COLLISION PROBABILITY ASSESSMENT FOR THE RAPIDEYE SATELLITE CONSTELLATION

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ABSTRACT

Within the last three years, the Joint Space Operations Center (JSpOC) detected 85 close approaches between the RapidEye constellation and secondary space objects. Most of the approaching objects were non-operational, such as debris from the Chinese Fengyun 1C satellite.

In order to actively mitigate this risk for the five satellites, RapidEye entered into collaboration with the ESA's Space Debris Office (SDO). A collision avoidance assessment service is provided where SDO supplies information on the criticality of close approach events. The information is supplemented with a recommendation as to whether RapidEye should perform a collision avoidance manoeuvre by adjusting the orbit of one or more of its satellites.

1 INTRODUCTION

The number of satellites in Earth orbit is steadily growing and with the high amount of space debris, either crossing through or resident in orbit, collision probabilities between two such objects can become critical. 85 close approaches between the RapidEye constellation and secondary space objects were detected. These close approaches constitute an increased risk for RapidEye's remote sensing satellites not only during nominal operations but also during orbit maintenance periods.

In their 630 km altitude low Earth orbit, the RapidEye satellites are subject to perturbing accelerations, which result in a continuous altitude decrease of the constellation. Therefore, RapidEye regularly performs orbit maintenance manoeuvres to ensure that optimal constellation properties are maintained with respect to the imaging and daily revisit capabilities. Typical manoeuvre campaigns comprise height changes of up to 600 m, which are achieved by thrust arcs that can be distributed over up to three separate orbits manoeuvres.

RapidEye has taken the approach to partner with external agencies to provide assessments of collision probability [1]. The European Space Agency (ESA) was chosen in this capacity, since the Space Debris Office has a long history in space debris research, operational collision risk analysis and avoidance manoeuvre planning.

RapidEye provides constellation GPS data to the ESA SDO on a daily basis. As Fig.1 shows, this data will be used to perform orbit determinations (OD), orbit predictions (OP), and to generate covariance (COV) matrices. The results of the calculations are available to RapidEye in turn. Once the RapidEye constellation enters a phase of orbit maintenance, RapidEye plans for manoeuvres and sends the characteristics which are necessary for evaluation to ESA. ESA computes the orbit prediction and converts the orbit that contains the manoeuvre to JSpOC format so JSpOC can screen the orbits against their internal catalogue. Once the result of the screening is available to ESA, it generates manoeuvre advice (continue, abort, change, wait) for RapidEye.

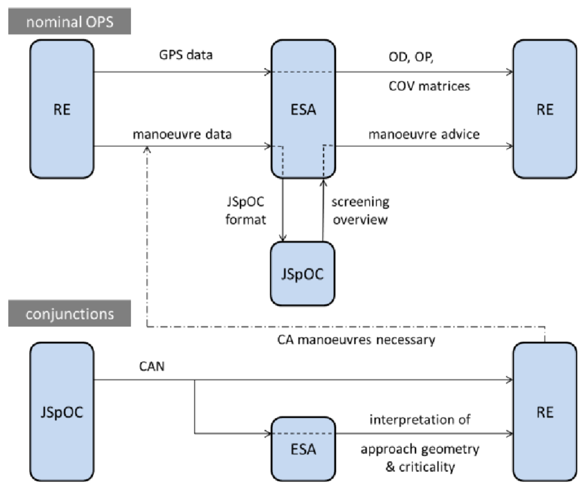

Figure 1: Information flow for the collision probability assessment service

In the case of close conjunctions, ESA is copied on the close approach notifications (CAN) that RapidEye receives. ESA accordingly generates an interpretation of the approach geometry and the criticality of the event. If the collision probability is considered to be critical, RapidEye prepares collision avoidance (CA) manoeuvres and sends the data to ESA. The data flow from that point will be analogous to the manoeuvre planning in nominal operations.

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2 THE RAPIDEYE MISSION

To meet the mission objectives, the RapidEye constellation must be able to revisit every target on Earth within one day. This daily revisit capability is based on a sun-synchronous orbit with an 11:30 a.m. descending node and the ability to perform roll manoeuvres in the across track direction. The RapidEye constellation images on the descending path using five multispectral bands: red, green, blue, near infrared (NIR), and red-edge.

2.1 Satellite tasking

In order to incorporate the latest weather forecast, acquisition planning for the constellation is done twice a day. The morning planning session plans for image acquisitions in North and South America (acquired between 13:00 – 24:00 UTC) and the evening planning session sets up imaging for the orbits over Australia, Asia, Europe, and Africa (acquired between 0:00 – 13:00 UTC). The finalized plans are then uploaded through RapidEye's spacecraft control centre (SCC) to schedule the satellites.

In order to have minimal impact on the data acquisition process, the decision to introduce a collision avoidance manoeuvre must be made before the respective planning session starts. For manoeuvres during the orbits that image over North and South America a decision must be taken by 7:00 UTC on the same day, whereas for the remaining regions, the decision must be taken by 12:30 UTC on the previous day. This poses an additional boundary condition on the collision avoidance manoeuvre planning.

To support the planning process at the RapidEye headquarters in Berlin and the data acquisition process at the ground station in Svalbard, orbit information is based on JSpOC Two-Line Elements (TLEs). TLEs are usually sufficient and more accurate ephemeris data to support conjunction risk analysis was not available before collaborating with ESA.

2.2 Constellation Management

Orbit maintenance manoeuvres are necessary to keep the constellation in an optimal formation with respect to the imaging and daily revisit capabilities [4]. These maintenance operations ensure that the satellites are brought back to a reference orbit of around 630 km altitude. The orbital elements are further optimized for a target phase difference of 72° between the satellites.

Fig. 2 shows the pre and post manoeuvre progression during one such orbit maintenance period for RE-2 and RE-5. The data, which is derived from the on-board GPS, is presented as the deviation from the target phase and the target semi-major axis (SMA). In the graph, the lower right part of the parabola is derived from pre manoeuvre data. It shows the natural decay in orbit altitude in connection with the phase shift. The vertical lines in the data represent the rise of the orbit altitude and thus are caused by a manoeuvre.

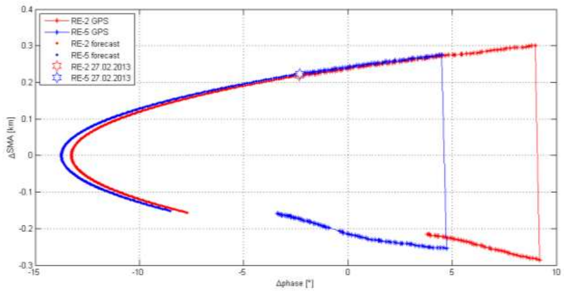

Figure 2: ΔPhase and ΔSMA progression pre and post orbit maintenance for RE-2 and RE-5

Once a satellite exhibits a positive ΔSMA it will follow the upper part of the parabola towards the apex with decreasing ΔPhase. After reaching the apex, it will follow the lower part with increasing ΔPhase until another maintenance manoeuvre is carried out. Fig. 2 corresponds to a satellite altitude decay of approximately 4.5 m/day and does not only show the GPS data but also a forecast based on this decay. Typical manoeuvres comprise height changes of about 400 m and velocity changes of about 0.2 m/s.

3 CLOSE APPROACH EVENTS

Tab. 1 summarizes the close approaches that were reported by the Joint Space Operations Center (JSpOC) for the RapidEye constellation. The reports are triggered when a conjunction event occurs within the next 72 hours and is closer than 200 m in the radial direction and 1 km overall to a RapidEye satellite. Between 13 and 20 events occurred for each of the five satellites. Tab. 1 shows that only the minority of the objects involved are operated satellites, such as the Delfi C3 [6]. The majority of the objects are rocket bodies (R/B) or satellite debris (DEB), which originates from the Chinese Fengyun 1C [3] or the Cosmos-2251/Iridium-33 collision [2], for example.

Table 1: Overview on RapidEye's close approach events

Satellite	# Events	Secondary Objects
RE-1	19	• Atlass 41 E DEB • Cosmos 2221 • Cosmos 2251 DEB (3x) • Cosmos 373 DEB • SL-14 R/B (10x) • "known" (3x)

RE-2	15	• Atlass 41 E DEB • Cosmos 2251 DEB • CZ-2D DEB • Delfi C3 • Fengyun 1C DEB (3x) • Iridium 33 DEB • Pegasus R/B • PSLV DEB • Yaogan 1 DEB • “known” (4x)
RE-3	20	• C/NOFS • Cosmos 2251 DEB (2x) • CZ-2C DEB • Delta 1 DEB • Fengyun 1C DEB (4x) • Index • OV1-2 • PSLV DEB (2x) • SL-14 R/B (4x) • SL-8 DEB • “known” (2x)
RE-4	18	• Cosmos 2084 • Cosmos 2251 DEB • CZ-4 DEB • CZ-4B DEB • Demosat/Falcon 1 • Fengyun 1C DEB (4x) • PSLV R/B • SL-12 R/B(1) • SL-14 R/B (3x) • Step 2 • Yaogan 10 • “known” (2x)
RE-5	13	• Cosmos 2251 DEB (3x) • CZ-4B DEB • Delta 1 DEB • Delta 1 R/B • Fengyun 1C DEB (2x) • Resurs O1 DEB • SEEDS • SL-14 R/B • SL-18 DEB • Pegasus R/B
total	85	

The close approach notifications (CAN), which are created by JSpOC and sent to satellite operators, usually contain the miss distance vectors and the error vectors of the involved objects. The error vectors and thus the uncertainty in position and velocity determination depend on the tracking frequency by JSpOC. They usually improve during CAN update notifications.

Fig. 3 shows an example of a close approach event, of which three updates were received after the original notification. The distance of the RapidEye satellite to the secondary object is plotted in radial (u), in-track (v), and cross-track (w) directions and is plotted to show the absolute distance between the two objects. The error in the respective direction is also shown and it can be seen that the error tends to decrease as time converges to the time of closest approach (TCA). Further, the values for the distances seem to converge over time.

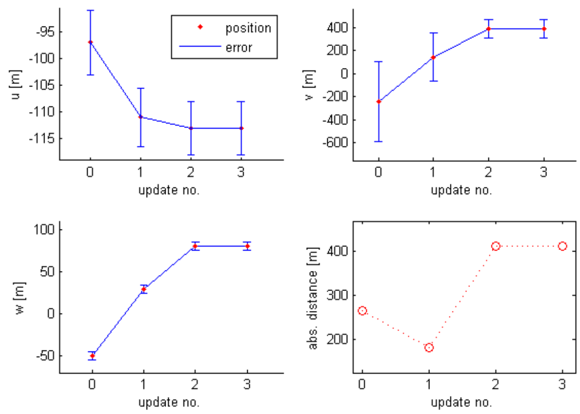

Figure 3: An example of the progression of distances and errors during JSpOC updates

4 COLLISION PROBABILITY ASSESSMENT

Before the Cosmos 2251 and Iridium 33 collision in 2009, orbital information of the debris population was available only in the form of the US TLE catalogue. TLEs have serious shortcomings for the purpose of collision risk assessment: They provide mean orbital elements and so no direct way to derive osculating elements at a conjunction epoch is available. Furthermore, they are provided without any information concerning accuracy, i.e., without any covariance information, and there are only coarse estimates of TLE-related covariances available [11].

A collision risk assessment based on TLEs would therefore require large separations at the time of closest approach and consequently a high number of comparatively large manoeuvres (several 100 m separations in radial and/or cross-track direction for head-on conjunctions would be required for LEO missions).

For the operated spacecraft (“target”), better orbit information, i.e., higher and known accuracy, may be available from the owner/operator depending on the mission operations concept employed. However, for the conjunction partner (“chaser”), better orbit information can only be obtained by tracking with radar or telescopes (unless the chaser is also an operational SC –

an exception at least in LEO). Radar tracking has been implemented by ESA in the past for its LEO missions ERS-2, Envisat, and Cryosat-2 [9] and is available today as a backup. However, this approach cannot practically be carried over to the spaceflight community as a whole and, technically, this is also not needed since the tracking is already performed when building the TLE catalogue and it is only a matter of introducing a more flexible data sharing policy to obtain the high accuracy orbit information with the associated covariances.

Following the Cosmos 2251 and Iridium 33 collision in 2009, the US data policy changed and the data necessary for collision risk assessment is today made available by JSpOC in the form of conjunction summary messages (CSM). The algorithm to quantify the collision risk of a conjunction is given in Section 4.1 below. Every conjunction will have a non-zero collision risk and it is necessary to determine which risks should be tolerated.

Manoeuvres deserve special attention: On one hand, operators do not favour changing the trajectory in a way that leads to a conjunction with a high risk; on the other hand, JSpOC by default does not know a priori when a manoeuvre is performed and needs time after the manoeuvre to acquire and process tracking data that leads to a well determined orbit. Therefore, JSpOC offers owners/operators the option to send orbit ephemeris data to them containing manoeuvres. This allows JSpOC to detect conjunctions following a manoeuvre and at the same time facilitates the orbit determination process.

Within the frame of the collaboration between RapidEye and ESA, the CSMs are analysed by ESA's SDO and advice concerning the need for a collision avoidance manoeuvre is given to RapidEye, including a first estimate of the time and size of the manoeuvre if applicable. To support decisions on the execution of manoeuvres (whether to avoid a collision or just for nominal maintenance operations), manoeuvres are propagated and ephemeris sent by the SDO to JSpOC for screening. Accurate orbit ephemeris is needed for the process. Since nominal operations rely on TLEs (for station scheduling/pointing, manoeuvre planning, etc.), no accurate orbit information is by default available; however, GPS data is available as part of the RapidEye payload data. This data is provided to SDO and an orbit determination based on them is run daily in order to have an accurate orbit available at any time. This collaboration has been in place in a precursor mode since October 2012 and is fully operational since March 2013.

4.1 Close Approaches

Probability of collision

Several formulations for the collision risk associated with a near-miss encounter are available in the literature [5]. Most of them make use of the Gaussian three-dimensional probability function for both objects involved in the encounter. Typically, during an encounter (due to its short duration), the object motion can be considered rectilinear; the uncertainty in velocity is negligible and the position uncertainty for both objects can be considered constant. Since the errors in the orbit states of both objects are considered to be uncorrelated, both contributions can be combined into a common covariance matrix. In this matrix, only the (3×3) sub-matrix, corresponding to the position uncertainties, is taken into account. Since the position error is assumed to have a 3D normal distribution, the probability density function $p(\Delta\underline{r})$ in the vicinity of the point of closest approach can be described as follows.

$$p(\Delta\underline{r}) = \frac{1}{\sqrt{(2\pi)^3 det\left(\underline{\underline{C}}\right)}} exp\left(-\frac{1}{2}\Delta\underline{r}^T \underline{\underline{C}}^{-1}\Delta\underline{r}\right) \qquad (1)$$

Assuming spherical objects, a collision occurs if the centres of the objects get closer than the sum of the radii. The probability of such an event is the integral of the probability density given above (equation 1) over a sphere of this combined radius, centred in the miss vector:

$$P_c = \frac{\int_{(V_c)} exp\left(-\frac{1}{2}\Delta\underline{r}^T \underline{\underline{C}}^{-1}\Delta\underline{r}\right) dV}{\sqrt{(2\pi)^3 det\left(\underline{\underline{C}}\right)}} \qquad (2)$$

This integral can be simplified to two dimensions by projecting it to a plane perpendicular to the relative velocity, the B-plane. The latter integral can then be integrated numerically, e.g., as is done at the SDO.

Selection of Probability Threshold

An important criterion for the decision whether or not to perform an avoidance manoeuver is the probability of collision as computed with the methods given above. In this respect, it is crucial to determine the threshold probability that should be used for triggering a manoeuver. If this threshold is set too high, a significant number of conjunctions are disregarded and therefore a significant risk may be accepted by the operator over the mission's lifetime. If on the other hand the threshold is set too low, the number of manoeuvres might be very high with most of them avoiding only a small overall risk. In order to assist this threshold selection, ESA has developed the DRAMA (Debris Risk Assessment and Mitigation Analysis) [7] tool.

Input to DRAMA is a model of the population of objects orbiting Earth in order to predict collision fluxes. DRAMA makes use of MASTER [8] modelling data. DRAMA then computes the annual collision risk for the specified spacecraft orbit using statistical methods based on the probability computation method outlined above. Besides the orbit, the annual collision risk is dependant on the population, the spacecraft size and the accuracy of the spacecraft orbit and of the orbits of the encountered objects. The time dependencies of the covariances are considered. DRAMA also computes the mean number of conjunctions with collision risk for a variety of values chosen as the threshold.

Fig. 4 demonstrates this for a single RapidEye satellite and typical orbit determination accuracies based on GPS data, described below, and covariance levels as expected for CSM data. The diagram shows the risk accumulated from all events in a year for those events that are avoided (i.e., they trigger an alarm because they violate the accepted collision probability level and a manoeuver would need to be performed) and for those events that would be ignored (i.e., they are below the accepted collision probability level). The diagrams assume a reaction time of 1 day and use the maximum span of a RapidEye satellite (1.7 m diameter) to generate a conservative circular collision cross-section.

The following is a guide for how to read the diagrams: Consider a (relaxed) collision avoidance reaction threshold of 0.01 per event. Only a few events in a year will exceed this threshold (actually, less than one). Very few avoidance manoeuvres will be necessary in this case, and the avoided risk is therefore small. On the other hand, there will be many events which trigger lower probabilities (the lower the probability, the more events of that probability can be found in a year). All these would be ignored as they fall below the reaction threshold. The risk that is accumulated from them can be very high even though the individual risk contribution might be low; the high number of occurrences accumulates a higher risk. The sum of the ignored and avoided risk is the natural collision risk of the mission per year.

The other extreme case would be a reaction threshold of 10^{-6} (hence, manoeuvres are triggered only at very low probabilities). The associated number of manoeuvres may be high, but this avoids a lot of risk and ignores correspondingly few risks.

It should be noted that the USSTRATCOM catalogue, which is the data source for CSMs, contains only a subset of the space object population. Limited sensitivity and observational constraints limit the coverage of this catalogue to objects of approximately >10 cm in LEO. Even within the covered diameter region, the catalogue is not complete. Thus, collision avoidance is only possible for a limited subset of the actual space object population. The terms “ignored” and “avoided” risk refer to the risk associated to the objects contained in the USSTRATCOM catalogue only. There is an “unavoidable” background risk caused by the population of objects that are too small to be tracked by USSTRATCOM, which consequently cannot be considered for collision avoidance analyses and are therefore ignored here.

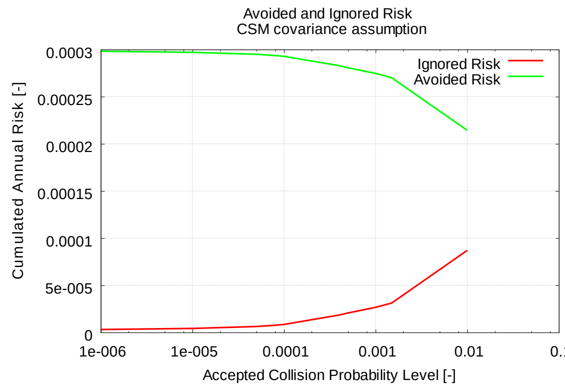

Figure 4: Ignored and avoided risk as a function of the accepted collision probability level (threshold)

Fig. 5 shows the number of alerts that can be expected as a function of the accepted collision probability threshold. This simulation is based on the status of the space environment in the year 2001. It should be noted that the environment changed after the Jan 11, 2007 Chinese anti-satellite test and the Feb 10, 2009 collision between Iridium-33 and Cosmos-2251 - the contribution of these events is not considered in the analysis. In the RapidEye operational altitudes there was an increase in collision risk by approximately 50% after these events. An additional degradation of the environment remains to be added to the model. For this reason, the alert rate in the diagram has been scaled with a factor of 2 to reflect these changes in the environment.

The three quantities (number of manoeuvres, avoided risk, and ignored risk) as a function of the accepted collision probability are the key figures in the process of identifying suitable probability-based alert thresholds. Ideally, the selected reaction threshold (accepted collision probability level) avoids the clear majority of the avoidable risk in order to provide a meaningful service. It can be seen that an accepted collision probability level of 10^{-4} can provide meaningful results while saturation in the avoided risk is reached. The associated alert rate (i.e., the number of expected collision avoidance manoeuvres) is estimated to be less than 0.2 per year, per spacecraft. The associated manoeuvre rate seems practically possible from a fuel budget and mission interruption point of view. It should be stressed, however, that in practical operations other less quantifiable criteria like number and age of measurements should be taken into account.

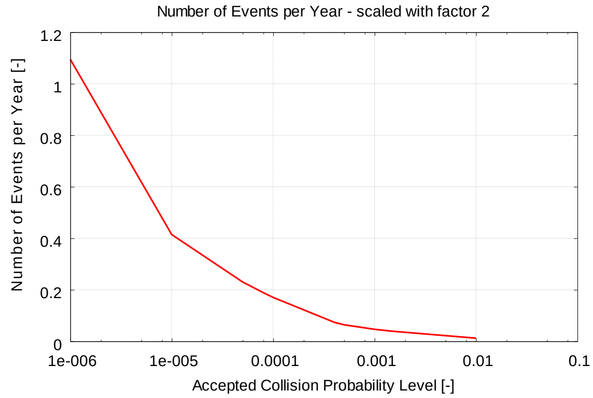

Figure 5: Manoeuvre rate as a function of the accepted collision probability level (threshold)

Operational Collision Avoidance

When JSpOC reports a close approach, a CAN message is provided via email, and usually a CSM is available for download. Based on the CSM information and the secondary object's properties, extracted from the DISCOS [10] database, the SDO computes the probability of collision using the probability algorithm described above, as well as other useful information about the close approach (geometry of the conjunction, orbital information, properties of both objects, etc.). In addition, the SDO provides the most recent orbit to JSpOC for further screening.

If RapidEye's probability threshold is reached, SDO recommends performing an avoidance manoeuvre. Different reactions will be quickly assessed in cooperation between the RapidEye operators and the SDO. Once a decision is made by RapidEye, the predicted orbit containing the manoeuvre will be sent to JSpOC for screening against the SP (Special Perturbations) catalogue. If the response is positive and confirms that the conjunction will be avoided and that no other conjunctions appear, the manoeuvre will be performed. This sequence of actions shall be finished within a maximum of two days – the actual timeframe is given by the time of the first warning (not earlier than 72 h before the conjunction) and the latest time for manoeuvre commanding which can be up to half a day before the conjunction. Typical times for the processing of a screening request are around 6 to 8 hours and in the worst case scenario, decisions must be taken without final screening results.

As previously mentioned, it is crucial in this process to provide JSpOC with an accurate orbit containing the manoeuvre. Therefore, for this interaction with JSpOC the manoeuvre is propagated numerically starting from the ephemeris obtained during the orbit determination run by SDO using the GPS data.

Previous close approaches have shown a good agreement between the results returned by JSpOC using the provided orbit and their internal SP orbit, as can be observed in Tab 2.

Table 2: Comparison of JSpOC reported distances in real CANs based on SP catalogue only vs. using the SDO determined orbit (OO)

	Distance at TCA [m]			
Method	**total**	**radial**	**along track**	**cross track**
SP vs SP	910	-94	-164	-890
OO vs SP	865	-94	-152	-847
Difference	45	0	-12	-43
SP vs SP	998	77	33	-995
OO vs SP	997	76	9	-995
Difference	1	1	24	0
SP vs SP (Update)	980	90	7	-976
Difference	-17	14	-2	19
SP vs SP	847	107	-73	838
OO vs SP	821	99	-72	812
Difference	26	8	-1	26
OO vs SP	657	-33	48	655
SP vs SP	684	-48	45	682
Difference	-27	15	3	-27

4.2 Orbit Maintenance Manoeuvre

Once the RapidEye constellation enters a phase of orbit maintenance, RapidEye plans for manoeuvres and sends the according characteristics to ESA. These data include the orbit prediction and the orbit containing the manoeuvre (converted to JSpOC format). JSpOC can then screen the orbits against their internal catalogue. The result of the screening is available to ESA who generates manoeuvre advice (continue, abort, change, wait) for RapidEye (refer to Fig. 1).

Due to the possibility of errors in the resulting altitude change, the orbit prediction quality prior to the manoeuvre execution is limited. The orbit can evolve in such a way that the JSpOC screening volume is exited quickly. For example, a manoeuvre error of 5%, equivalent to a Δv error of 1 cm/s for typical manoeuvres, leads to a difference between predicted and real orbit that grows by 2.6 km per day. This effect can be seen in Fig. 6, where the comparison between the orbit estimated before the manoeuvre and determined after the manoeuvre, plotted for 2 manoeuvre sessions, shows that the satellites exit the screening volumes quite fast. Hence, the predicted orbit that accounts for the manoeuvre is valid only for a short time.

From Fig. 7 and Fig. 8 one may also infer that JSpOC's internal orbit differs from the real orbit by more than the screening volume for a couple of days.

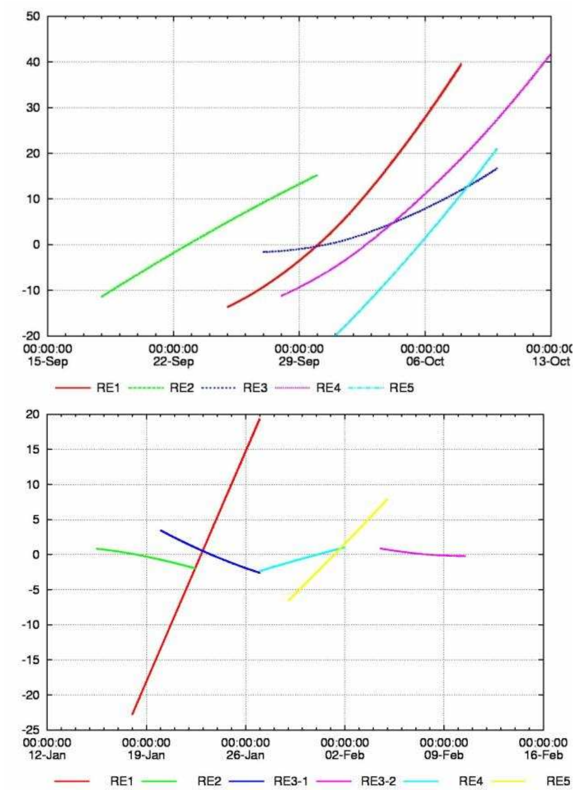

Figure 6: Orbit comparison (along-track differences in km) between the orbit pre and post manoeuvre orbits for 2 manoeuvre seasons.

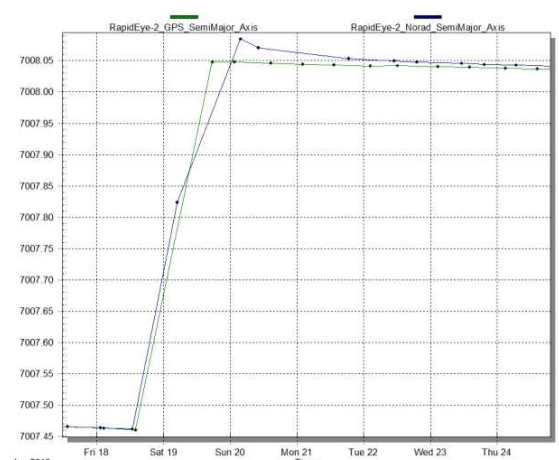

Figure 7: TLE vs. GPS for RE-2 SMA

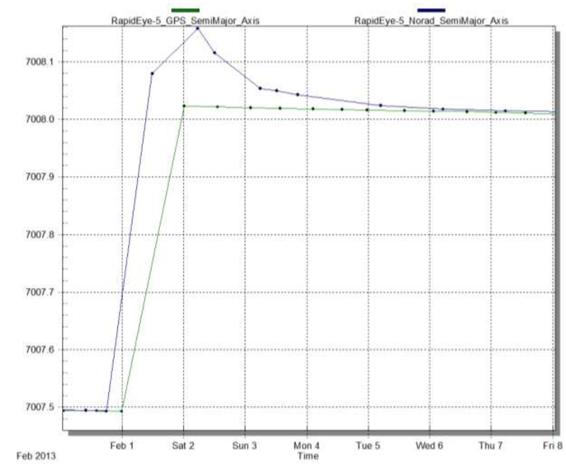

Figure 8: TLE vs. GPS for RE-5 SMA

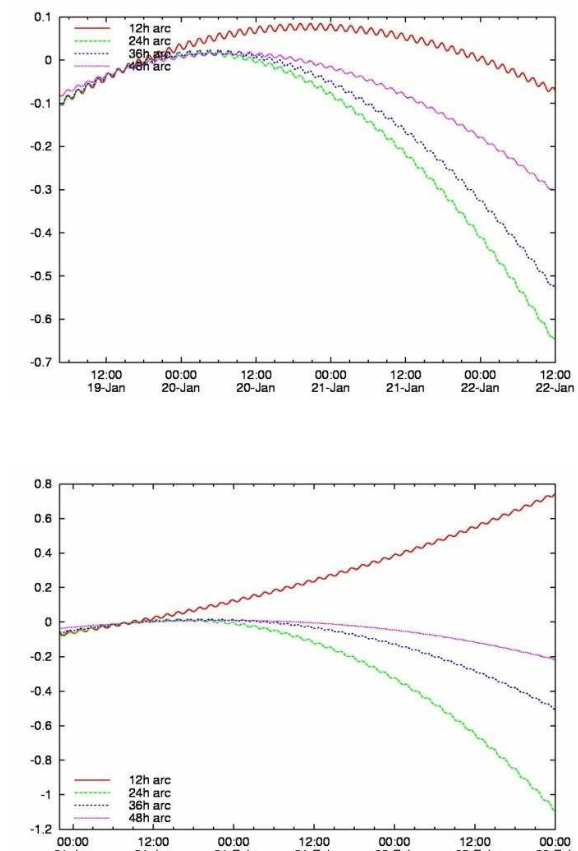

Figure 9: Orbit comparison (along-track differences in km) between orbit determination with arcs of 12, 24, 36 and 48h after a manoeuvre and OD of 3 days after the manoeuvre (top: performed on 18/19 Jan 2013 for RE-2, bottom: performed on 30 Jan 2013 for RE-4)

For this reason, as soon as possible after the manoeuvre a manual OD is necessary which takes into account only

GPS data (post-manoeuvre) and the computed orbit is then sent to JSpOC for a re-screening.

The determination of the orbit after a manoeuvre using different arc lengths is shown in Fig. 9. Using 12 hours of data already provides an orbit with an error smaller than 1 km after 3 days, which is more accurate than the orbits provided before the manoeuvre to JSpOC and within the screening volume. Extending the arc length increases the quality of the orbit determination compared to the reference one.

5 SUMMARY

A collision probability assessment for the RapidEye constellation was presented. The assessment, based on JSpOC CSM and GPS data of the five RapidEye satellites, was carried out in collaboration with the ESA SDO. Two cases are therefore considered.

In case of a close approach notification by JSpOC, the according collision probability will be calculated and compared to a probability threshold, which was pre-defined using ESA's DRAMA tool. If the threshold is exceeded, RapidEye plans an avoidance manoeuvre.

The second case occurs when RapidEye enters a phase of orbit maintenance; RapidEye plans for manoeuvres and sends the according characteristics to ESA. In both cases the predicted orbit containing the manoeuvre will be sent to JSpOC for screening against the SP (Special Perturbations) catalogue. If no (further) conjunctions are reported, RapidEye executes the manoeuvres.

This paper presented results of two orbit maintenance periods. Pre and post manoeuvre orbits were shown along with a comparison of GPS and TLE data. Further, SP catalogue based results were compared with owner/operator ephemeris data. Based on the data of recent close approaches, it was shown that there is a good accordance between the results by JSpOC and SDO. Thus, the introduced collision probability assessment serviced reached operational readiness and is part of RapidEye's daily operations.

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