IMPLEMENTATION AND ASSESSMENT OF A NEW BLENDED WHOLE ATMOSPHERE MODEL IN REENTRY SERVICES FOR SPACE SURVEILLANCE & TRACKING OPERATIONS AS PART OF SWAMI H2020 PROJECT

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ABSTRACT

As part of the Horizon 2020 Space Weather Atmosphere Model and Indices (SWAMI) project, a new whole atmosphere model has been produced by combining and developing improved neutral atmosphere and thermosphere models. Deimos coordinates the activities of the consortium, in which CNES, the Met Office and GFZ-Potsdam are partners. Simultaneously, new geomagnetic activity indices with higher time cadence have been developed to enable better representation of thermospheric variability in the models, as well as their improved forecast.

The project aims to develop a unique new MOdel of the Whole Atmosphere model (MOWA), by extending and blending the Unified Model (UM), which is the Met Office weather and climate model, and the CNES Drag Temperature Model (DTM), which is a semi-empirical model that covers the 120-1500 km altitude range and is already the most accurate thermosphere model presently available, with relative errors in the 200-300 km altitude range between 5-10%. A user-focused operational tool for satellite applications is being developed based on this, the MOWA Climatological Model (MCM). In addition, the improved geomagnetic index Hp is being introduced in DTM for enhanced nowcast and forecast capabilities.

As a result of this project, which was presented in the previous edition of this workshop, the MCM is being developed and integrated into operational SST re-entry services at Deimos, where its performance and capacities are going to be compared against other typical models used in these environments, like JB2008 or NRLMSISE-00. This analysis will consider different values at LEO regime for altitude, eccentricity and inclination, at different epochs to cover a representative range of seasonal variations and solar activity, and different orbit lifetime estimations.

Also, a more detailed analysis will be carried out with objects whose ephemeris are published in precise format to depart from a more trusted reference. We will consider well-known cases and re-entered objects to compare the predictions using MCM and the available ephemeris.

Keywords: SST; SWAMI; DTM; MCM; DTM2020; orbit propagation.

1. INTRODUCTION

The Space Weather Atmosphere Models and Indices (SWAMI) is a H2020 project with the purpose of developing a model of the whole atmosphere by means of blending the Unified Model (UM) from the MetOffice in the UK for the atmosphere (0 to 120 km) and the Drag Temperature Model (DTM2020) from the Centre National d'Études Spatiales (CNES) in France covering the thermosphere, from 120 to 1500 km. The model, called MCM (MOWA Climatological Model), provides point-wise estimates of temperature, density and wind up to 120 km, and temperature, total and partial densities above 120 km. The drivers for the thermosphere model are the solar radio flux F10.7 and the planetary geomagnetic index Kp.

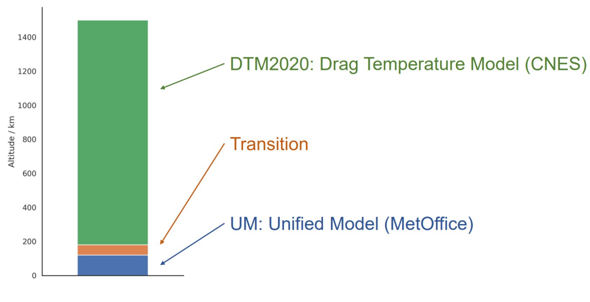

Figure 1. MCM model.

The MOdel of the Whole Atmosphere (MOWA) [2] consists on blending two existing models together: the Unified Model (UM, from Met Office) and the Drag Temperature Model (DTM, from CNES), as shown in Figure 1

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On the one hand, the UM is a climatological model used for weather predictions in the lower atmosphere, and has been expanded to cover higher altitudes: up to 150 km. On the other hand, the DTM is a thermosphere model that is valid from 120 km to 1500 km. It has been updated to the DTM2020 version using the most recent space data.

Due to the computational requirements of the UM, the MOWA Climatological Model (MCM) has been created, using data tables from the lower part of the atmosphere (which are interpolated) and the DTM2020 model for higher altitudes. Both models have been blended to a soft transition to create a single model that is efficient, smooth, and complete.

In this activity, MCM, Jacchia-Bowman 2008 (JB2008) and NRLMSISE-00 empirical atmospheric models are compared in terms of orbital propagation in the LEO region. Due to the perigee altitudes considered in this study, only the DTM2020 part of the MCM is actually being called. Because of that, the names DTM2020 and MCM are interchangeable in this paper. In Figure 2 is shown the density profile between the surface and 200 km for MCM and NRLMSISE-00 for different levels of solar activity (measured by the F10.7 solar flux). One can observe that the influence of the solar activity appears above 120 km.

Semi-empirical thermosphere models are used in the computation of the atmospheric drag force in satellite orbit determination and prediction, as well as in atmospheric studies. They predict point wise temperature and density at a given location (altitude, latitude, longitude, local solar time), solar and geomagnetic activities (in the form of space weather indices), and season. These models, NRLMSISE-00 [2], JB2008 [3] and DTM2009 [4] (now updated to DTM2020), are also the ISO (International Organization for Standardization) models for the neutral upper atmosphere [5]. The ECSS (European Cooperation for Space Standardization) also selected NRLMSISE-00 and JB2006 as their recommended neutral upper atmosphere models [6].

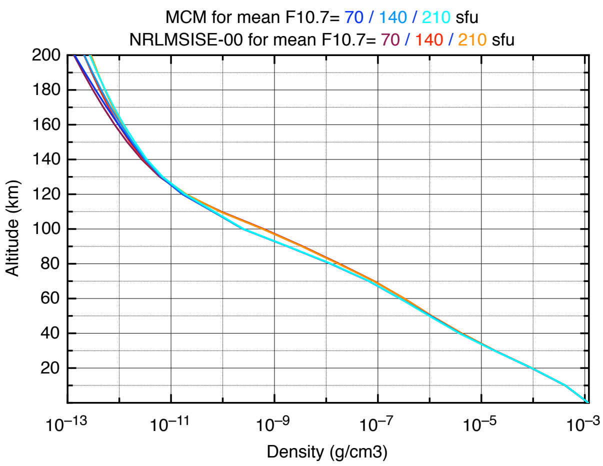

Figure 2. Density profile for MCM and NRLMSISE-00 for different solar flux values.

This work is done in two steps: firstly, a comparison done on five well-known objects with precise orbital reference data, and secondly, a large-scale comparison using Two-Line Elements (TLE) data. Two things will be considered in the comparison: how well the model compares to reference data, and how performant is the model. The latter is important in large-scale processing systems like SST operational centres, where cataloguing, re-entry and collision avoidance services are continuously propagating objects. The cheaper (computationally) it is to get the density at a certain location, more processing capabilities will the service have.

2. COMPARISON AGAINST PRECISE REFERENCE DATA

In this first step, five objects in the LEO region with well-known characteristics is carried out. Some orbital properties and physical characteristics of these objects have been collected in Table 1. These objects are all in the LEO region, with perigee altitudes between 250 and 800 km and have low eccentricity, therefore these objects are subject to atmospheric drag for their whole orbit.

For the comparison, the first state vector (epoch, position and velocity) is taken from the precise reference data and is given to the numerical propagator that includes the three atmospheric models to be compared: NRLMSISE-00, JB2008 and MCM. The numerical propagator includes in its perturbations the atmospheric drag, the solar radiation pressure, non-spherical Earth (16×16) and third-body perturbations from the Sun and the Moon.

The results of the propagation can be found in Figure 3. As expected, the differences between the numerical propagations and the reference data grow as the perigee altitude diminishes. In this sample of objects, MCM and JB2008 outperform NRLMSISE-00 for objects with perigee altitude below 500 km. Above that, the three models seem to behave similarly.

The difference with the reference data might come from the values used for mass, area or drag coefficient, meaning that they are not good enough. These values are the basis of the ballistic coefficient, which is a big component in drag computation. The other large component is the air density provided by the model itself. Since all simulations consider the same ballistic coefficient, the differences in the numerical propagations must come from the differences in the densities provided by the thermospheric models.

3. MASSIVE COMPARISON AGAINST TLE DATA

The second part of this work compared the numerical propagation using these three models with single data points based TLE data. TLE data is publicly available and is

Table 1. Characteristics of the objects used for the precise reference comparison, at 2019-09-17.

NORAD ID	Name	COSPAR	Mass [kg]	Area [m^2]	Perigee altitude [km]	Apogee altitude [km]
43476	GRACE-FO-1/2	2018-047A	600	1.89	491	499
39068	STSAT-2C	2013-003A	100	0.92	263	527
39451	Swarm-B	2013-067A	473	2.65	498	516
7646	Starlette	1975-010A	46.58	0.05	798	1109
36508	CryoSat-2	2010-013A	720	5.69	704	736

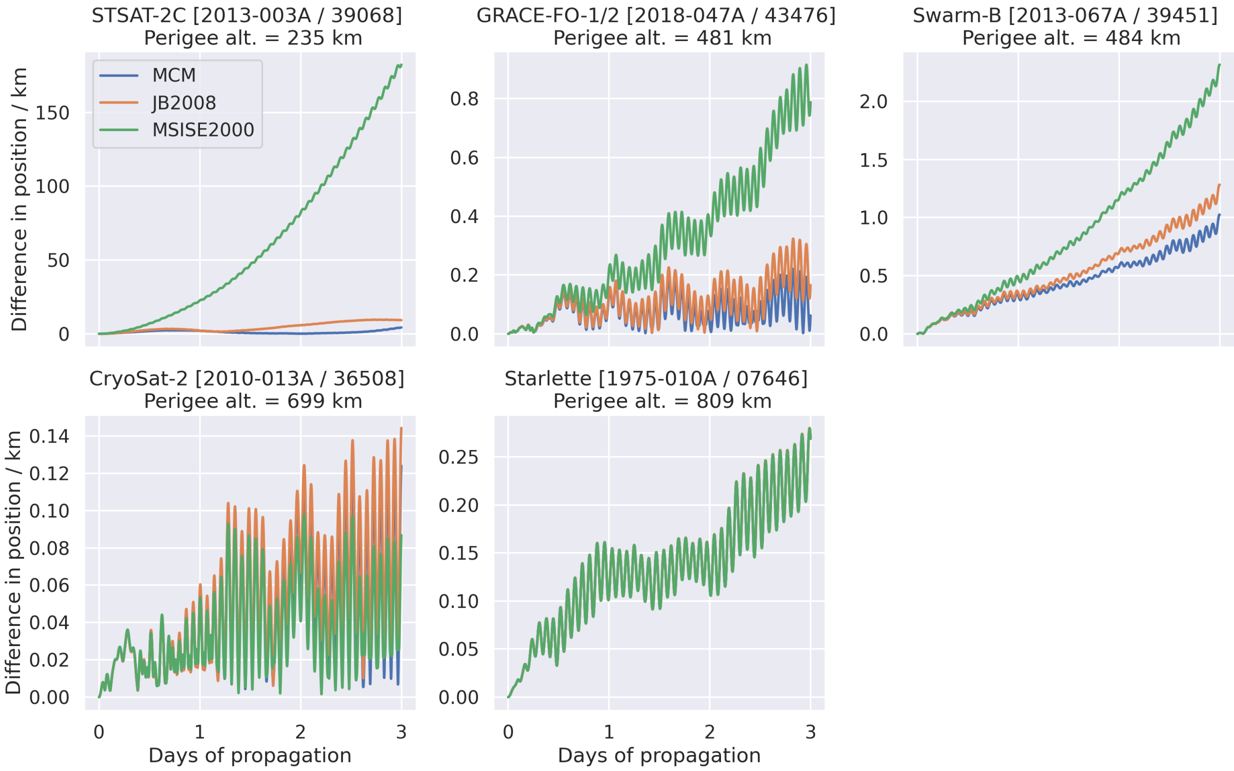

Figure 3. Comparison of the five objects using MCM, JB2008 and NRLMSISE-00 against precise reference data.

useful for analysis where using realistic orbit state vectors is interesting. It is important to consider that TLE data is not very precise and therefore it is important to account for this in the analysis [7, 8]. To find underlying patterns, a large-scale analysis is going to be made. This way, if there are important differences in terms of goodness of the model or performance, they will show.

For that, TLEs for non-manoeuvrable objects in orbit between 2016 and 2019 in the LEO region are considered, amounting to a total of 394 objects. The distribution of the selected objects in terms of inclination, apogee and perigee altitudes is shown in Figure 4. One can see that most objects have an inclination about 90 degrees and have an apogee and perigee altitudes centred about 500 km. This means that most of the selected objects have polar orbits.

Then, each TLE is transformed to a state vector in the proper reference frame and is propagated to the next available TLE. This propagation is done with the three air density models included in this comparison: MCM (DTM2020), JB2008 or NRLMSISE-00. This way, it is possible to account for the deviation that each atmospheric model might include, since two different reference data points are being used.

Also, to cover for different solar activity levels, six epochs are considered in this analysis: January 2016, October 2016, July 2017, April 2018, January 2019 and October 2019. When all of this is taken into consideration, it adds up to almost 38000 simulations.

In Figure 5 is shown the RMS of the deviation of the propagation with respect to the second TLE data point for different values of the perigee altitude. For a closer look to the perigee altitude range below 400 km, Figures 6 and 7 are also included.

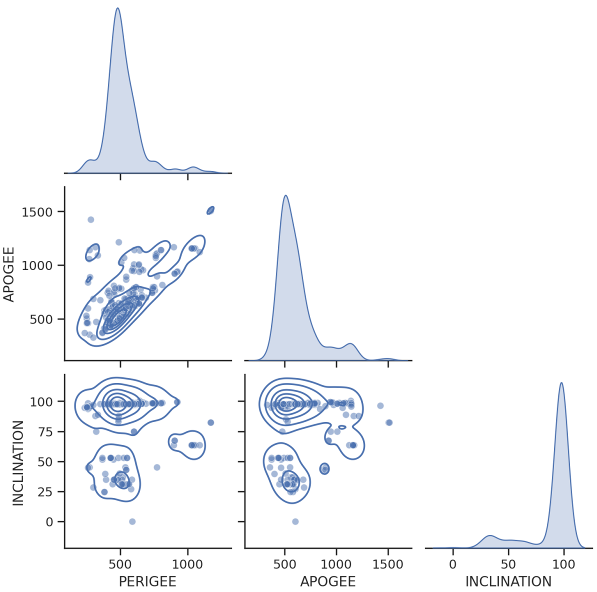

Figure 4. Distribution of the TLEs used in this study in terms of orbital elements: paired distribution and kernel density estimation for each orbital element.

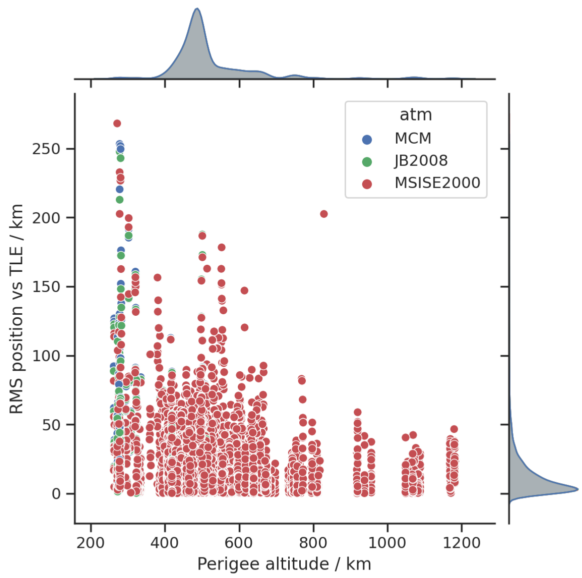

Figure 5. Distribution of the RMS in position in perigee altitude.

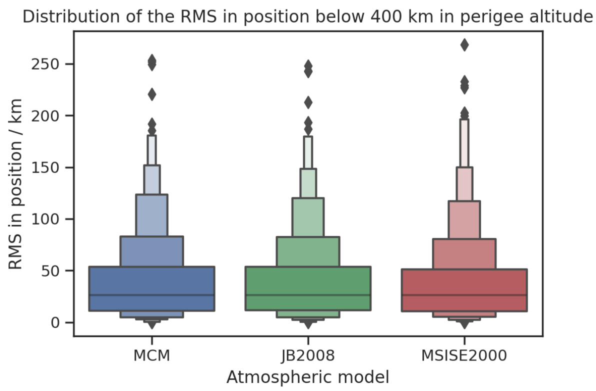

Figure 6. Distribution of the RMS in position below 400 km in perigee altitude.

This massive analysis show that the models do not behave very differently when compared to TLE data. There are no significant, clear and relevant differences in terms of the model itself. Only in Figure 6 one can appreciate that NRLMSISE-00 has a larger tail (more outliers). Even when that is considered, the three models (NRMSISE-00, JB2008 and MCM) do not show remarkable differences at this perigee altitude range.

It seems that the differences start to appear below 300–350 km, but nothing clear can be extracted from the results. Going below the perigee altitude of 250 km should be the next step in this analysis. When passing through that altitude range, the objects start to decay more rapidly and the differences should grow bigger between the models. That way, it will be possible to discriminate which model is more interesting for operational use in SST services.

Finally, in terms of performance, in Figure 8 is shown the distribution of the ratio between simulated time and computation time. This metric can be interpreted as the hours that can be simulated for every second spent in computing. As such, it is better the higher the metric is. One can see that MCM (DTM2020) and NRLMSISE-00 perform similarly and are better in terms of performance than JB2008, i.e. MCM is doing more or less equally well. When the atmospheric model is used in SST services it is important that they are as computationally cheap as possible, because that would improve the processing capabilities of the cataloguing, re-entry or collision avoidance services. This makes MCM especially interesting for SST operational centres.

4. CONCLUSIONS AND FUTURE WORK

MCM (DTM2020) seems to perform better than NRLMSISE-00 and JB2008 when compared to precise propagation data. When the comparison is done in a larger scale using TLE data (not precise), none of the three models outperform the others. A more thorough analysis should be done using precise reference data to find underlying differences that the small sample of five objects was not able to show. Also, it would be interesting to include NRLMSISE 2.0 in the comparison, an updated version of the well-known NRLMSISE-00 released in October 2020.

In terms of computing performance, in the large-scale comparison it was shown that MCM (DTM2020) and NRLMSISE-00 clearly work better than JB2008, making

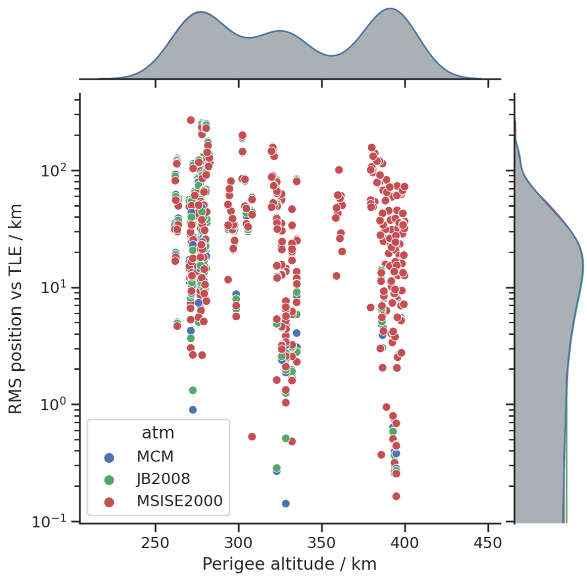

Figure 7. Distribution of the RMS in position below 400 km in perigee altitude, scatter.

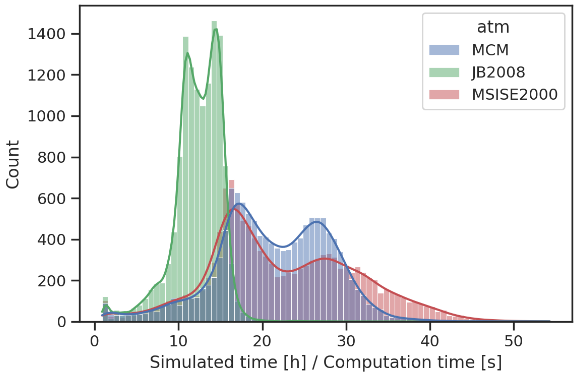

Figure 8. Distribution of the simulated time in hours per second spent computing (the greater the value, the better).

MCM a suitable candidate to substitute NRLMSISE-00 in SST operational centres. Since MCM covers the whole atmosphere, it is especially interesting in re-entry services.

About future activities, the MCM model will be publicly available very soon since the SWAMI project has recently ended. MCM will also provide a density uncertainty-related measure at all altitudes, which is again is very interesting for re-entry analyses and orbit determination processes. Wind information will also be included in the model for a certain range of altitudes thanks to the UM contribution to the model.

The final model will be also evaluated using high-precision propagation data points in lower altitudes than the ones shown in this work. Analysing objects with perigee altitudes below 200–250 km is also a next step in the evaluation of the MCM model.

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