UPDATE OF ESA DRAMA ARES: COMPARISON OF ENVISAGED COLLISION ALERTS WITH OPERATIONAL STATISTICS AND IMPACT OF CATALOGUE ACCURACY

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ABSTRACT

An upgrade of the DRAMA (Debris Risk Assessment and Mitigation Analysis) tool is currently under development by TUBS (Technische Universität Braunschweig) and DEIMOS Space. The upgraded tool comprises six modules which address different aspects of debris mitigation. This paper deals with the ARES (Assessment of Risk Event Statistics) module, which provides an assessment of the annual collision risk and manoeuvre rate for a given satellite. For the upgrade of the ARES module, typical uncertainties associated with NORAD TLE and JSpOC CSM were determined. This paper briefly describes the ARES tool, describes the method used to determine the uncertainties, and shows examples of the tool applied to some missions.

Key words: ESA, DRAMA, ARES, TLE, CSM, covariance.

1. INTRODUCTION

The DRAMA tool was created in 2004, as a mean to enable ESA space program to assess compliance with the recommendations in European Code of Conduct for Space Debris Mitigation. This tool is currently undergoing an upgrade to enhance existing modules with additional features and to add new modules.

Upgraded DRAMA comprises six individual software applications, which have been designed and developed to address different aspects of debris mitigation:

1. Collision avoidance manoeuvres
2. Collision flux and damage statistics
3. End-of-life disposal manoeuvres
4. Re-entry survival
5. Re-entry risk analysis
6. Cross-section computation

This paper focuses on the upgrade of the ARES (Assessment of Risk Event Statistics) module. ARES is the tool which deals with the collision avoidance manoeuvres. In detail, it provides the following functionalities:

1. Global debris population flux and annual collision probabilities
2. Mean number of collision avoidance manoeuvres per year
3. Required ΔV for collision avoidance, for different avoidance strategies
4. Required propellant mass fraction for the collision avoidance manoeuvres

In order to provide the functionalities listed above, ARES requires a model debris population, and information on the covariances of the catalogued debris population.

The debris population is modelled by the ESA MASTER (Meteoroid and Space Debris Terrestrial Environment Reference) model, which provides a semi-deterministic debris population. The MASTER model can be upgraded by means of so-called "Population clouds". These upgrades can be downloaded from the MASTER website.

The knowledge of the position of potentially harmful objects is critical for defining an adequate collision avoidance strategy. The larger the position uncertainties of potentially harmful objects, the larger the number of close-approach warnings. This might lead to unnecessary avoidance manoeuvres.

The uncertainty in the position of these objects depends on (1) the size of the object, (2) the performance of the cataloguing and tracking system, (3) the type of orbit, and (4) the propagation interval up to the time of close approach event.

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1. In order to deal with the size, ARES provides different covariances for objects, depending on their size. Objects with a radar cross section smaller than 0.1 m^2 are considered small, and the rest are considered large. In general, small objects show larger uncertainties due to the smaller cross section and the fewer observations.

2. ARES provides different covariances to simulate the performances of USSTRATCOM TLEs (Two-Line Elements) based on standard SGP-4 (Simplified General Perturbations) propagation, and CSMs (Conjunction Summary Message) issued by JSpOC. Additionally, users are allowed to enter custom covariances and scaling factors for all provided covariance values.

3. The type of orbit has a definite influence on the covariances of any object. The following should be taken into account:

    - Perigee altitude: influences the decay rate and the range-dependent observability
    - Inclination: influences the line of sight observability and, together with the apogee altitude, determines the number of tracks per day.
    - Eccentricity: influences the decay rate and, together with the apogee latitude, the range-dependent observability of highly eccentric orbits

    In order to take the influence of the orbit type into account, ARES provides separate covariances for the types of orbits shown in table 1. It can be assumed that all objects within these groups have approximately the same determination uncertainties. The groups were chosen based on the groups proposed in [1] and [2], and the results from this study (detailed in [3]).

4. ARES provides catalogue covariances for different propagation intervals, ranging from one to seven days. Therefore, the impact of the propagation interval is taken into account.

Table 1. Bins which define the orbit groups used in ARES covariance tables

Nr.	Ecc.	Inc. ($\circ$)	Perigee alt. (km)
1	< 0.1	< 30	$0 - 450$
2	$0.1 - 1$	$30 - 60$	$450 - 600$
3		$60 - 80$	$600 - 800$
4		$80 - 90$	$800 - 25000$
5			> 25000

2. ARES THEORETICAL BACKGROUND

In this section we provide an brief outline of the theoretical background of functionalities provided by the ARES tool. A thorough description of all ARES functionalities and algorithms can be found in [2] .

2.1. Collision probability

ARES provides the user with the annual collision probability. This is computed from the population flux provided by the MASTER-2009 model, by means of adding the contributions of all population groups by means of the formula:

$$ACP = \sum_{j=1}^{n} F_j \cdot \pi \cdot (R_{sc} + r_j)^2 \quad (1)$$

where F_j is the annual flux provided by MASTER, corresponding to the current population group R_{sc} is the spacecraft radius and r_j is the size of the corresponding debris element. From the whole population flux provided by MASTER, only a fraction will be trackable. If F_d is the flux due to detectable objects only, the annual collision probability due to trackable objects is:

$$ACP_d = \sum_{j=1}^{n} F_{d,j} \cdot \pi \cdot (R_{sc} + r_j)^2 \quad (2)$$

2.2. Mean number of avoidance manoeuvres and risk reduction

The most common way of computing the collision probability for a given encounter makes use of the density distribution of the so-called miss-vector (see references [9], [10], [11], [12] and [13]). This distribution can be reduced to a two-dimensional problem in the B-plane (plane which is perpendicular to the relative velocity of the objects involved in the encounter).

$$P = \frac{1}{2\pi\sqrt{det(C)}} \int_{-R}^{R} \int_{-\sqrt{R^2-x^2}}^{\sqrt{R^2-x^2}} e^{-\frac{1}{2}\delta\vec{r}^T C^{-1} \delta\vec{r}} \, dydx \quad (3)$$

where R is the sum of the radii of the two objects involved in the encounter (both objects are assumed to be spherical), $\vec{\delta r}$ is the vector between a point in the B-plane and the point where the encounter is predicted, and C is the covariance matrix, sum of the covariances of target and chaser objects.

Given an encounter, an avoidance manoeuvre would be performed if the collision probability computed from equation 3 is larger than the Accepted Collision Probability Level (ACPL), that is, the collision risk taken by the spacecraft operator.

ARES provides its results by means of a non-deterministic formulation, based on the method outlined above. As the debris population is provided as an annual flux, it is necessary to define a mean encounter event. To to this, the population flux returned by ARES is divided into bins, depending on their impact elevation and azimuth. For each of these bins, a mean event geometry can be computed. Once the mean event geometry is known, it is possible to use the deterministic model (equation 3) to compute the area of the B-plane which would involve a collision avoidance manoeuvre. This area comprises all the points of the B-plane with a collision probability greater or equal than the collision probability input by the user. When this manoeuvre area is known, it is possible to obtain the manoeuvre rate for all population groups, similarly to the collision probability:

$$M_A = \Delta t_{1year} \sum_j \int_{A=0}^{A_{ACPL}} F_j dA \quad (4)$$

This manoeuvre rate represents the number of manoeuvres per year required to avoid all collision events with a risk larger than the ACPL.

Rewriting equation 2 with P from equation 3:

$$ACP_d = \sum_j \left[\int_{A=0}^{A_{ACPL}} PF_j dA + \int_{A_{ACPL}}^{A_\infty} PF_j dA \right] \quad (5)$$

Where the first integral is the reduced risk, that is, the risk that can be prevented when all collision avoidance manoeuvres are performed. The second integral represents the residual risk, which is not intended to be prevented. Finally, subtracting the reduced risk from the annual collision probability due to the whole debris population (equation 1), the remaining risk is obtained. This risk is the sum of the risk due to undetectable objects (therefore, unpreventable) and the risk not intended to be reduced by the operator.

2.3. False alarm rate

Equation 4 provides the average annual collision avoidance manoeuvres at a certain ACPL. Equation 5 provides the annual collision probability (with detectable objects) as the sum of the reduced and residual risks associated with a mean collision avoidance manoeuvre. From those equations, it is possible to determine the ratio between the number of mean manoeuvres and the risk which is not reduced by then. This ratio is known as False Alarm Rate (FAR):

$$FAR = 1 - \frac{\sum_j \int_{A=0}^{A_{ACPL}} PF_j dA}{M_A} \quad (6)$$

2.4. ΔV and propellant mass fraction required for collision avoidance manoeuvres

The determination of an optimal avoidance manoeuvre depends on a series of constraints that are unknown at the time of using ARES. ARES provides, however, an estimation of the cost of the collision avoidance manoeuvres in terms of ΔV and propellant mass fraction

The ΔV computed by ARES is for a given number of manoeuvres involving a mean event. It is not possible to define the orbit altitude for such mean event (and that parameter is required to compute the required ΔV. To circumvent this issue, ARES uses the so-called orbit reference altitude. This reference altitude is defined by dividing the orbit into a number of intervals $J(e) \leq 20$ (depending on the orbit eccentricity):

$$h_{ref} = \sum_{j=1}^{J(e)} h_j \frac{\Delta T(h_j)}{T_{orb}} \quad (7)$$

The computation of the required ΔV relies on an user-entered parameter called Allowed Minimum Miss Distance (AMMD). Manoeuvres are computed so the miss distance is greater or equal than the user-entered AMMD. This parameter must be in line with the ACPL, that is, all points in the B-plane whose collision probability is greater than the selected ACPL must be at a distance smaller than the AMMD. When such situation does not happen, ARES adjusts the user-entered ACPL automatically.

ARES assumes two kinds of avoidance manoeuvres: short-term and long-term. The short term manoeuvre is a ΔV applied in a direction normal to the flight direction, at the point opposite to that where the close approach is foreseen. Long-term manoeuvres involve an along-track impulse a number of orbit periods before the close approach. Long-term manoeuvres are less demanding than short-term in terms of ΔV, and the sooner the manoeuvre is performed, the greater the ΔV savings. Both kinds of manoeuvres assume two impulses of the same module (one for changing the satellite orbit, and the other for restoring it after the close-approach).

ARES computes a short-term manoeuvre and up to 10 long-term manoeuvres (for different user-entered number of revolutions before the event). For each of the avoidance manoeuvres, the Propellant Mass Fraction (PMF) is computed as:

$$PMF_{am} = \frac{m_p}{m_0} = \left[1 - e^{\frac{-\Delta V}{I_{sp} g}} \right] \quad (8)$$

3. ARES COVARIANCE DATA

ARES provides position uncertainty information for the debris populations. Two kind of covariances are provided: based on TLE accuracy and based on JSpOC CSM accuracy. These covariances were the result of an extensive study described in [3] and [4]. In those references:

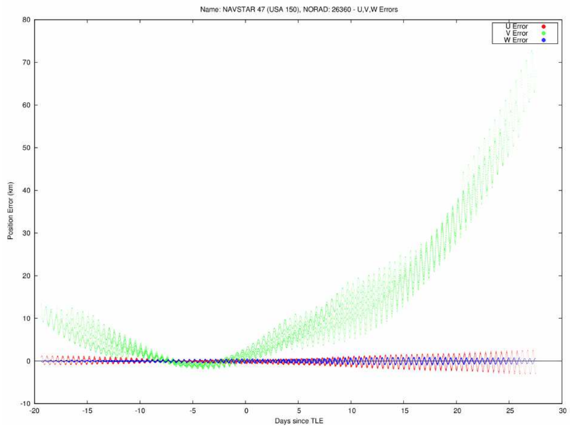

Figure 1. Example of position uncertainties, as predicted by standard SGP-4 propagation

- CSM typical uncertainties were obtained by averaging the CSM-provided covariance matrices as a function of the time to event.
- TLE typical uncertainties were obtained by comparing a large number of precise (post-processed) reference orbit arcs with the orbit arcs predicted by TLEs.

Figure 1 shows the TLE-type position uncertainties for an example satellite, as a function of the SGP-4 propagation interval. For each orbit regime, uncertainties from several satellites are averaged. The results for the most common orbit regimes are shown in figures 8, 9 and 10.

ARES users can use the pre-computed covariances for the debris population and (optionally) for the spacecraft determination. In addition to this, it is possible to define arbitrary scaling factors for the covariances, and even use a custom covariance set.

4. OPERATIONAL EXAMPLES

4.1. Envisat

Envisat is a large Earth observation satellite which was active between 2002 and 2012, and was operated by the ESA. It performed 10 collision avoidance manoeuvres between 2003 and 2010, according to its operator.

In order to compare these values with the results provided by ARES, the following assumptions are made:

- All close-approaches with a collision risk greater than $1 \cdot 10^{-4}$ involve a manoeuvre
- Not all the close-approaches were known to Envisat operators (due to the incompleteness of the cataloguing systems)

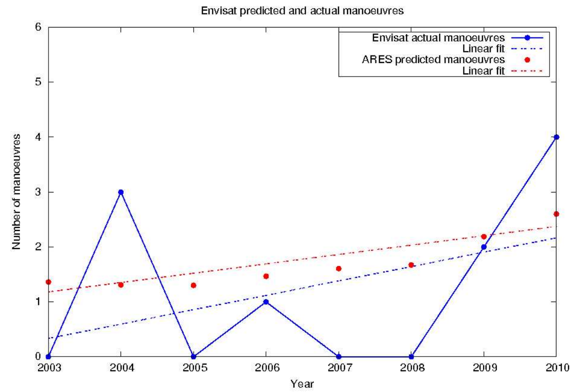

Figure 2. Collision avoidance manoeuvres performed by Envisat and foreseen by ARES

- The decision to perform a manoeuvre were taken after a careful tracking of the colliding object. Therefore, precise CSM-type covariances are selected for the debris population.
- The performance of the cataloguing systems has steadily increased during the 2003-2010 period. For the simulation described here, only objects greater than 10 cm are assumed to be catalogued. This way, the effect of the increasing performance of cataloguing systems does not influence the results.

Seven simulations (one per year) were performed. Figure 2 shows the number of manoeuvres predicted for each year (at an ACPL=$1 \cdot 10^{-4}$), and the actual manoeuvres performed by Envisat. Additionally, linear trendlines are provided.

The figure shows an steady increase of the manoeuvre numbers predicted by ARES (as a result of the increase in the debris population provided by MASTER). The number of manoeuvres predicted by ARES is in line with the actual manoeuvres.

4.2. Deimos-I

Deimos-I is an Earth observation satellite operated by Deimos Imaging. It is a small cubic satellite (approximate 1-meter side length), flying a heliosynchronous orbit. Although it flies a densely populated region, its small cross section accounts for a small number of close-approach alerts.

Table 2 lists all the CSMs provided to Deimos-I operators during 2010. All CSMs are listed in the second column. Some close approaches involve several CSMs, for different time to event values. The third column of the table shows only one CSM per collision event. When a collision event has more than one associated CSM, the CSM nearest to the event date is selected.

Table 2. CSMs concerning DEIMOS-I in 2010

Time to event (days)	CSMs	unique CSMs
0-1	2	1
1-2	2	2
2-3	2	1
4-5	1	1

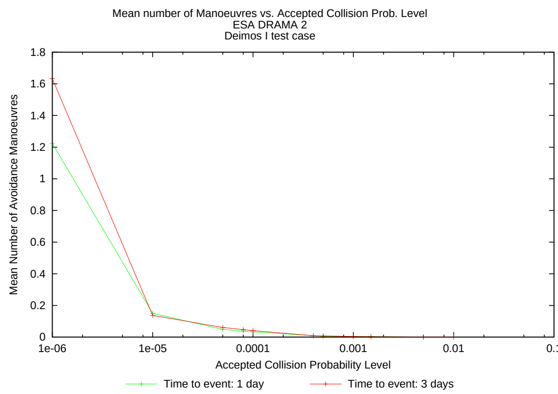

Figure 3. Average manoeuvre rates predicted by ARES for Deimos I in 2010 (1-day and 3-day time to event)

In order to compare this information with the output provided by ARES, some assumptions have to be made. In the first place, it must be borne in mind that JSpOC issues a CSM whenever a close approach with a miss distance smaller than 1 km overall, or 200 m radial, is foreseen. Due to this criteria, close approaches which fulfil the aforementioned condition cause an CSM to be released, even when the actual collision probability is very small. In the case of Deimos-I, analysis with in-house tools shows that the collision probability of all the CSMs in 2010 was well below $1 \cdot 10^{-6}$. Therefore, these CSMs resulted in no collision avoidance manoeuvres.

Two simulations for Deimos-I with CSM covariances (for satellite and debris population) were performed. The simulations have different times to event (1 days and 3 days). The time to event setting influences the uncertainties (they are bigger in the 3 day case).

The annual collision probabilities are shown in table 3. As these collision probabilities depend only on the debris population fluxes, and not on the debris covariances, they are the same for the two cases.

Table 3. Annual collision probabilities for Deimos I for the year 2010

ACP (whole population)	ACP (detectable population)
0.1582E-03	0.3863E-04

Figure 3 shows the average number of manoeuvres predicted by ARES for the year 2010. The number of manoeuvres at ACPL=$1 \cdot 10^{-4}$ is less than 0.1 per year. These results are in line with the fact that no manoeuvres were performed during that year.

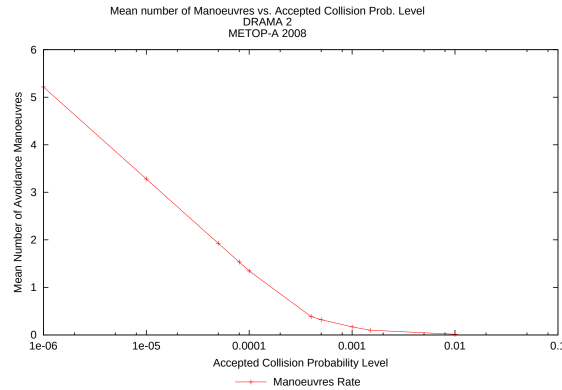

Figure 4. Collision avoidance manoeuvres foreseen for Metop-A (2008)

4.3. Metop-A

Metop-A is the first vehicle of a series of polar orbiting satellites. It was launched in 2006. Its successor (Metop-B) was launched in 2012.

Reference [15] explains that Metop-A performed 3 collision avoidance manoeuvres in 6 years. This accounts for approximately 0.5 manoeuvres per year. Additionally, it states that during the 14 months prior to the date of that document, 3 close-approaches with a risk larger than $1 \cdot 10^{-5}$ were foreseen.

A simulation for Metop-A during 2008 has been performed (2008 is chosen as a representative year of the Metop-A mission). The satellite is modelled as a sphere whose volume is approximately equal to the Volume of the Metop-A satellite. The annual collision probabilities computed by ARES are shown in table 4.

Table 4. Annual collision probabilities for Metop-A for the year 2008

ACP (whole population)	ACP (detectable population)
0.1521E-01	0.1188E-02

CSM-type covariances for the satellite and the population were used. Figure 4 shows 1.3 manoeuvres per year (at an ACPL of $1 \cdot 10^{-4}$), which is in line with the actual number of manoeuvres performed. Additionally, if all risk above $1 \cdot 10^{-5}$ were to be mitigated, about 3.25 manoeuvres would need to be performed. This number is also in line with the number of close approaches described by Metop operators.

When collision avoidance manoeuvres are performed, the average collision risk is reduced accordingly. Figure 5

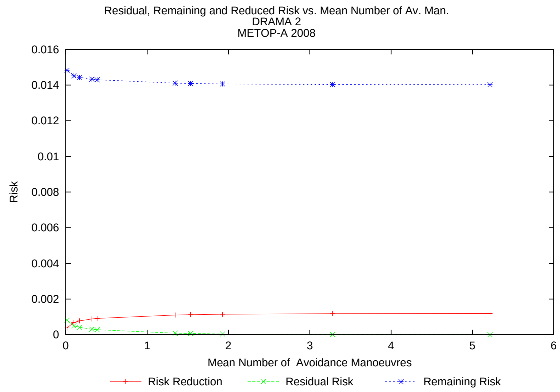

Figure 5. Risk reduction for Metop-A (2008)

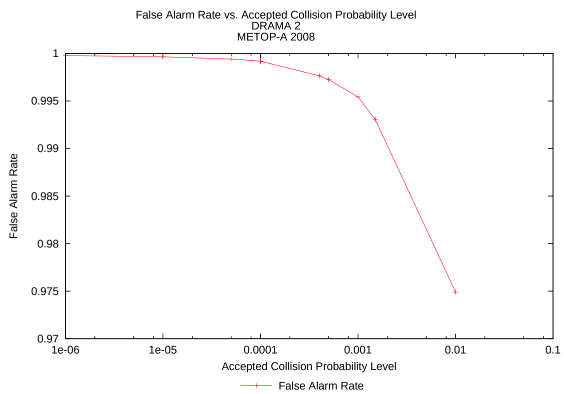

Figure 6. Risk reduction for Metop-A (2008)

shows the effect of the manoeuvres in the annual collision risk. The risk caused by undetectable objects can never be reduced. Therefore, the remaining risk (blue curve) is greater than the annual collision probability due to detectable objects. The only risk that can be reduced is the one caused by detectable objects. The red curve shows that a relatively small number of manoeuvres reduces almost all the risk caused by detectable objects. It should be noticed that the risk that cannot be reduced is caused by the smaller objects (from 1 cm to) in this case. The reduced risk is due to larger objects (which are more likely to cause a catastrophic collision).

Most of the predicted close approaches eventually turn out to be false alarms. Figure 6 shows the false alarm rate for the current example. The figure shows that even with very strict ACPL values, most of the close approaches are actually false alarms.

The annual avoidance manoeuvres shown in figure 4 require a ΔV. For this simulation, an acceptable minimum miss distance of 1.5 km has been set. Figure 7 shows the annual ΔV required for the number of collision avoidance manoeuvres determined in figure 4. Reference [16] describes the operators decision process. The decision of performing a manoeuvre usually involves more factors

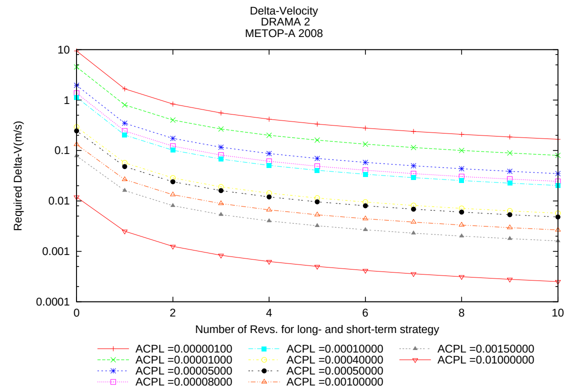

Figure 7. Required ΔV for Metop-A (2008)

than merely collision avoidance considerations. Therefore, a comparison of ARES results with actual operational values is not possible. However, some remarks can be made. The two collision avoidance manoeuvres described in [16] are 15 mm/s 6.5 orbits before the time of close approach, and 25 mm/s 7.5 orbits before the time of close approach. These numbers are similar to those displayed in figure 7 (ACPL=$1 \cdot 10^{-4}$)

4.4. Galileo

The future European Galileo constellation satellites will orbit at an altitude which is increasingly becoming more populated, as GPS, GLONASS, Beidou and Galileo satellites are launched. Although currently the risks in MEO orbits are low, this situation will change in the future.

A simulation for a typical Galileo satellite for 2020 yields an annual collision probability of 0.2261E-05 (due to the whole population) and 0.4943E-07 (due to detectable objects). This is because the debris population fluxes are several orders of magnitude smaller than more populated regions (for example, Low Earth Orbits).

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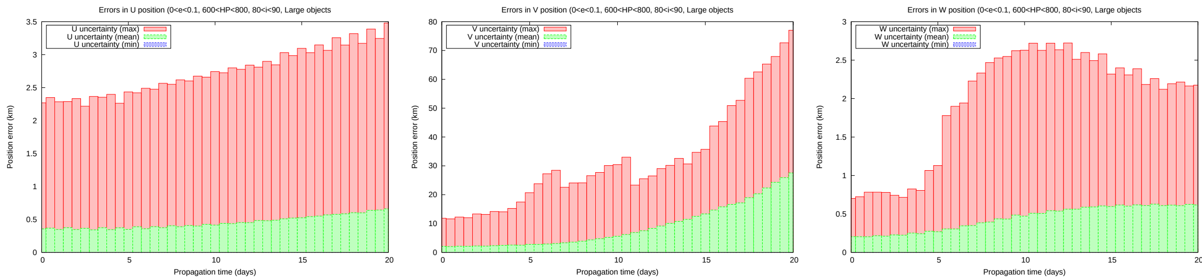

Figure 8. TLE-type uncertainties (U, V and W) included in ARES (heliosynchronous-type orbits)

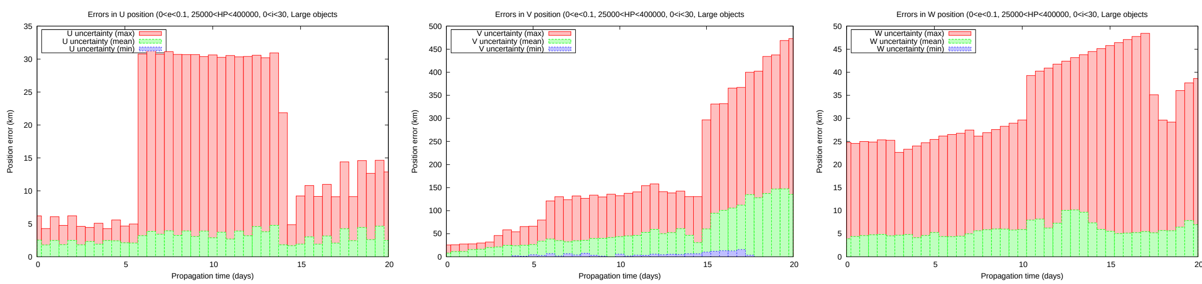

Figure 9. TLE-type uncertainties (U, V and W) included in ARES (geostationary-type orbits)

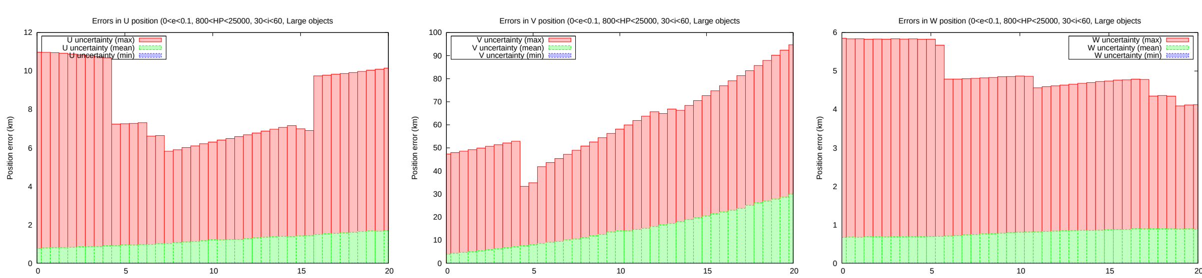

Figure 10. TLE-type uncertainties (U, V and W) included in ARES (GPS-like MEO orbits)