	0.00E+00	100%	10

Table A.54 Sentinel-2B Reachability analysis and probability from the three distances computed using range-range rate.

A.4 Analysis on real scenarios

The last analysis of the project is the one performed on real scenarios. Fifteen different scenarios have been used. The distances and the probabilities are presented in one table for each scenario. The tables show the number of manoeuvres in each segment (column 2), the statistical distances computed using only range-range rate and the probability of manoeuvre occurence. The MD is in column 3, the KLD is in column 5 and the BD and its coefficient are in columns 7 and 8 respectively. The probability computed from each distance is presented in the adjacent column of each one, on the right.

Scenario 1

Segment	Manoeuvre	MD(R, R_r)	PR	KLD (R,R_r)	PR	BD (R, R_r)	ρ BD (R, R_r)	PR
1	0	8.49E-01	0%	2.26E+00	0%	8.52E-01	4.26E-01	0%
2	0	3.70E-01	0%	4.66E+00	0%	2.13E+00	1.19E-01	0%
3	2	2.58E-01	0%	7.03E+00	0%	3.33E+00	3.57E-02	5%
4	0	8.99E-01	0%	6.05E+00	0%	2.17E+00	1.14E-01	0%
5	0	4.65E-01	0%	6.08E+00	0%	2.87E+00	5.69E-02	0%
6	0	2.69E-01	0%	7.09E+00	0%	3.37E+00	3.44E-02	6%
7	0	3.88E-01	0%	4.44E+00	0%	2.04E+00	1.30E-01	0%
8	0	4.78E-01	0%	7.18E+00	0%	3.39E+00	3.37E-02	6%
9	0	4.65E-01	0%	4.80E+00	0%	2.21E+00	1.10E-01	0%
10	0	2.94E-01	0%	5.48E+00	0%	2.53E+00	7.96E-02	0%
11	2	3.76E+00	100%	2.58E+01	0%	4.21E+00	1.49E-02	15%
12	0	2.99E-02	0%	2.24E+01	0%	3.13E+00	4.35E-02	3%
13	0	2.96E-01	0%	4.21E+00	0%	1.98E+00	1.38E-01	0%

Table A.55 Scenario 1 probability from the three distances computed using range-range rate.

Scenario 2

Segment	Manoeuvre	MD(R, R_r)	PR	KLD (R,R_r)	PR	BD (R, R_r)	ρ BD (R, R_r)	PR
1	0	2.05E-01	0%	1.51E+00	0%	6.12E-01	5.42E-01	0%
2	0	1.17E+00	0%	7.57E+00	0%	3.41E+00	3.30E-02	6%
3	0	4.60E-01	0%	5.88E+00	0%	2.77E+00	6.28E-02	0%
4	0	1.74E+00	56%	1.68E+01	0%	3.04E+00	4.78E-02	1%
5	0	2.85E-01	0%	5.63E+00	0%	2.69E+00	6.80E-02	0%
6	0	1.61E+00	45%	1.86E+01	0%	3.21E+00	4.04E-02	4%

Segment	Manoeuvre	MD(R, R_r)	PR	KLD (R,R_r)	PR	BD (R, R_r)	ρ BD (R, R_r)	PR
7	0	5.30E+00	100%	2.26E+02	68%	5.93E+00	2.67E-03	33%
8	2	5.01E+00	100%	2.25E+01	0%	5.17E+00	5.68E-03	26%
9	0	7.50E-02	0%	6.17E+00	0%	2.99E+00	5.05E-02	1%

Table A.56 Scenario 2 probability from the three distances computed using range-range rate.

Scenario 3

Segment	Manoeuvre	MD(R, R_r)	PR	KLD (R,R_r)	PR	BD (R, R_r)	ρ BD (R, R_r)	PR
1	0	3.28E-01	0%	2.63E+00	0%	8.64E-01	4.21E-01	0%
2	0	2.10E-01	0%	2.70E+01	0%	3.18E+00	4.15E-02	3%
3	0	6.90E-01	0%	5.21E+00	0%	2.29E+00	1.01E-01	0%
4	0	2.46E-01	0%	6.93E+00	0%	3.30E+00	3.67E-02	5%
5	0	7.87E-01	0%	5.55E+00	0%	2.27E+00	1.03E-01	0%
6	2	2.95E-01	0%	7.17E+00	0%	3.40E+00	3.35E-02	6%
7	0	2.25E+00	84%	1.24E+01	0%	2.75E+00	6.40E-02	0%
8	0	7.13E-01	0%	6.03E+00	0%	2.78E+00	6.23E-02	0%
9	0	1.19E-01	0%	4.57E+00	0%	2.18E+00	1.13E-01	0%
10	0	1.18E+00	1%	1.72E+01	0%	3.14E+00	4.33E-02	3%
11	0	5.89E-01	0%	4.97E+00	0%	2.24E+00	1.07E-01	0%

Table A.57 Scenario 3 probability from the three distances computed using range-range rate.

Scenario 4

Segment	Manoeuvre	MD(R, R_r)	PR	KLD (R,R_r)	PR	BD (R, R_r)	ρ BD (R, R_r)	PR
1	0	1.31E+00	16%	8.05E+00	0%	1.87E+00	1.53E-01	0%
2	2	3.62E+00	100%	1.68E+01	0%	4.09E+00	1.67E-02	14%
3	0	3.42E+00	99%	2.44E+01	0%	3.87E+00	2.10E-02	12%
4	0	1.08E+00	0%	8.21E+01	14%	3.29E+00	3.73E-02	5%
5	0	3.49E-01	0%	4.38E+00	0%	2.01E+00	1.34E-01	0%
6	0	3.73E-01	0%	6.41E+00	0%	3.05E+00	4.76E-02	1%
7	0	5.17E-01	0%	5.13E+00	0%	2.17E+00	1.15E-01	0%
8	0	5.99E-01	0%	6.95E+00	0%	3.26E+00	3.86E-02	4%
9	0	5.90E-02	0%	4.63E+00	0%	2.11E+00	1.21E-01	0%
10	1	1.19E-01	0%	5.72E+00	0%	2.74E+00	6.44E-02	0%

Table A.58 Scenario 4 probability from the three distances computed using range-range rate.

Scenario 5

Segment	Manoeuvre	MD(R, R_r)	PR	KLD (R,R_r)	PR	BD (R, R_r)	ρ BD (R, R_r)	PR
1	0	2.82E-02	0%	2.89E+00	0%	1.27E+00	2.80E-01	0%
2	0	5.01E-02	0%	4.33E+00	0%	2.07E+00	1.27E-01	0%
3	0	4.36E-01	0%	7.12E+00	0%	3.36E+00	3.46E-02	6%
4	0	6.70E-01	0%	5.07E+00	0%	2.23E+00	1.08E-01	0%
5	2	1.09E+00	0%	6.61E+00	0%	2.78E+00	6.19E-02	0%
6	0	2.81E-01	0%	6.94E+00	0%	3.30E+00	3.68E-02	5%
7	0	8.19E-01	0%	4.94E+00	0%	2.08E+00	1.24E-01	0%
8	0	9.81E-01	0%	7.20E+00	0%	3.28E+00	3.78E-02	4%
9	0	2.57E-02	0%	4.37E+00	0%	2.05E+00	1.29E-01	0%
10	0	8.11E-01	0%	7.55E+00	0%	3.50E+00	3.01E-02	7%
11	0	1.42E+00	27%	8.59E+00	0%	2.13E+00	1.19E-01	0%

Segment	Manoeuvre	MD(R, R_r)	PR	KLD (R,R_r)	PR	BD (R, R_r)	ρ BD (R, R_r)	PR
12	2	2.85E+00	97%	1.13E+01	0%	3.89E+00	2.05E-02	12%
13	0	3.64E-01	0%	5.19E+00	0%	2.30E+00	1.01E-01	0%
14	0	1.28E+00	12%	3.36E+01	0%	3.23E+00	3.97E-02	4%

Table A.59 Scenario 5 probability from the three distances computed using range-range rate.

Scenario 6

Segment	Manoeuvre	MD(R, R_r)	PR	KLD (R,R_r)	PR	BD (R, R_r)	ρ BD (R, R_r)	PR
1	0	8.43E-01	0%	3.85E+00	0%	1.33E+00	2.65E-01	0%
2	0	5.36E-01	0%	6.64E+00	0%	3.12E+00	4.41E-02	2%
3	0	8.77E-01	0%	5.96E+00	0%	2.46E+00	8.56E-02	0%
4	0	4.71E-01	0%	6.27E+00	0%	2.94E+00	5.31E-02	0%
5	0	6.82E-01	0%	1.59E+01	0%	2.94E+00	5.28E-02	0%
6	0	1.51E-01	0%	4.27E+00	0%	2.01E+00	1.34E-01	0%
7	0	1.01E+00	0%	6.99E+00	0%	3.13E+00	4.37E-02	3%
8	0	6.41E-01	0%	5.73E+00	0%	2.15E+00	1.16E-01	0%
9	3	8.17E-01	0%	6.98E+00	0%	3.22E+00	3.99E-02	4%
10	0	7.61E-01	0%	4.57E+00	0%	1.95E+00	1.42E-01	0%
11	0	6.76E-01	0%	5.96E+00	0%	2.69E+00	6.80E-02	0%
12	0	5.57E-01	0%	5.43E+00	0%	2.18E+00	1.13E-01	0%
13	0	1.02E+00	0%	1.61E+01	0%	3.09E+00	4.55E-02	2%

Table A.60 Scenario 6 probability from the three distances computed using range-range rate.

Scenario 7

Segment	Manoeuvre	MD(R, R_r)	PR	KLD (R,R_r)	PR	BD (R, R_r)	ρ BD (R, R_r)	PR
1	0	1.03E-01	0%	2.71E+00	0%	1.26E+00	2.84E-01	0%
2	0	7.36E-01	0%	7.05E+00	0%	3.28E+00	3.78E-02	4%
3	0	2.72E+00	95%	2.08E+01	0%	3.19E+00	4.12E-02	3%
4	0	9.76E-01	0%	7.63E+00	0%	3.50E+00	3.02E-02	7%
5	0	1.31E+00	15%	6.59E+00	0%	2.24E+00	1.06E-01	0%
6	0	4.44E-01	0%	6.08E+00	0%	2.87E+00	5.69E-02	0%
7	0	5.06E-02	0%	4.43E+00	0%	2.11E+00	1.22E-01	0%
8	0	1.06E-01	0%	7.36E+00	0%	2.95E+00	5.25E-02	0%
9	0	9.04E-01	0%	5.76E+00	0%	2.29E+00	1.02E-01	0%
10	2	2.34E-01	0%	6.89E+00	0%	3.27E+00	3.82E-02	4%
11	0	4.89E-03	0%	4.93E+00	0%	2.37E+00	9.38E-02	0%
12	0	1.27E-02	0%	6.62E+00	0%	3.13E+00	4.36E-02	3%
13	0	1.76E+00	58%	3.61E+01	0%	3.22E+00	3.99E-02	4%
14	0	2.93E-01	0%	4.56E+00	0%	2.08E+00	1.25E-01	0%
15	0	1.62E+00	46%	8.44E+00	0%	3.63E+00	2.66E-02	9%
16	0	7.18E-01	0%	5.90E+00	0%	2.30E+00	1.00E-01	0%
17	0	4.59E-01	0%	7.39E+00	0%	3.49E+00	3.06E-02	7%
18	0	7.83E-02	0%	5.21E+00	0%	2.17E+00	1.14E-01	0%

Table A.61 Scenario 7 probability from the three distances computed using range-range rate.

Scenario 8

Segment	Manoeuvre	MD(R, R_r)	PR	KLD (R,R_r)	PR	BD (R, R_r)	ρ BD (R, R_r)	PR
1	0	1.12E+00	0%	3.80E+01	0%	1.91E+00	2.20E-05	0%
2	0	1.15E-01	0%	6.21E+00	0%	2.96E+00	4.27E-05	0%
3	0	8.25E-01	0%	5.06E+00	0%	2.20E+00	4.54E-05	0%
4	0	7.48E-01	0%	2.46E+01	0%	3.09E+00	2.93E-05	2%
5	0	8.95E-01	0%	5.64E+00	0%	2.15E+00	5.02E-05	0%
6	0	8.78E-01	0%	7.57E+00	0%	3.50E+00	2.68E-05	7%
7	0	4.99E-02	0%	4.76E+00	0%	2.25E+00	6.55E-05	0%
8	0	1.81E+00	61%	7.72E+00	0%	2.98E+00	1.27E-05	1%
9	0	1.95E-01	0%	4.72E+00	0%	2.21E+00	9.36E-06	0%
10	0	2.75E-01	0%	2.34E+01	0%	2.99E+00	1.25E-05	1%
11	0	1.64E+00	48%	7.76E+00	0%	2.32E+00	6.52E-05	0%
12	2	5.88E-01	0%	7.37E+00	0%	3.47E+00	5.17E-05	7%
13	0	2.69E-01	0%	4.52E+00	0%	2.03E+00	3.88E-05	0%
14	0	8.87E-01	0%	7.81E+00	0%	3.62E+00	5.49E-05	9%
15	0	2.55E+00	92%	2.04E+01	0%	2.82E+00	6.87E-06	0%
16	0	7.50E-01	0%	6.43E+00	0%	2.97E+00	3.05E-05	0%
17	0	2.04E+00	75%	8.13E+00	0%	2.71E+00	2.81E-05	0%
18	0	1.53E+00	37%	5.40E+01	0%	3.28E+00	3.10E-05	5%
19	0	1.25E+00	8%	7.28E+00	0%	2.32E+00	4.93E-05	0%

Table A.62 Scenario 8 probability from the three distances computed using range-range rate.

Scenario 9

Segment	Manoeuvre	MD(R, R_r)	PR	KLD (R,R_r)	PR	BD (R, R_r)	ρ BD (R, R_r)	PR
1	0	8.48E-01	0%	3.15E+00	0%	9.99E-01	3.68E-01	0%
2	2	1.04E+00	0%	8.54E+00	0%	3.94E+00	1.94E-02	12%
3	0	2.37E+00	88%	1.03E+01	0%	2.83E+00	5.90E-02	0%
4	0	2.30E+00	86%	2.66E+01	0%	3.59E+00	2.76E-02	8%
5	0	5.69E-01	0%	7.67E+00	0%	3.61E+00	2.71E-02	9%
6	0	1.95E-01	0%	5.41E+00	0%	2.39E+00	9.21E-02	0%
7	0	2.87E+00	97%	1.40E+01	0%	4.08E+00	1.68E-02	14%
8	0	7.67E-01	0%	7.23E+00	0%	2.80E+00	6.10E-02	0%
9	0	7.63E-01	0%	6.03E+00	0%	2.58E+00	7.59E-02	0%

Table A.63 Scenario 9 probability from the three distances computed using range-range rate.

Scenario 10

Segment	Manoeuvre	MD(R, R_r)	PR	KLD (R,R_r)	PR	BD (R, R_r)	ρ BD (R, R_r)	PR
1	0	4.14E-01	0%	1.06E+00	0%	3.65E-01	6.94E-01	0%
2	0	5.59E+00	100%	1.21E+02	35%	6.25E+00	1.93E-03	35%
3	0	7.04E-01	0%	4.28E+00	0%	1.79E+00	1.67E-01	0%
4	0	6.17E-01	0%	7.24E+00	0%	3.40E+00	3.33E-02	6%
5	0	4.69E-01	0%	5.85E+00	0%	2.71E+00	6.66E-02	0%
6	0	6.69E-01	0%	7.23E+00	0%	3.39E+00	3.38E-02	6%
7	2	1.47E-01	0%	6.29E+00	0%	3.03E+00	4.83E-02	1%

Table A.64 Scenario 10 probability from the three distances computed using range-range rate.

Scenario 11

Segment	Manoeuvre	MD(R, R_r)	PR	KLD (R,R_r)	PR	BD (R, R_r)	ρ BD (R, R_r)	PR
1	0	7.03E-01	0%	2.75E+00	0%	1.14E+00	3.20E-01	0%
2	0	4.99E-01	0%	6.81E+00	0%	2.69E+00	6.76E-02	0%
3	0	4.07E-01	0%	6.43E+00	0%	3.05E+00	4.73E-02	2%
4	0	7.80E-01	0%	9.37E+00	0%	4.42E+00	1.21E-02	18%
5	2	1.19E+01	100%	1.07E+02	28%	2.07E+01	9.86E-10	90%
6	0	1.23E+00	6%	9.38E+00	0%	2.96E+00	5.21E-02	0%

Table A.65 Scenario 11 probability from the three distances computed using range-range rate.

Scenario 12

Segment	Manoeuvre	MD(R, R_r)	PR	KLD (R,R_r)	PR	BD (R, R_r)	ρ BD (R, R_r)	PR
1	0	8.16E-01	0%	1.61E+00	0%	4.38E-01	6.46E-01	0%
2	0	1.19E+00	2%	3.47E+01	0%	2.89E+00	5.58E-02	0%
3	0	3.54E-01	0%	6.54E+00	0%	3.11E+00	4.44E-02	2%
4	0	3.13E-01	0%	5.90E+00	0%	2.81E+00	6.02E-02	0%
5	0	1.06E+00	0%	9.40E+00	0%	2.69E+00	6.79E-02	0%
6	0	9.09E-02	0%	6.35E+00	0%	3.04E+00	4.78E-02	1%
7	0	5.48E-01	0%	7.81E+00	0%	2.77E+00	6.28E-02	0%
8	2	1.69E+00	52%	8.28E+00	0%	3.37E+00	3.45E-02	6%
9	0	2.71E+00	95%	6.82E+01	4%	3.51E+00	2.99E-02	7%
10	0	3.95E-01	0%	3.59E+00	0%	1.65E+00	1.93E-01	0%

Table A.66 Scenario 12 probability from the three distances computed using range-range rate.

Scenario 13

Segment	Manoeuvre	MD(R, R_r)	PR	KLD (R,R_r)	PR	BD (R, R_r)	ρ BD (R, R_r)	PR
1	0	8.86E-01	0%	5.51E+00	0%	1.40E+00	2.46E-01	0%
2	0	1.13E+00	0%	6.09E+00	0%	2.57E+00	7.65E-02	0%
3	0	6.89E-01	0%	8.80E+00	0%	4.15E+00	1.58E-02	15%
4	0	1.42E+00	27%	6.49E+00	0%	2.54E+00	7.87E-02	0%
5	0	6.62E-01	0%	8.31E+00	0%	3.91E+00	2.00E-02	12%
6	0	7.99E-01	0%	5.61E+00	0%	2.50E+00	8.21E-02	0%
7	0	7.52E-01	0%	7.59E+00	0%	3.54E+00	2.91E-02	8%
8	0	4.47E-01	0%	5.26E+00	0%	2.37E+00	9.33E-02	0%
9	1	4.04E-01	0%	7.58E+00	0%	3.58E+00	2.78E-02	8%
10	0	5.42E-01	0%	5.05E+00	0%	2.30E+00	1.00E-01	0%
11	0	1.67E+00	51%	7.87E+00	0%	2.45E+00	8.65E-02	0%
12	0	5.28E-01	0%	8.26E+00	0%	3.91E+00	2.01E-02	12%
13	0	1.01E+00	0%	5.85E+00	0%	2.55E+00	7.79E-02	0%

Table A.67 Scenario 13 probability from the three distances computed using range-range rate.

Scenario 14

Segment	Manoeuvre	MD(R, R_r)	PR	KLD (R,R_r)	PR	BD (R, R_r)	ρ BD (R, R_r)	PR
1	0	6.41E+00	100%	1.27E+02	38%	5.99E+00	2.51E-03	33%
2	1	7.53E-01	0%	6.83E+00	0%	2.50E+00	8.24E-02	0%
3	4	4.16E+00	100%	1.58E+01	0%	5.30E+00	5.01E-03	27%
4	2	9.99E-01	0%	6.75E+00	0%	2.98E+00	5.06E-02	1%

Segment	Manoeuvre	MD(R, R_r)	PR	KLD (R,R_r)	PR	BD (R, R_r)	ρ BD (R, R_r)	PR
5	2	4.09E-01	0%	6.95E+00	0%	3.28E+00	3.78E-02	4%

Table A.68 Scenario 14 probability from the three distances computed using range-range rate.

Scenario 15

Segment	Manoeuvre	MD(R, R_r)	PR	KLD (R,R_r)	PR	BD (R, R_r)	ρ BD (R, R_r)	PR
1	0	9.46E+00	100%	1.60E+03	100%	1.18E+01	7.55E-06	69%
2	1	6.28E+00	100%	3.17E+01	0%	7.95E+00	3.53E-04	48%
3	1	6.62E+00	100%	5.12E+01	0%	7.90E+00	3.71E-04	48%
4	3	4.57E-01	0%	7.51E+00	0%	3.54E+00	2.90E-02	8%
5	2	3.72E+00	100%	1.58E+01	0%	4.74E+00	8.74E-03	21%

Table A.69 Scenario 15 probability from the three distances computed using range-range rate.

Appendix B
Resumen en español

Título: Análisis de Medidas de Distancia para la Detección de Maniobras para Satélites en Órbitas Bajas con datos de Radar.

Palabras clave: Detección de Maniobras, Divergencia de Kullback-Leibler y Distancia de Bhattacharyya.

B.1 Introducción

Uno de los problemas principales en el sector espacial es la cantidad de objectos que se encuentran orbitando la Tierra. Actualmente, hay decenas de miles de objetos en órbita, y se espera que este número continúe creciendo en el futuro. Algunos de estos objetos realizan ocasionalmente maniobras, por ejemplo, para mantener su posición orbital o para realizar un cambio de órbita. Este aumento en la población de objetos espaciales incrementa la amenaza potencial para todos los vehículos y lanzamientos, y hace que las actividades de operación de satélites supongan cada vez un reto mayor.

Mencionar que la población espacial no solo está formada por satélites activos, sino que hay una gran cantidad de desechos espaciales en órbita alrededor de la Tierra. Los desechos orbitales son cualquier objeto creado por humanos que se encuentra en órbita alrededor de la Tierra y que ya no es útil. Se estima que el número de desechos espaciales en órbita terrestre se encuentra alrededor de 29000 para objetos de más de 10 cm, 670000 de más de 1 cm y más de 170 millones de más de 1 mm [1]. Son, por ejemplo, naves espaciales no funcionales, etapas de vehículos de lanzamiento o escombros de fragmentación. De hecho, la mayoría de los escombros se originan por rupturas en órbita, explosiones o colisiones. Estos objetos viajan a muy alta velocidad (en particular, en órbitas terrestres bajas, estos objetos orbitan en diferentes planos por lo que el impacto a esta altura puede ocurrir a una velocidad del orden de km/s) por lo que la colisión con un satélite o nave espacial en funcionamiento puede causar un gran daño [2].

Debido a esto, la conciencia situacional en el espacio y la actualización de los catálogos se ha vuelto un tema relevante. La detección de maniobras es de gran importancia para el Space Surveillance and Tracking. Cuando un satélite realiza una maniobra desconocida, tratar de asociar las nuevas observaciones con las órbitas de referencia previamente conocidas es un reto. Una de las principales razones de la importancia de la detección de maniobras es que puede reducir el número de objetos no correlacionados detectados. La mayoría de estos objetos son simplemente satélites conocidos, que han realizado maniobras desconocidas, por lo tanto, sus nuevas órbitas no coinciden con las predicciones.

Este proyecto se basa en un algoritmo de detección de maniobras desarrollado por el grupo de investigación del tutor del trabajo. Este algorítmo es un método de detección de maniobras en órbita baja con datos de radar y es aplicable sobre objetos cuya órbita es conocina. La idea principal es comparar la posición predicha del satélites, la cual se calcula mediante la propagación de su órbita, con los datos obtenidos por el radar en el siguiente pase del satélite. esta comparación se realiza utilizando la distancia de Mahalonobis (MD). Sin embargo, existen otras métricas que pueden usarse para determinar si un objeto está o no correlacionado con los datos anteriores. Las estudiadas en este proyecto son la divergencia de Kullback-Leibler (KLD) y la distancia de Bhattacharyya (BD).

B.2 Objetivo del proyecto

El objetivo final de este proyecto es utikizar datos de radar para detectar posibles maniobras de objetos conocidos en órbitas bajas; la idea es calcular la probabilidad de que ocurra una maniobra. Una de las piezas principales del algoritmo en el que se basa el proyecto es la métrica de la distancia entre la propagación de la órbita y los datos del radar. Es aquí donde radica el objetivo de este proyecto. Se busca determinar qué distancia estadística (la original, la distancia de Mahalonobis, o las otras dos distancias antes mencionadas, la divergencia Kullback-Leibler y la distancia Bhattacharyya) ofrece mejores resultados, es decir, detecta un mayor número de maniobras y evita un mayor número de falsos positivos .

El algoritmo depende de otros parámetros, tanto de los datos del Escenario del satélite como los aspectos específicos del algoritmo. Algunos de los parámetros que definen el Escenario son la órbita o las características físicas del satélite, su masa o su coeficiente balístico. Por otro lado, la propagación de la incertidumbre es un aspecto del algoritmo que debe tenerse en cuenta. Este proyecto también pretende caracterizar el impacto de estos parámetros en la detección de maniobras.

B.3 Teoría de distancias

La idea fundamental del proyecto es comparar el rendimiento del algoritmo utilizando diferentes distancias estadísticas. Se han utilizado la divergencia Kullback-Leibler y la distancia Bhattacharyya, y ambas se han comparado con la distancia original empleada, la distancia de Mahalanobis. Las tres distancias miden la similitud entre dos distribuciones de probabilidad. A continuación se explica cómo se ha calculado la probabilidad de ocurrencia de maniobra a partir de cada una de las distancias:

B.3.1 Distancia de Mahalanobis

El cuadrado de esta distancia se distribuye como una χ^2 con n grados de libertad, siendo n el número de variables. Con el objetivo de reducir falsos positivos, si la MD tiene una probabilidad menor del 50%, se asume que no hay maniobra. Por el contrario, si la probabilidad es superior al 50%, se resta 50 de la probabilidad y se multiplica por 2. Así, se obtiene el siguiente cálculo de la probabilidad:

$$PR = \max\left\{0,(\chi^2(MD^2,n) - 0.5)\cdot 2\right\}\cdot 100 \tag{B.1}$$

B.3.2 Divergencia de Kullback-Leibler

Como la distribución que sigue esta métrica es desconocida, se ha ajustado a una distribución Gamma con la aplicación Distribution Filter App de MATLAB.

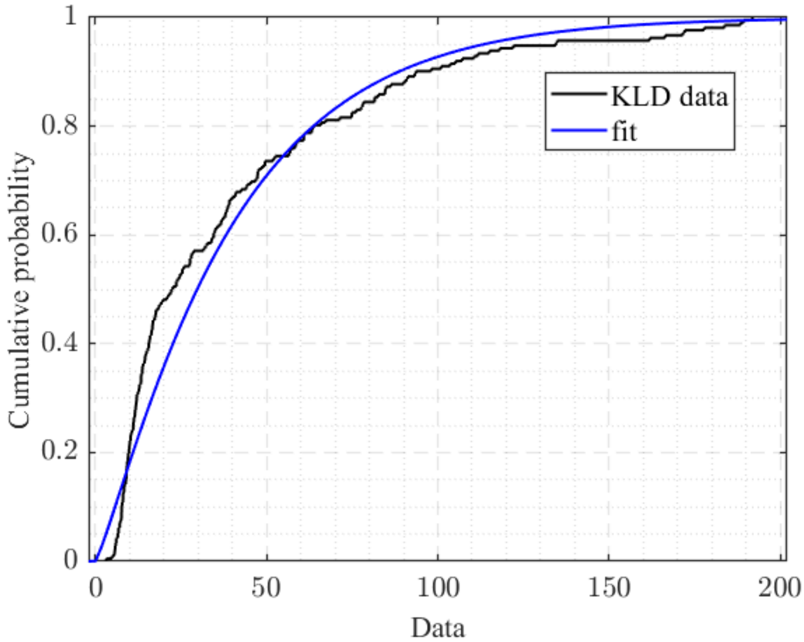

Figure B.1 Función de distribución acumulativa de la KLD.

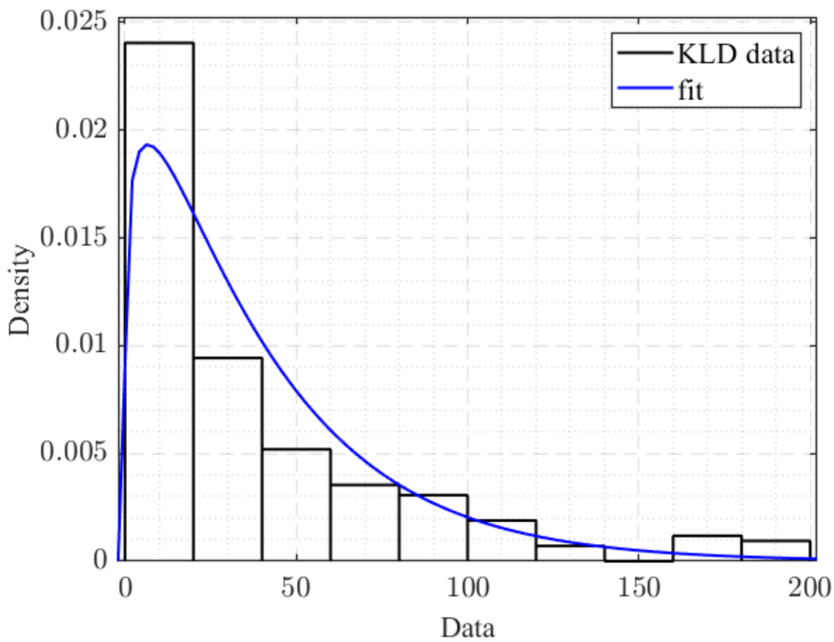

Figure B.2 Función de densidad de probabilidad de la KLD.

Con el objetivo de reducir falsos positivos, si la KLD tiene una probabilidad menor del 50%, se asume que no hay maniobra. Por el contrario, si la probabilidad es superior al 50%, se resta 50 de la probabilidad y se multiplica por 2. Así, se obtiene el siguiente cálculo de la probabilidad:

$$PR = \max\{0, (\Gamma(KLD, 0.6328, 183.7) - 0.5) \cdot 2\} \cdot 100 \tag{B.2}$$

B.3.3 Distancia de Bhattacharyya

Como la distribución que sigue esta métrica es desconocida, se ha utilizado el coeficiente que se calcula a partir de la distancia y se ha escalado mediante una constante calculada con la aplicación Distribution Filter App de MATLAB, ajuntando la muestra mediante una distribución exponencial.

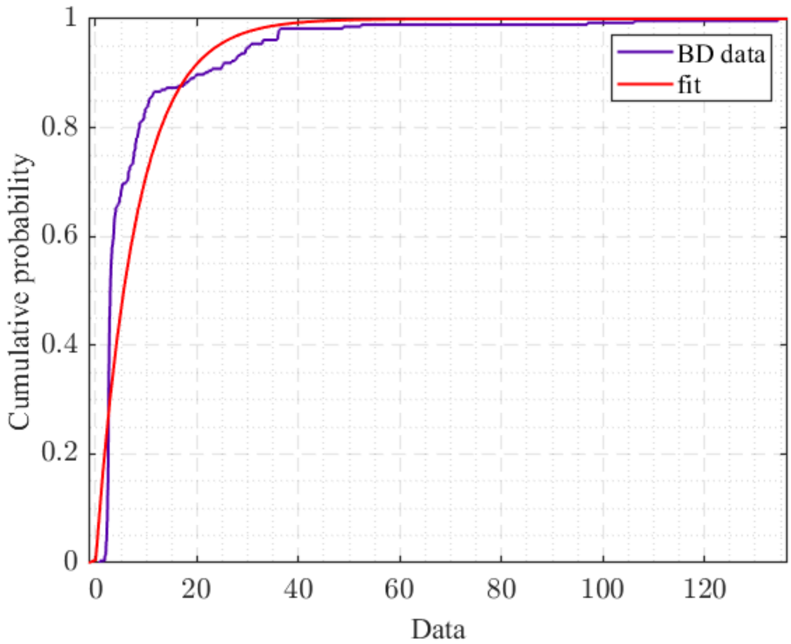

Figure B.3 Función de distribución acumulativa de la BD.

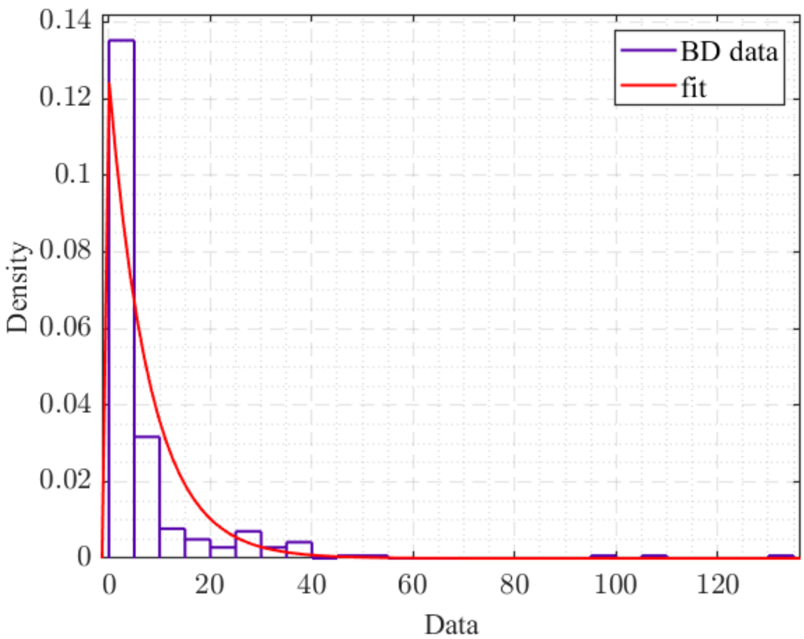

Figure B.4 Función de densidad de probabilidad de la BD.

Con el objetivo de reducir falsos positivos, si la KLD tiene una probabilidad menor del 30%, se asume que no hay maniobra. Por el contrario, si la probabilidad es superior al 30%, se resta 0.3 de la probabilidad y se divide entre 0.7. Así, se obtiene el siguiente cálculo de la probabilidad:

$$PR = \max\left\{0, \left[\left(1-\rho^{\frac{1}{4\cdot n}}\right) - 0.3\right]/0.7\right\} \cdot 100 \tag{B.3}$$

B.4 Resultados

A continuación se presentan los resultados obtenidos de los distintos análisis realizados. Tanto la comparación de distancias como el estudio del impacto de algunos parámetros.

B.4.1 Análisis de distancias

Analizando los resultados, se pueden obtener las siguientes conclusiones:

- Distancia de Mahalanobis:
  - Usando sól range-range rate el algoritmo es más sensible.
  - Empleando solo elevación-azimut, se detecta un 42 % menos de maniobras.
  - Calculando la distancia con todos los datos, se obtiene aproximadamente el mismo porcentaje de maniobras que usando solo range-range rate, pero introduce falsos positivos.
  - Se detectan todas las maniobras de alta intensidad.
  - Se detectan la mayoría de maniobras de intensidad media.
  - Las maniobras de baja intensidad se detectan en general en los casos fuera del plano e híbridos. Algunas de ellas se detectan en el caso tangencial, aunque la mayoría no.
- Divergencia de Kullback-Leibler:
  - Usando solo elevación-azimut siempre resulta positivo, por lo que no es válida. Por otro lado, empleando solo range-range rate, se obtienen buenos resultados, especialmente evitando falsos positivos.
  - Se detectan todas las maniobras de alta intensidad.
  - Se detectan maniobras de intensidad media, excepto en el caso tangencial.
  - Las maniobras de baja intensidad generalmente no se detectan en el caso tangencial. En el caso fuera del plano e híbrido, las maniobras se detectan en el 40 % de los casos.
- Distancia de Bhattacharyya:
  - Calcular la BD con range-range rate presenta excelentes resultados.
  - Usar solo elevación-azimut y todos los datos casi siempre detecta maniobra, por lo tanto, ninguna de las dos opciones son válidas.
  - Se detectan todas las maniobras de alta intensidad.
  - En general se detectan las maniobras de intensidad media.
  - Se detectan maniobras de baja intensidad, excepto en el caso tangencial.

La conclusión común de las tres distancias es que el tiempo entre la maniobra y la siguiente medición de radar no parece afectar estos resultados. Esto es general para todos los escenarios, así como el hecho de que las distancias que se calculan usando solo range-range rate son más sensibles, y las calculadas usando elevación y azimut introducen una gran cantidad de falsos positivos.

Comparando los resultados de las tres distancias, se pueden sacar algunas conclusiones. La distancia que detecta más maniobras es la MD, con un 87 % de verdaderos positivos. No obstante, la BD también detecta un gran número de ellas, un 83 %. En cuanto a los falsos positivos, la KLD y la BD son las distancias que detectan más escenarios sin maniobras, 94 % y 92 %, respectivamente.

Por tanto, la MD es la mejor opción para la detección de maniobras. Por otro lado, la KLD ofrece los mejores resultados evitando falsos positivos. Sin embargo, los resultados de la BD están muy cerca de estos máximos en ambos objetivos. Así, podríamos concluir que la mejor opción para la detección de maniobras es la BD.

	MD(R, R_r)	KLD (R,R_r)	BD (R, R_r)	MD (el, az)	KLD (el, az)	BD (el, az)	MD (All)	BD (All)
% Negativos verdaderos	81%	94%	92%	79%	0%	18%	76%	0%
% Falsos positivos	19%	6%	8%	21%	100%	82%	24%	100%
% Positivos verdaderos	87%	66%	83%	45%	100%	70%	83%	100%
% Falsos negativos	13%	34%	17%	55%	0%	30%	17%	0%

Table B.1 Resultados de todos los satélites para 247 escenarios (102 sin maniobra y 135 con maniobra).

	MD(R, R_r)	KLD (R,R_r)	BD (R, R_r)
Precisión	0.824	0.918	0.914
Recall	0.874	0.659	0.830
F_1	0.848	0.767	0.870
F_β ($\beta = 0.5$)	0.834	0.851	0.895

Table B.2 Precisión, recall, F_1 and F_β ($\beta = 0.5$).

Escenario del Sentinel-1A

	MD(R, R_r)	KLD (R,R_r)	BD (R, R_r)	MD (el, az)	KLD (el, az)	BD (el, az)	MD (All)	BD (All)
% Negativos verdaderos	95%	91%	100%	82%	0%	23%	82%	0%
% Falsos positivos	5%	9%	0%	18%	100%	77%	18%	100%
% Positivos verdaderos	93%	85%	89%	48%	100%	63%	93%	100%
% Falsos negativos	7%	15%	11%	52%	0%	37%	7%	0%

Table B.3 Resultados del satélite Sentinel-1A para 49 escenarios (22 sin maniobra y 27 con maniobra).

Escenario del Sentinel-1B

	MD(R, R_r)	KLD (R,R_r)	BD (R, R_r)	MD (el, az)	KLD (el, az)	BD (el, az)	MD (All)	BD (All)
% Negativos verdaderos	82%	82%	94%	82%	0%	12%	65%	0%
% Falsos positivos	18%	18%	6%	18%	100%	88%	35%	100%
% Positivos verdaderos	93%	70%	96%	44%	100%	74%	81%	100%
% Falsos negativos	7%	30%	4%	56%	0%	26%	19%	0%

Table B.4 Resultados del satélite Sentinel-1B para 44 escenarios (17 sin maniobra y 27 con maniobra).

Escenario del Sentinel-2A

	MD(R, R_r)	KLD (R,R_r)	BD (R, R_r)	MD (el, az)	KLD (el, az)	BD (el, az)	MD (All)	BD (All)
% Negativos verdaderos	89%	100%	100%	89%	0%	5%	84%	0%
% Falsos positivos	11%	0%	0%	11%	100%	95%	16%	100%
% Positivos verdaderos	89%	67%	89%	41%	100%	89%	89%	100%
% Falsos negativos	11%	33%	11%	59%	0%	11%	11%	0%

Table B.5 Resultados del satélite Sentinel-2A para 46 escenarios (19 sin maniobra y 27 con maniobra).

Escenario del Sentinel-2B

	MD(R, R_r)	KLD (R,R_r)	BD (R, R_r)	MD (el, az)	KLD (el, az)	BD (el, az)	MD (All)	BD (All)
% Negativos verdaderos	92%	96%	96%	84%	0%	16%	92%	0%
% Falsos positivos	8%	4%	4%	16%	100%	84%	8%	100%
% Positivos verdaderos	74%	44%	63%	44%	100%	100%	70%	100%
% Falsos negativos	26%	56%	37%	56%	0%	0%	30%	0%

Table B.6 Resultados del satélite Sentinel-2B para 52 escenarios (25 sin maniobra y 27 con maniobra).

Escenario del Swarm-C

	MD(R, R_r)	KLD (R,R_r)	BD (R, R_r)	MD (el, az)	KLD (el, az)	BD (el, az)	MD (All)	BD (All)
% Negativos verdaderos	42%	100%	68%	58%	0%	32%	53%	0%
% Falsos positivos	58%	0%	32%	42%	100%	68%	47%	100%
% Positivos verdaderos	89%	63%	78%	48%	100%	26%	81%	100%
% Falsos negativos	11%	37%	22%	52%	0%	74%	19%	0%

Table B.7 Resultados del satélite Sentinel-1B para 44 escenarios (17 sin maniobra y 27 con maniobra).

B.4.2 Maniobras pequeñas

Tangent	MD(R, R_r)	KLD (R,R_r)	BD (R, R_r)	MD (el, az)	KLD (el, az)	BD (el, az)	MD (All)	BD (All)
5 s	20%	0%	0%	13%	100%	73%	7%	100%
2.5 s	7%	0%	0%	27%	100%	87%	20%	100%
1 s	20%	0%	0%	27%	100%	80%	20%	100%
0.5 s	0%	0%	0%	27%	100%	80%	7%	100%

Table B.8 Resultados para maniobras tangenciales.

Out-of-plane	MD(R, R_r)	KLD (R,R_r)	BD (R, R_r)	MD (el, az)	KLD (el, az)	BD (el, az)	MD (All)	BD (All)
500 s	80%	73%	100%	20%	100%	80%	80%	100%
250 s	87%	47%	60%	33%	100%	87%	73%	100%
50 s	20%	0%	20%	27%	100%	87%	13%	100%
10 s	13%	0%	0%	27%	100%	80%	20%	100%

Table B.9 Resultados para maniobras fuera de plano.

Hybrid	MD(R, R_r)	KLD (R,R_r)	BD (R, R_r)	MD (el, az)	KLD (el, az)	BD (el, az)	MD (All)	BD (All)
50 s	100%	40%	93%	33%	100%	80%	87%	100%
10 s	47%	0%	20%	27%	100%	87%	40%	100%
5 s	20%	0%	7%	27%	100%	80%	27%	100%
1 s	7%	0%	0%	13%	100%	80%	7%	100%

Table B.10 Resultados para maniobras híbridas.

B.4.3 Análisis del impacto de los diferentes parámetros

Masa

MD (R,Rr)	% Negativos verdaderos	% Falsos positivos	% Positivos verdaderos	% Falsos negativos
1000 Kg	94%	6%	83%	17%
1500 Kg	94%	6%	83%	17%
2000 Kg	85%	15%	91%	9%
2500 Kg	89%	11%	83%	17%
3000 Kg	91%	9%	85%	15%

Table B.11 Resultados de la MD calculada con sólo *range-range rate*.

KLD (R,Rr)	% Negativos verdaderos	% Falsos positivos	% Positivos verdaderos	% Falsos negativos
1000 Kg	94%	6%	65%	35%
1500 Kg	98%	2%	69%	31%
2000 Kg	96%	4%	69%	31%
2500 Kg	94%	6%	65%	35%
3000 Kg	94%	6%	65%	35%

Table B.12 Resultados de la KLD calculada con sólo *range-range rate*.

BD (R,Rr)	% Negativos verdaderos	% Falsos positivos	% Positivos verdaderos	% Falsos negativos
1000 Kg	98%	2%	76%	24%
1500 Kg	100%	0%	74%	26%
2000 Kg	96%	4%	78%	22%
2500 Kg	98%	2%	78%	22%
3000 Kg	98%	2%	80%	20%

Table B.13 Resultados de la BD calculada con sólo *range-range rate*.

Coeficiente balístico

MD (R,Rr)	% Negativos verdaderos	% Falsos positivos	% Positivos verdaderos	% Falsos negativos
1	96%	4%	89%	11%
1.5	87%	13%	89%	11%
2	94%	6%	83%	17%
2.5	87%	13%	85%	15%
3	96%	4%	89%	11%

Table B.14 Resultados de la MD calculada con sólo *range-range rate*.

KLD (R,Rr)	% Negativos verdaderos	% Falsos positivos	% Positivos verdaderos	% Falsos negativos
1	94%	6%	67%	33%
1.5	98%	2%	69%	31%
2	94%	6%	65%	35%
2.5	89%	11%	70%	30%
3	96%	4%	70%	30%

Table B.15 Resultados de la KLD calculada con sólo *range-range rate*.

BD (R,Rr)	% Negativos verdaderos	% Falsos positivos	% Positivos verdaderos	% Falsos negativos
1	100%	0%	74%	26%
1.5	98%	2%	80%	20%
2	98%	2%	76%	24%
2.5	98%	2%	76%	24%
3	100%	0%	80%	20%

Table B.16 Resultados de la BD calculada con sólo *range-range rate*.

Modelo atmosférico

MD (R,Rr)	% Negativos verdaderos	% Falsos positivos	% Positivos verdaderos	% Falsos negativos
Marshall	94%	6%	87%	13%
Harris Priester	94%	6%	83%	17%

Table B.17 Resultados de la MD calculada con sólo *range-range rate*.

KLD (R,Rr)	% Negativos verdaderos	% Falsos positivos	% Positivos verdaderos	% Falsos negativos
Marshall	96%	4%	67%	33%
Harris Priester	94%	6%	65%	35%

Table B.18 Resultados de la KLD calculada con sólo *range-range rate*.

BD (R,Rr)	% Negativos verdaderos	% Falsos positivos	% Positivos verdaderos	% Falsos negativos
Marshall	98%	2%	78%	22%
Harris Priester	98%	2%	76%	24%

Table B.19 Resultados de la BD calculada con sólo *range-range rate*.

Orden de Taylor

MD (R,Rr)	% Negativos verdaderos	% Falsos positivos	% Positivos verdaderos	% Falsos negativos
Taylor 2	94%	6%	83%	17%
Taylor 3	94%	6%	83%	17%
Taylor 4	94%	6%	83%	17%

Table B.20 Resultados de la MD calculada con sólo *range-range rate*.

KLD (R,Rr)	% Negativos verdaderos	% Falsos positivos	% Positivos verdaderos	% Falsos negativos
Taylor 2	94%	6%	65%	35%
Taylor 3	87%	13%	65%	35%
Taylor 4	87%	13%	65%	35%

Table B.21 Resultados de la KLD calculada con sólo *range-range rate*.

BD (R,Rr)	% Negativos verdaderos	% Falsos positivos	% Positivos verdaderos	% Falsos negativos
Taylor 2	98%	2%	76%	24%
Taylor 3	98%	2%	76%	24%
Taylor 4	98%	2%	76%	24%

Table B.22 Resultados de la BD calculada con sólo *range-range rate*.

Propagación de la incertidumbre

MD (R,Rr)	% Negativos verdaderos	% Falsos positivos	% Positivos verdaderos	% Falsos negativos
Taylor and Monte Carlo	94%	6%	83%	17%
UT	94%	6%	83%	17%

Table B.23 Resultados de la MD calculada con sólo *range-range rate*.

KLD (R,Rr)	% Negativos verdaderos	% Falsos positivos	% Positivos verdaderos	% Falsos negativos
Taylor and Monte Carlo	94%	6%	65%	35%
UT	91%	9%	70%	30%

Table B.24 Resultados de la KLD calculada con sólo *range-range rate*.

BD (R,Rr)	% Negativos verdaderos	% Falsos positivos	% Positivos verdaderos	% Falsos negativos
Taylor and Monte Carlo	98%	2%	76%	24%
UT	96%	4%	76%	24%

Table B.25 Resultados de la BD calculada con sólo *range-range rate*.

B.4.4 Análisis en escenarios reales

	MD (R, Rr)	KLD (R, Rr)	BD (R, Rr)
% Negativos verdaderos	88%	99%	78%
% Falsos positivos	12%	1%	22%
% Positivos verdaderos	42%	0%	67%
% Falsos negativos	58%	100%	33%

Table B.26 Resultados de 162 segmentos reales (138 sin maniobra y 24 con maniobra).

	MD(R, R_r)	KLD (R,R_r)	BD (R, R_r)
Precisión	0.772	0	0.754
Recall	0.417	0	0.667
F_1	0.541	-	0.708
F_β ($\beta = 0.5$)	0.659	-	0.735

Table B.27 Precisión, recall, F_1 y F_β ($\beta = 0.5$).

B.5 Conclusiones

El proyecto se centra en la detección de maniobras de objetos conocidos en órbitas bajas utilizando datos de radar. La idea principal del algoritmo empleado es estudiar la correlación entre la propagación de la órbita del satélite y los datos de radar de la siguiente pasada del satélite sobre este. Los conceptos desarrollados a lo largo del proyecto han sido aquellos necesarios para comprender la forma en la que opera el algoritmo y los cambios que se han implementado en el mismo, con el objetivo de intentar mejorar la detección de maniobras.

Los primeros análisis (realizados para comparar las distancias y estudiar el impacto de los parámetros en los resultados) se han realizado con datos sintéticos. Posteriormente, el algoritmo se ha aplicado a escenarios reales. Así, se ha podido analizar la sensibilidad del algoritmo con las diferentes distancias en casos reales.

Se aprecia que las tres distancias se comportan bien en escenarios sintéticos. Todas ellas dan como resultado un alto valor de F-score, especialmente la BD, que resulta tener también el valor más alto con escenarios reales. El rendimiento del algoritmo se reduce considerablemente en casos reales. La KLD no puede utilizarse en estos casos porque el algoritmo no detecta ninguna maniobra en casos reales cuando se utiliza esta métrica.

Por otra parte, mientras que la órbita parece tener un gran efecto en los resultados, los parámetros de propagación no parecen tener un gran impacto sobre estos. El algoritmo detecta más o menos el mismo porcentaje de maniobras independientemente de la masa o el coeficiente balístico del satélite.

Otro aspecto importante del algoritmo, que se ha explicado a lo largo del proyecto, es la propagación de la incertidumbre. Esto no solo afecta a los resultados, sino también al tiempo de computación del algoritmo. El orden de Taylor aumenta considerablemente el tiempo de computación, sin embargo, no aumenta el número de maniobras detectadas, por lo que elegir el segundo orden de Taylor es la mejor opción. Por otro lado, utilizar el método *uncented transform* en lugar del álgebra diferencial de Taylor y montecarlo (con el segundo orden de Taylor y 50000 muestras para el montecarlo) reduce el tiempo de cálculo en un 35%, sin detrimento de los resultados.

List of Figures

List of Tables

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