Astrodynamics and the Space Environment – Where Are We Now?

M. Ziebart
Professor of Space Geodesy
University College London
Gower Street, London WC1E 6BT
UNITED KINGDOM

m.ziebart@ucl.ac.uk

ABSTRACT

The trajectories of space debris and active satellites are shaped primarily by natural forces arising from the nature of the space environment. The accurate computation (both estimation and prediction) of such trajectories depends in turn upon the accuracy of the mathematical modelling of those forces. Considerable progress has been made in the last 20 years in both understanding and modelling forces upon objects in space. However, crude representations of resident space object trajectories are still in wide use, predicated upon two line element methods. Whilst it is a non-trivial undertaking to use more advanced modelling approaches, they are within reach and have a strongly proven track record. Fundamental aspects of several key forcing mechanisms are discussed and the relevant research that has led to dramatic improvements in orbit determination and orbit prediction capability is described briefly.

1.0 INTRODUCTION

This document presents an introductory overview of those elements of the space environment that create forcing effects on resident space objects (RSO) pertinent to the discussion around progressing space domain awareness (SDA). The material concentrates upon the background to concepts that may be less well known to the audience of the lecture series. It provides underpinning material necessary to place in context the following lectures. The material focusses mainly upon non-conservative photon-based effects as these are the least understood (but relevant) forcing problems in the wider SDA community.

Background

Calculating the trajectory of an object in the space environment is predicated fundamentally upon understanding and describing mathematically the forces that act upon it. A subsidiary, but no less subtle and complex problem is the definition of suitable spatial and temporal reference frames within which to describe both the forces and the motion. These problems have been under attack since the dawn of the space age (and indeed before) and have drawn attention from some of the finest intellects of the human race, such as Newton, Gauss and Legendre. In the last twenty years significant advances have been made, primarily through the scientific exploitation of GPS and GNSS (Global Navigation Satellite Systems), and through the requirement to compute very high accuracy orbits for low earth orbiting satellites used to measure global sea level change. GPS satellite orbits are now estimated routinely with accuracies of 2.5cm (e.g. [*Ziebart et al.*, 2007]), orbits for the Jason class of satellites used to measure global variations in sea level are accurate at the level of 1cm [*Haines*, 2004]. Such developments produce ancillary data products and techniques applicable to calculating the trajectories of any object in the space environment. Pertinent to the material of this lecture series we concentrate here upon dynamics – the definition and modelling of forces upon RSOs.

When discussing forces that act upon RSOs, a useful distinction can be made between conservative and non-conservative forces. This distinction is largely one of convenience – all forces could be considered conservative if sufficient levels of detail were considered when modelling a complex system. In practice by conservative forces we refer to gravitational effects caused by the Earth, the Moon, the Sun and other planets. The energy of such a system (consisting of potential and kinetic components) is conserved. By contrast, we define non-conservative forces as those that change the energy state of the system, particularly in a secular sense. The following are all considered non-conservative: radiation pressure; atmospheric drag; outgassing effects; Lorentz forces [*Bhattarai et al.*, 2014; *Shapiro and Jones*, 1961].

Space debris in orbit about the Earth can be broadly and usefully divided into two classes:

1) Those objects, that by virtue of their orbital altitude and area to mass ratio will gradually (or even rapidly) lose altitude and eventually burn up in the atmosphere or fall to Earth.
2) Those objects that will remain on orbit for a sustained period of time, and which, by virtue of their size or mass present some form of long term hazard to safe operation in the space environment.

We are not concerned with resident space objects falling below a mass/area threshold that present no threat (at least as far as we can foretell at this point), and similarly objects whose orbits decay in a terminal fashion are unlikely to create a long term problem.

Objects in class (b) are the problem.

Such objects are no longer under the orbital control of any agency, and are free to move in the space environment, essentially driven by the natural forces acting upon them. To understand how the orbits of these objects will evolve over the long term is one of our key goals. To pursue that goal then requires several areas of knowledge:

1) A clear understanding of all significant forcing mechanisms that shape RSO trajectories.
2) Models of sufficient accuracy of those forces such that credible orbital prediction can be performed.
3) Data describing the existing RSO population in terms of its materials, mass, state (at least position and velocity in an inertial reference frame), number, spin state and behaviour, optical and thermal properties, charge accumulation rates and existing charge.

That is clearly an extensive list, and one that is far from complete. This lecture series is a step towards gaining and promulgating that knowledge.

Let us start with a list of known forcing mechanisms – broadly in order of magnitude (the ranking obviously depends in part upon the orbit parameters of the object in question and its own properties):

- Earth gravity due to the monopole (that is, modelling the Earth as a single point mass).
- Earth gravity perturbations due to the non-homogeneity of density and mass distribution (modelled conventionally as the derivative with respect to space of the Earth's geopotential, which is in turn expressed as a spherical harmonic expansion to a given degree and order).
- Gravity forcing due to the Moon.
- Gravity forcing due to the Sun.
- Solar radiation pressure.
- Atmospheric drag and lift.

- Forcing due to the anisotropic emission of thermal radiation.
- Earth radiation pressure (due to both radiation reflected and emitted by the Earth).
- Gravity forcing due to other planets (Venus, Mars and so on).
- Tidal effects in Earth gravity.
- General relativistic forcing effects.
- Lorentz forcing due to the interaction of surface charge with the space environment magnetic field.
- Pole tide effects.

Whilst it is beyond the scope of this document to cover all those effects in detail, what follows gives sufficient insight into theory and data sources to appreciate the level of maturity of modelling of the main effects as well as some basic formulation to aid understanding.

Reference Frames and Trajectory Models

The primary reference frames used to define coordinates for trajectory analysis in the space environment are Earth Centred Inertial (ECI) and Earth Centred, Earth Fixed (ECEF) systems. Both rely upon exacting sets of standards that are rigorously developed and defined by the IERS (International Earth Rotation Service). It is worth noting that for the latter (ECEF) frame, plate tectonic motion is modelled explicitly in the coordinates of terrestrial tracking stations.

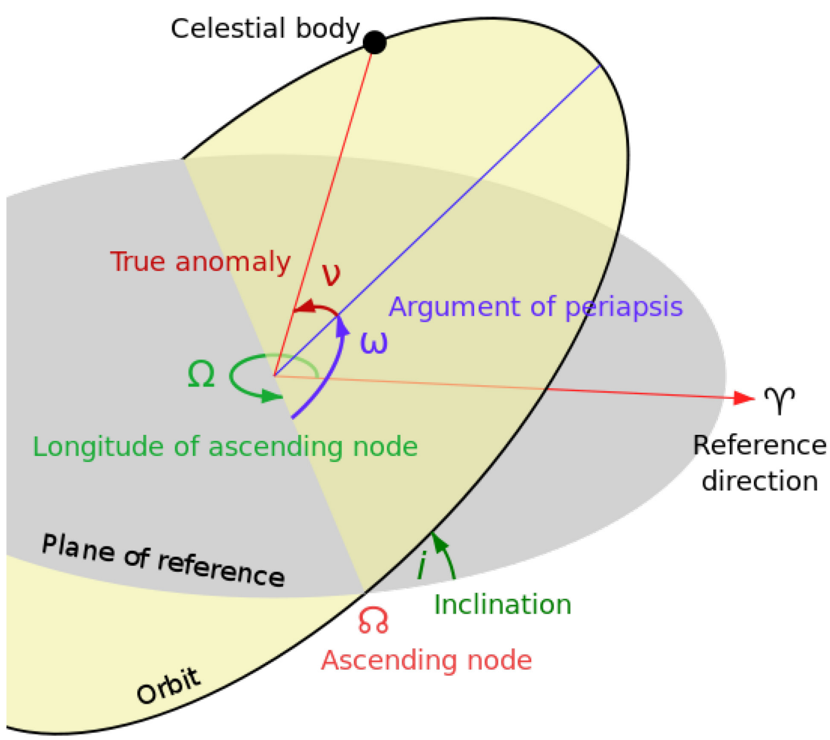

Figure 1: Keplerian Elements[1].

[1] By Lasunncty (talk). - Lasunncty (talk), CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=8971052.

There are many choices of form and file format for trajectory models, but the most intuitive uses a set of six Keplerian elements to define the position of an RSO instantaneously in inertial space. Conventional two line element sets use a slightly extended concept to model not only the instantaneous position of am RSO, but also to model how the orbit evolves with time. Whilst the concept sounds appealing, in practice the TLE representation is actually very crude, based on little more than a monopole Earth gravity field model. Unfortunately many agencies regard TLEs as a definitive way of recording both the instantaneous RSO position, but also as a means of propagating the orbit many years into the future.

2.0 GRAVITY

2.1 Newton's Law of Gravity

Isaac Newton hypothesised that a universal force called gravity acted according to an inverse square law such that the force between a planet of mass m_1 and a body of mass m_2 in orbit around that planet could be described thus:

$$m_2\ddot{\boldsymbol{r}} = -\frac{Gm_1m_2}{r^3}\boldsymbol{r}$$

where $\boldsymbol{r}$ is the time dependent position vector of the orbiting body with respect to the centre of mass of the planet, and G is Newton's gravitational constant. Newton used this 'law' to explain the motion of the Moon about the Earth. However, there is no proof of this law. Instead what we observe is that the 'law' makes useful predictions about how objects move. Precise measurements of orbital motion show quickly that the law above alone is insufficient to describe how objects truly move. Keplerian elements are predicated upon such a 'two body' problem.

However, Newton's law gives rise to some very useful ideas – and for our purposes here the concept of 'gravitational potential' is key.

Say we define some quantity *U, gravitational potential energy* to be:

$$U = \frac{Gm_1}{r}$$

This defines a property of near-Earth space, a potential energy field varying as a function of distance from the centre of mass of the planet. Taking the first derivative of U with respect to the radial distance r we get:

$$\frac{\partial U}{\partial r} = -\frac{Gm_1}{r^2}$$

which is the acceleration due to gravity, expressed as a vector quantity thus:

$$\ddot{\boldsymbol{r}} = -\frac{Gm_1}{r^3}\boldsymbol{r}$$

From which we derive easily our simple force equation:

$$m_2\ddot{\boldsymbol{r}} = -\frac{Gm_1m_2}{r^3}\boldsymbol{r}$$

The derivative of gravitational potential with respect to space gives us acceleration.

Gravitational potential is a property of the distribution of mass in space. This quantity for a real planet is conveniently described using spherical harmonics (explanatory material can be found in any modern astrodynamics text):

$$U(\varphi,\lambda,r)=\frac{GM}{r}\left\{1+\sum_{n=2}^{\infty}\sum_{m=0}^{n}\left(\frac{a}{r}\right)^{n}P_{n,m}(\sin\varphi)\left[C_{n,m}\cos m\lambda+S_{n,m}\sin m\lambda\right]\right\}$$

For our purposes it is the *spherical harmonic coefficients* ($C_{n,m}, S_{n,m}$) which provide the detail in the geopotential model enabling high accuracy orbit determination. Given a set of these coefficients to an appropriate degree and order, and taking the derivatives of the expansion with respect to space, we can compute a high resolution and high accuracy gravitational acceleration field. The successful development, launch and analysis of novel forms of measurement of geopotential models by dedicated gravity field missions such as GRACE, CHAMP and GOCE revolutionised knowledge of Earth's gravity (e.g. [*Tapley et al.*, 2004]). This has led to understanding of the time variation of many of the geopotential coefficients allowing for time variable gravity. In addition, tidal variations in the field are easily computed. New dedicated gravity field missions will be flown in the near future. Current high resolution geopotential models are complete to degree and order 2159. To put that in perspective, gravity fields from the 1990s were complete only to degree and order 360.

To summarise – the modelling of the Earth's gravity field involves taking the spatial derivatives of the Earth's gravitational potential expressed in spherical harmonics. The accuracy of such geopotential models has improved dramatically in the last twenty years and provides a tried and tested resource for astrodynamics today.

2.2 The Gravitational Effect of Other Planets

So-called third body effects require knowledge of the position and mass of the planets that comprise the solar system. The JPL Developmental Ephemeris is a set of polynomials describing the trajectories of all major solar system bodies. It is the toolset used in the design of inter-planetary missions, and is itself derived from the solution of the equations of motion of the planets. Third body effects induce very large orbit perturbations to missions such as GPS. The centimetre level accuracy orbits determined routinely for GPS would not be possible without the JPL DE series, and indeed, the validation of those orbits shows independently how accurate is the current knowledge of both planetary ephemerides and their masses. The JPL DE is publicly available and many software tools are in the public domain to read and interpolate the orbital trajectories.

2.3 General Relativistic Effects

General relativity enters our domain problem in two ways. In the first instance we apply a linear correction to the Newtonian gravitation based on a truncated series expansion of the rigorous special relativistic model dealing primarily with effects due to speed of recession. The second problem relates to the treatment of precision oscillators (effectively clocks) on board space vehicles such as GPS satellites. Without treating relativistic effects due both to speed of recession and to differences in geopotential between space-borne clocks and those maintained in ground stations GPS ranging would be in error by tens of kilometres after only a day. In practice ranging to GPS satellites (using the satellite signals) is at the level of a few centimetres. This provides very clear evidence that the 'laws' derived from Einstein's relativity work very effectively.

3.0 NON-CONSERVATIVE EFFECTS: RADIATION AND DRAG

3.1 Radiation Pressure

The space environment is filled with electro-magnetic energy from a variety of sources, primarily the Sun and radiation both reflected and emitted by the Earth. What is sometimes surprising is that this radiation induces a force upon objects in the space environment. This force is systematic and induces long term, secular characteristics in RSO orbits.

The Scottish physicist James Clerk Maxwell first showed the theoretical basis for radiation pressure as a consequence of his theory of electro-magnetic radiation in 1873. The Russian physicist Pyotr Nicholaevich Lebedev demonstrated experimental evidence in 1900 [*Lebedew*, 1901], followed shortly afterwards by the work of E.F. Nichols and G.F. Hull in the USA in 1901 [*Nichols*, 1901]. Einstein's Special Theory of Relativity postulates a relationship between the energy of a photon and momentum:

$$E^2 = (m_0 c^2)^2 + (\rho c)^2$$

where:

E = energy of the particle
m_0 = mass of the particle
c = speed of light in vacuum
ρ = momentum of the particle (expressed as a scalar)

For a photon, $m_0 = 0$, therefore:

$$E = c\rho$$

Hence, if a photon is absorbed by an RSO then momentum E/c is transferred to the RSO body. Now, Max Planck's Quantum Hypothesis relates the energy of a photon to the frequency of the electro-magnetic radiation such that $E = h\nu$, where h is Planck's constant and ν is the photon frequency.

Hence:

$$\rho = \frac{h\nu}{c}$$

This establishes a relationship between photon frequency and momentum transfer. From here we can develop a simple relationship between forcing due to incident radiation and the total solar irradiance. Let the average number of solar photons of frequency ν striking a surface area of one square metre per second at one astronomical unit from the sun be $n(\nu)$.

The change in momentum per unit area per unit time for the body struck by the photons is:

$$\frac{d\rho_{n(\nu)}}{dt} = \frac{n(\nu)h\nu}{c}$$

Hence $\frac{d\rho_{n(\nu)}}{dt}$ is the force per unit area due to photons of frequency ν.

Summing over the frequencies of the solar electromagnetic spectrum we have:

$$F_{absorbed\ radiation} = \sum_{i=1}^{m} \left(\frac{h}{c}\right) n(v_i)\, v_i$$

but:

$$\sum_{i=1}^{m} h\, n(v_i)\, v_i$$

is the total solar irradiance (W) in Joules per square metre.

Hence at one astronomical unit from the sun the force per unit area due to absorbed radiation is:

$$F_{absorbed\ radiation} = \frac{W}{c}$$

In the broadest possible sense this is the basis for radiation pressure modelling – given knowledge of the characteristics of the incident radiation flux and an understanding of the profile of a resident space object presented to the flux we can calculate the force induced by the radiation.

In practice there are several complicating factors which will change the calculated force due to incident photons:

- Some of the incident radiation will be reflected, resulting in a recoil force of some kind depending upon the direction and distribution of the reflected radiation.
- Some of the absorbed radiation will be re-radiated as thermal energy, resulting in a recoil force (and possibly with a time lag due to thermal inertia).
- Some of the absorbed radiation will be conducted through the RSO and possibly converted to another form of energy (e.g. electrical energy if the absorbing surface is a solar panel).

We have established that a photon *absorbed* by an RSO imparts momentum to it. Conversely, a photon *emitted* by an RSO, either through the deliberate emission of a signal in the form of a carrier wave or in a pulse of radiation used for remote sensing, or as thermal emission, creates a recoil force on the RSO according to Newton's third law. Hence we define, in near earth space, the four principal ways in which photons are either incident on, or emitted by, an RSO:

- Direct impact and reflection of solar photons.
- Direct impact and reflection of photons either emitted by, or reflected from, the Earth (we loosely define these two fluxes – adopting the Earth Radiation Budget community classification - as long and short wave respectively, that is thermal emission and albedo or reflection).
- Thermal emission of heat by the RSO (either as a natural consequence of re-radiation of incident energy or as part of a passive or active thermal control system).
- Signal transmission by a space vehicle.

In a later section we will see the nature of the perturbations caused by radiation forces.

Key data sets that enable the precise modelling of photon forcing effects describe the radiation fluxes in the space environment. Primarily these are the Total Solar Irradiance (TSI) and the Earth radiation budget modelling radiation reflected and emitted by the Earth.

The determination of the total solar irradiance (TSI) has been addressed by a mature community of scientists over many years. This is because the measured value and its variations are critical inputs to the analysis of the Earth radiation budget, which is itself a component of climate change analysis. The primary measurements contributing to the value are derived from space-borne cavity radiometers. Such instruments have been flown in space for several decades and provide a long term data set from which to infer patterns and trends. However, a key issue has been calibration to align measurements across multiple instruments and missions [*Frohlich*, 1998]. The Earth radiation budget scientific community has dealt vigorously with the problems of instrumentation, measurement, calibration, validation and the publication of standard data products.

On a daily basis the solar irradiance varies depending in part upon the current sunspot number, and in part upon the phase of the solar rotation. The sunspot number varies approximately with the solar cycle (period between 9 and 14 years). To assess the extent of this variability the mean solar irradiance derived from the data in Figure 2 gives 1365.88 +/- 0.56 Wm^{-2}, the one sigma uncertainty here reflecting the distribution of values across the 35 years of the dataset. Relevant experimental data sets include ERBE and CERES. Useful references include [*Bush and Young*, 2002].

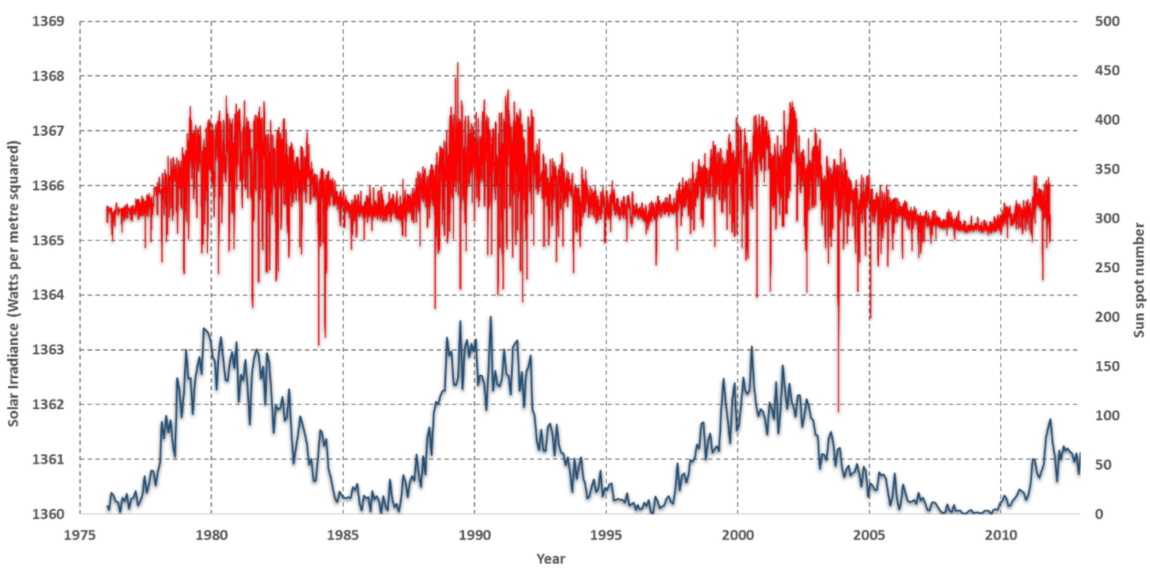

Figure 2: Total Solar Irradiance and Sunspot Number Over the Last 35 Years.

The variation of the solar irradiance over the solar cycle is of the order of 1.4 Wm^{-2}, which is approximately 0.1% of the mean value.

From the flux modelling perspective the Earth acts both as an emitter and a reflector of radiation. Crudely this can be broken down into 'long wave' (LW) thermal emissions from the Earth, and 'short wave' (SW) reflected radiation. To first order the spectrum of this radiation is similar to that from the Sun. The short wave component is due broadly to the so-called 'albedo' of the Earth – that fraction of the incident solar radiation that is reflected by the Earth's surface and its cloud layer, or is simply back scattered from the gases in the Earth's atmosphere.

The long wave component is due to radiation into space by thermal emission from the Earth's surface. Both these features (SW and LW components) have strong geographical and temporal variations, with the latter varying diurnally, seasonally and annually.

An added complication (compared to dealing with the solar flux) is that the Earth is a near-field emitter and reflector. So, whereas the solar flux can be treated as a homogeneous, planar wave front for modelling purposes, components of the Earth radiation flux arrive from different directions, and with differing magnitudes. This effect is more marked depending upon the satellite's orbital altitude, the most complex being for low earth orbit.

As for the solar radiation flux, the Earth radiation budget has been extensively studied for many years due to its contribution to climate modelling. Hence, rich, mature data sets are available. Moreover, this data, as for the solar case, has been measured in the space environment by space-borne sensors, making it ideal for our purposes. There are two primary sources of data available from which to construct models and from which to gain insights into the scale of the effect. These are the ERBE and CERES catalogues. ERBE is the Earth Radiation Budget Experiment. It represents the first multi-satellite mission attempt to measure and model in a comprehensive manner the complete Earth radiation budget [*Barkstrom*, 1984], combining sensors on both polar and inclined LEO space vehicles. The ERBE instrument flew on NASA's ERBS (Earth radiation budget satellite, LEO, i = 57°, $a \approx$ 6978 km, 1984-2005) and on two NOAA satellites (NOAA-9, i = 98.9°, a = 7228 km, 1984-1998 and NOAA-10, i = 98.6°, a = 7182 km, 1986-2001). The CERES data set is a continuation of the ERBE data [*Wielicki et al.*, 1998]. The CERES instrument was first flown on NASA's Tropical Rainfall Measuring Mission (i = 35.0°, a = 7402 km, 1997-), and subsequently on the EOS Terra (i = 95.0°, a = 7078 km, 1999-) and Aqua (i = 98.1°, a = 7078 km, 2002-) platforms, and more recently on the Suomi NPP (National Polar-orbiting Partnership) mission (i = 98.7°, a = 7078 km, 2011). Both the ERBE and CERES data sets use a grid of 10,368 cells of 2.5° x 2.5°, at an altitude of 30 km (this being defined as TOA – top of atmosphere). For each cell a monthly mean value of the SW and LW radiation intensity in Wm^{-2} is provided. A key consequence of this work is the availability, to those agencies and institutions conducting orbit determination and orbit prediction tasks, of a robust (robust in the sense that it does not rely upon just one instrument or mission) data set modelling Earth radiation fluxes from 1984 to the present day, with ongoing coverage for the foreseeable future.

There are two principal limitations to the utility of these datasets: they do not account for variability of cloud cover from day to day; and there is a discontinuity at the boundary from month to month.

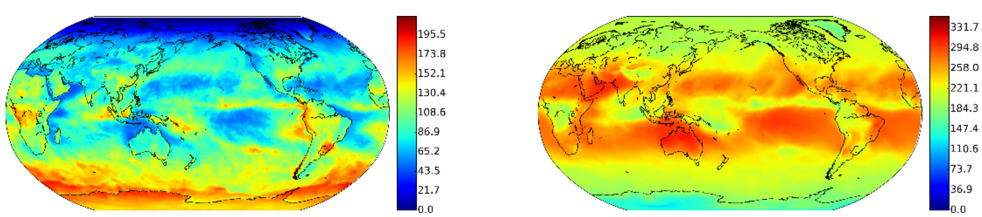

Figure 3: Typical Shortwave (left) and Longwave (right) Top of Atmosphere Fluxes (watts per square metre).

As a first order approximation the TOA Earth radiation flux on the sunlit side of the planet is of the order of 300 Wm^{-2}.

To put these effects into an approximate numerical basis the first order solar radiation effect on a GPS satellite (if ignored in the orbit prediction process) leads to orbit errors of the order of 200 metres after 12 hours. Earth radiation effects (at the MEO altitude) are more subtle (introducing errors of the order of a decimetre) but have been shown to be essential in reaching cm level orbit prediction and orbit determination.

3.2 Drag Forces

Atmospheric drag is an important forcing effect primarily for RSOs with altitudes below 1,000 km. Drag forces scale with the square of the orbital speed with respect to the atmospheric gases present on orbit. Accurate modelling of the force relies intrinsically upon the accuracy of the applied atmospheric density model. Many such models exist. The more sophisticated models require access to some kind of excitation parameter that allows the analyst to compute the level of energy input to the atmosphere derived from coupling between the solar and terrestrial magnetic fields. Historically this has set limits on atmospheric density modelling accuracy because of the crude nature of the excitation data (using e.g. the kp index and/or F10.7 flux data). A recent and successful development in this area is the use of FUV/EUV excitation proxies derived from on-orbit data by Bruce Bowman [*Bowman et al.*, 2008].

4.0 SAMPLE TRAJECTORY ANALYSIS TO ILLUSTRATE PERTURBATIONS

To put some of these ideas into a more accessible form the following charts show orbit perturbations (as time varying Keplerian elements) a particular high-area-to-mass ratio object. The chosen object (the instrument cover MSG2) is in a near GEO orbit. Its high area-to-mass ratio makes it particularly sensitive to non-conservative force effects. The simulations are run over five years, using a Runge-Kutta 7(8) integrator with a monopole gravity field model and various perturbing accelerations. Hence each chart shows the variation in the Keplerian elements due to the individual force effects.

Object characteristics:

Mass: 8.4 kg
Area: 1.9 m^2
Surface reflectivity: 0.65
Surface specularity: 0.5
Attitude: fixed in inertial space

Initial conditions:

Epoch (UTC): 2002 02 21 13 h 38 m 40.0 sec

Position and velocity (inertial space, J2000):

X	-37620.7299926867	km
Y	18607.8182157577	km
Z	1543.41861267524	km
U	-1.36697367349601	kms^{-1}
V	-2.75648363474697	kms^{-1}
W	0.0725259567196874	kms^{-1}

Keplerian elements[2]:

a	41917.565223416488	km
e	0.0027287996838664	
i	2.49988798611838	degrees
Ω	96.2998394460469	degrees
ω	281.595636306614	degrees
ν	135.811548089865	degrees

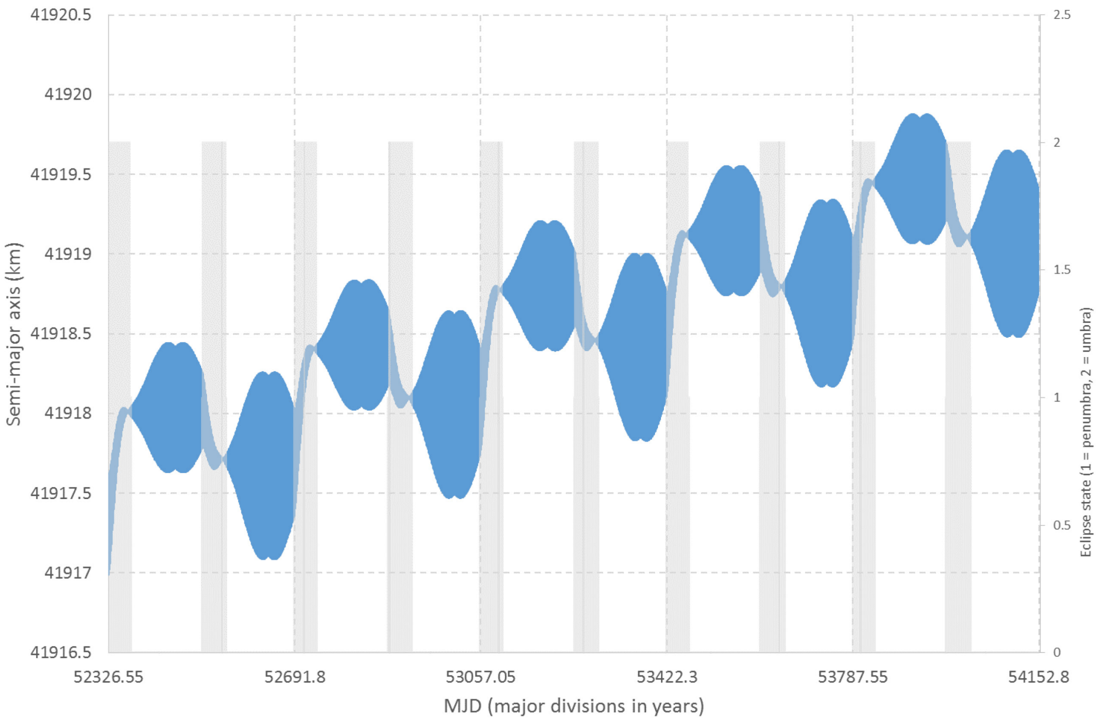

Figure 4: Variations in the MSG2 Semi-Major Axis Due to Solar Radiation Pressure (the grey vertical bands are eclipse seasons).

[2] Precision retained to facilitate checking if required.

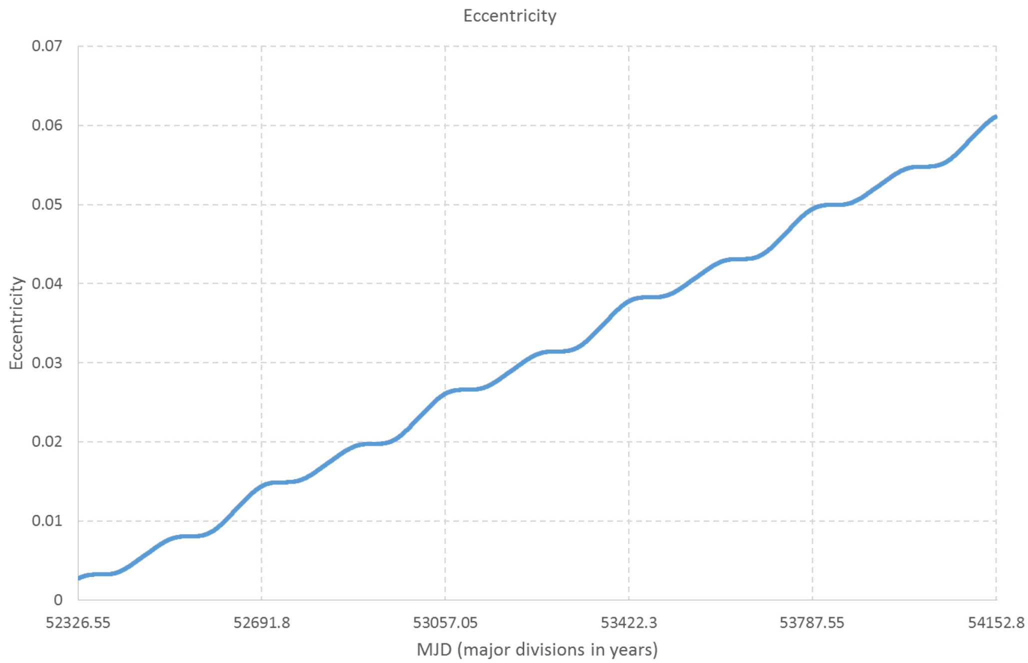

Figure 5: Variations in the MSG2 Eccentricity Due to Solar Radiation Pressure.

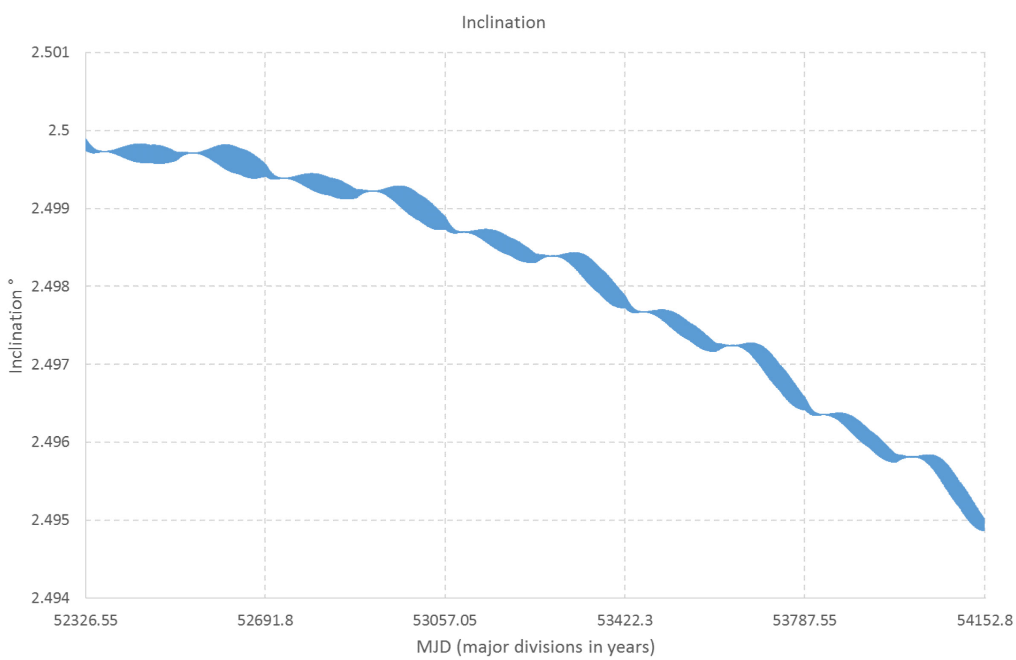

Figure 6: Variations in the MSG2 Inclination Due to Solar Radiation Pressure.

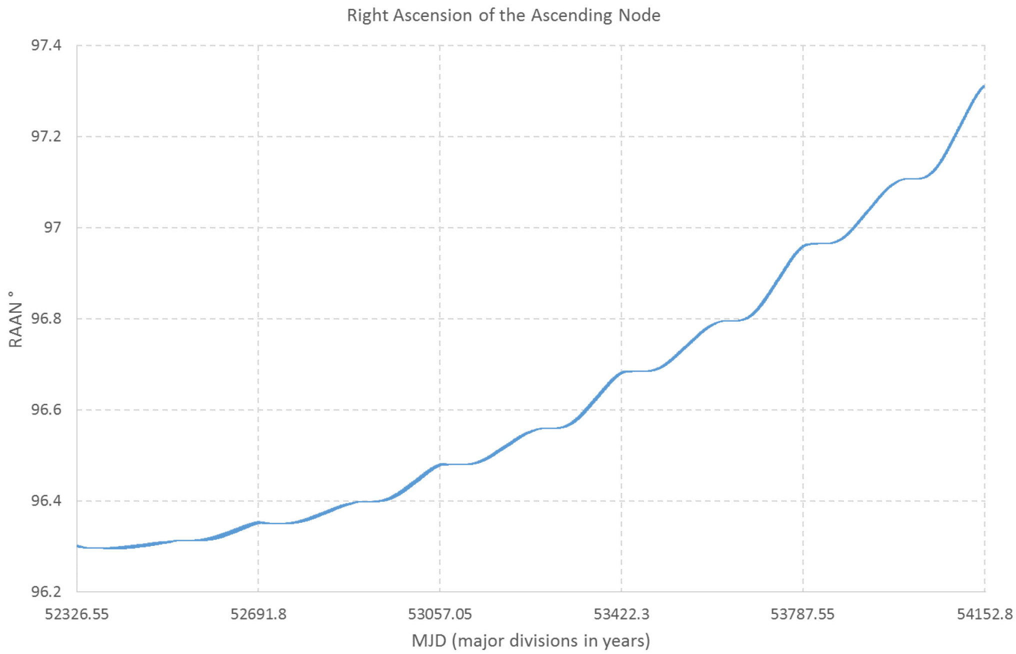

Figure 7: Variations in the MSG2 RAAN Due to Solar Radiation Pressure.

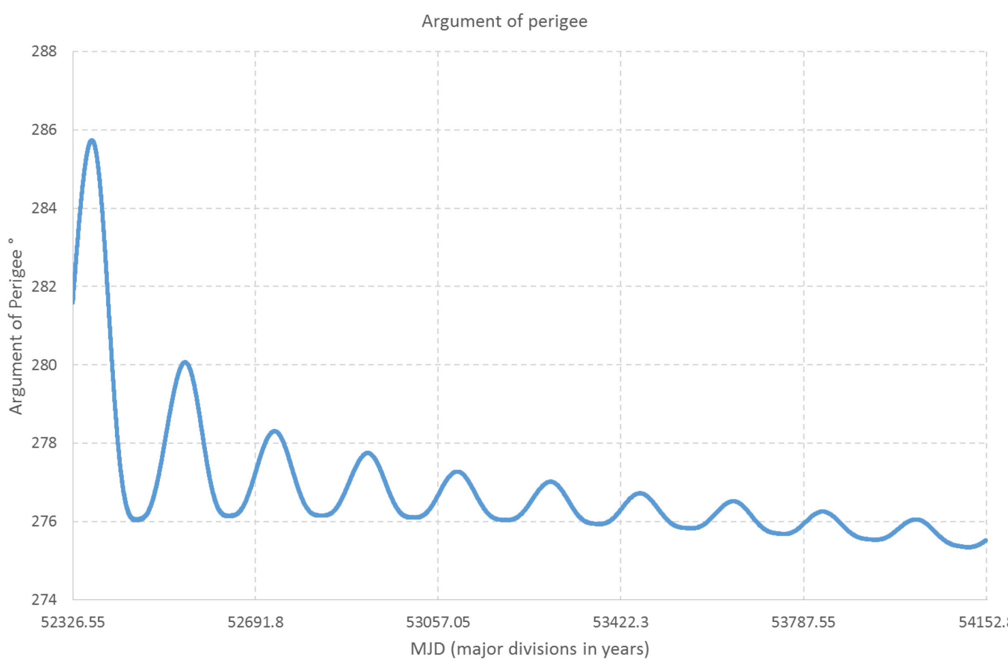

Figure 8: Variations in the MSG2 Argument of Perigee Due to Solar Radiation Pressure.

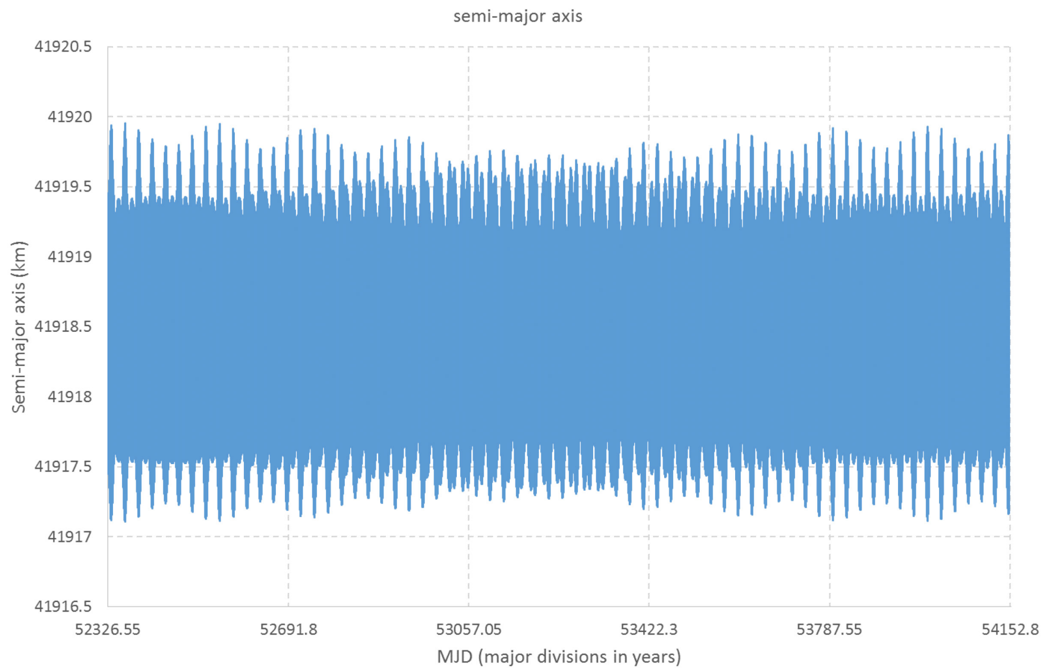

Figure 9: Variations in the MSG2 Semi-Major Axis Due to Third Body Lunar Gravity.

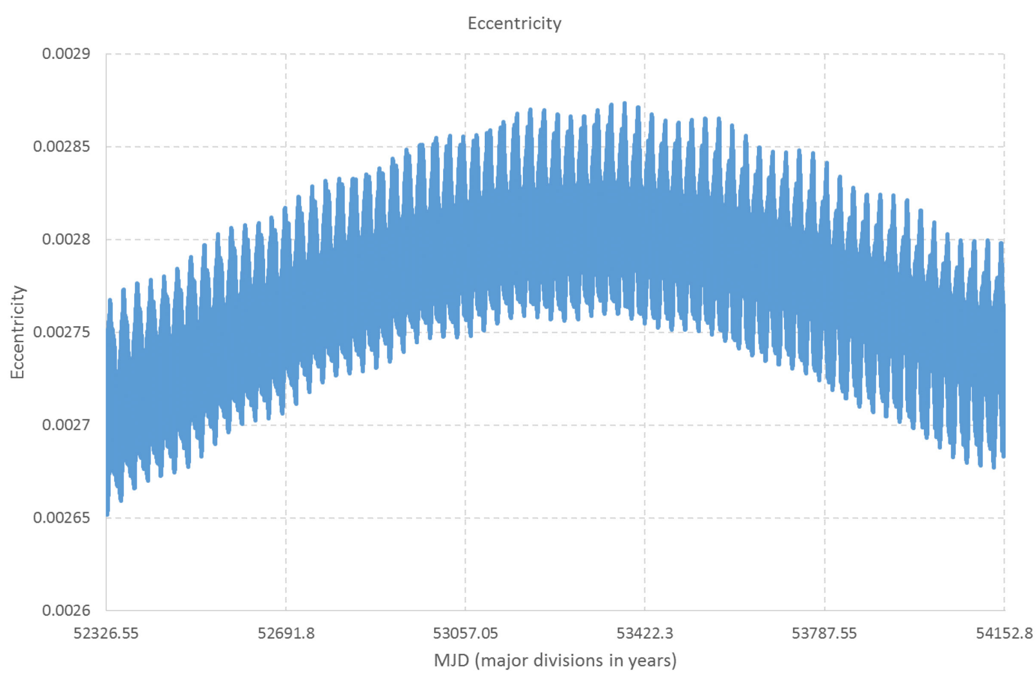

Figure 10: Variations in the MSG2 Eccentricity Due to Third Body Lunar Gravity.

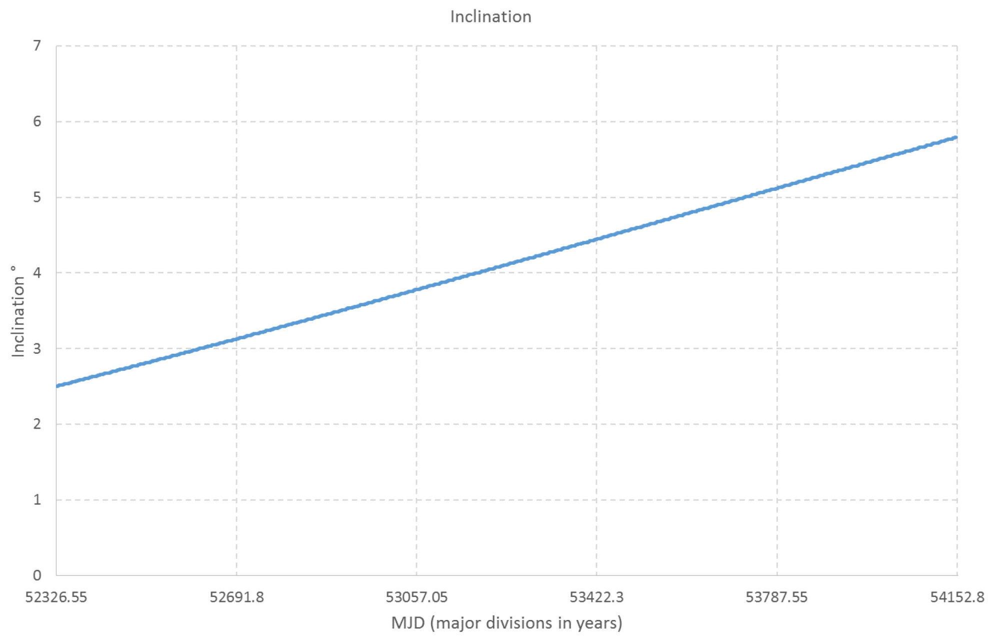

Figure 11: Variations in the MSG2 Inclination Due to Third Body Lunar Gravity.

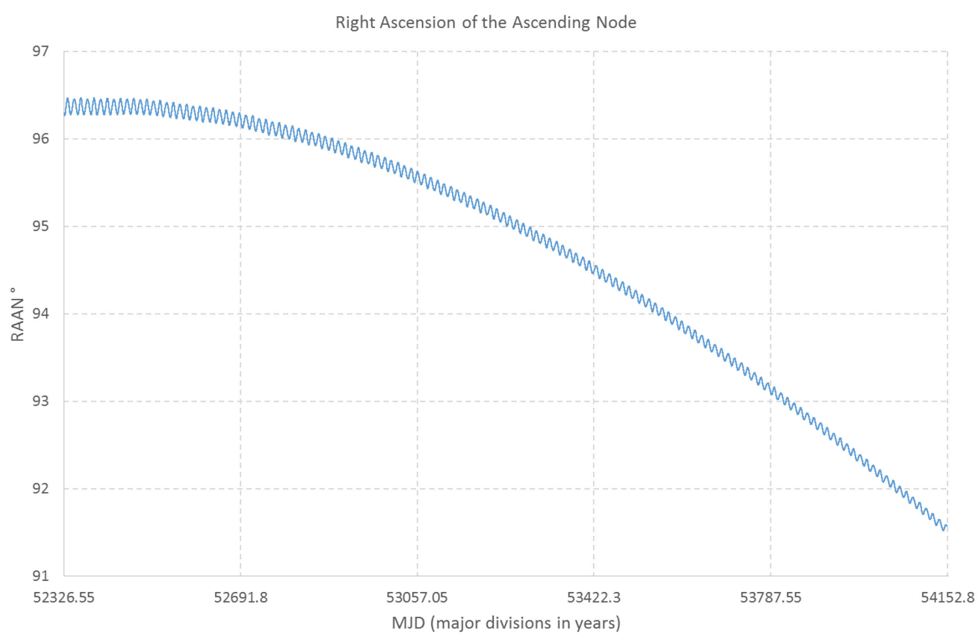

Figure 12: Variations in the MSG2 RAAN Due to Third Body Lunar Gravity.

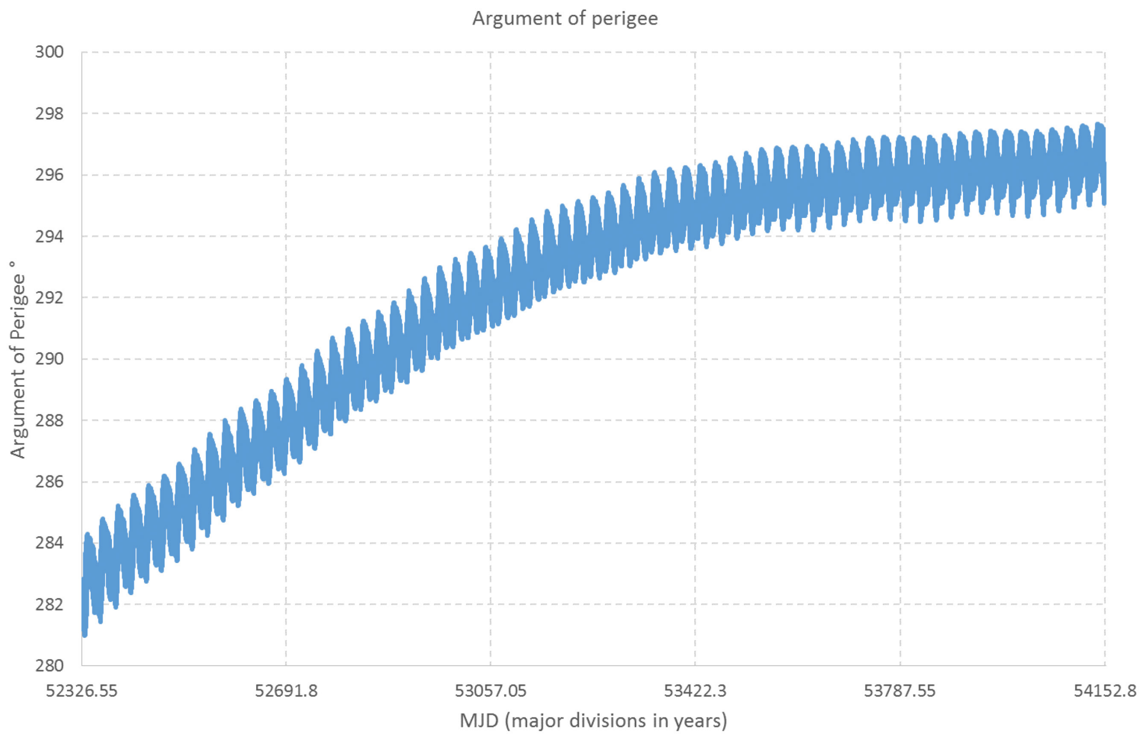

Figure 13: Variations in the MSG2 Argument of Perigee Due to Third Body lunar Gravity.

From all of the above it can be seen that the modelling of dynamics in the space environment has developed rapidly over the last twenty years. Significant data sets are publicly available – geopotential models, planetary ephemerides, radiation flux data, atmospheric density models and models of the Earth's magnetic field. These data sources have been proven highly effective in supporting the orbit determination of a range of missions easily accurate to the level of a decimetre, and in many cases accurate to the level of a centimetre.

5.0 SUMMARY

The trajectories of objects moving in the near Earth space environment are shaped by two fundamental drivers. The first of these, and without doubt the dominant characteristic of almost all motion, is that caused by the influence of the natural environment. Broadly speaking those effects can be classified as conservative gravitational forces, non-conservative radiation and particulate (drag) forces and finally electro-magnetic forces derived from the interaction between the geo-magnetic field and accumulated electric charge. The second driver is that due to deliberate thruster activity required for station keeping and trajectory control. The very significant scientific advances in the understanding and modelling of the former set of forces present an opportunity for space domain awareness to reap the benefits of decades of research. To date the SDA community has not grasped that opportunity despite the considerable gains that are to be made. Existing approaches to trajectory characterisation and prediction using crude modelling techniques limit severely our ability to both estimate and predict RSO motion. Whilst it is a non-trivial undertaking to use more advanced modelling approaches, they are within reach and have a strongly proven track record.

6.0 ACRONYMS AND ABBREVIATIONS

AT	Antenna Thrust
BFS	Body Fixed System
CCAR	Colorado Centre for Astrodynamics Research
CERES	Clouds and the Earth's Radiant Energy System
CODE	Centre for Orbit Determination in Europe
CSR	Centre for Space Research, University of Texas at Austin
DORIS	Doppler Orbitography and Radio positioning by Satellite
EOS	Earth Observing System
ERBE	Earth Radiation Budget Experiment
ESOC	European Space Operations Centre
GEO	Geostationary Earth Orbit
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GSFC	Goddard Space Flight Centre
HCL	Height, Cross track, aLong track
JPL	Jet Propulsion Laboratory
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
MLI	Multi-layered Insulation
NASA	National Aeronautics and Space Administration
POD	Precise Orbit Determination
PRP	Planetary Radiation Pressure
RSO	Resident Space Object
SLR	Satellite Laser Ranging
SRP	Solar Radiation Pressure
SV	Space Vehicle
SVN	Satellite Vehicle Number
TOA	Top of Atmosphere
TRR	Thermal Re-radiation
UCL	University College London
VLBI	Very Long Baseline Interferometry

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