EXPLAINED AND UNEXPLAINED MOMENTUM IMPULSE TRANSFER EVENTS

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ABSTRACT

Since January 1, 2015, ExoAnalytic Solutions has collected more than 110 million correlated astrometric measurements of deep space Resident Space Objects (RSOs). Orbit Determination (OD) on several inactive RSOs in sub-synchronous (e.g., spent upper stages) and super-synchronous (e.g., retired satellites) orbits routinely reveals occasional momentum impulse transfer events (MITEs) with in-track velocity changes of 0.2 to 10 mm/s. A simple model with an isotropic spherical solar radiation acceleration does not explain the observed MITEs. Models which include an additional solar radiation pressure component perpendicular to the solar direction were fitted to the first year of data and then used to predict the second year resulting in accurate predictions within roughly 2 km over the year.

1 INTRODUCTION

The development, application, and verification of motion models for resident space objects is an important activity which significantly benefits from dense, longduration observation. Ideally, gaining a high fidelity understanding of the traffic population in deep space will allow future motion predictions for all observable objects. To achieve this, it is necessary to develop models that capture the physics observed over longdurations (> 6 months). In the case of debris objects (including fragments, spent rocket body upper stages, and defunct satellites) an effective model would accurately capture the relationships among the object's geometry, mass, and surface material, and their reactions to the known forces which pervade the space environment. This paper evaluates the degree to which these relationships are captured via a fitted model which predicts future motions for long durations. The accuracy with which the motions can be predicted and the duration for which this accuracy can be maintained make a useful set of metrics for the evaluation of an RSO model representation.

The following sections of this paper report on recent progress toward achieving this end. In Section 2, we describe our observation network. Section 3 demonstrates a routine validation of the network's timing and line-of-sight accuracy against objects which report their ephemeris. Section 4 summarizes a 2-year collection campaign focused on multiple spent rocket body upper stages, which was used to extend the solar radiation pressure beyond the standard cannonball model to include terms which capture anisotropy and perpendicular acceleration geometries. Furthermore, we evaluate the ability of these extended models to predict the motion over the following full year that containing multiple eclipse seasons. Lastly, in Section 5 we discuss the application of this type of analysis to defunct satellites and discuss the observed MITEs which are not explained by any of the models tested. The activity outlined in this paper represents a data-rich approach to the evaluation of various debris types. Furthering this pursuit, the authors hope to collaborate with members of the orbital debris community to create a better understanding of all the objects which will indefinitely orbit our planet.

2 THE EXOANALYTIC GLOBAL TELESCOPE NETWORK

The ExoAnalytic Global Telescope Network (EGTN) is a global Space Situational Awareness (SSA) telescope network distributed among more than 20 observatories and 150 telescopes on 5 continents and three islands of Hawaii. Fig. 1 shows the geographic distribution of the EGTN.



Figure 1: EGTN Observatory Locations

EGTN telescopes detect, track, and correlate objects in geosynchronous Earth orbit (GEO), highly elliptical orbits (HEO), and medium Earth orbits (MEO). The network passively collects high volumes of both angles and brightness measurements (right ascension (RA) and declination (DEC) as well as apparent magnitude) on active RSOs and debris. Fig. 2 summarizes the 2016 collection volumes of the 10 most observed active space objects.



Figure 2. Top 10 Most-Observed RSOs for CY 16

Over the past four years, thousands of correlated measurements have been collected on thousands of GEO and near-GEO satellites and debris objects. Observation data is continuously correlated to space objects in near-real time within the ExoAnalytic Solutions Command Center using data from the globally distributed observatory network which enables dense observation data for objects exhibiting large long-term drift behaviour. The current EGTN collection rate is greater than 8 million correlated measurements per month of man-made satellites and debris. Data from the EGTN represents a valuable tool for the collaborative study of deep space objects, including many forms of debris.

3 EGTN ASTROMETRIC ACCURACY

Using in-frame astrometric registration techniques, EGTN sensors provide highly precise angular position measurements. Typically, the measurement accuracy for EGTN sensors is 1 to 2.5 microradians. EGTN sensor performance has been demonstrated during collections on satellites with known ephemerides including Global Positioning System (GPS) satellites, Wide Area Augmentation System (WAAS) satellites, and commercial communications satellites. Sensor collections for GPS and WAAS satellites are routinely used as part of the standard EGTN calibration process.

Fig. 3 illustrates the RA and DEC measurement residuals for EGTN sensors compared to the WAAS data from Galaxy-15 over a period of 150 days between October 2016 to February 2017. Galaxy-15 ephemerides (position, velocity, and acceleration) are available online in 256-second intervals. During the comparison period, EGTN sensors collected approximately 155,000 measurements for Galaxy-15.

Fig. 4 shows the ensemble statistics for the RA and

DEC residuals. The {RA, DEC} residuals mean is $\{0.20, 0.61\}$ urad and statistical uncertainty has a standard deviation of $\{2.5, 2.1\}$ urad. This comparisons aids in the calibration of the shutter delay for different sensor types.



Figure 3. RA/DEC Residuals in WAAS Data 2016-2017



Figure 4. Distribution of WAAS Residuals

The results highlighted in Fig. 3 and Fig. 4 demonstrate the ability of EGTN sensors to provide precise astrometric measurements over long durations. Maintaining accurate astrometric calibration provides confidence that structure observed in the residuals between a model fit and measures can be attributed to a short-fall of the model. Either the model is incorrect or the data supports additional physical phenomenology to be added to the model. Long duration fits (>60 days) are useful in searching for missing phenomenology. The next section discusses the application of EGTN data to long-duration observations of RSOs to develop enhanced-fidelity models for use in long-term motion prediction.

4 LONG-DURATION UPPER STAGE OBSERVATION, MODELING, PREDICTION, AND VERIFICATION

Today, satellites in deep space are often deployed using direct-to-GEO chemical launches, which carry massive upper stages to deep space as well. On many occasions, EGTN sensors have observed deep space launches from T+5 min until GEO insertion, payload separation, and upper stage fuel dump. Current GEO launch practices have resulted in many massive pieces of debris requiring continuous tracking in the altitudes between LEO and GEO. The motions of these large pieces of debris can be reasonably well predicted using a standard cannonball model. Through the long-duration observation campaign, however, observations illustrated that this model does not account for some of the force variations observed in the periods where the rocket body traverses the Earth or Moon shadow. These unmodeled phenomena, when accounted for, significantly improved the forward prediction of the RSO's motion over longer durations.

Significant prior work on GEO RSOs has focused heavily on the evolution of debris populations and the behaviour of High Area-to-Mass Ratio (HAMR) objects. The relative importance of solar radiation pressure on such objects has been identified [1-3], and its effects on the orbital eccentricity and semi-major axis have previously been described. The modelling in [1] relies on a typical cannonball-style model for the RSO which a simulation of behaviour over a long period Reference [2] acknowledges that a is conducted. cannonball model is simplistic, but that it is more tractable, too. Other work tends to focus on advanced mathematical techniques [4] for modelling, which may or may not account for every long-term variation in physical forces on an RSO. Note that modelling in [4] extends only to 50 orbits: much of the long-term propagation work is aimed at enabling the acquisition of additional data within a few days or weeks (by limiting the search volume then containing the RSO) rather than at projecting accurate orbits months or years in the future [4-6].

Additionally, [7] shows how the basic assumptions of the cannonball model are gradually being revisited, although they are not extended beyond revising the spherical model to a flat-plate model in [7], and then working through the divergences in the simulated results. Reference [7] also notes that most of the objections to using non-spherical models focus on the data and model handling complexity challenges with non-simple associated models and the computational demands that attend their use. Highaccuracy propagation is currently limited to about ten days for purposes of conjunction management, and to perhaps 50 days for catalogue maintenance purposes. Finally, [7] shows how the spin rate of a flat plate can have a significant effect on the accuracy of orbit propagation, indicating that the fine-tuning of parameters used for non-spherical models (as would be possible in the case of perfect knowledge of the RSO's geometry and behaviour, or empirically in the case of substantial data) can have a major effect on propagated orbit accuracy, and that a non-spherical model captures more effects than does a spherical cannonball model.

Almost all prior related work uses advanced modelling techniques and mathematics, rather than large datasets, to drive improvement. Only occasionally are data available to inform or serve as bases for models. This is in some ways a fundamental limitation to the state of the art in orbit modelling and, consequently, long-duration orbit propagation.

4.1 Observation Campaign

The observation campaign focuses on six different upper stages from March 27, 2015 to March 28, 2017. Information for each upper stage rocket body is provided in Tab. 1.

Table 1: Six rocket bodies analysed over 2 years

NORAD ID	Int'l ID Code	Description	Inclination First Year Number of Observations		Second Year Number of Observations	
02222	1966- 053J	TITAN 3C R/B	1.3812	16665	38424	
03292	1968- 050J	TITAN 3C R/B	0.9895	16552	43053	
09998	1974- 033F	SMS 1 AKM	2.3754	4218	10795	
36359	2010- 002B	BREEZE-M R/B	4.3678	19030	32221	
39376	2013- 062B	BREEZE-M R/B	1.4372	21388	33336	
39614	2014- 010C	BREEZE-M R/B	1.2678	14160	32385	

Fig. 5 shows the probability distribution for the number of observations taken on any given night over two years.



Figure 5: Probability distribution of nightly observations over the 2 years of collection

Fig. 6 illustrates the geographic distributions of the observations taken on each of the studied rocket bodies. This data provides the ability to compare how well the standard model fits the measurements taken in the first year, and predicts the following year of measurements.



Figure 6. Geographic distribution of rocket body observations

One consequence of moving an RSO to a graveyard orbit near GEO is that it begins a slow drift about the globe. Although this drift is sufficiently unhurried that multiple nights' worth of data can be collected on a given RSO from one sensor site on the ground, it is also the case that there will be extended periods when that same given sensor cannot collect on the RSO as it completes the portion of its drift that passes slowly over the antipodal half of the globe. Thus, in order to maintain a constant stream of observations on an RSO for a long period of time (which constitute a critical underpinning for the modelling methods utilized in this paper), a global network of sensors is required. Fig. 6 illustrates the distribution of observations across the globe that the EGTN provides.

4.2 Standard Model Performance

The standard cannonball model used to fit the observations taken during the campaign is based on accepted gravitational components of acceleration including:

- Earth Gravitational Model: WGS84 with EGM2008 coefficients to n=8;[8]
- Earth Orientation in J2000 calculated using software and data provided by the International Astronomical Union's Standard of Fundamental Astronomy (SOFA) and the International Earth Rotation and Reference Systems Service (IERS)
- Luni-Solar gravity using JPL/NASA DE430 ephemeris software.

In addition to these forces, the next-largest magnitude components to the acceleration model are associated

with the solar radiation pressure (SRP) force. The cannonball model assumes that this force is purely in the direction of the RSO position vector in heliocentric coordinates. This may be expressed as:

$$\overrightarrow{d}_{SRP} = \frac{\phi}{c} AMR_o \widehat{s}_{||} \tag{1}$$

In this way, all objects are treated as spheres regardless of their physical geometry or reflectance properties. This model is a seven-parameter fit (6 parameters for the state vector and 1 for the solar radiation pressure) which can be used to predict the motions of the observed rocket bodies. Fig. 8 illustrates the overall fit accuracies achieved for each of the rocket bodies using this model.



Figure 8: Fit residuals for cannonball model over the first year of data

Fig. 8 is colour coded to show the residuals specific to each rocket body, and has an accompanying trend line calculated by displaying the median residual value for each day over the course of the one year fit. The shaded regions in the plot highlight the eclipse seasons experienced by the objects during the year. The sevenparameter model can fit all the data over the entire year to within a few hundred microradians. For reference, a microradian at the geosynchronous altitude of 35786 km equates to approximately 36 meters as viewed from Earth's Surface. This level of performance is not as good as typical EGTN performance when observing objects which provide their ephemeris, and it should be noted that the duration between eclipses is often fit to a level of about 100 microradians, which is much closer to the nominal performance. The divergences observed immediately preceding or following eclipse events imply that more than simply turning the SRP force off during the eclipse is required to adequately capture the behaviour of the rocket bodies at these times.

When employing the best fitting 7-parameter model to the first year and using the model to predict the measurements taken over the course of the next year, the divergence illustrated in fig. 9 is observed.



Figure 9: Prediction fit residuals for cannonball model fit over the second-year collection data

The pattern of divergence from the baseline predicted position is clear in Figure 9, which shows the orbit residuals growing steadily over the course of the year prediction. Some of the residuals peak at over 5000 microradians (more than 180 km) away from the prediction, and the overall pattern of divergence indicated by the slope remains steady. (The exception of NORAD 39614 is notable, and may be due to the relatively recent transition of this RSO into an inactive state. As discussed further in Section 5, it is possible that this RSO's behaviour will evolve further with due time, and this possibility will be the topic of future research.)

A close look at Fig. 9 shows that connections between eclipse season and changes in the overall slope of the residuals may exist. This indicates a likelihood that the overall divergence is being driven in part by an incomplete modelling of the interaction between solar radiation and the RSOs' behaviours.

It should be noted that the residuals present in the plots, not only allow for appropriate amplification of the rather small deviations being analysed, but also remove some of the naturally-varying features of an orbit in order to make clear the varying features not yet accounted for in the modelling. In this instance, residual is defined to be the difference between the RSO's predicted position, derived from the best fitting multi-parameter model, and the RSO's actual position, as determined from the actual observation data.

4.3 Modelling Enhancements

To more effectively handle the behaviour observed during the eclipse events experienced by the rocket bodies throughout both the fit and prediction durations two simple enhancements beyond the typical isotropic SRP force model are considered. The first extends the constant isotropic SRP force model to include a term which quantifies a Yarkovsky-like effect.

$$\overrightarrow{d}_{SRP} = \frac{\phi}{c} AMR_o \widehat{s}_{||} + \frac{\phi}{c} AMR_Y \widehat{s}_{\perp}$$
(2)

The Yarkovsky effect [9-10] describes a component of force in the direction perpendicular to the heliocentric position vector (and for our analysis is also solely in the In-Track direction) which is caused by the uneven heating and cooling of a rotating body. By including a component in this direction, additional accelerations perpendicular to the RSO-Sun line can also be fit during the eclipse periods.

A further enhancement to a tumbling rocket bodies is to approximate its mean surface shape over a tumble revolution as a Diffuse Ellipsoid. This model extends upon the constant isotropic SRP force by adding an additional component in the direction perpendicular and parallel to the RSO-Sun vector directions that has a twice a year modulation in both the parallel and perpendicular directions. In addition to the magnitude of the asymmetry, the phase of the asymmetry over the year is needed. For a diffuse ellipsoid, the ratio of the perpendicular amplitude modulation compared to that of the parallel is about 0.42. Higher harmonics and different ratios are attained using different shape hypothesize. The Diffuse Ellipsoid model is perhaps the simplest asymmetric shape that provides an improved model for the observed anisotropy in SRP acceleration.

$$\vec{a}_{SRP} = \frac{\phi}{c} AMR_o \hat{s}_{||} + \frac{\phi}{c} AMR_2 [a_2 \cos(2\psi_2) \hat{s}_{||} + b_2 \sin(2\psi_2) \hat{s}_{\perp}]$$
(3)

This model makes intuitive sense given the typical behaviour of tumbling rocket bodies, which tend to start with an axis of rotation nearly aligned with the axis of symmetry of the body but, over time, allow that axis to move until it is aligned with the axis of largest inertia. This axis is most often perpendicular to the axis of symmetry for the upper stage, making disc shaped surfaces of revolution over long periods of time that the Diffuse Ellipsoid Model is intended to represent.

4.4 **Performance of Enhanced Models**

Application of the enhanced models to the data is shown in Fig. 6 and Fig. 7. It is clear to see that the results are improved both in fitting the data over the duration of the collection and in predicting the future motion of the rocket bodies even through the eclipse seasons. Figs. 10 and 11 illustrate the overall fit residuals achieved for the Sphere plus Yarkovsky and Diffuse Ellipsoid models, respectively.



Figure 10: Right Ascension residuals for the Sphere + Yarkovsky Model 1-Year Fit



Figure 11. Right Ascension residuals for Diffuse Ellipsoid Model 1-Year Fit

It is encouraging to see that the updated models achieve residuals much closer to the anticipated accuracies of EGTN measurements as in Section 3. Being able to capture this accurate a fit over an entire year is promising, but there is still structure within these residuals, and further work is necessary to define a model that will capture even more of the observed dynamics.

Figs. 12 and 13 show the accuracy with which these two model fits can predict the motion of the six studied rocket bodies over the following year. As seen in Fig. 13, the orbit residuals based on a year-long fit using the Diffuse Ellipsoid Model are significantly reduce compared to Fig. 9 using the Cannonball Model. The largest residual seen is approximately 100 microradians, or about 4 km from the prediction. Recall that 100 microradians was the cannon-ball model performance between eclipses. Additionally, the slopes have flattened noticeably, indicating the possibility of increase duration predictions which preserve sufficient position accuracy to be effective.



Figure 12: Sphere + Yarkovsky model 1-Year Prediction Performance



Figure 13: Diffuse Ellipsoid Model 1-Year Prediction Performance

implication of this work with substantial One importance is the potential ability to perform long orbit predictions (>4 weeks), with high accuracy (< 2 km), for debris objects that otherwise may closely approach active RSOs. If a debris object could have its position projected out for months in advance, to within 1-3 km of its actual position, then knowledge of its behaviour well in advance of the close approach warning and postcedent avoidance manoeuvres that would otherwise be required could be incorporated into standard manoeuvre planning for any active RSOs which would be subject to such close approach warnings caused by said debris. That is, a window of such accurate knowledge so long in advance would permit stationkeeping objects at GEO simply to plan their stationkeeping manoeuvres such that, when the debris object drifted through their position box, they would already have been positioned as far away as possible inside the box, with the minimal use of delta-V that advanced foreknowledge enables.

To illustrate the improved performance of the enhanced models implemented and tested, Tab. 2 summarizes the RMS of the right ascension and declination residuals for the cannonball, Sphere plus Yarkovsky, and Diffuse Ellipsoid models for the fit and prediction periods.

		Radiation Pressure Model's Residual RMS (urad)								
NORAD ID	Year	Cannonball		Yarkovsky		Diffuse Ellipsoid				
		RA	DEC	RA	DEC	RA	DEC			
02222	Fit	46.9	4.1	15.5	3.4	6.9	3.3			
	Pred	1395.0	39.7	34.3	12.5	43.0	12.9			
03292	Fit	49.6	4.5	20.1	3.7	6.2	3.7			
	Pred	1541.0	42.4	27.6	9.4	8.2	9.7			
09998	Fit	116.6	8.2	27.6	4.4	9.3	4.4			
	Pred	3227.0	85.9	123.8	7.8	61.1	10.1			
36359	Fit	40.4	6.1	20.7	3.9	5.3	3.4			
	Pred	1193.0	111.4	76.2	6.4	38.0	12.			
39376	Fit	66.0	4.6	16.2	3.7	11.0	3.7			
	Pred	1656.0	51.5	28.3	11.0	34.0	12.5			
39614	Fit	7.5	3.8	7.5	3.5	7.2	3.7			
	Pred	110.0	17.1	22.4	12.9	35.0	14.3			

Table 2: Long term fit and prediction performance

It is worth noting here that the Diffuse Ellipsoid is the overall best performing model but not necessarily the best performing model for every individual object. This does leave room for evaluating multiple models when analysing the long duration behaviour of these objects, all of which are at their own evolutionary state in their Further analysis may even provide dynamics. explanations as to why a Sphere plus Yarkovsky model fits a rocket body motion better than a Diffuse Ellipsoid model given the known features of the object. At this point in our research it is satisfying knowing that either enhanced model does enable improved fit and prediction performance which accounts for the observed departure motions not captured by the cannonball model. In the next section, there is a discussion on the observations of a defunct satellite and the current activities to model, fit, and predict its future motions.

5 ANALYSIS OF DEFUNCT SATELLITES' POST-DISPOSAL MOTIONS

As we continue to provide large volumes of dense collections on deep space objects, there is ample opportunity to learn improved models and methods for fitting observations and predicting RSO motions. Given that the clear majority of the observable objects are in fact debris, developing effective models for all types of debris is an important step in developing a reliable baseline for understanding space traffic as it evolves. To this end, we illustrate the analysis of data collected on AMOS-5 following its apparent failure on 11/21/2015.

5.1 AMOS-5 Analysis

It was reported in the press [11] that communications were lost with AMOS-5 at 04:44 UTC on 11/21/2016. As part of our continuous operations, many observations of this satellite have been collected. When analysing this data, the stark difference in the behaviour of the satellite can be initially observed by viewing the residuals to a cannonball model fit taken a few days after the loss in communications.



Figure 14: Significant behavioural change observed in pre-and post-fit residuals

Fig. 14 summarizes this change in behaviour. The scale shows in microradians the significant departure from the cannonball model during active operations prior to the event. During the fit duration spanning from 12/26/2015 to 2/25/2016 the residuals are very well behaved, achieving the accuracy distributions expected from the measurement noise of our sensor network. The post-fit residuals require a close analysis and are shown in more detail in Fig. 15.



Figure 15: Post-fit residuals of AMOS-5 display uncaptured Momentum Impulse Transfer Events

Day 450 of the analysis dataset marks the onset of significant behaviour not captured by the cannonball The fit residual magnitudes increase at a model. significant rate indicating a failure of the model to capture the behaviour of the acceleration. It is not lost on the authors that this occurs during the eclipse duration, a fact that was exploited to improve the acceleration models used to better model the behaviour of the rocket bodies analysed in this paper. However, the enhanced acceleration models also do not adequately capture this event, indicating that a more complex model will likely be required to more accurately track this object in the future, or that the observed events in this period are attributable to the object itself (possibly including reorientations, thruster firings, or other activities that could be triggered during safe mode or other recovery operations).

This highlights an important distinction regarding the term Momentum Impulse Transfer Events (MITES), which are not necessarily manoeuvres. It is usually best to assume that MITES are important features of the object's motion profile which can be used to inform enhanced models and to enable long-term accurate predictions of motion for the observed object. However, when these higher-accuracy fits are achieved for increasing durations, it is possible that observed MITES are attributable to object behaviour, events such as collisions, or other short-duration occurrences which result in small but appreciable changes in the space object's momentum.

It is important that when these events are observed to characterize them including an assessment of the time of occurrence and the magnitude of the resulting delta-V. Fig. 16 illustrates this process where a 7-parameter cannonball model is fit over a duration containing the time of the observed MITE. A typical residual structure observed here, indicates that unmodeled acceleration exists which invalidates the assumption that the motion was purely ballistic over the fit duration. Using a 10parameter fit, which includes 3 additional parameters for the velocity after the MITE, obtains better behaviour in the residuals, as well as provides a preliminary estimate for the velocity of the MITE which has a deltav in the in-track direction of approximately 0.7 mm/s..

Following the characterization of observed MITES, it is sometimes possible to derive additional model characteristics which further explain the observed motions of the RSO. In the case of the analysed rocket bodies in this paper, the magnitude and timing of the observed MITES illuminated that an un-modelled asymmetry in the solar radiation pressure was the potential cause for departures in residuals observed during the transit of the RSO through the Earth and Moon shadows. This approach is validated by observing the enhanced model prediction perform to better than 1 km for one year following the initial fit. Further development and testing of additional models to capture these results for objects, such as AMOS-5 are possible by working with others who analyse space debris.



Figure 16: Localized analysis of an observed MITE characterizing the event time and magnitude

5.2 Developing Model Enhancements

One key component of the modelling approach applied in this paper is the use of a parametrized ellipsoid model which governs how SRP affects the modelled objects. Although, these parameters are estimated using a long period of data, they are then fixed for the prediction period. The actual characteristics of a defunct RSO that govern how it responds to SRP may vary, generating slight but noticeable changes in the appropriate ellipsoid model parameters. For example, external coatings of a vehicle may degrade as they experience the space environment, or components of a recently-depowered vehicle may gradually lose their ability to point and begin to exhibit compliance with increasing spin, altering the apparent appearance of the RSO.

These effects may be especially pronounced in newlydefunct objects, although much older and simpler objects, such as rocket bodies from decades ago, may be expected not to display any additional evolution in their behaviour. Work following this paper will analyse photometric data from RSOs, both recently defunct and long-disused, to assess whether the possibility exists to extract features of the parameters as they alter during an RSO's natural post-use period. It is suspected that some of the structures remaining as-yet unaccounted for in the residual plots in Fig. 8, Fig. 10, and Fig. 11 may be the result of phenomena such as this. Additional enhancements to the Diffuse Ellipsoid Model which incorporate time evolution of parameters and subsets of the model parameters allowing for a more detailed physical shape of the modelled RSO (including, e.g., a model which permits solar arrays to be modelled distinctly from the bus and extruding payloads) is a goal for future work on this topic.

6 Discussion and Conclusions

Long-term orbit propagation is still a challenge, currently being addressed primarily by means of advanced mathematical techniques for detailed orbit modelling, rather than by data-enabled models.

Additionally, [12] shows that observations made in the presence of non-continuous coverage of an orbit (as modelled, at least) may diverge up to 4 degrees in just 1.5 hours, indicating a relative inability to model orbits in the face of limited data. Notably, though, if multiple observations spanning a three-hour window can be maintained, many of the errors drop to less than 0.5 degrees. This shows both the typical upper limit of orbit propagation (when based on standard sizes of datasets) of a few days, and the general trend of increased accuracy over longer periods in propagated orbits with improved coverage and concurrently larger datasets. Errors of 0.1 degrees or less become feasible when observation coverage extends beyond about 3 days, although they are not completely removed.

The work presented in this paper shows the potential for high-accuracy propagation of orbits for RSOs in deep space, which in turn may greatly enable methods of avoiding future GEO collisions, which are known to have lasting consequences for the environment there [13]. The unprecedented scale, accuracy, and coverage of debris objects enabled by the EGTN represents a significant opportunity for the community to develop and test models which are rooted in dense observation over long durations. Significant opportunity exists for the scientists at ExoAnalytic and members of the orbital debris community to work together to further understand deep space debris and validate models which are effective in their analyses.

7 REFERENCES

- 1. Pardini, C., and Anselmo, L. (2008). Long-Term Evolution of Geosynchronous Orbital Debris with High Area-to-Mass Rations. *Trans. Japan Soc. Aero. Space Sci.* Vol. 51, No. 171, pp. 22-27.
- 2. Rosengren, A. J., and Scheeres, D. J. Long-term dynamics of high area-to-mass ratio objects in high-Earth orbit. *Advances in Space Research* 52 (2013), 1545-1560.
- 3. Frueh, C., Kelecy, T. M., and Jah, M. K. Coupled Orbit-Attitude Dynamics of High Area-to-Mass Ratio (HAMR) Objects: Influence of Solar Radiation Pressure, Earth's Shadow, and the Visibility on Light Curves. *Celest. Mech. Dyn. Astr.* (2013).
- Woollands, R., Younes, A. B., Macomber, B., Probe, A., Kim, D., and Junkins, J. L. Validation of Accuracy and Efficiency of Long-Arc Orbit

Propagation Using the Method of Manufactured Solutions and the Round-Trip-Closure Method. AMOS Conference 2014.

- Cordelli, E., Vananti, A., and Schildknecht, T. Optimization of Optical Follow-up Strategies Based on Covariance Analysis. 6th European Conference for Aerospace Sciences. 2015.
- 6. Hinze, A., Fiedler, H., Schildknecht, T. Optimal Scheduling for Geosynchronous Space Object Follow-up Observations Using a Genetic Algorithm. AMOS Conference 2016.
- 7. Lachut, M., and Bennett, J. Towards Relaxing the Spherical Solar Radiation Pressure Model for Accurate Orbit Predictions. AMOS Conference 2016.
- 8. Pavlis, N. K., Holmes, S. A., Kenyon, S. C., and Factor, J. K. (2008). An Earth gravitational model to degree 2160: EGM2008. Presented at 2008 General Assembly of the European Geosciences Union, Vienna, 13-18 April 2008.
- 9. Bottke, Jr., W. F. et al. (2006). The Yarkovsky and YORP Effects: Implications for Asteroid Dynamics. *Annu. Rev. Earth Planet. Sci.* 34: 157-191.
- Vokrouhlicky, D., Milani, A., and Chesley, S. R. Yarkovsky Effect on Small Near-Earth Asteroids: Mathematical Formulation and Examples. *Icarus* 148, 118-138 (2000).
- De Selding, P. B. "Spacecom Stock Tumbles Following AMOS-5 Failure." November 23, 2015. URL: http://spacenews.com/spacecom-stocktumbles-following-amos-5-failure/.
- Hinze, A., Schildknecht, T., and Vananti, A. Followup strategies for MEO observations. Proceedings of 38th COSPAR Scientific Assembly, Bremen, Germany. 2010.
- 13. Johnson, N. L. Evidence for Historical Satellite Fragmentations in and Near the Geosynchronous Regime, 2001.