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A Preliminary Investigation of Space Junk Positioning and Tracking Techniques

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ABSTRACT

The prediction of motion of space objects have had a history of half a century since the first Russian satellite Sputnik I was launched in 1957. With the advancement in technology, space positioning and tracking techniques have been also enhanced, which leads to the accuracy improvement of positioning from metres or even kilometres to now centimetres and opens up new methods of space object tracking. Complex calculations and state-of-the-art models have been developed to accurately predict the movement of space objects, and constant refining of prediction models are employed. However, with insufficient spatial data, our current achievable prediction is still insufficient to accurately predict space objects and their orbit to our space industry's satisfaction.

Atmospheric density is currently the major error factor affecting signals that propagate through the atmosphere, with atmospheric density models that are only accurate to 85%. Numerous different methods have been developed to manipulate existing data to formulate and achieve better predictions, such as modelling errors of a model or using least squares to put weight on different factors, but yet to achieve an acceptable standard. This paper first reviews a number of methods of positioning and tracking and their pros and cons are assessed. The key factors affecting the accuracy of positioning and tracking, such as the atmospheric density and the atmospheric drag are identified and some preliminary conclusions are given.

KEYWORDS: Atmospheric Density; Space Junk; Space Debris; Positioning; Tracking

1. INTRODUCTION

The prediction model of satellite's movement has been investigated for half a century, since1957, when the Sputnik I was launched. Factors affecting the motion have been identified such as gravity, radiation pressure, atmospheric drag, geoid modelling, solid earth and ocean tides and troposphere. Most of these major factors have already been accurately measured, processed, analysed and modelled, with remaining errors which are deemed insignificant. However atmospheric drag, or aerodynamic drag, stands as the most dominant factor when determining orbits of satellites operating in earth's upper atmosphere below approximately 600 km. It affects the precision of Satellite Orbit Determination (SOD) and prediction, collision warnings and avoidance, re-entry prediction, lifetime estimates and attitude dynamics.

The precise orbit determination and prediction of all space debris objects is vital information for any aerospace mission from maintenance of our International Space Station to launching a space vehicle. This is due to National Aeronautics and Space Administration (NASA) estimation of approximately 100,000 uncatalogued debris objects with size greater than 100 mm and tens of millions debris objects less than 10 mm in near earth Space (NASA, 2004b). To prevent damage or collision to any space vehicles, the orbital information relating to sizable space debris require detail monitoring, and regular updates and improvements in orbit determination. Innovative methods and the latest technologies are employed to determine and enhance the prediction of space debris, such as laser ranging, compared to traditional radar and optical tracking. However, this innovation is still inadequate and limited by the accuracy of the Atmospheric Density Models (ADMs). It is therefore vital to develop precise new ADMs and/or look at improvements over existing ADMs.

2. SPACE JUNK

Space junks or space debris are unwanted objects or rubbish which are left floating in space, it is classified into two different categories, orbital debris and meteoroids. Meteoroids are the "natural substance" in space, including fragment of asteroids and bits of comet, it is capable of travelling on an average speed of 20 km/sec in its orbit. Orbital debris are man made objects that are left in space, this is caused by a variety of reasons, for example, parts of space vehicle that had fallen off, such as small bolts, these objects can travel on average speed of 9 km/sec (NASA, 2004a). Impacts from space debris on any space shuttle or space station can cause a catastrophic effect, leading to irreparable damages or even failure of space missions This demonstrates the importance of a space debris monitoring network as a guidance tool to locate space debris, because it reduces the possibility of space vehicle to space debris collision, thus benefiting our space industry.

The space industry concerns lie in space debris which are between 10 mm to 100 mm, because the current technologies are only capable of monitoring space debris down to 100mm cross sectional diameter, but modern space vehicles can only withstand the high speed collision impacts from space debris of up to 10 mm in cross sectional diameter. Some space vehicles are smartly "designed" with approximately 200 different types of "whipple shields", preventing disastrous damage from space debris (ESA, 2005a), composed of protective cladding on the external surface of space vehicles and ceramic with Kevlar materials, used in bullet proof vest, therefore small space debris of less than 10 mm are expected to collide in space (NASA, 2004a).

Due to the limitations of providing sufficient protection for space vehicles in the case of a collision, avoidance of space debris becomes the only solution to the problem, Figure 1 illustrates space debris around earth in the Low Earth Orbit (LEO) and Figure 2 for space debris around the High Earth Orbit (HEO) (NASA, 2007). To avoid space debris, their location and orbit must be known at a point in time when the space vehicle travels through the space debris' orbit. Different organisations have their own system of space debris monitoring, most commonly known ones are Space Surveillance Network (SSN) (NASA, 2004b) monitored by the Department of Defence in the United Sates, or the Database and Information System Characterising of Objects in Space (DISCOS) operated by the European Space Agency's (ESA) Operation Centre (ESOC) (ESA, 2005b).

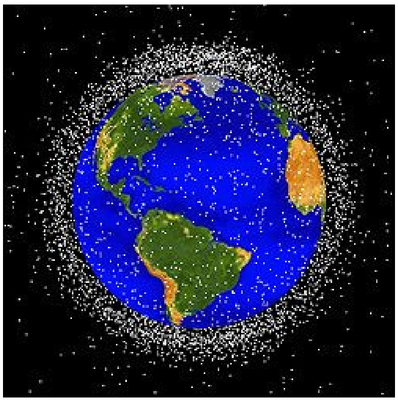

Figure 1. Space Debris in LEO

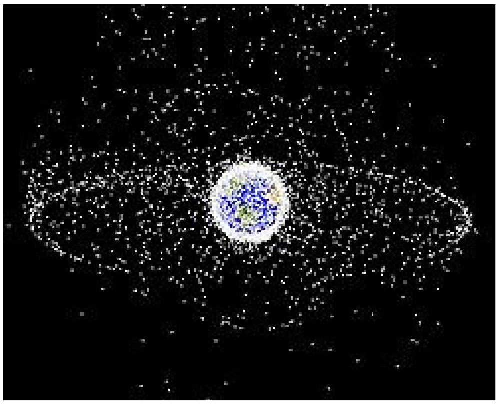

Figure 2. Space Debris in HEO

3. POSITIONING AND TRACKING TECHNIQUES

There are mainly two parts in space debris monitoring system, determination and prediction. Determination refers to determining the location of space objects at a point in time. Prediction is using the existing data to estimate the future path of the space object of concern. It involves a collaboration of both determination and prediction to successfully track and position space objects. Traditionally, there are two ways of positioning and tracking space objects, which is via radar or optical method, but as the importance of space debris monitoring develops to become a key issue in the industry, new space debris positioning and tracking techniques are established.

3.1 Radar

Radar tracking is used mainly for Low Earth Orbit (LEO) tracking, it electronically controls the radar beam to search and track for space objects and is capable of operating twenty four hours a day, refer to Table 1. Different modes of tracking allow the radar to trace and follow space objects, observe over a period of a few minutes, obtaining data, such as angular direction and range rate. These elements are useful to deriving orbital elements by evaluating direction and velocity as a function of time. Manipulating observable data as parameters, vital characteristics of space objects can be derived such as; orbital elements and lifetime, altitude and mass, size, shape and material properties (United Nations, 1999). But radar requires enhanced technology, the cost factor is a negative aspect to radar tracking as well as the ability to only able to track space debris of greater than 100 mm, but attempts have been made to track objects below 100 mm.

Radar range is measured using two methods, one-way transmission and two-way transmission. One-way transmission is when the receiving sensor receives a transmitted signal direct from the satellite, but this is the case only for satellites with radar transmitters, therefore it cannot be used for debris tracking. Two-way transmission is when the signal is transmitted from ground to the space object, either a satellite or debris, and reflected back to the receiving sensor. Partial signals are lost at the point of contact to the space debris, because only part of the signal will get reflected back. The signals also weaken as it travels through the atmosphere to the space debris and back through the atmosphere again to the receiver. The equation for ranging can easily be derived (Vallado, 2001):

$$\rho = \frac{c\Delta t}{2} \tag{1}$$

where, ρ is the range; c is the speed of light; Δt refers to the change in time between when the signal is sent t_{trans} and when it is received t_{rec}.

The above Equation 1 is a simplified version of measuring range to the space debris. The range is derived by multiplying time difference and speed of light, it is then divided by two, because it is a two-way transmission, signals to and from the space debris. This equation has yet included any of the associated error sources, main one being Atmospheric Density Corrections discussed later on in this paper.

3.2 Optical

Optical tracking involves observing space debris via telescopes. It is capable of observing space debris in mainly the HEO, but as with all optical observation, is only operational at night in a dark environment to observe stars and space objects, refer to Table 1. The major issue affecting the accuracy is visibility. Density of clouds along with weather conditions around the area can strongly impact the observation, because it determines how much the observer can “see”. Different telescopes are designed differently to serve different observation purposes, for example in Japan, the Japan Space Forum and National Aerospace Laboratory of Japan has a telescope that is 0.5 m aperture and 2 degrees field of view, designed more for wider angle with lower magnifying capabilities, compared to one of the NASA owned telescope that is 3.0 m in aperture and 0.3 degree of view, which is reversely capable of magnification, but with limited field of view (United Nations, 1999).

The Ground-based Electro-Optical Deep Space Surveillance (GEODSS), for example, is assigned mainly for purposes of SSN, two of the telescopes used are capable of “seeing” objects which are approximately 10,000 times dimmer than objects human eye can see. Cameras are mounted with the telescope along with computers, so it is capable of taking snap shots of space, these snap shots are overlayed by using stars as fixed points which will show debris which are moving at a different rate (AFSPC, 2003). Figure 3 illustrates a photograph of the cameras mounted on an Optical and Laser ranging telescope in Mt. Stromlo, inside Observatory of Electro-Optics Systems, Canberra, Australia.

Figure 3. Cameras of Optical Telescope, photographed at Mt. Stromlo Observatory

Table 1. Comparison between 3 types of positioning and tracking methods

Method	Advantages	Disadvantages	Comments
Radar	• 24 hours automated tracking • Different radar signals can be transmitted	• Largely effected by atmospheric densities • Only part of the signals get reflected back to receiver • Cost implications	• Capable of monitoring LEO objects • Significant research already done in this area
Optical	• Can see objects 10,000 times brighter • Less effected by atmospheric densities	• Effected by local weather and cloud densities • Must operate in dark sky	• Capable of monitoring HEO objects • Different purpose telescope for different purpose • Significant research already done in this area
Laser	• Inexpensive • Capable of monitoring a number of space objects	• Less efficient in finding new objects • Only part of the signals get reflected back to receiver	• Big cost involved in development and improvements as it is a new technology

3.3 Laser

Laser ranging concept is similar to radar ranging, by sending beams to the space debris and measures the return signals, therefore the errors associated are also similar, refer to Table 1. However laser is considered a more advanced technology compared with the conventional radar and optical, it is operated by manipulating parameters that affect the laser beam, such as the laser power and beam divergence. Contributions that allow current laser technology to be employed for space debris tracking, included ability to magnify the laser power, but with great cost. The beam divergence is also reduced 10 times or 2 orders of magnitude from traditionally 25 μrad to 2.5 μrad. Along with these improvements, other minor parameters are also taken into account, such as dome vibration, wind and thermal factors, because each factor can cause error up to 1 - 2 μrad. Safety issue to the eye was also of concern prior to current development due to the radiations emitted from laser signals, sufficient protection and reduced in human eye exposure is presently capable (Greene, 2003).

Laser tracking is relatively inexpensive and capable of tracking a larger number of space debris, but it is not as competent in finding new space objects, however it outperforms in tracking and positioning.

3.4 Data Processing

Technology has not only allowed the space industry to locate and trace finer space debris, but also improved in data processing. Historically, real time data tracking was an expensive tool to use in space debris monitoring, it involved great computer power that not all laboratories could offer, because it automatically positions and tracks space debris while constantly measuring its location. Therefore Post Processing was commonly used, which involves locating and observing same debris over a period of time, then input the observations into the computer to predict its movements and compare computed prediction to the actual measured, so the predictions can be refined. But with the research and development in computer technology, it has significantly improved and shortened the post processing time. It is estimated that in the next five years, there will be minimal difference between real time and post processing with the use of super computers.

4. ATMOSPHERIC DENSITY MODELS (ADM)

ADMs are established to model real atmospheric environment that affects the signals as it travels through the atmosphere. It requires the user to input particular parameters into the model, however some of these parameters maybe not be accurately measured, therefore the result of the ADM will be largely effected by the errors associated with the parameters.

ADM consists of many different components with major one being temperature, which is affected by solar activity (Knipp et al., 2005), location, time and other factors, but in theory, it could be formulated as a diffusion equation (Jacchia, 1971). As the atmosphere is a known error factor, existing ADMs have included very complex but critical information, with different mathematical models to predict, at best, with errors greater than 15% of the measured density values under stable atmospheric conditions. Under unstable occasions, errors can propagate greater than 20 – 30%, due to the insufficient temporal and spatial data. With this percentage of error, avoiding space debris collision and predicting decay of debris object is very challenging. A solution is to investigate an adopted density model using tracking data of some space objects, then iteratively generate an improved model leading to improved predictions (Bergstrom et al., 2002; Yurasov et al., 2004).

Atmospheric Drag as described above, as one of the dominating factor that affects Precise Orbit Determination (POD) for earth's upper atmosphere below approximately 600km. For highly accurate atmospheric drag models, it includes measurements for a ballistic co-efficient, as also known as measurement of projection (Bowman, 2002). Equation 2 demonstrates the components of Orbital Drag Accelerations acting on a space object (Marcos et al., 2004):

$$a_D = \frac{\rho V^2}{2} \times \frac{C_D A}{M} \qquad (2)$$

where a_D is the atmospheric drag; ρ is the atmospheric total mass density; A is the cross sectional area of the space object; M is the mass of space object; C_D is the atmospheric drag coefficient; V is the velocity, whereas $C_D A/M$ can also be defined as the ballistic coefficient (B)

In the above equation, refer to Equation 2, total atmospheric drag is derived by; velocity, ballistic coefficient and the atmospheric total mass density. But with the insufficient accuracy in atmospheric data it poses a great challenge to accurately model Atmospheric Drag. The 'Drag' factor is mainly driven by the solar activities, it falls into two components, the Solar Extreme Ultra-Violet (EUV) radiation, which is the heat source and affects mainly between the low to mid-orbit and accounts for approximately 80% of the heating of the thermosphere. Geomagnetic activities is the other dominant factor in drag, it is a stream of charged particles (electrons and protons) which escaped from the sun's gravity due to high temperature, and it is highly active, but this only accounts for approximately 20% of the heating (Marcos et al., 1997).

There is currently one commonly used method to solve for the errors of ADM. It involves accurately modelling errors of specially chosen objects with proper space tracking data, the errors tend to fall into particular patterns which the model is capable of identifying. The results will be the "errors of the ADM", hence Atmospheric Density Correction Model (ADCM). These errors will then be used for refining the model, it is an iterative process, but theoretically the more data the model process, the accuracy will improve. Another method to solve for ADM errors is currently under investigation, it involves separating each component of the atmospheric equation, then distribute the total error to each of these components. This approach contain a crucial unresolved problem to date, there is only one error associated with each observation from the ADM, for example, the 15% inaccuracy previously stated, the problem lies in mathematically distributing the amount of "error" by weight, into different all the components of the equation. Once this problem is resolved, it will definitely produce better prediction of space debris orbit, because the error is known for each of the component of the equation rather than just implanting historical data to improve on existing models to generate predictions. But either method is designed for more accurate debris location determination and debris orbit predictions

5. CONCLUDING REMARKS

This paper first reviews a number of methods of positioning and tracking and their pros and cons are assessed. Because space debris has become one of the key topics in the space industry due to the catastrophic effects if not avoided. As the number of space debris increase, either due to nature or man-made reasons, more accurate models and predictions must be developed. The key factors affecting the accuracy of positioning and tracking, such as the atmospheric density and the atmospheric drag are identified and some preliminary conclusions are given. By improving accuracies in Atmospheric Density Models and by employing more accurate and reliable data, alongside with inventions to new methods of error mitigation must be investigated. As space technology builds on, eventually there will be easier, more accurate and cost effective methods of tracking and positioning, benefiting our whole space industry internationally.

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