

Space debris attitude simulation - ι OTA (In-Orbit Tumbling Analysis)

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ABSTRACT

Today, there is little knowledge on the attitude state of decommissioned intact objects in Earth orbit. Observational means have advanced in the past years, but are still limited with respect to an accurate estimate of motion vector orientations and magnitude. Especially for the preparation of Active Debris Removal (ADR) missions as planned by ESA's Clean Space initiative or contingency scenarios for ESA spacecraft like ENVISAT, such knowledge is needed.

ESA's "Debris Attitude Motion Measurements and Modelling" project (ESA Contract No. 40000112447), led by the Astronomical Institute of the University of Bern (AIUB), addresses this problem. The goal of the project is to achieve a good understanding of the attitude evolution and the considerable internal and external effects which occur. To characterize the attitude state of selected targets in LEO and GTO, multiple observation methods are combined. Optical observations are carried out by AIUB, Satellite Laser Ranging (SLR) is performed by the Space Research Institute of the Austrian Academy of Sciences (IWF) and radar measurements and signal level determination are provided by the Fraunhofer Institute for High Frequency Physics and Radar Techniques (FHR).

The In-Orbit Tumbling Analysis tool (ι OTA) is a prototype software, currently in development by Hyperschall Technologie Göttingen GmbH (HTG) within the framework of the project. ι OTA will be a highly modular software tool to perform short- (days), medium- (months) and long-term (years) propagation of the orbit and attitude motion (six degrees-of-freedom) of spacecraft in Earth orbit. The simulation takes into account all relevant acting forces and torques, including aerodynamic drag, solar radiation pressure, gravitational influences of Earth, Sun and Moon, eddy current damping, impulse and momentum transfer from space debris or micro meteoroid impact, as well as the optional definition of particular spacecraft specific influences like tank sloshing, reaction wheel behaviour, magnetic torquer activity and thruster firing.

The purpose of ι OTA is to provide high accuracy short-term simulations to support observers and potential ADR missions, as well as medium- and long-term simulations to study the significance of the particular internal and external influences on the attitude, especially damping factors and momentum transfer. The simulation will also enable the investigation of the altitude dependency of the particular external influences. ι OTA's post-processing modules will generate synthetic measurements for observers and for software validation. The validation of the software will be done by cross-calibration with observations and measurements acquired by the project partners.

1. INTRODUCTION

At altitudes between 700 and 1000 km the long-term evolution of the space debris environment is driven by catastrophic collisions involving large objects like upper stages or abandoned or decommissioned spacecraft. One

approach to reduce the risk of such collisions is the removal of these large objects from orbit through Active Debris Removal (ADR) missions as planned by ESA's Clean Space initiative. For ADR missions or contingency scenarios for spacecraft like ENVISAT detailed knowledge of the attitude state and attitude motion of the target object is needed. The accuracy of the motion vector orientation and magnitude determination is limited for the particular observation methods, like optical observations, satellite laser ranging (SLR) or radar imaging. Combining the data of multiple observation methods one can achieve a more accurate attitude state, e.g. by improving synthetic aperture radar (SAR) images using the spin axis direction and spin period determined from SLR measurements. However, the attitude prediction models currently available fail to accurately reproduce the observed behaviour for many objects.

To accurately predict the attitude evolution of a tumbling object in orbit, complex modelling of all relevant internal and external effects on the attitude and attitude motion is needed. The attitude simulation has to account for external forces and torques caused by gravitational influences of Earth, Sun and Moon, aerodynamic torques, solar radiation pressure, outgassing or leakage and impulse transfer from small object impact like micrometeoroids. Also eddy current damping and damping through internal moving parts, tank sloshing in particular, have to be included in the simulation. Eventually, the simulation results have to be cross-calibrated using different types of measurements.

Led by the Astronomical Institute of the University of Bern (AIUB), the goal of ESA's "Debris Attitude Motion Measurements and Modelling" project (ESA Contract No. 40000112447), is to achieve a good understanding of the attitude evolution of intact decommissioned objects in Earth orbit and the considerable internal and external effects which occur. Combining multiple observation methods the attitude state of selected targets in LEO and GTO is being characterized. Optical observations are carried out by AIUB, SLR measurements are performed by the Space Research Institute of the Austrian Academy of Sciences (IWF), and radar measurements and signal level determination are provided by the Fraunhofer Institute for High Frequency Physics and Radar Techniques (FHR) using their Tracking and Imaging Radar (TIRA). The six degrees of freedom (6DoF) "In-Orbit Tumbling Analysis" tool **iOTA** is being developed by Hyperschall Technologie Göttingen GmbH (HTG) within the framework of the project. In addition to the modelling of the above mentioned relevant external and internal forces and torques, iOTA will also allow to include user-defined events like non-destructive space debris impact and the behaviour of pre-defined attitude and orbit control system (AOCS) components like up/down spinning of reaction wheels, magnetic torquer activation and thruster firing.

2. SOFTWARE ARCHITECTURE DESIGN

2.1. Software requirements and features

iOTA is a standalone tool programmed in C++. One of the key features of the software is the approach of high modularity for the simulation of the relevant effects, as well as regarding the used environmental models, enabling easy updates of existing models and an easy implementation of new models released. Except for the gravitational influence of the Earth, the user will be able to choose which particular effects shall be included in the simulation. For spacecraft related simulation modules like AOCS component behaviour or tank sloshing and for space debris impact events, the user will have to specify the needed input parameters. iOTA will be able to run in two modes, a GUI driven initialization mode, where the input needed will be provided directly by the user, and a command line mode, running without direct user input after execution of the program. For the latter, the user will have to provide pre-defined configuration files for each simulation module that shall be used. This execution mode will allow to run iOTA using scripted simulation jobs, which enable a rough uncertainty estimation through Monte-Carlo variation of input parameters like the initial attitude of the object. Because the simulation is fully deterministic for the initial release of iOTA, this will be the only way of uncertainty quantification.

In order to reduce to overall computation time and depending on available hardware resources, especially number of unused CPU cores, the parallelization of the force and torque simulation modules is planned.

Another key feature of the tool is the ability to generate synthetic measurements from the simulation results. Managed by the post-processing modules, iOTA will be able to simulate light curves and SLR data and generate optical images as well as simplified radar images. It will also be able to provide the radar cross-section (RCS) under simplified

assumptions. The visualization of the simulation results and the generated synthetic measurements will be done using the standalone graphical user interface (GUI) driven visualization module.

2.2. Modular architecture design

The process hierarchy of ι OTA is shown in Fig. 1. ι OTA is highly modular with a flat hierarchy structure. The particular software modules are called by the ι OTA host process. Fig. 2 displays the decomposition of the software, including the software modules, the data flow from the model and input data (blue) to the particular modules, as well as the data flow from the simulation (yellow) and propagation (red) modules to the particular destination. The post-processing branch (green) provides the final processing and visualization of the simulation results.

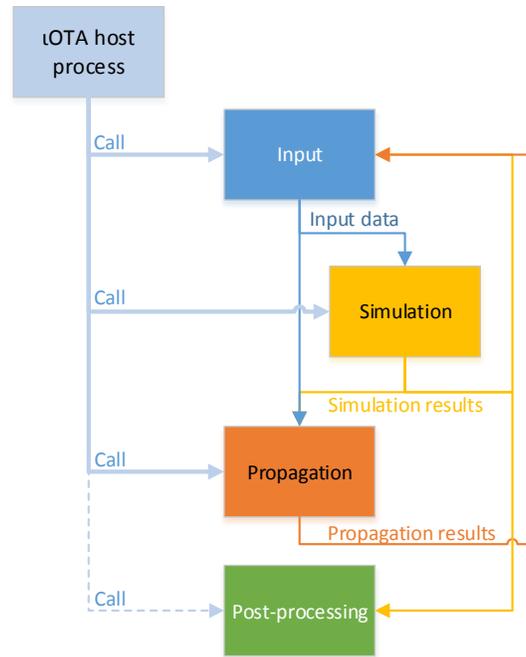


Fig. 1. ι OTA process hierarchy and functional architecture

The ι OTA host process is the driver of the ι OTA tool and controls the calling sequence of the particular modules for the complete duration of the simulation. For the duration of the attitude simulation and propagation, the following calling sequence is used in a loop.

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1. Input allocation module
 2. Simulation modules
 3. Propagation module

Subsequent to the completed attitude simulation and propagation, the post-processing modules are called, if these modules were selected.

The call of the ι OTA host process will allow to run it with or without a GUI for simulation module and input model selection. Also the user can choose between using configuration files for simulation parameter input or provide the parameters using the GUI. Running ι OTA from command line only, the simulation modules, as well as particular non-standard input models that shall be used have to be specified in the particular simulation module configuration files. If not all simulation results are required, only particular post-processing modules may be selected or post-processing may be switched off entirely. The visualization module will run autonomously and independent from the whole simulation.

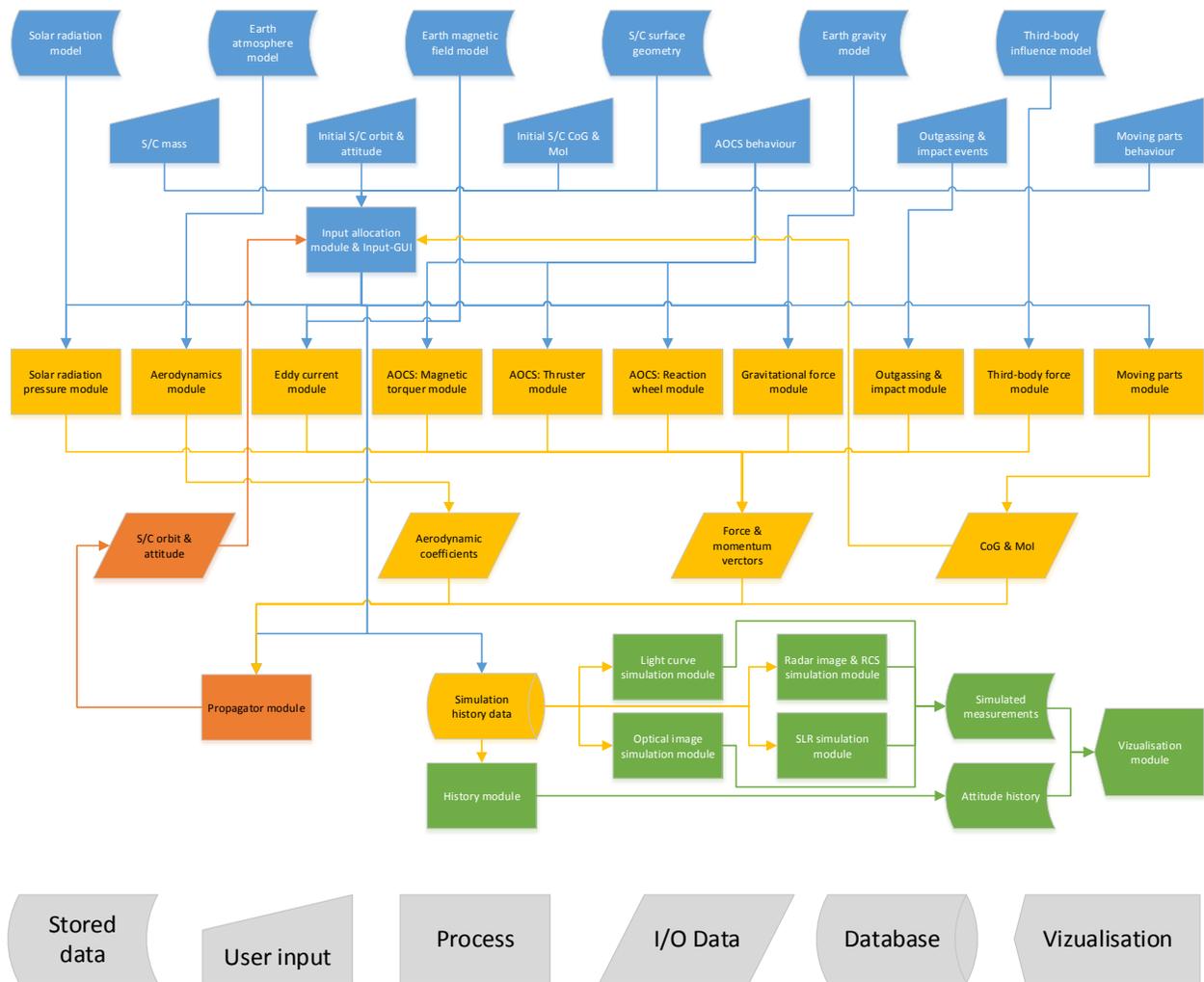


Fig. 2. iOTA software architecture decomposition and interface diagram

iOTA comprises the input allocation module, 10 simulation modules, the propagation module, 5 post-processing modules and the standalone visualization module. The simulation and post-processing modules are listed below.

Simulation modules for environmental influences

- Aerodynamics forces and torque
- Eddy current damping
- Gravitational acceleration and torque (Earth)
- Impact of micrometeoroids or space debris
- Solar radiation pressure
- Third-body acceleration (Sun and Moon)

Simulation modules for optional spacecraft related influences

- AOCS behaviour: Magnetic torquer activation
- AOCS behaviour: Reaction wheel behaviour
- AOCS behaviour: Thruster firing
- Moving parts (tank sloshing)
- Outgassing or leakage

Post-processing modules for

- History module: Output and storage of all relevant (selected) simulation data
- Light curve modelling
- Optical image generation
- Radar image generation and Radar Cross Section estimation
- Satellite laser ranging measurement simulation

3. SIMULATION INPUT AND MODELING

3.1. Spacecraft related input

For the attitude simulation, the user has to provide spacecraft specific mandatory input that is needed regardless of which simulation modules have been selected in particular. Additional input is needed, if the user chooses to include AOCS activation, tank sloshing or specific impact or leakage events into the simulation.

Mandatory input for the simulation is the initial spacecraft orbit and attitude, as well as the epoch. Also a panel based surface geometry model of the spacecraft as shown in Fig. 3 for the Delta-II second stage, has to be provided by the user. The spacecraft mass, moments of inertia (MOI) and the center of mass (CoM) position within the surface geometry model have to be defined by the user.

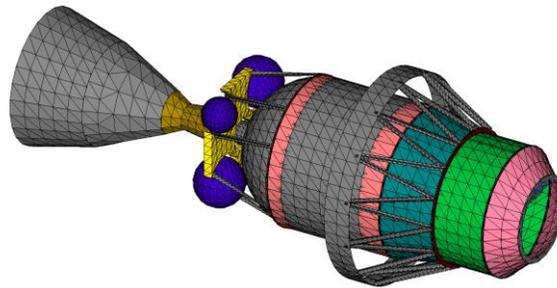


Fig. 3. Panel based geometry model of Delta-II second stage

The optional input depends on which particular simulation modules are selected. For the AOCS behaviour modules, the user has to provide activation event definition files for each of the three systems that shall be used selected. The even definition for reaction wheels and magnetic torquers is based on the time of the event and the particular force and torque vectors resulting from the activation of the component. For the thruster firing simulation, the user has to define the thruster position(s) as well as the thrust direction vector prior to the simulation, while the corresponding event definition file contains information on the activation time, duration and power. For the simulation of tank sloshing, the user has to define the tank properties (tank volume, tank centre of volume inside of spacecraft geometry) and the amount of fuel inside tank (mass of liquid content, mass of pressure gas) for each tank. Outgassing or leakage events will be defined by the time and force and torque vectors resulting from the particular event.

3.2. Environment conditions

The environmental conditions for the attitude simulation comprise the modelling of forces and torques resulting from atmospheric drag, gravitational influences from Earth, Sun and Moon, eddy current damping caused by the tumbling motion inside the Earth's magnetosphere, solar radiation pressure and impulse transfer through micrometeoroid and small space debris impact.

To simulate the influence of atmospheric drag, the aerodynamic force and torque coefficients are calculated for the stream facing side of the spacecraft using the spacecraft surface geometry model and including shadowing effects resulting from the objects actual attitude. The standard atmosphere model used by iOTA is *NRLMSISE-00* [1].

The calculation of gravitational effects is done separately for the acceleration and torques caused by Earth and the third-body accelerations caused by the Sun and Moon. The geoid models implemented and supported by *iOTA* are *EGM96* [2] and *EGM2008* [3], both up to order and degree 100. To determine the gravitational acceleration caused by Sun and Moon, the solar and lunar positions are calculated using the free (LGPL) Celestial Mechanics, Astrometry and Astrodynamics library *libnova* [4]. The accuracy of the calculated third-body positions has been verified using high-precision ephemeris from NASA's HORIZONS Web-Interface [5].

One of the essential effects on satellites in Earth orbit and particularly relevant for ADR missions is eddy current damping. The properties of the Earth magnetic field needed for the simulation are provided by the latest World Magnetic Model *WMM2015* [6]. The eddy current modelling in *iOTA* will be limited to a simplified geometry of the object structure like a sphere, cylinder or box to keep the computational cost to a reasonable level. Similar eddy current damping simulations have been performed by Praly et al., 2012 [7] for a rotating capsule and by Natalia Ortiz Gómez and Scott J.I. Walker, 2015 [8] for a simplified box-shaped model of ENVISAT. In addition to the simplified eddy current modelling, *iOTA* will provide an option for a user-defined eddy current damping coefficient which may be obtained through observations.

The acting acceleration and torques resulting from solar radiation pressure are calculated using the solar constant at 1 AU. For the actual attitude of the spacecraft the illuminated surface parts as well as the angle of incidence for each surface geometry panel are determined based on the solar position and the surface geometry model, including shadowing effects by Earth and the spacecraft geometry itself.

Based on ESA's Meteoroid and Space Debris Terrestrial Environment Reference (MASTER) [9], the impulse transfer from micrometeoroid and orbital debris impact is modelled.

To provide a baseline for the development of *iOTA*, the angular accelerations by gravitational, aerodynamic and solar radiation pressure acting on a Delta-II second stage in a low earth orbit (LEO) have been simulated with the SCARAB (Spacecraft Atmospheric Re-entry and Aerothermal Break-up) software [10]. Their values are plotted in Fig. 4 as function of the flight altitude for several orbits.

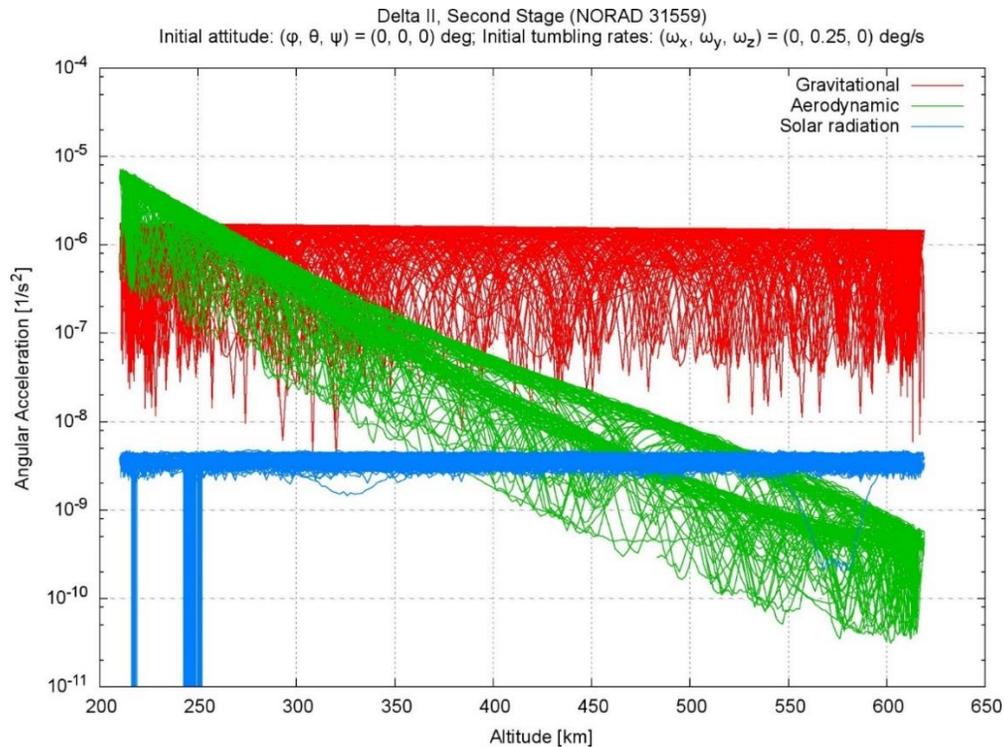


Fig. 4. Delta-II second stage: Altitude dependent angular acceleration resulting from aerodynamics, solar radiation pressure and gravitational influences, including solar and lunar third-body perturbations

The gravitational angular acceleration is due to the gravity gradient of Earth's gravity field. Its maximum value (for maximum out-of-equilibrium attitude) scales with the distance to the Earth center, and is therefore for LEOs quite insensitive to variations in the flight altitude. Its minimum values are zero for the equilibrium attitudes. The solar radiation induced angular acceleration scales with the distance to the Sun and is therefore even less sensitive to the flight altitude than the gravitational angular acceleration. In detail it depends on the spacecraft attitude relative to the sunlight and on the optical properties of the surface. It is zero if the spacecraft is in the Earth shadow. The aerodynamic angular acceleration scales with the atmospheric density, which is a function of the altitude above the Earth surface. Therefore the aerodynamic angular acceleration varies strongly with the flight altitude. In detail it depends on the attitude relative to the flight direction and on the material properties of the surface.

4. SYNTHETIC MEASUREMENTS AND VALIDATION BY OBSERVATIONS

Reliable models of the well understood effects of aerodynamics, solar radiation pressure and gravitational influences by Earth, Sun and Moon enable a good estimation of difficult to model effects by comparison of the simulation results and real observations. Especially for the determination of an eddy current damping coefficient such a validation is needed. ι OTA will be able to simulate to a certain level different type of measurements by using the physical properties and current attitude state of the object. The physical properties will be defined by the surface geometry, CoM position, MOI and surface reflectivity properties. The visualization itself will be based on a simple diffuse lighting algorithm. Together with the spacecraft surface mesh, the individual attitude of each surface element will be available. This information has to be combined with sun/laser light illumination/reflection for optical observations, or electromagnetic microwave absorption/reflection for radar observations.

Fig. 5 shows the basic synthetic measurement generation and validation process, including the inputs and outputs.

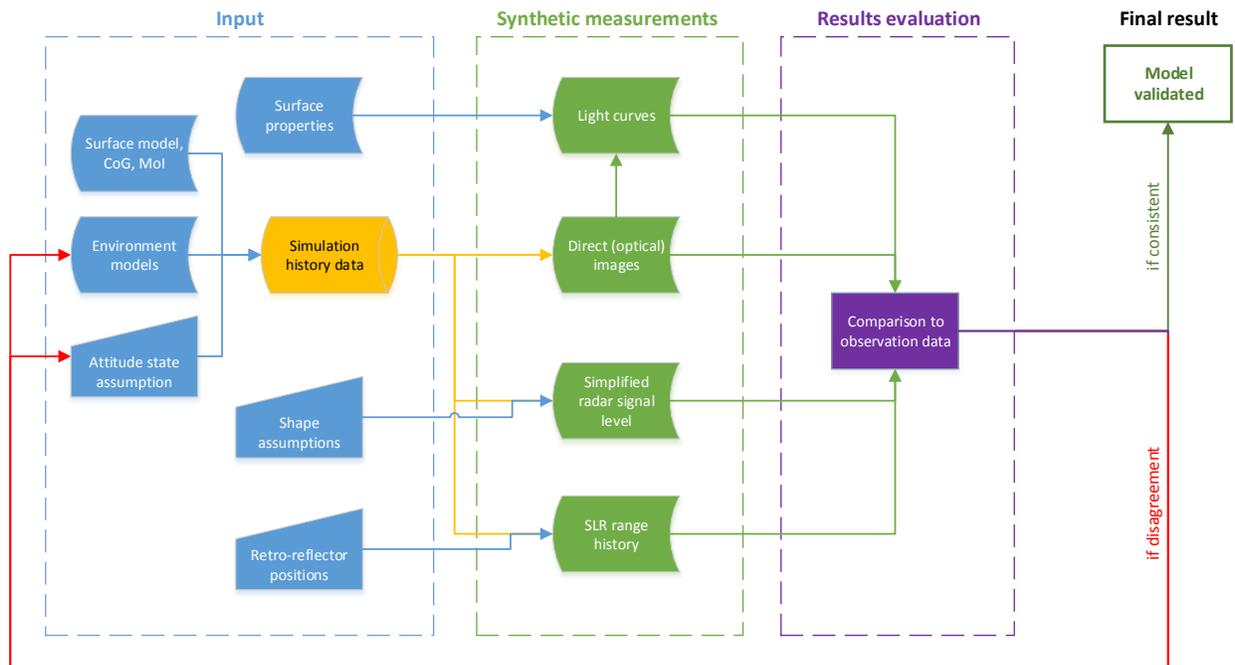


Fig. 5. ι OTA synthetic measurement generation and validation process

The input parameters are

- the attitude state assumption based on real observations, e.g. initial values for spin rate and spin axis direction determined from SLR data, from direct imaging or from SAR images,

- environmental conditions,
- the 3D surface geometry/shape of the target,
- the CoM determined from International Laser Ranging Service (ILRS) network data or Doppler Orbitography and Radio-positioning Integrated by Satellite (DORIS) measurements or obtained from models,
- the MoI obtained from the manufacturer data or models,
- the surface properties, diffuse and specular reflection,
- the retro-reflector positions according to the CoM and to the surface geometry,
- shape assumption, e.g. sphere or box-wing model (necessary to simplify the simulated radar signal-to-noise data).

The synthetic data generated will be compared to real observation data. If the results show a good agreement, the assumed input attitude state model and environmental conditions can be considered to be valid. In case there will be disagreement between the data, a refined initial state and environment conditions have to be created and then used as new input to the pipeline for additional iteration.

4.1. Preliminary SL-8 light curve modelling and observations

Knowing the surface geometry of a target, the position of the observer and the Sun, through defining the attitude of the model the total incoming flux (intensity) from the object detected by the observer can be obtained. From the incoming flux as a function of time we can construct a synthetic light curve. An example of such an approach is shown in Fig. 6, where a synthetic light curve of an SL-8 upper stage model (also displayed) is plotted. For this case we created the light curve by using images generated by the 3D render software *blender* [11] and by using our own 3D model of the SL-8 upper stage. For the 3D model's attitude we assumed two different spin rates, spin around the inertial axis X and spin (precession) around inertial axis Z. The values were 39.3 s and 139.1 s, respectively. Additionally, we applied a Fast Fourier Transformation (FFT) to extract the apparent spin rates present in the light curve. Results of this analysis can be seen in Fig. 7. The determined values are 23.1 s, which is close to the half value of the small period and 133.3 s which is close to the value of the larger period.

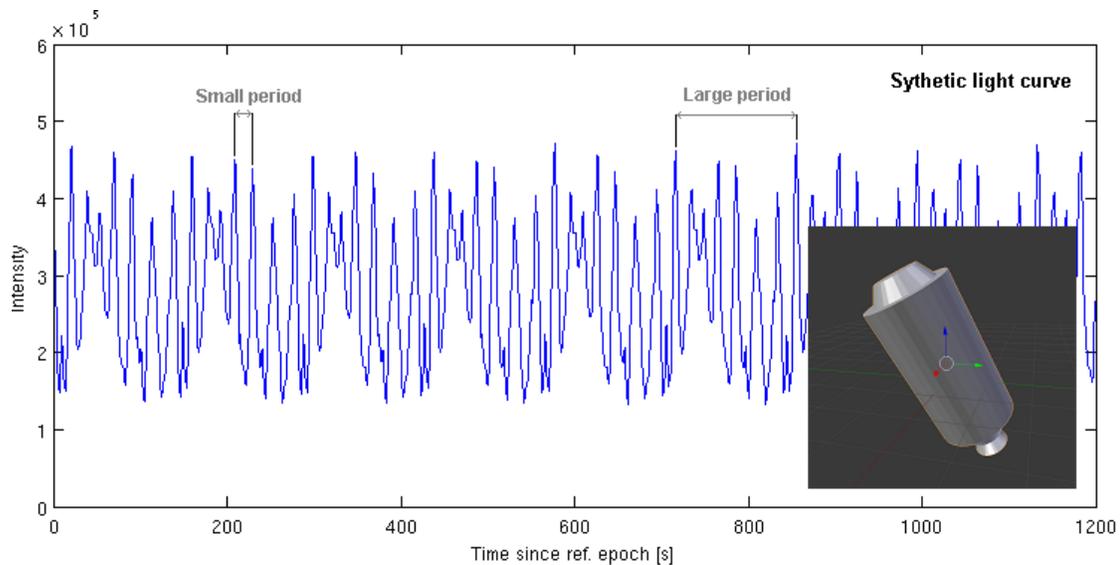


Fig. 6. SL-8 R/B model: The synthetic light curve shows the total measured intensity as a function of time, which was extracted from images created by the 3D render software using a model of the SL-8 upper stage (bottom right).

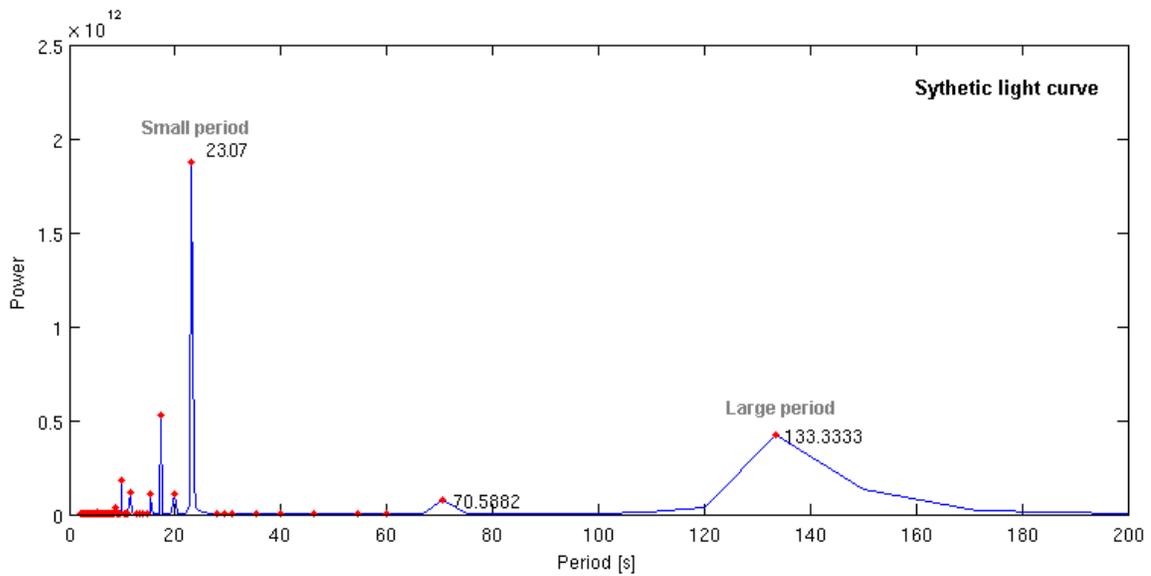


Fig. 7. SL-8 R/B model: The power spectrum of the light curve (Fig. 6) after the Fast Fourier Transform shows the period (inverted frequency) compared to its power.

The synthetic light curve plotted in Fig. 6 was generated in order to simulate real data, namely the light curve of the SL-8 upper stage (1968-081E) which was acquired in November 2012 by the ZIMLAT telescope [12] situated at Zimmerwald observatory, Switzerland. The light curve is plotted in Fig. 8. By applying the FFT we extracted the apparent spin rates equal to 19.9 s and 139.1 s. Here it is good to point out that for the synthetic light curve we did not take into account the brightness variation rising from the different geometry between observer and the target. However, this effect will be implemented into tOTA to simulate the light curves as realistic as possible.

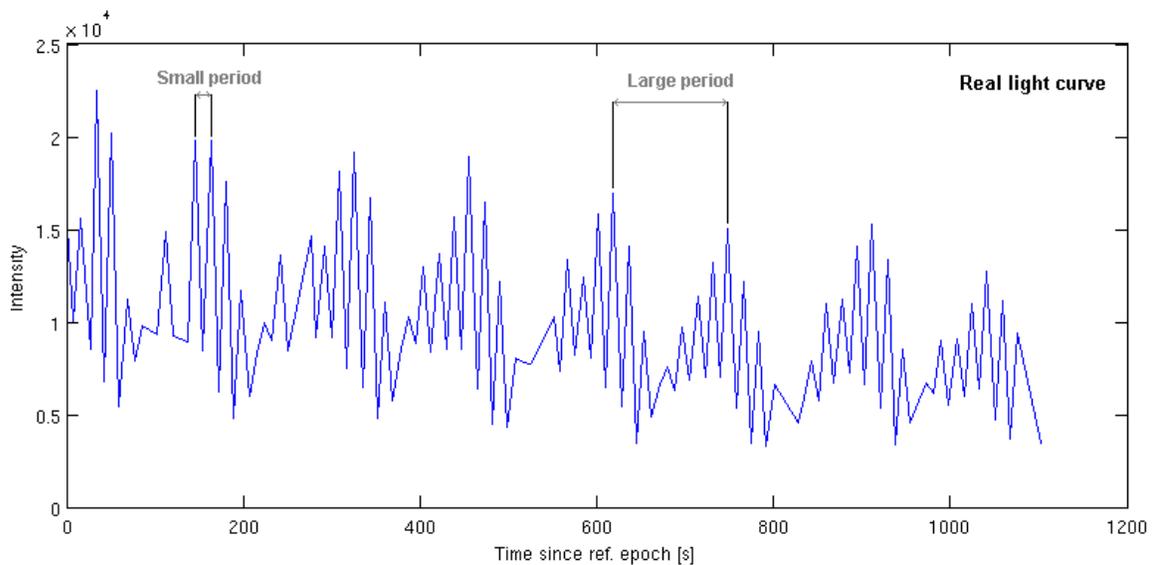


Fig. 8. Light curve of object 1968-081E (Titan 3C Transtage R/B), acquired by ZIMLAT. The reference epoch is 2012-11-08 01:09:05 (UTC)

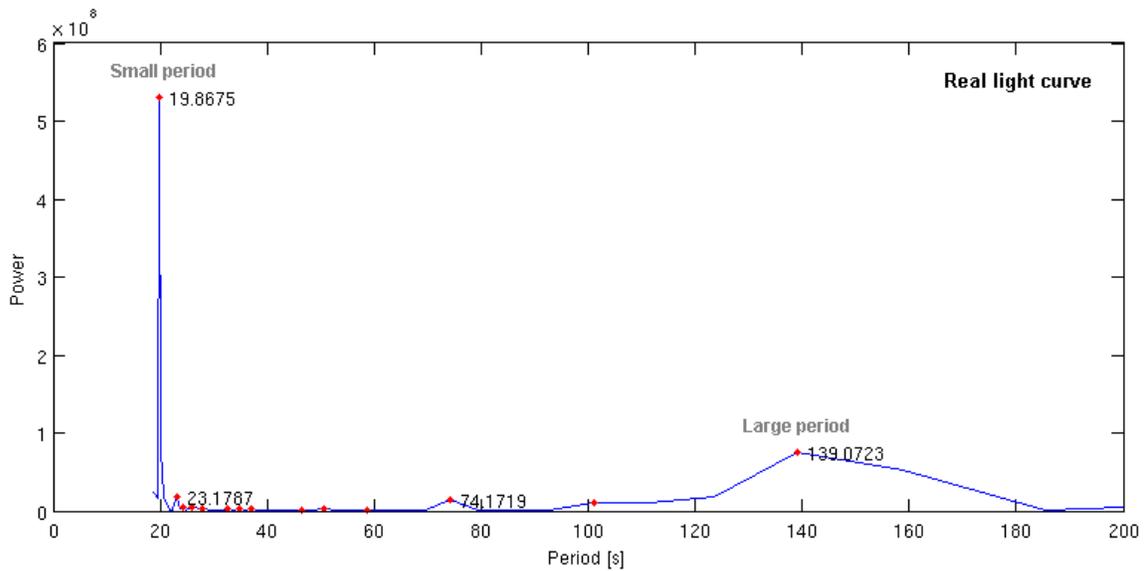


Fig. 9. Object 1968-081E (Titan 3C Transtage R/B): power spectrum of the light curve (Fig. 8) after the Fast Fourier Transform.

4.2. Observations on GLONASS 57 and TOPEX/Poseidon

Spacecraft with a box-wing shape usually have more complex light curves as the ones in Fig. 6 and Fig. 8 mostly due to their complex shape. For this type of objects specular reflections which have a very high and thick peak in intensity/magnitude (flashes) are common. An example of such a complex light curve can be seen in Fig. 10, where the light curves of the defunct satellites GLONASS 57 (1992-045A) (Global Navigation System Satellite orbit) and TOPEX/Poseidon (1992-052A) (LEO) are plotted. The light curves were acquired by the ZIMLAT telescope on 14th and 16th of July 2015, respectively. The first target was acquired by CCD, for that reason the used frame-rate was about ~3s. The second target was acquired with a sCMOS camera [13], where a very high frame-rate is possible to use. During the light curve acquisition for this target we used frame-rate equals to 16 frames/s which resulted in a very high resolution light curve.

For the GLONASS object the spin period was estimated to be around ~210 s. A typical GLONASS satellite is a box-wing spacecraft with cylindrically shaped bus and two solar panels attached to it. Due to the large number of satellites in this group and thanks to the retro-reflectors installed on them, the GLONASS is a very suitable population for attitude determination testing purposes. This applies for the light curves as well for the SLR type of measurements. GLONASS satellites can also be used for the synthetic data generation and its evaluation. For this reason the light curves of these targets will be used for refinement of the synthetic light curves generated by tOTA. TOPEX/Poseidon was a typical SLR target which is equipped by retro-reflectors. The apparent spin rate for this target is currently around ~10s. Its light curve shows a very strong specular reflection pattern (a very thin peak which repeats every ~10 s). Thanks to its altitude around 1338 km and retro-reflectors installed, TOPEX/Poseidon is a very good candidate for the attitude determination study by using different manners observation methods.

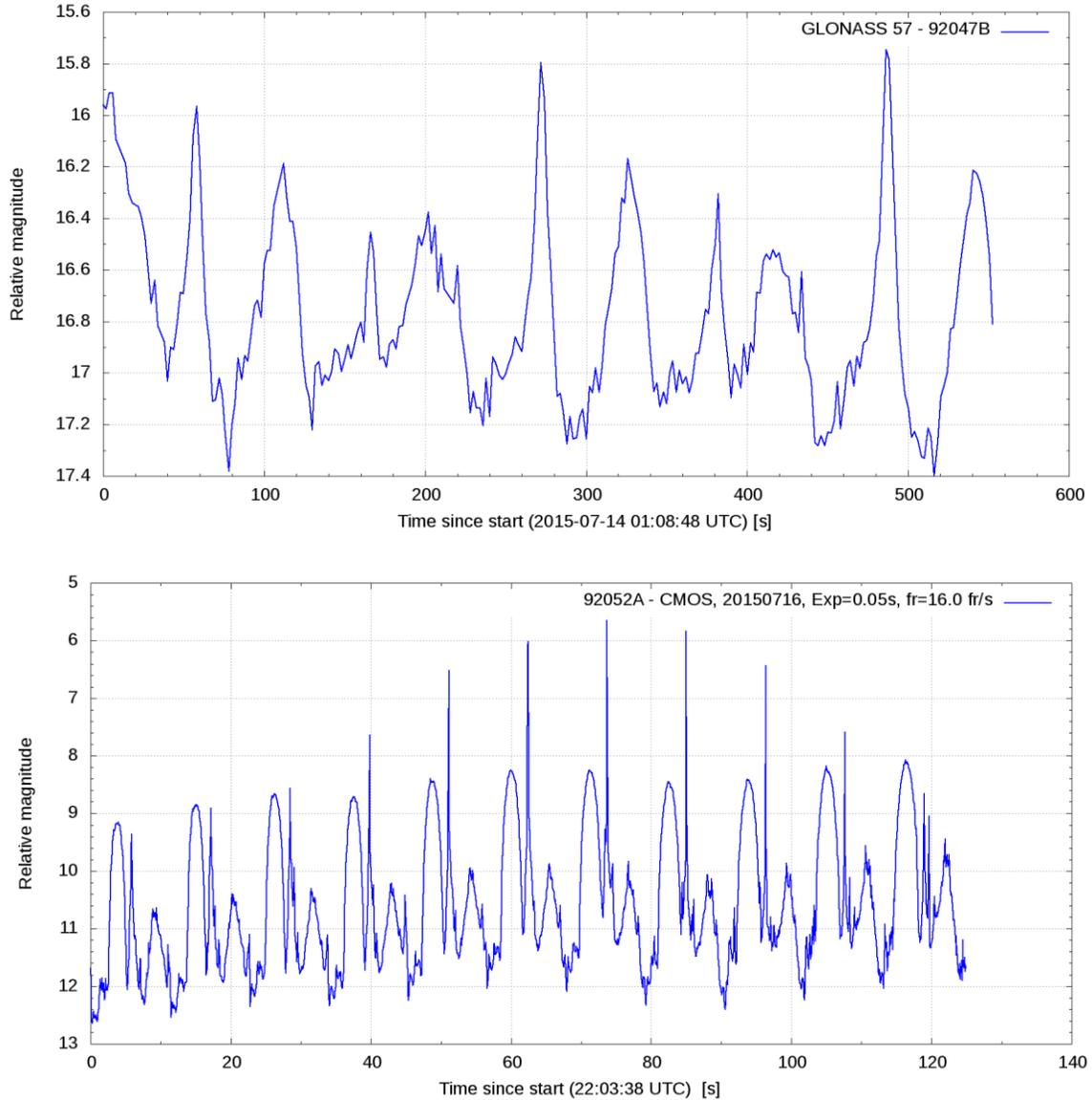


Fig. 10. Light curve of GLONASS 57 (1992-45B) (upper figure) and TOPEX/Poseidon (1992-052A) acquired by ZIMLAT telescope in July 2015.

5. OUTLOOK: POTENTIAL FUTURE FEATURES AND IMPROVEMENTS

During the ongoing development of tOTA, several potential improvements and additional features for future releases emerged. These range from computational cost optimizations and model improvements to the implementation of Space Weather influences to mimic effects caused by the dynamical behaviour of the near-earth environment caused by solar activity. Also a method for uncertainty quantification could be implemented directly in the software. In the following section, some of these features and improvements will be discussed briefly.

5.1. Model granularity improvement and optimizations

For the simulation of eddy current damping, modelling is very much simplified, especially to keep the computational cost on a reasonable level. But also the approach to only use the surface geometry model of an object, neglecting the

inner structure is limiting the obtainable accuracy of the eddy current modelling. Improving the model granularity by user-defined particular elements of the inner structure which correspond to the main eddy current damping drivers, would increase the simulation accuracy. But simultaneously the computational cost would rise.

The initial release of iOTA limits the spherical harmonics degree and order for gravitational models to 100. The use of even higher coefficients will probably not increase the accuracy of simulation due to the order of magnitude of other influences and due to simulation uncertainty. A sensitivity study for the estimation of the significant degree and order however, would provide a basis for an optimization of iOTA regarding the reduction of computational cost and thus reducing the overall simulation time.

5.2. Space Weather influences

The current model implementation of the Earth's atmosphere and magnetosphere are based on pre-defined static modelling. The total solar irradiance is constant at all times. The initial user-defined simulation input includes the F10.7 and Ap index values, but during the whole simulation these values are fixed. The magnetosphere model does not provide any method to account for Space Weather effects.

An approach for a Space Weather module would include a variable, time-dependent solar irradiance due to user-defined Space Weather events, to account for increased solar radiation pressure caused by solar flares. For the result of the simulation however, the influence of solar flares will be negligible. X class flares e.g. increase the total solar irradiance by 10^{-4} to 10^{-3} W/m², while the solar constant is approximately 1367 W/m². Thus the solar radiation pressure variation caused by solar flares is only relevant due to the uncertainty increase. For the atmosphere modelling the F10.7 and Ap index values would have to be dynamically managed, enabling the atmosphere module to mimic the effects of Space Weather events. Due to a similar event definition method as the one that is used for the space debris impact module, this would be easy to implement. The event definition itself could be based on the NOAA Space Weather scales or could be completely user-defined, if the user chooses to.

Dynamically altering the magnetic field model however is not trivial. To do so, the Space Weather module would have to account for magnetospheric variations due to changes of the solar wind speed, as well as for dedicated user-defined coronal mass ejection (CME) impacts. Also, due to the short-term magnitude change of the eddy current damping compared to the overall simulation time, the implementation of such a dynamic magnetosphere model might not provide any significant accuracy improvement.

The implementation of a Space Weather module for a future release of iOTA would be limited to the time-dependent model input parameters for the Earth's atmosphere, namely the F10.7 and the Ap index values. The variation of the total solar irradiance caused by solar flares would be negligible for the simulation results, but could be of interest due to an increased uncertainty. The simulation of a dynamic magnetosphere seems not to be promising, especially considering the high implementation effort that would be needed.

5.3. Uncertainty quantification

iOTA is a fully deterministic tool. Thus the only method for uncertainty quantification using the initial release is to run multiple attitude simulations with varying initial states. This Monte-Carlo analysis is time consuming due to its high computational cost.

One possible approach for a more effective uncertainty quantification method would be to use the parallelization capability of the iOTA host process to run several simulation modules at the same time. For the uncertainty analysis, one particular simulation module would be called multiple times with varying input parameters during one attitude propagation step, enabling a Monte-Carlo analysis for each simulation module within certain predefined intervals, e.g. 2 σ around the average value of the particular result from the previous propagation step. To prevent drastically increasing computational costs, the number of parameter variations for each simulation module would have to be limited.

6. SUMMARY AND CONCLUSION

Especially for ADR missions the accurate attitude state of target objects in LEO are needed. The combination of multiple observation methods, namely optical observations, SLR and radar measurements, increases the accuracy of tumbling motion determination and provides a better understanding of the relevant forces and torques that act on space debris in Earth orbit, which is the goal of ESA's "Debris Attitude Motion Measurements and Modelling" project. The In-Orbit Tumbling Analysis tool iOTA is a highly modular software, currently in development within the framework of the project. The software includes simulation modules for all relevant internal and external effects that occur. Environmental influences are simulated using state-of-the-art models of the Earth's atmosphere, geoid and magnetosphere. For the modelling of eddy current damping the initial approach will use simple geometric shapes only. User-defined event based AOCS behaviour, outgassing, leakage or space debris impact extends the capabilities of the attitude evolution simulation to study the influence of particular events that may also occur. iOTA will provide the ability to perform short-term high accuracy simulations, as well as mid- and long-term trend analysis. The set of post-processing modules will enable the generation of synthetic measurement data to support observers and to provide the capability for observation method cross-calibration of the tool. Within the project, iOTA will be validated and refined using the combined data of the measurements and observations performed. Due to its fully deterministic nature, uncertainty quantification will need multiple simulation runs with varying initial states. A future evolution of the tool might include an improved uncertainty analysis capability, as well as the option to mimic the effects of user-defined Space Weather events.

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