Consideration of Space Debris Mitigation Requirements in the Operation of LEO Missions

Holger Krag[1], Tim Flohrer[2] and Stijn Lemmens[3]
ESA/European Space Operations Centre, Darmstadt ,Germany,64293

Space debris is an emerging factor in the operation of spacecraft in the Low Earth Orbit regime (LEO) where some altitude bands are densely populated with man-made objects. The consequences are the perturbation of operations through frequent warnings and, casually, collision avoidance manoeuvres. ESA is operating three spacecraft in sun-synchronous orbits. Conjunctions have been monitored since 2004 and the process has been considerably improved and is now significantly assisted by the warning bulletins submitted by the Joint Space Operations Center (JSpOC). The number of warnings to process and collision avoidance manoeuvres to perform is a function of the probability thresholds used in the various procedures and the object density which again depends on altitude. This paper addresses the number of warning events as a function of the operating altitude for LEO spacecraft. It demonstrates the experience made in ESA with their collision avoidance process and criteria.

In order to mitigate the exponential growth of the number of man-made objects in space, technical guidelines have been proposed that are partly design related, partly related to operations. The most relevant requirement for operations is the request to limit the orbital lifetime of the spacecraft to a period not longer than 25years after the end of mission. Successful operations of this kind that have been performed with ESA's ERS-2 in September 2011 will be presented. Further to this, analysis will be shown to which degree this good practice is maintained in a global view. For this purpose, ESA has developed a method to determine the operational state of running missions, by monitoring their manoeuvre activity with the help of the publicly available orbit data distributed by the US Strategic Command (USSTRATCOM). This paper analyses the degree of global compliance from a statistical point of view.

I. Introduction

The LEO altitude regime is the most frequently used region in space, and, today, the only region in which manned spacecraft are placed. As a consequence of this traffic, the global maximum of the spatial density of space objects is at around 800km altitude, where the influence of the atmosphere on the orbital lifetime is small. However, even in orbits used for human spaceflight, despite of the denser atmosphere, the population of space objects is steadily evolving due to new fragmentations (approx. 5 per year) that over-compensate the decay of space objects.

A. Status of the Environment

Since the largest fraction of these objects are not detectable by the available sensors, space debris models, like ESA's MASTER (Meteoroid and Space Debris Terrestrial Environment) model are used to assess and describe the spatial distribution and physical properties of space objects in Earth orbits[6].

The high impact velocities, which can reach 15km/s for most missions in LEO, are the reason for the destructive energy, even despite of the small object sizes. Most of these impacts will not cause any noticeable degradation of the spacecraft function. Micrometer-sized objects can generate pits on surfaces and optical sensors, degrading their performance. Such particles also generate charges during their impact which could influence electrical components. Particles larger than ca. 1mm could, under special circumstances, terminate the function of payloads and thus endanger the mission. The likelihood for that rises with increasing impactor diameters. A number of recorded incidents (NOAA 7 in 1997, Cosmos-539 in 2002, UARS in 2007,…) are believed to be caused by physical damage

[1], [2] Space Debris Analysist, HSO-GR, Robert-Bosch Str. 5, 64297 Darmstadt, Germany
[3] Young Graduate Trainee, HSO-GR, Robert-Bosch Str. 5, 64297 Darmstadt, Germany

from objects in space, which became obvious from a slight orbit change. The events become more obvious and more critical to the environment when the kinetic energy reaches levels that shatters the satellite into several fragments. Such catastrophic collisions are believed to occur when an energy-to-target-mass ratio (EMR) of 40J/g is exceeded. So far, there are four recorded examples in this domain (1991 between the inactive payload COSMOS-1034 and a fragment of the COSMOS-296 spacecraft, 1996 between the active French CERISE micro-satellite and a fragment of an Ariane -1 upper stage, 2005 between a Thor Burner IIA upper stage and a fragment of a CZ-4B, third stage, 2009 between the active Iridium-33 satellite and the decommissioned Cosmos-2251 satellite).

Table 1 compares the mean times between collisions of space objects with a spherical target of $1m^2$ cross-section for a few representative space missions. The numbers are a result of a collision flux analysis with MASTER-2009. We can see that sun-synchronous orbits in around 800km altitude suffer from higher exposures to debris flux.

Table 1: Mean time between collisions of objects with a spherical target of $1m^2$ cross-section for some representative orbits and selected impactor diameters

Altitude	>0.1mm	>1mm	>1cm	>10cm
400km	4,5 days	37 years	2,416 years	41.667 years
800km	0,1 days	2,9 years	133 years	2.483 years
GEO	17,3 days	556 years	128.205 years	1.488.095 years

With today's annual launch rates of 60 to 70, the amount of objects in space is steadily increasing. The rising object numbers also enhance the probability of collisions in frequently used orbital regions. Today, it is a great concern, that collisions could become the main future source for new debris objects, possibly leading the space debris environment into a chain reaction, rendering some orbital regions with an unacceptably risk for operations (an effect first postulated by NASA's Donald Kessler in 1978).

B. Countermeasures

Since the first awareness of the problem in the early 1960s, the global dimension of this problem has been understood today. A first important step to an international application of debris mitigation measures was taken by the IADC (Inter –Agency Space Debris Coordination Committee) which was founded in 1993 as a forum for technical exchange and coordination on space debris matters. In 2002, the IADC published the "IADC Space Debris Mitigation Guidelines" and presented them to the UNCOPUOUS Scientific & Technical Subcommittee. In the meantime, space agencies in Europe developed more technically specific guidelines named "European Code of Conduct" which was signed by ASI, BNSC (now UKSA), CNES, DLR and ESA in 2006 and which is building up on the work of the IADC. At ESA, these guidelines have been translated into mandatory, technical requirements, the "Requirements on Space Debris Mitigation for Agency Projects" (ESA/ADMIN/IPOL(2008)2 Annex 1)[7], which apply to ESA missions procured after April 1st , 2008. In parallel to these requirements, standardization of mitigation measures is important in order to achieve a common understanding of the required tasks leading to transparent and comparable processes. This is the task of normative international standardization bodies like ISO (Technical Committee 20 and Sub-Committee 14, e.g. ISO/WD 24113 Space Debris Mitigation) and ECSS (European Cooperation for Space Standardization).

The major driver for future debris proliferation, besides the intentional and unintentional release of objects, is the continuance of objects with large masses and sizes in orbit that could be involved in catastrophic collisions. Mitigation measures thus concentrate on the prevention of object release (explosions, mission-related objects, SRM (Solid Rocket Motor) exhaust products), the disposal of objects and active collision avoidance. As ESA's simulations show, the most effective means of stabilizing the space debris environment is the removal of mass from regions with high spatial densities. A limitation of the residence time of controlled objects in altitudes below 2000km to 25 years followed by either atmospheric re-entry or reboost to higher altitudes allows to limit the growth of object number in the densely populated LEO environment (see Figure 1)

Active collision avoidance is another means to mitigate generation of fragmentation debris. Less than 10% of the catalogued objects in LEO are under control. Accordingly, the efficiency of this measure is rather limited. However, collision avoidance is mainly performed anyway in order to preserve the health of the spacecraft.

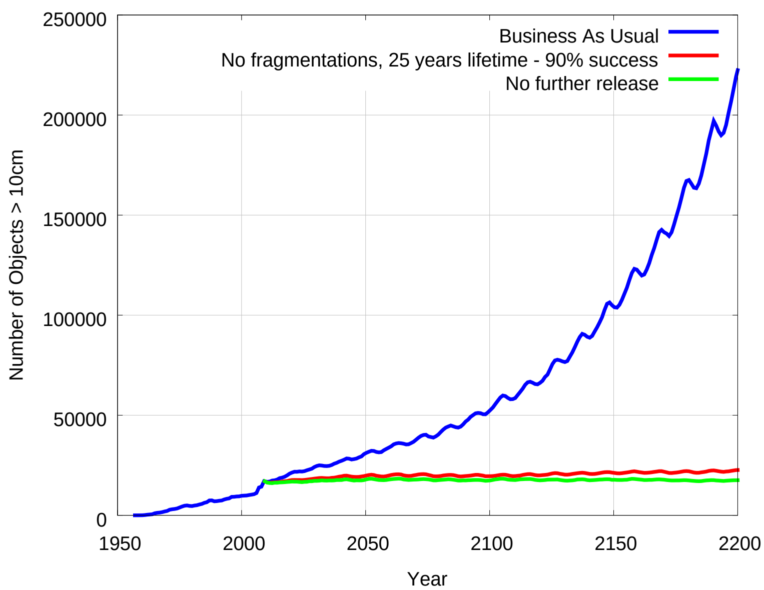


Figure 1: ESA predictions for the evolution of the number of objects> 10cm in LEO under the assumptions of a Business as Usual Scenario (no mitigation), 90% of success in implementing the 25year lifetime rule and no further release of objects

II. Collision Avoidance at ESA

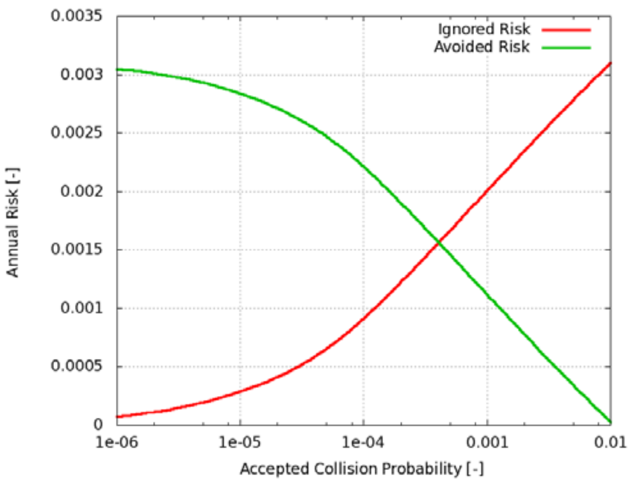
A. The Collision Avoidance Process

ESOC (the European Space Operations Centre) is providing collision avoidance services to ESA's major Earth observation mission since several years (ERS-1, ERS-2, Envisat, Cryosat-2, Cluster-II). The services and associated procedures in place are mission independent and could be applied to all kind of missions likewise. Different steps need to be performed in order to result in a decision for or against a collision avoidance manoeuvre. These steps, as explained in the following, are to a large degree implemented in the Collision Risk Assessment Software "CRASS" [1].

ESA's collision avoidance service was setup in 2004 and was based on the screening of publicly available TLE sets provided by USSTRATCOM, enriched by assessed covariance values[4]. Due to the relatively poor accuracy of TLEs, many alarms were raised. European independent tracking capabilites (such as the FHR TIRA radar) have been tasked to track the chaser object. With the subsequent orbit determination performed by ESA, the accuracy of the orbit information could be improved by a factor of 10 or more. In most cases, the event turned out to be a false alert.

Today, the collision avoidance process fully relies on the so-called Conjunction Summary Messages (CSM), that are published to operators by JSpOC (Joint Space Operations Centre) since 2010. The CSMs report on conjunctions that have been defined by JSpOC based on their high precision SP (Special Perturbation) data. This data encompasses orbit information for all objects observed by the USSTRATCOM Space Surveillance Network and thus a much larger number compared to what is published in the form of TLEs.

Another advantage is the accuracy of the orbit information. Rough estimates suggest that the covariance associated with the SP data is on the order of up to 50 times smaller than that associated with TLEs for orbits in 800km altitude. High accuracy implies more reliable conjunction predictions, while high collision risks do only occur for critical cases. In turn, this means that the number of false alarms goes back dramatically when compared to conjunction assessments with TLE. Figure 2 compares the avoided risk (i.e. risk accumulated from conjunctions that had risks above the reaction threshold) to the ignored risk (risk accumulated from conjunctions that had risks below the reaction theshold) as a function of the collision risk threshold.This exercise is repeated for typical covariance levels of CSMs.



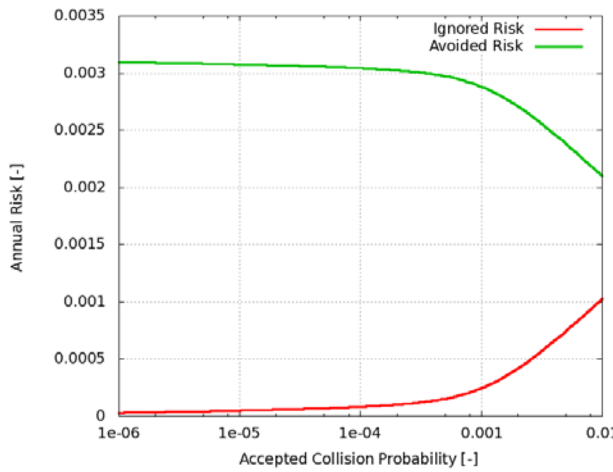


Figure 2: Ignored and avoided risk for collision avoidance procedures based on collision probability levels, for estimated orbit covariances for typical TLE and CSM

We can observe that for the threshold levels for the accepted collision probability, the use of CSMs allows for more efficient risk avoidance, which is a direct consequence of a more reliable identification of critical conjunctions through the improved accuracy. As a side effect also the absolute number of alerts above the threshold is significantly reduced through the CSMs.

The CSMs also contain accompanying information on the orbit determintion process and covariance matrices for both objects at the conjunction epoch. From this, the collision probability can be computed. The same software as for the previous TLE screening, CRASS, can be re-used for this purpose. This software makes use of formulations provided by Alfriend and Akella[2]. It is assumed that the position uncertainties of both, target and chaser, can be described by separate and uncorrelated Gaussian distributions. Further, the problem is simplified to a linear one, i.e. orbit curvatures and changes in the velocities are ignored.

The two error covariance matrices are combined into a common covariance matrix by simple addition of the two matrices. The 1σ position uncertainties expressed through the combined covariance span a three-dimensional error ellipsoid. In parallel, the combined target and chaser collision cross section is determined. Both objects are assumed to have a spherical cross section. A collision can only occur if these two spheres intersect[8].

In order to simplify the computation of the probability for this case (i.e. the collision probability), this three-dimensional problem is reduced to a two-dimensional one through projection of the conjunction geometry and uncertainties onto the B-plane (see Figure 3). The B-plane is perpendicular to the relative velocity $\Delta \underline{v}_{tca}$ at the time of conjunction and

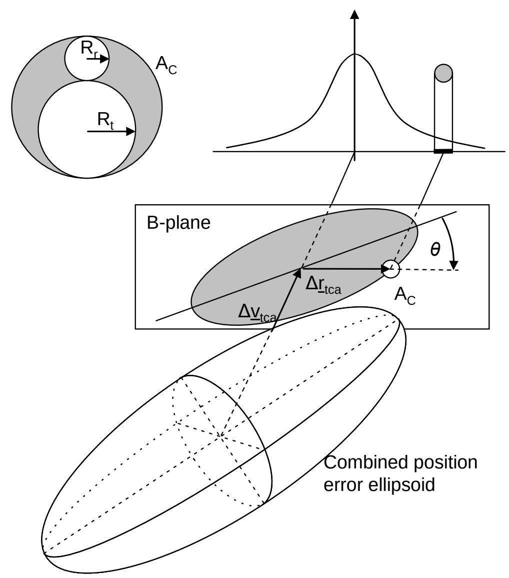


Figure 3: Mapping of the combined position uncertainty onto the B-plane, where θ is the angle between the semi major axis of the projected ellipse and the fly-by distance vector $\Delta \underline{r}_{tca}$.

contains the conjunction range vector $\Delta \underline{r}_{tca}$. The projection transforms the combined error ellipsoid into an ellipse and the spherical collision volume into circular collision area of the same radius.

The two-dimensional Gaussian probability density for the combined position error in the B-plane is then integrated over the circular collision cross-section, which is centered in the predicted fly-by location, separated by the stand-off distance from the maximum of the Gaussian, representing the most probable position error, centered at the target location[8]. Information on the object radii and other object properties (cross section, type, name and identifiers) is taken from ESA's DISCOS database[3] (see Figure 4).

The collision risk assessment software automatically compiles a bulletin for the conjunction events and distributes it by Email. The bulletin contains all relevant information on the conjunction geometry and uncertainties in order to allow space debris analysts and mission operators to make a decision for or against a collision avoidance maneuver and to design the manoeuvre in case[5].

Prior to collision avoidance or orbit maintenance manoeuvres, an ephemeris file that reflects the planned manoeuvre is supplied to JSpOC for a screening prior to the manoeuvre execution. Only when sufficient clearance for the changed orbit is confirmed, the manoeuvre is executed.

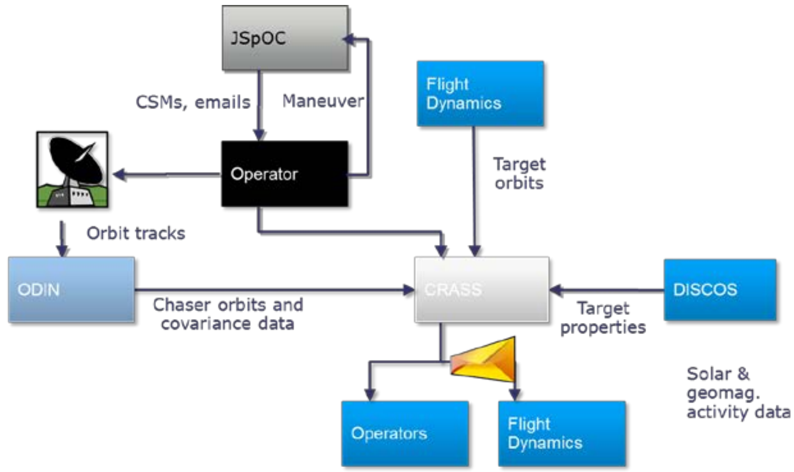


Figure 4: ESA's collision avoidance process based on CSMs[5]

The capability to ingest tracking data from European sensors is maintained in order to further improve chaser orbit information, but now it is rarely used due to the excellent quality of the data contained in CSMs.

B. Statistics

All data associated with the conjunction events have been archived for reporting reasons since the initiation of the process in 2004. The statistical exploitation of this long-term archive provides some interesting insights into the history of the environmental conditions that ESA's satellite are exposed to. While the CRASS analysis based on publicly available TLEs reported on the order of 15 events with fly-by distances of less than 300m per year for the first five years, this changed dramatically in the following years.

An anti-satellite test performed in Jan 2007 using the chinese FengYun 1C satellite (860km altitude) as a target and the collision between the defunct Cosmos-2251 and the Iridium-33 satellite in Feb 2009, triggered two step increases to the object density in the vicinity of the operating altitude of ESA's satellites (near 800km). With some delay, which is attributed to the time required by the US Space Surveillance Network to detect and correctly correlate the new fragment before they are published, the number of conjunction events rose signifantly. With the number of conjunction events also the number of radar tracking campaigns and avoidance manoeuvres increased.

The first CSMs appearing in 2010 helped to reduce the radar tasks which then became superfluous in 2011. The number of collision avoidance manoeuvres went back to a moderate level thanks to the better accuracy of the data contained in the CSMs.

Figure 5 shows the number of conjunction events in 2011 for the three satellites operating near 800km altitude. Since size is a major driver for the collision probability, most of the avoidance manoeuvres are attributed to Envisat (which has a span of 27m compared to 5m of Cryosat). 12 manoeuvres so far had to be performed by ENvisat to avoid critical conjunctions. One routine manoeuvre had to be rescheduled for the same reason. 4 of these manoeuvres had to be performed in 2011 alone. The following examples of the past two years underline the criticality of the current situation:

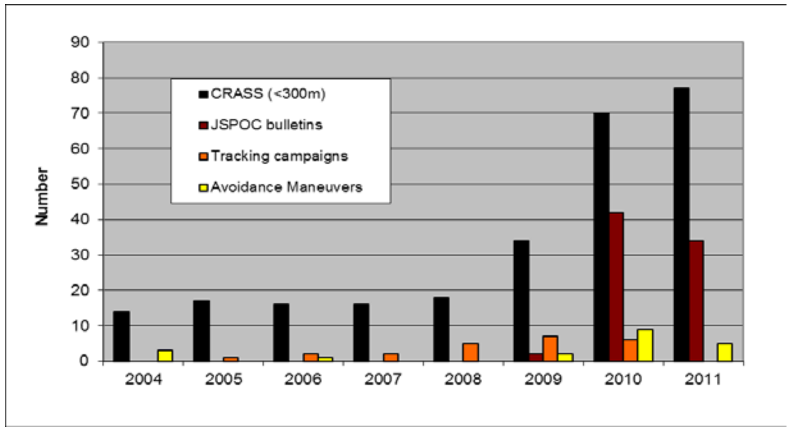


Figure 5: Statistics on Collision avoidance for ERS-2, Envisat and Cryosat (since 2010). The results labelled "CRASS" are for TLE screening. JSpOC bulletins are available since 2010. ERS-2 has been de-orbited in Sep. 2011

- On January 21st 2010, ENVISAT had a close conjunction with a CZ 2C rocket body (4t of mass) which has just been inserted one month before. Using refined orbit data (through radar tracking) the miss distance was 48m and the collision probability 1/77.
- On December 21st, 2010, ENVISAT underwent a series of three conjunction vents with a fragment of the collided Iridium-33 spacecraft. The most critical of the three events had a total separation of only 47m and a collision probability of 1/49 based on CSM information.

On the basis of TLE the threshold of 1:10,000 for the collision probability is exceeded roughly 80 times per yer for all three satellites. The conjunctions reported through CSMs and based on SP data seldomly reach such values. However, once the miss distance is small, very high values can be reached. The level of 1:100 has been exceeded twice for Envisat in the past two years.

Besides the quantity, also the type of conjunction changed over the time. In 2006, conjunction events were dominated by large, intact (i.e. physically intact, in one piece, but not necessarily operational) objects. After 2008, fragments started to dominate the conjunction events. One quarter is attributed to the fragment of the chinese ASAT test alone. Due to the vicinity to the Irdium operational orbits, after 2010 about half of the conjunction events are triggered by Cosmos-2251 and Iridium-33 fragments.

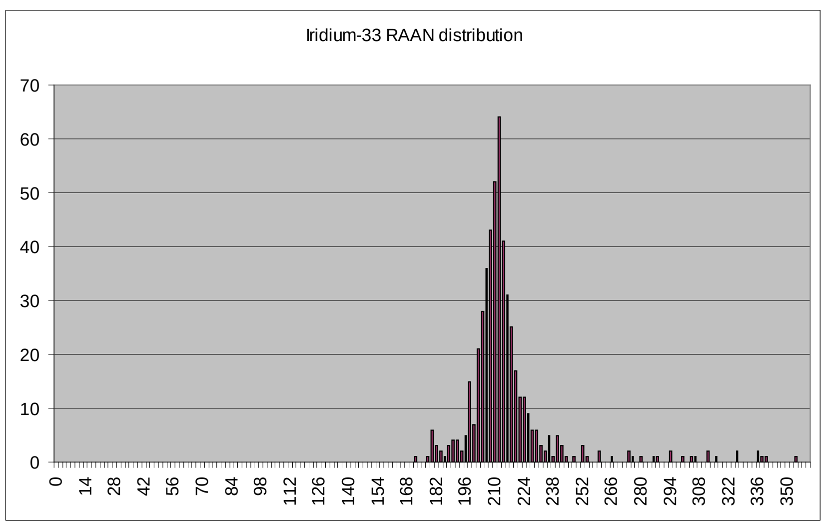


Figure 6: Dispersion of the Right Ascensions of the Ascending Node (RAAN) of the Iridium-33 fragments on Nov. 20th, 2010

The distribution of orbital nodes of the cloud of Iridium-33 fragments thereby offers a striking particularity to the conjunction assessment process. The distribution of the orbits w.r.t. this orbital parameter is far away from being uniform which is due to the very low J2-induced perturbation for the orbits that are inclined with 86deg (Figure 6). As a consequence, the orbital planes are not yet far dispersed. In periods of roughly 9 months, the orbital planes of the ESA satellites operating in the vicinity drift into a co-planar but counter-rotating geometry w.r.t. these fragment orbit. This constellation offers the highest likelihood for the occurance of conjunction events. This effect is clearly visible in the conjunction statistics and will persist over the next few years as a particular operational burden.

III. Orbital Lifetime Reduction

The active reduction of the orbital lifetime for LEO objects to at least 25 years, is a firm requirement for all ESA missions procured after April 1st 2008 (the day where ESA's mitigation requirements entered into force). All missions that have been procured before that date are encouraged to follow these requirements to the maximum possible degree.

ERS-2, launched in 1995, after 16 years of successful operations, was the first ESA object that lowered its orbit at the end of the mission in 2011 in order to comply with the rule.

ERS-2 has an on-orbit mass of 2080kg and operated in 790km altitude at 98.6deg inclination. The satellite concept is based on the re-utilisation of the Multi-mission Platform, developed within the French SPOT programme. This platform provides the major services for the satellite and payload operation, in particular attitude and orbit control, power supply, monitoring and control of payload status, telecommunications with the ground segment. At the time of launch, ERS-2 and its sister spacecraft ERS-1 were the most sophisticated Earth observation spacecraft ever developed and launched by Europe. These highly successful ESA satellites collected a wealth of valuable data on Earth's land surfaces, oceans, and polar caps and were called upon to monitor natural disasters such as severe flooding or earthquakes in remote parts of the world. Both ERS satellites were built with a core payload of two specialised radars and an infrared imaging sensor. ERS-2 included an extra instrument to monitor ozone levels in the atmosphere.

In July 2011, ERS-2 was retired and the process of deorbiting the satellite began. In 6 weekly blocks of several manoeuvre pairs, a permanent decrease of the altitude while maintaining a certain circularity of the orbit has been achieved. A circular orbit was desired due to a combination of requirements to clear the operational orbit, ground station coverage and platform constraints. Up to ca. 2m/sec delta-v per burn at beginning of de-orbiting campaign, led to a semi-major axis drop by ca. 40 km a week, based on weekly pattern of 5 manoeuvering days (see Figure 7)

After that the target altitude was maintained while fuel depletion burns alternatily increased and decreased eccentricity until tank pressure dropped below operational levels. The decommissioning of the ERS-2 satellite was successfully completed on 5 September 2011, after it reached the target circular orbit at around 570km altitude. This ensures that the re-entry on the atmosphere will be performed in less than 15 years. Although ESA's Space Debris Mitigation Requirements are only applicable for missions procured after April 1st 2008, ERS-2 fully complied with the associated rules.

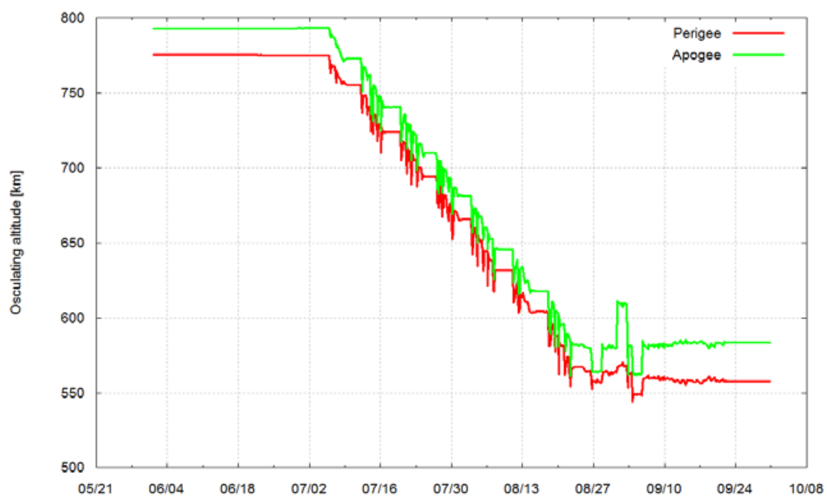


Figure 7: De-orbiting of ERS-2 during July, August and September 2011

Once placed in its final orbit, the ERS-2 has been "passivated" (the batteries were disconnected and the communication system was switched off once all the fuel was depleted). Since September 5th, 2011 13:16 UTC, no telemetry data have been acquired.

IV. Global compliance to the 25-year rule

Individual achievements are important examples, however, a significant damping of the growth rate of the environment can only be achieved if efforts are taken globally. This chapter will therefore look into the degree of compliance achieved in the world with respect to the guideline of limiting orbital lifetimes in LEO to 25 years. Such an overview on the global level of implementing lifetime control is important to reflect the acceptance of such rules in individual missions and to raise awareness by pointing out extreme cases of non-compliance. To oversee the global compliance is also important to predict the future evolution of the environment and finally to verify if additional measures need to be applied.

A. Approach

This work plans to lay the grounds for a yearly report that concentrates on LEO missions that reached end-of-life in the past year. The analysis will be based on surveillance data and lifetime estimations for the selected objects are performed independently. The major difficulty is to identify whether an object has reached its end of life and thus is eligible for the analysis of orbital lifetime compliance. A number of conventions and assumptions have to be established for this purpose:

1. Upper-stages are analysed if they are:
   - launched in 2011 (i.e. immediate EOL assumed)
   - and have perigee altitudes < 2000km at the time of reporting (could miss out some high-eccentric cases)
2. Payloads are analysed if they are:
   - Having perigee altitudes <2000km at the time of reporting and are launched after 1990
   - And:
     - More massive than 50kg (according to DISCOS[3])
     - and if they are found to be manoeuvring in 2010, but not in 2011 (see later slides)
   - Or:
     - if they are lighter than 50kg (assumed to be non-manoeuverable)
     - and launched in 2000 (i.e. ten years of operational lifetime assumed)
   - Or:
     - If they are launched in 2010 and decayed in 2010 or 2011

This approach currently misses payloads > 50kg, launched in 2000 without manoeuvre capability. For payloads a manoeuvre detection mechanism will have to be implemented in order to determine the end of manoeuverability (assumed to correspond to the end of operational life) and in order to detect de-orbiting attempts.

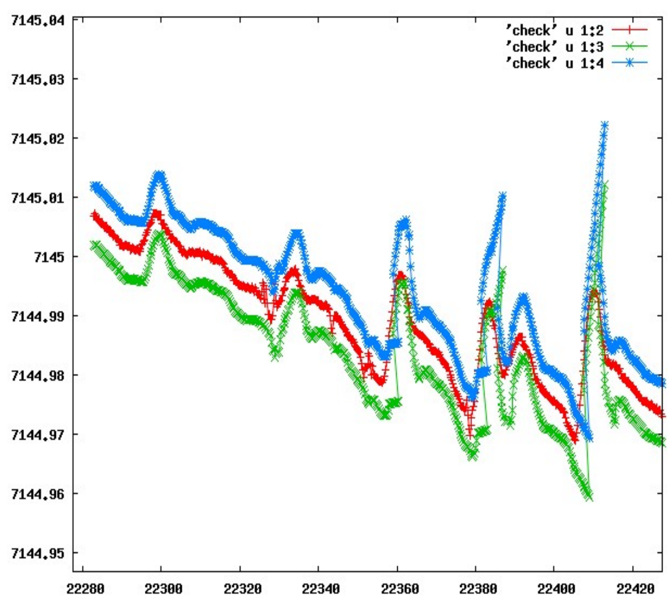


Figure 8: History of the semi-major axis [km] of Envisat between January 1st and April 1st (in modified Julian days) (in red), upper (blue) and lower (green) boundary of the moving window

The algorithm used to detect maneuvers in TLE derived time-series is essentially based on the moving window approach. The time and orbital-parameter dimensions of the window are allowed to vary automatically while processing the time-series, which makes this approach independent of the orbital-parameters selected for the detection of maneuvers and reduces the fine-tuning effort required from an operator. The dimensions of the moving window are calculated directly from the time-series by techniques from robust statistics and harmonic regression.

It has to be noted that the detection performance of the algorithm is a function of the altitude regime and the type of manoeuvre. Along-track manoeuvers (ie. Typical orbit maintenance manoeuvres), in high altitudes are the most simple case for detections and manoeuvres of a few mm/s can be identified. Figure 8 gives an example for the semi-major axis of Envisat between 1/1/11 and 1/4/11 (in red). The blue and green curves are the boundaries of the moving window. As some maneuvers are of the same order of magnitude as the expected noise level of the series, the algorithm will ignore them. Three larger maneuvers, with a difference of about 10 meters in semi major axis, are correctly identified. Accordingly, manual checks are required.

The next step, after identifying the end of mission life, is to determine remaining orbital lifetime. For this, the ballistic coefficient is fit to the orbit information using a propagator (see Figure 9). With the obtained ballistic coefficient the initial lifetime estimate is performed by straight forward application of King Hele`s formulations[9]. Based on this initial estimate, a refined analysis is performed with different fidelity (and computing power) according to the outcome. If the initial estimate leads to lifetimes of less than 100 years, King Hele's formulations are applied iteratively. Semi-analytical propagation is applied if the initial estimate results into less than 1 year.

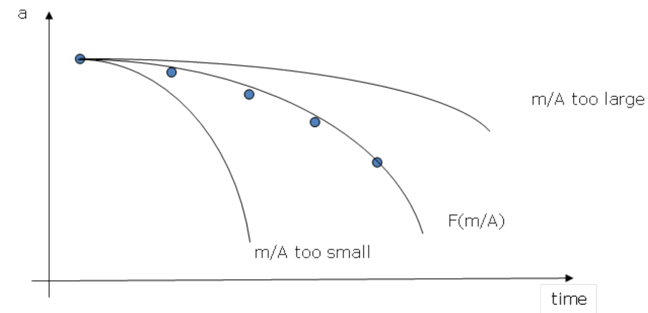


Figure 9: Iteration to fit a mass/area ratio into a history of orbital data

B. Results

The results shall be analysed first from the perspective of upper-stages in a statistical way. A generous condition has been applied to separate between compliant and non-compliant cases. 53 upper-stages have been injected into LEO-crossing orbits in 2011. 42 comply with the 25year rule and 11 don't. 26 of them already decayed within a year. Figure 10 compares the share of initial orbit types for compliant and non-compliant cases. Obviously, there is a similar degree of compliance between the major two orbit types LEO and GTO. The accumulated mass of compliant upper-stages is found to be 127,317kg compared to the mass of non-compliant upper-stages which accumulates to 23,916kg.

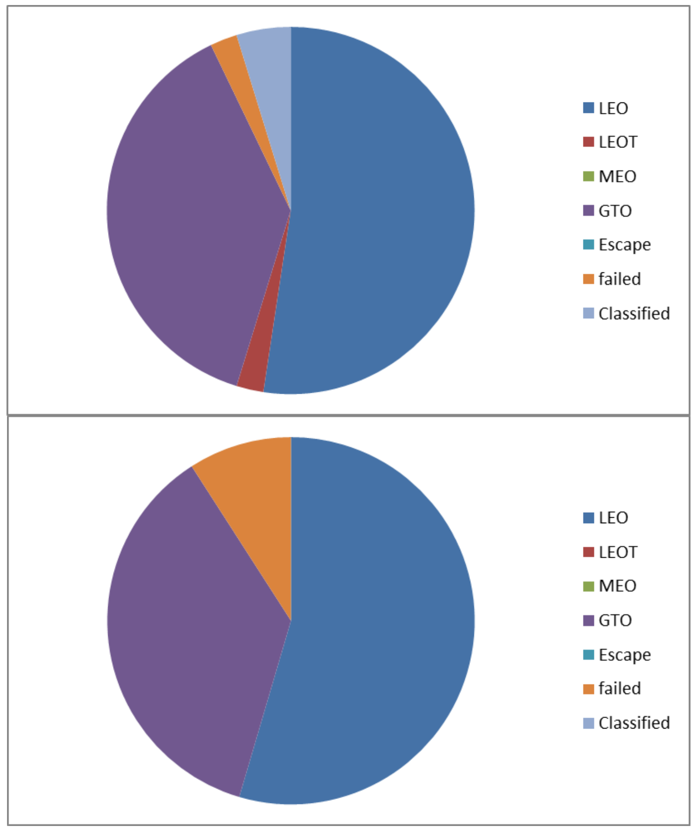


Figure 10: Share of target orbits for compliant upper-stage injections (above) and non-compliant upper-stage injections (below)

On the side of the payloads, 47 LEO objects have reached their end of life in 2010/2011. Out of these 17 comply with the 25-year rule. 14 of them already decayed (out of which 11 are cubesats). For spacecraft with masses larger than 50kg, still being in orbit today and altitudes below 1300km (de-orbit expected), only 1 out of 9 objects complies (see Figure 11). Accordingly, the performance in this critical altitude regime is poor.

For spacecraft with mass below 50kg, 11 Microsats that reached end-of-life are still in orbit. Out of these, only 2 comply with the 25 year rule. As can be depicted from Figure 11 all these spacecraft, despite not having any manoeuvre capability, have been launched into orbit altitudes that do not allow for a natural re-entry within 25 years

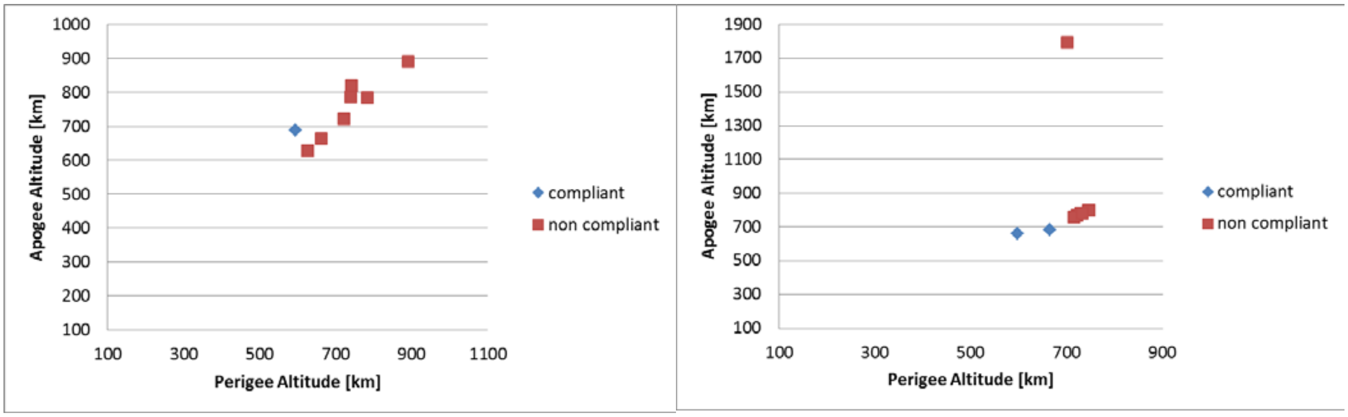


Figure 11: Apogee and perigee altitudes of compliant and non-compliant payloads in orbit. Payloads > 50kg and altitudes below 1300km (left), payloads < 50kg and all altitude (right)

V. Conclusions

The current space debris environment has its highest density between 800 and 1000km. Collision avoidance is applied at ESA for all ESA operated satellites in this regime. Recent major events have lead to an increased risk and intensified action in the area of collision avoidance. Current estimations predict a considerable growth in the population if the countermeasures proposed by the IADC are not consistently applied. A particular relevance is associated with the rule to clear the LEO region within 25 years. Following this rule, ESA has successfully de-orbited ERS-2 after 16 years of operational life. However, a global application of this rule is required in order to preserve the environment. A method has been setup to analyse the degree of compliance achieved in this field per year. It has been found that upper stages tend to comply better than payloads. Here, GTO and SSO type of orbits seem to suffer equally from non-compliances. For payloads, the performance in critical regions [800km-1000km] is poor. On the order of 40t of mass annually remain in space longer than "allowed". The degree of compliance has to be improved considerably, or additional measures (e.g. active debris removal) need to be taken into consideration.

References

Conference Papers

[1] Alarcon J.-R. "Development of a Collision Risk Assessment Tool", Final report, ESA contract 14801/00/D/HK, GMV S.A., 2002

[2] Alfriend K., Akella M., Lee D., Frisbee J., Foster J. "Probability of Collision Error Analysis" Space Debris, no.1:21-35, 1999

[3] Hernandez de la Torre C., F. P. Caballero, N. Sanchez Ortiz, H. Sdunnus, H. Klinkrad, "DISCOS Database and Web Interface, Proceedings of the Third European Conference on Space Debris, ESOC, Darmstadt, ESA SP-473, 19-21 March 2001.

[4] Krag H., H. Klinkrad H., Alarcón-Rodríguez J. R. "Assessment of Orbit Uncertainties for Collision Risk Predictions at ESA", Proceeding of the 2nd IAASS conference, Chicago, USA, 2007, SP-645

[5] Flohrer, T., H. Klinkrad, H. Krag, B. Bastida Virgili, K. Merz, Operational Collision Avoidance for LEO Satellites at ESA, In: Proceedings of the 28th International Symposium on Space Technology and Science (ISTS), Japan, June 5-12, 2011,

Other

[6] Flegel S. "Maintenance of the MASTER Model", Final Report ESA contract 21705/08/D/HK, version 1.1, June 7th 2011

[7] ESA "Requirements on Space Debris Mitigation for ESA projects", ESA/ADMIN/IPOL(2008)2, Annexes 1, Paris, 1 April 2008

Text books

[8] Klinkrad H. "Space Debris – Models and Risk Analysis", ISBN 3-540-25448-X, Springer Praxis Publishing Ltd, Chichester, UK, 2006

[9] King-Hele "Methods for Predicting Satellite Orbital Lifetime", Royal Aircraft Establishme Farnborough, Defense Technical Information Center, 1977