IMPACT OF DEBRIS MODEL UPDATES ON RISK ASSESSMENTS

Vitali Braun

IMS Space Consultancy at European Space Agency, Space Debris Office, Robert-Bosch-Str. 5, 64293 Darmstadt, Germany, Email: vitali.braun@esa.int

ABSTRACT

The Meteoroid and Space debris Terrestrial Environment Reference (MASTER) model has undergone a significant model upgrade in the recent past. One major outcome is the re-calibration (from MASTER-2009 to the new MASTER-8 model) of the Fengyun-1C breakup event from 2007 which resulted in an increase in flux of approximately 50% in the vicinity of its breakup altitude around 850 km. This clearly has an impact for any mission that is designed to operate in that altitude regime from the perspective of risk assessment.

In this paper, the impact on risk assessments due to model upgrades shall be discussed. How does the flux, provided by MASTER, change for different orbits but also for the assumed future evolution of the environment? How would the change in the MASTER model affect currently planned missions? Moreover, the Assessment of Risk Event Statistics (ARES) tool utilises MASTER's flux output to come up with an estimate of the expected collision avoidance manoeuvre rate. Besides the change in the background debris model, ARES saw another upgrade in its uncertainty database, which is now entirely based on information from Conjunction Data Messages (CDM) compared to Conjunction Summary Messages (CSM) and Two-Line Elements (TLE) in the former version. The impact on the manoeuvre rate is also highlighted in this paper.

Keywords: MASTER; DRAMA; ARES; debris flux; risk assessment; CDM.

1. INTRODUCTION

With an increasing knowledge about our space debris environment, it appears only reasonable that our ability to predict the orbital evolution and to assess risks associated with space debris would improve over time. This is partly true, but the very dynamic nature of the environment forces us to re-assess our current model assumptions with every piece of information collected. A continuous monitoring is therefore essential, which comes with all kinds of limitations mostly related to observational constraints.

The Meteoroid And Space debris Terrestrial Environment Reference (MASTER) model provides a comprehensive description of our environment for human-made debris and micrometeoroids ranging from 1µm to 100 m. It is being used to assess incoming flux in mission design and to estimate the associated risk to individual surfaces exposed to the environment (for instance, to evaluate solar array degradation) but also for the whole mission (e.g. the loss of a subsystem or the entire satellite) in the Low-Earth Orbit (LEO) up to the Geostationary Orbit (GEO) orbit region and, in MASTER-8 even for Lagrange point missions.

A rising number of debris in the very same orbital regions spacecraft are being operated comes with an increasing number of close approaches and therefore the growing demand to regularly perform collision avoidance manoeuvres (CAM) during satellite operations. The Assessment of Risk Event Statistics (ARES) software has been designed to address the need of an estimate of the annual manoeuvre rate in early mission design. This allows to account for additional propellant but also to identify requirements related to conjunction data analysis, team availability but also mission unavailability during a CAM.

Both, MASTER and ARES have undergone significant upgrades in the recent past. In this paper, the implications of the changes in the models shall be highlighted, also reflecting on how the dynamic nature of the space debris environment but also improvements in data quality and even sharing may result in completely different results when comparing with previous versions. With the new models representing the current state-of-the-art it is essential to quickly adapt them in favour of their predecessors. One example is MASTER, which is the recommended model by the environment standard of the European Cooperation for Space Standardization [ECSS-E-ST-10-04C, 2008]. The 2008 standard recommends using MASTER-2005 (which, as will be shown in this paper, is severely outdated) but a currently on-going revision of that standard entails the transition to the latest model MASTER-8.

After a short introduction to MASTER and ARES in Section 1.1 and Section 1.2, the model upgrades will be presented in Section 2. Section 3 compares latest and previous versions to give an idea how different the results can be due to environment and model changes.

Proc. 1st NEO and Debris Detection Conference, Darmstadt, Germany, 22-24 January 2019, published by the ESA Space Safety Programme Office
Ed. T. Flohrer, R. Jehn, F. Schmitz (http://neo-sst-conference.sdo.esoc.esa.int, January 2019)

Both MASTER and ARES, the latter as part of the Debris Risk Assessment and Mitigation Analysis (DRAMA) tool suite, can be downloaded for free via `https://sdup.esoc.esa.int`.

1.1. MASTER

The development of the MASTER model started in the early 1990's with the idea to approximate the real environment through the simulation of individual debris-generating events including on-orbit breakups, solid rocket motor (SRM) firings, reactor coolant releases and degradation products such as paint flakes and ejecta.

Three-dimensional directional flux information can be obtained from the model for quarterly (in the past) or yearly (for the future) population snapshots to assess impact probabilities for individual surfaces of a spacecraft and specific mission profiles.

1.2. ARES

The ARES software has been developed as part of the DRAMA tool suite since 2004 [8]. It allows to assess the annual rates of close approaches between an operational spacecraft and trackable objects in Earth orbits along with statistics on the required number of collision avoidance manoeuvres and associated Δv and propellant mass.

As an example, for any planned mission, the first step is to define how much of the known collision risk on the operational orbit the mission is going to mitigate, followed by a selection of the Accepted Collision Probability Level (ACPL) as a result of a typical risk mitigation analysis with ARES.

2. SPACE DEBRIS MODEL UPGRADES

In this section, the upgrades for the underlying models in MASTER and ARES are presented in the context of the changes observed in the space debris environment but also in view of the evolution of data collection and sharing practices on ground which changed in the past years or decades. For MASTER, the comparison is for the three models MASTER-2005, MASTER-2009 and the latest version, MASTER-8. It was considered to also show MASTER-2005, as it is still recommended by the applicable ECSS environment standard [ECSS-E-ST-10-04C, 2008].

2.1. From MASTER-1995 to MASTER-2001

The first model was released in 1995 and contained all known objects from the Two-Line Elements (TLE) catalogue as well as fragments larger than 100 μm from simulated breakup events known to have happened in the past. The small particle population was validated by examining impact features on the returned hardware from the Long Duration Exposure Facility (LDEF), which had been in orbit between 1984 and 1990.

For the next version, MASTER-97, additional 345 hours of Haystack observations were used to validate for the sub-population with object sizes too small to be part of the TLE catalogue but still large enough to be detected from ground [6].

In MASTER-99, additional source models were added: SRM slag and dust based on a record of past SRM firings; Sodium-potassium (NaK) droplets which were used as coolant in the Soviet Union's Radar Ocean Reconnaissance Satellite (RORSAT) programme and were released into space during reactor core ejection events; paint flakes resulting from surface degradation through atomic oxygen and Extreme Ultra-Violet (EUV) radiation; ejecta generated from surface impacts; Additional means for validation became available through the solar arrays of both the European Retrievable Carrier (EuReCa) platform, which was in orbit from 1992 to 1993 and the Hubble Space Telescope (HST), where the solar array was replaced during Service Mission 1 in 1993. Moreover, the lower size limit was reduced to 1 μm in this version.

MASTER-2001 was the first model to provide a continuous coverage with population files from 1960 through 2050 (before snapshots only existed for ± 10 years around the reference epoch). Moreover, with the new development of the Program for Radar and Optical Observations Forecast (PROOF), it was possible for the first time to simulate entire measurement campaigns and compare them to actual ones. The German Tracking and Imaging Radar (TIRA) has been used since 2000 to regularly obtain detections within dedicated measurement campaigns. An important change was also the transition from the former Battelle breakup models to NASA's EVOLVE 4.0 model [5].

2.2. MASTER-2005

Among many improvements in the usability of the MASTER flux browser and the entire tool chain to iteratively generate and validate population snapshots, MASTER-2005 entailed considerable improvements in all source models, for instance: the correction of the size distribution of the breakup model below 1 mm; or the selection of a bi-modal size distribution based on the Rosin-Rammler equation which has been used to describe droplet size distributions in other studies.

With another Shuttle service mission in 2003 (HST-SM3B) an additional source for the validation of the small particle environment became available. Beam-park experiments (BPE) conducted by TIRA and the 100 m radio telescope in Effelsberg, as well as passive optical surveys by ESA's Space Debris Telescope (SDT) in Tenerife contributed to the validation of the large object population via PROOF.

The event database on May 1, 2005 consisted of:

- 203 fragmentation events;
- 1076 SRM firings;
- 16 reactor core ejection events.

2.3. MASTER-2009

The upgrade to MASTER-2009 happened in a time period where the two most severe breakup events happened: the anti-satellite test in January 2007 resulting in a fragmentation of Fengyun-1C and the first collision between two intact satellites in February 2009, Cosmos-2251 and Iridium-33. As the time required to get fragments from new clouds catalogued may be on the order of months or even years, the modelling of those two events involved some uncertainty due to the limited time for the MASTER-2009 upgrade activity.

Additional improvements included:

- Consideration of different laws for payloads and rocket bodies in the breakup simulation;
- Update of the released NaK droplet mass per core ejection event to 5.3 kg, as well as mass conservation;
- New debris source: Multi-Layer Insulation (MLI) resulting from fragmentation events;
- Lower size threshold for future population was reduced down to 1 µm;

For the validation, European Incoherent Scatter Scientific Association (EISCAT) data was used for the very first time. Measurement campaigns with more than 100 days of total observation time between 2007 and 2009 also recorded overflights of the Fengyun-1C and Cosmos-Iridium clouds.

Yearly BPEs and survey campaigns by ESA's SDT between 2005 and 2007 provided additional insights.

The event database on May 1, 2009 consisted of:

- 220 fragmentation events;
- 1965 SRM firings;
- 16 reactor core ejection events.

The substantial increase in SRM firings was due to the addition of 843 retro burns of film return capsules from Soviet photo-reconnaissance satellites. A major finding in that time was an explanation of distinct impact features on LDEF due to those retro firings [11].

2.4. MASTER-8

The latest MASTER model is about to be released in Q1/2019. A new functionality often asked for by users has been added: flux uncertainties. Many more changes have been introduced, including:

- Updates in the breakup model according to [7];
- New NaK leakage model for two TOPAZ reactors. While the overall contribution is marginal, many of those NaK droplets are also part of the TLE catalogue;
- Target orbit propagation up to lunar altitudes as well as meteoroid flux evaluation for Lagrange point missions;
- The Grün model for meteoroids was added in addition to the previously existing one by Divine-Staubach.

It was also possible to re-calibrate the Fengyun-1C and Cosmos-Iridium events from the past, now that after a few years, fragment counts in the TLE catalogue seemed to have converged to a stable value. The number of catalogued fragments is an important input parameter for the calibration of the size distribution's power law. The updated numbers are given in Table 1.

Table 1: Number of fragments used for the MASTER-2009 reference epoch compared to the MASTER-8 values for the event clouds from Fengyun 1C, Cosmos 2251 and Iridium 33.

Parent object	M-2009	MASTER-8	Deviation
Fengyun 1C	1000	3430	+243 %
Cosmos 2251	1050	1668	+59 %
Iridium 33	467	628	+34 %

2.5. Estimating manoeuvre rates with ARES

The ARES software has been upgraded recently in two main aspects: firstly, the background space debris model the assessment is based on was replaced, switching from MASTER-2009 to MASTER-8. Moreover, an extensive analysis of CDMs has been performed to upgrade ARES' uncertainty tables.

The first ARES version, which was released in 2004 along with the DRAMA tool suite [8] was based on MASTER-2001 providing the debris flux, whereas uncertainties were derived from Two-Line Elements (TLE) data.

In the aftermath of the Cosmos-Iridium collision in 2009, the Joint Space Operations Center (JSpOC) started sharing more accurate conjunction data in so called Conjunction Summary Messages (CSM). Collecting those messages, which reflected the improved data quality, for a few operational ESA satellites and combining them with uncertainties derived from TLE for orbit regions that were not covered, it was possible to upgrade ARES' uncertainty tables which, in combination with a switch to the MASTER-2009 model, resulted in a second version of ARES released in 2014 [4].

Shortly after ARES 2 had been released, JSpOC introduced the Conjunction Data Message (CDM), which was a standardised format through the Consultative Committee for Space Data Systems [CCSDS 508.0-B-1, 2013]. Since then, more than 2 million CDMs have been collected by ESA's Space Debris Office for close approaches involving ESA satellites. The amount of data available through those CDMs rendered the usage of TLE-derived uncertainties needless and all orbital regions could be covered using CDM data only. In addition, with the availability of MASTER-8, the upgrade to ARES 3 has been initiated in 2016. It is foreseen for release in Q1/2019.

The theoretical background for ARES 3 has been published in [1]. A few examples from that paper are shown in the following to illustrate the changes. An updated view on how real collision avoidance statistics compare to different ARES versions is given in Section 3.2.

Figure 1 shows the estimated annual manoeuvre rate for ESA's Sentinel 2A spacecraft, which is operated at an orbit of about 790 km altitude and 98.5° inclination.

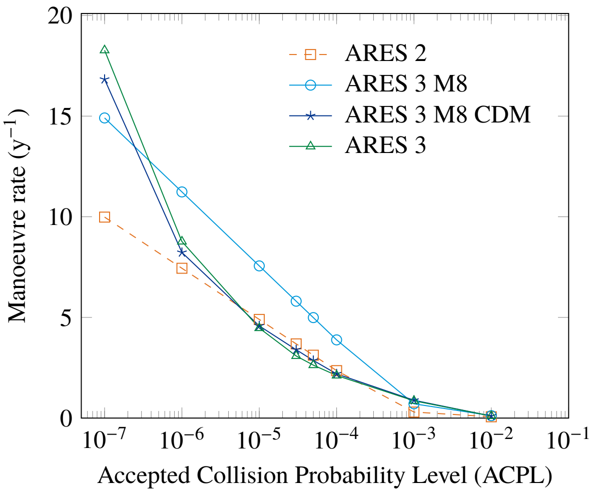


Figure 1: Annual manoeuvre rate for Sentinel 2A as a function of the ACPL evaluated at May 1, 2016 [1].

Four different graphs are shown, reflecting the step-wise transition from ARES 2 to ARES 3:

- **ARES 2** is the original ARES 2 software.
- **ARES 3 M8** shows the outcome due to a change in the background debris model, from MASTER-2009 to MASTER-8.
- **ARES 3 M8 CDM** reflects the transition from the previous step (ARES 3 M8) to an upgraded version with uncertainties coming from an extensive CDM analysis, thereby replacing the form CSM/TLE approach.
- **ARES 3** includes, as a last step, an update in the radar equation which appears to better reflect current observation network properties of the US Space Surveillance Network (SSN).

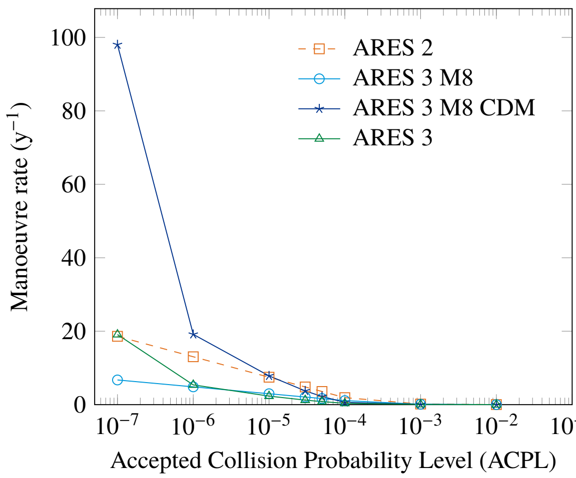


Figure 2: Annual manoeuvre rate for Swarm B as a function of the ACPL evaluated at May 1, 2016 [1].

It can be seen in Figure 1 that the manoeuvre rate with ARES 3 shows a more exponential increase towards smaller ACPL as soon as CDMs are introduced. While the manoeuvre rate in ARES 3 is smaller for higher ACPLs and, especially, around the usually selected value of 10^{-4}, it attains higher values than in previous ARES versions for ACPL smaller than $\approx 10^{-6}$.

The changes in the radar equation, where for ARES 3 a minimum diameter of 5 cm is foreseen at low altitudes, become obvious when looking at a low altitude mission. Figure 2 shows an example for Swarm-B (530 km altitude, 88 ° inclination).

While the former radar equation (graph labelled ARES 3 M8 CDM) results in a manoeuvre rate reaching up to 100 manoeuvres per year for an ACPL of about 10^{-7}, the updated radar equation with a 5 cm minimum diameter reduces that value to about 20.

3. MODEL COMPARISON

How do the new models for MASTER and ARES compare to their predecessors? This is always an important question, especially if a model undergoes an upgrade that would significantly affect the outcome for missions being currently designed or where the applicable model can still be changed.

3.1. How is MASTER-8 different from previous versions?

For the comparison of MASTER-2005, MASTER-2009 and MASTER-8, it was decided to show examples at the respective reference epochs. Figure 3 shows the three models at May 1, 2005, the reference epoch of MASTER-2005 for objects larger than 1 mm and 1 cm, respectively. It has to be noted that for MASTER-2005 this represented the state-of-the-art in 2005, whereas MASTER-2009 and MASTER-8 include corrections in the modelling but also the event database. One striking example is the peak observed for MASTER-8 in Figure 3b at around 1300 km, which is not present for the other two graphs. The reason is a new event, which happened in the past, but was added to the fragmentation database in MASTER-8 only: the nuclear powered Snapshot satellite (International designator: 1965-027A) started showing fragments in 1979 [9]. More than 150 fragments have entered the TLE catalogue since then (`space-track.org`, as of January 2019).

Another distinct feature in Figure 3b is the slight shift of the major peak below 1000 km seen for MASTER-8 with respect to MASTER-2009 and MASTER-2005. This is mainly due to a correction in the orbit propagation, where the Earth's shadow was not properly considered. This had a significant effect especially on high area-to-mass objects, resulting in a faster decay after the correction. The peak for MASTER-2009 and MASTER-2005 at around 900 km is mainly due to contributions of explosion fragments and NaK droplets. With the correction implemented in MASTER-8, the NaK droplets, which were all released in the 1980's, now have their peak around 810 km. This effect is also visible in Figure 3a, where MASTER-8 shows lower spatial density for mm-sized objects basically in the entire LEO regime.

Figure 4 shows the comparison at May 1, 2009, which is the reference epoch of MASTER-2009. This means that the spatial density from the MASTER-2005 model is a future projection, indicated by the dashed line. The most obvious difference is the deviation of MASTER-2005 from the other two models. The reason are the two breakup events of Fengyun-1C in 2007 and the Cosmos-Iridium collision in 2009. Of course, the model was not capable of predicting those events. This shows that the MASTER-2005 model was basically outdated the moment the breakup of Fengyun-1C happened. The difference between MASTER-2009 and MASTER-8 is the re-calibration of the Fengyun-1C event as discussed in Section 2.4. At the breakup altitude of about 850 km the spatial density is clearly increased for MASTER-8 with respect to MASTER-2009. For a mission operated in the vicinity of that altitude, this would translate to a flux increase of approximately 50%.

The effect of Snapshot at 1300 km looks less prominent in Figure 4, but one has to note that the scale of the ordinate axis has changed considerably.

Finally, Figure 5 shows the three models on November 1, 2016, which is the reference epoch of MASTER-8. For both, MASTER-2005 and MASTER-2009 this means a future projection according to the Business-as-usual scenario (see also [3]). Again, MASTER-2005 is clearly wrong, whereas MASTER-2009 seems to only slightly underpredict the spatial density in most altitudes (Figure 5b). MASTER-8 shows a clearly reduced number of objects larger than 1 mm (Figure 5a), especially at altitudes around 1500 km, which is due to the update in the propagation as mentioned before.

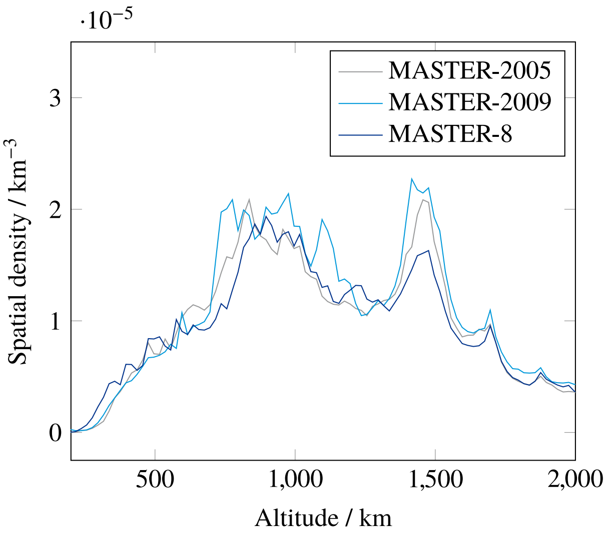
In general, model errors, including propagation, should be noticed during the validation phase. For the small object validation, returned surfaces are used. But as those few surfaces (EuReCa and HST solar arrays, LDEF) were in space only for a limited time and at very low altitudes (up to about 600 km for HST), the validation may still result in a good fit for those examples but deviate when extrapolated to different times and altiudes. One example for the validation using EuReCa's solar arrays is shown in Figure 6. MASTER-8 is in accordance with the measured impact craters, but as mentioned before, this does never guarantee that this would be the case for other time periods and orbital regions. In order to improve the situation, additional impact counts would be required. One such study, which is currently ongoing, is for the surface of the Columbus module on the International Space Station [10]. Results of that study are likely to be reflected in a future MASTER upgrade.

3.2. How do manoeuvre rates in ARES reflect real collision avoidance?

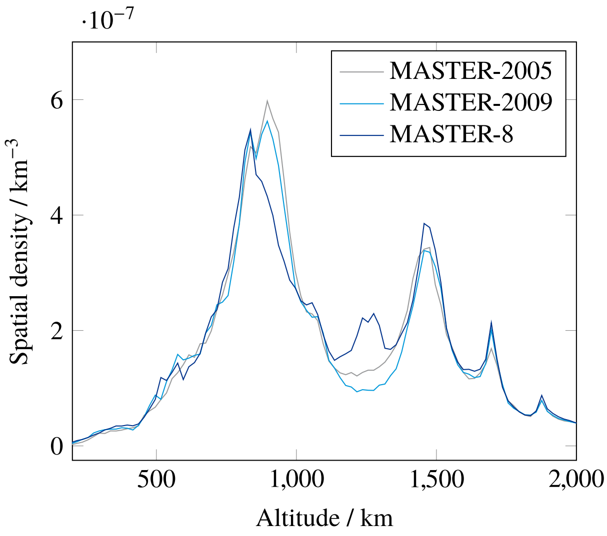
One can think of different ways of validating the results by ARES: for instance, it is possible to count real collision avoidance manoeuvres and compare them with the estimate. The collection of CDMs over some time period gives the additional opportunity to assess statistics not only for the ACPL selected for the mission but also for other ACPLs, as every CDM allows to compute a collision probability.

Figure 7 shows a histogram for Sentinel 2A counting CDMs with a lead time of one day to the time of closest approach (TCA) and being above the ACPL on the abscissa. As the manoeuvre rate given by ARES is per year, the CDM counts for Sentinel 2A have been normalised accordingly. It can be seen that there is a slight overprediction for ACPL $> 10^{-5}$ for both ARES 2 and ARES 3 with the latter still being a little closer to the value from the CDMs. For lower ACPLs, it can be clearly seen that ARES 3 follows the trend from the real encounters Sentinel 2A experienced, whereas ARES 2 is significantly underpredicting.

For the low altitude example, Swarm-B, Figure 8 indicates a clear improvement with the upgrades introduced in ARES 3. For example, ARES 2 gives an estimate of about 1.3 manoeuvres per year, whereas ARES 3 is at 0.3. For lower ACPLs, the trend is represented better by ARES 3. Coming back to the discussion on the radar

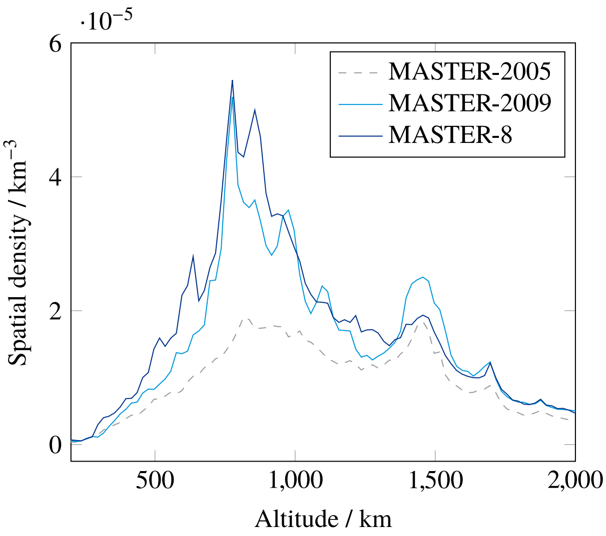


(a) *Objects ≥ 1* mm.

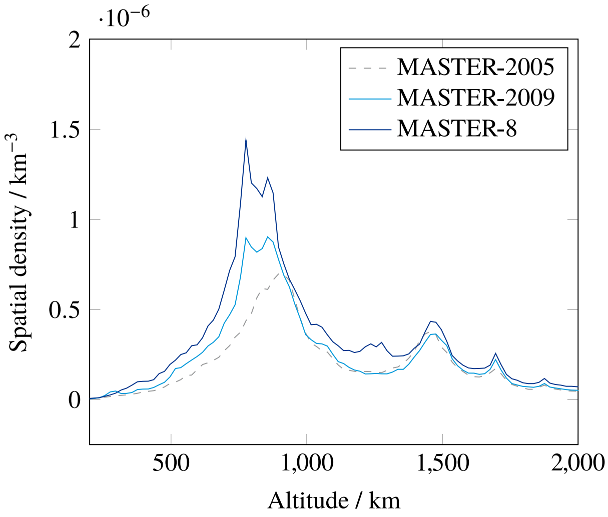


(b) *Objects ≥ 1* cm.

Figure 3: Comparison of different MASTER versions at May 1, 2005.



(a) *Objects ≥ 1* mm.



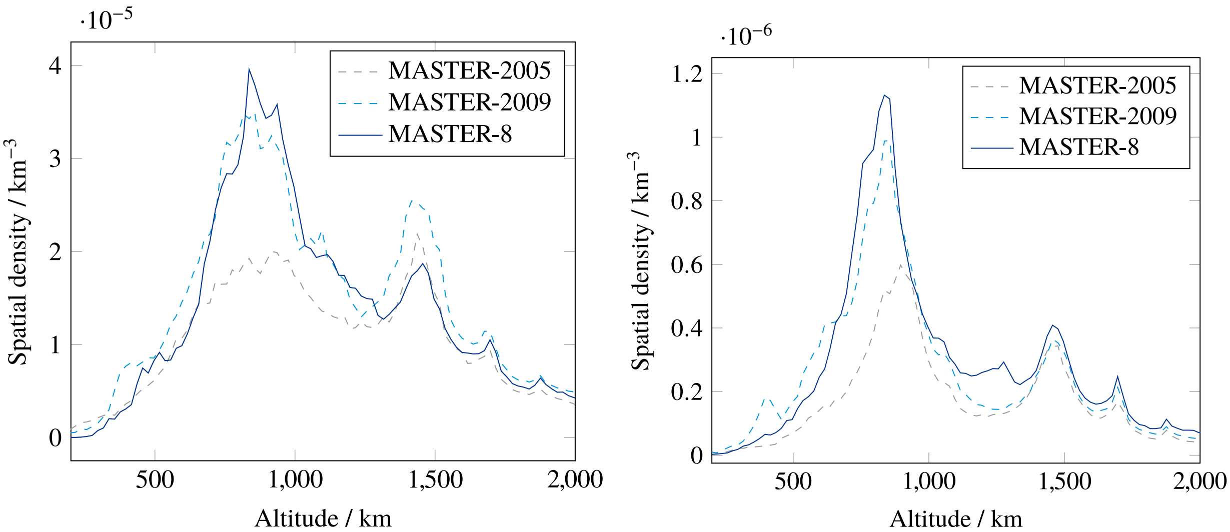
(b) *Objects ≥ 1* cm.

Figure 4: Comparison of different MASTER versions at May 1, 2009. The dashed line for MASTER-2005 indicates a BAU scenario forecast.

equation from Section 2.5, it can be seen that the actual number of close encounters at ACPL = 10^{-7} is around 14, so even lower than 20, which is the value obtained after introducing a 5cm minimum diameter cutoff.

Finally, one can compare actual collision avoidance manoeuvres performed in the past with ARES estimates. This is being done for ESA missions supported by the Space Debris Office and the current status (as of January 2019) is shown in Table 2. A rough estimate of the number of CAMs ESA performs annually is between 10 and 20, or approximately one per satellite per year, and this can be also seen in Tab. 3 since 2014. In that respect, 2018 appears to be an exceptional year with a total of 28 CAMs (SAOCOM 1A is not shown in Table 2, but it also had one CAM in 2018). The total ARES estimates on the annual manoeuvre rates are 14.6 (ARES 3) and 19.7 (ARES 2). The updated model seems to come closer to the actual statistics whereas ARES 2 tends to be on the high side, except for 2018. However, such statistics tend to provide more of a general impression rather than giving an accurate assessment on model performance. There are different reasons for this:

- In general, collision avoidance manoeuvres happen rather rarely, so the data given in Table 2 at the moment leads to low-number statistics. This is especially true, for instance, in the case of the Swarm satellites.



(a) Objects ≥ 1 mm.

(b) Objects ≥ 1 cm.

Figure 5: Comparison of different MASTER versions at Nov 1, 2016. The dashed lines for MASTER-2005 and MASTER-2009 indicate a BAU scenario forecast.

Table 2: Latest statistics on collision avoidance manoeuvres for ESA missions supported by the Space Debris Office. Comparison with manoeuvre rates obtained with ARES 2 and ARES 3 (as of Aug 31, 2018).

Mission	Year (20–)									Average	ARES 2	ARES 3
	10	11	12	13	14	15	16	17	18	# / y	# / y	# / y
Sentinel 1A					8	4	4	3	2	4.2	3.2	2.0
Sentinel 1B							3	3	5	3.7	3.3	2.0
Sentinel 2A						0	2	3	3	2.0	2.6	2.2
Sentinel 2B								1	3	2.0	2.8	2.2
Sentinel 3A							1	0	0	0.3	1.2	1.5
Sentinel 3B									4	4.0	1.3	1.5
Sentinel 5P								0	4	2.0	1.5	2.1
Cryosat 2	1	0	1	2	3	4	1	0	3	1.7	0.5	0.6
Swarm A					1	0	0	0	0	0.2	1.0	0.1
Swarm B					0	1	1	1	3	1.2	1.3	0.3
Swarm C					0	0	0	0	0	0.0	1.0	0.1

- Many of the satellites in Table 2 perform nominal orbit control manoeuvres (OCM). Some of the events counted into the statistics in Table 2 are actually modified OCMs that minimised a post-manoeuvre close approach risk of a foreseen event. Without an OCM, it could also happen that there would not be an avoidance manoeuvre after a potential orbit update prior to the event.

- There were single events which had a collision probability above the manoeuvre threshold, but it was too late to implement it as the notification came in on short notice. All ARES simulations were based on a lead time to TCA of 24 h. In several instances actually planned avoidance manoeuvres (and, potentially, already uplinked to the satellite) were cancelled after a late update on the event within those 24 h.

To give an instructive example, consider the statistics for Sentinel 2A. Table 2 gives 2 to 3 manoeuvres per year since 2016. If one compares this to Figure 7, one actually sees that the number of events with CDMs above the manoeuvre threshold (10^{-4}) is significantly below that value and corresponds to approximately one manoeuvre per year. Filtering manually the events where there were mainly operational constraints (such as advanced or postponed OCMs, miss distance-based CAM execution where covariance information was assessed to be too optimistic, already uplinked manoeuvres not cancelled after an update because of team or ground-station unavailability, etc.) leading to the CAM execution rather than the actual probability, one obtains one CAM in 2016 and 2017 and two in 2018. Overall, the average would drop to roughly one manoeuvre per year.

Another example to illustrate how difficult it is to compare ARES statistics to actually performed manoeuvres is what happened to Swarm B in 2018. Table 2 shows three

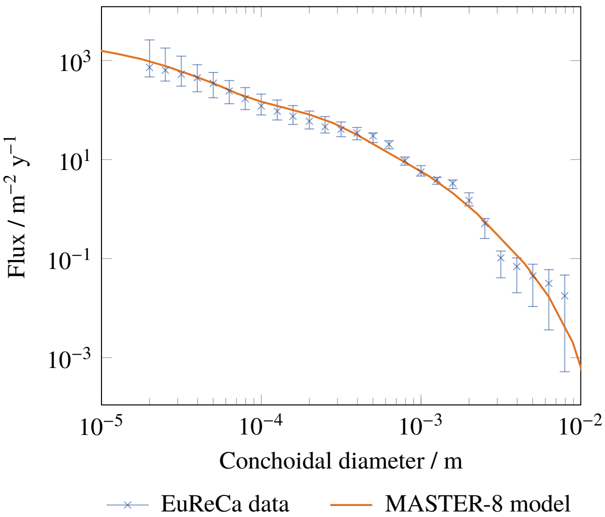


Figure 6: Comparison of simulated impacts based on the MASTER population with retrieved solar arrays from the European Retrievable Carrier (EuReCa).

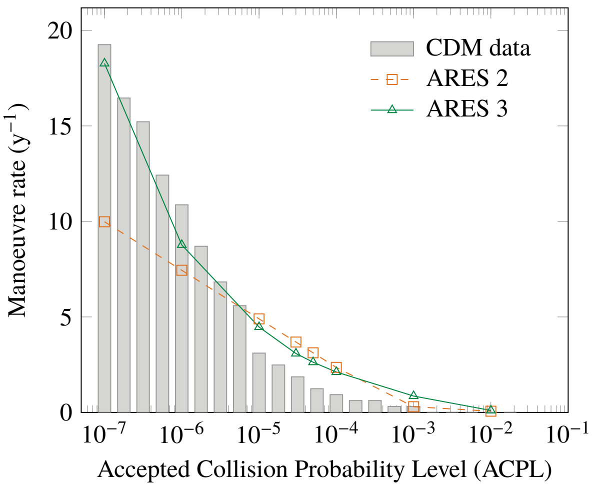


Figure 7: Comparison of ARES 2 and ARES 3 results with actual CDMs received for Sentinel 2A. Results shown for a lead time of one day to TCA [1].

CAMs although ARES 3 predicts merely 0.3 manoeuvres per year on average. The first event in April 2018 was a "nominal" one, with the collision probability being above the threshold (10^{-4}) with one day to TCA. In early October, another event began to materialise with a TCA on Sunday, October 7. A CAM was prepared and agreed on Friday, with about two days lead time. Afterwards, there was a significant orbit update for the chaser object on Saturday, but the decision taken on Friday was not revised and the CAM performed even though it was below the threshold. Coincidentally, the orbit change introduced by the CAM resulted in another event going above the threshold on the following Tuesday (October 9). This effect became obvious only one day to the event on Monday (October 8), so another CAM had to be performed by Swarm B.

The two examples above highlights the many subtleties

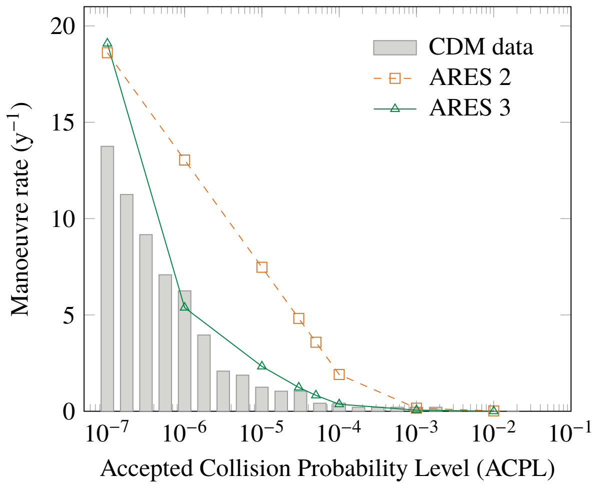


Figure 8: Comparison of ARES 2 and ARES 3 results with actual CDMs received for Swarm B. Results shown for a lead time of one day to TCA [1].

involved in real operations that are not reflected by the model and hence render a direct comparison arduous.

4. CONCLUSION

Recent model upgrades in MASTER and ARES have been presented. It became obvious that the most recent models should always be preferred over their predecessors - due to changes in the environment, but also due to changes in the way information is being collected or even distributed (as in the case with CDMs). In addition, errors in the model implementation are likely to be fixed in newer versions.

The evolution of the MASTER model shows an increasing number of sources used in the validation process. From experience, the validation part is the most demanding one in any model upgrade. For MASTER-8, significant improvements have been made towards more automation. But there are still many open tasks, including further automation, parallelisation or additional consistency checks. Such an evolution would enable a faster model update which is essential to better reflect the current state of the environment - especially after major breakup events.

The objective for ARES is to assess the number of annual CAMs. As such, it should be able to simulate the operational collision avoidance as good as possible. It was shown how many different aspects are still not adressed by the software, even though some important updates have been made with ARES 3. The future evolution may foresee taking operational constraints into account - such as post-poned OCMs or weekend unavailability of flight control teams.

REFERENCES

1. V. Braun, S. Lemmens, B. Bastida Virgili, and K. Merz. Expected Collision Avoidance Manoeuvre Rates in DRAMA-ARES based on a History of Conjunction Data Messages. In *IAC-18.A6.2.8x44771, 68th International Astronautical Congress (IAC), Bremen*, 2018.
2. European Cooperation for Space Standardization (ECSS). Space engineering - Space environment, Nov. 2008. ECSS-E-ST-10-04C.
3. S. Flegel, J. Gelhaus, and M. Möckel. Maintenance of the ESA MASTER model. *Final Report, ESA contract 21705/08/D/HK*, 2011.
4. J. Gelhaus, C. Kebschull, V. Braun, N. Sánchez-Ortiz, E. Parrilla Endrino, J. Correia de Oliveira, and R. Domínguez González. Upgrade of ESA's Space Debris Mitigation Analysis Tool Suite. *Final Report, ESA contract 4000104977/11/D/SR*, 2014.
5. N. Johnson, P. Krisko, J.-C. Liou, and P. Anz-Meador. Nasa's new breakup model of evolve 4.0. *Advances in Space Research*, 28(9):1377 – 1384, 2001.
6. H. Klinkrad, J. Bendisch, H. Sdunnus, P. Wegener, and R. Westerkamp. An Introduction to the 1997 ESA MASTER Model. In *Second European Conference on Space Debris, Darmstadt*, 1997.
7. P. Krisko. Proper Implementation of the 1998 NASA Breakup Model. *Orbital Debris Quarterly News*, 15(4), October 2011.
8. C. Martin, J. Cheese, N. Sánchez-Ortiz, K.-H. Bunte, H. Klinkrad, T. Lips, and B. Fritsche. Debris Risk Assessment and Mitigation Analysis (DRAMA) Tool. *Final Report, ESA contract 16966/02/D/HK*, 2005.
9. ODPO. Identification of a debris cloud from the nuclear powered snapshot satellite with haystack radar measurements. *Orbital Debris Quarterly News*, 10(3), July 2006.
10. R. Putzar, M. Gulde, D. Sabath, H. Fiedler, G. Drolshagen, A. Braukhane, A. Horstmann, C. Wiedemann, M. Schimmerohn, M. Schimmerohn, and F. Schäfer. Measuring impact craters on the ISS Columbus Module. In *IAC-18,A6,3,5,x43898, 68th International Astronautical Congress (IAC), Bremen*, 2018.
11. S. Stabroth, S. K. Flegel, C. Wiedemann, P. Vörsmann, H. Krag, and H. Klinkrad. Identification of Solid Rocket Motor Retro-Burns in the LDEF IDE Impact Data. In *AIAA/AAS Astrodynamics Specialist Conference, Honolulu, HI*, 2008.
12. The Consultative Committee for Space Data Systems (CCSDS). Conjunction Data Message, Recommended Standard, June 2013. CCSDS 508.0-B-1, Blue Book.