CONFIRMING THE ACCURACY OF ORBITAL ELEMENTS AND CLOSE-APPROACH PREDICTIONS IN GEO

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ABSTRACT

In order for close approach forecasting to have value the predictions need to be consistent, accurate and reliable. We have investigated the frequency of close approaches in GEO. The PIMS network of optical sensors was then used to verify the use of NASA TLEs for close approach forecasting in GEO. Multi-site trigonometric parallax observations offer an independent method of evaluating the accuracy of TLE orbit based close approach predictions. Examples of close approach observations are used to show that the public domain NASA TLEs are not well suited to close approach forecasting.

1. BACKGROUND

Observatory Sciences Limited has operated the PIMS network of optical space surveillance sensors under contract to the UK MoD since 1998. The PIMS network consists of five robotic 40 cm Schmidt Cassegrain telescopes, equipped with CCD detectors, at three locations: Herstmonceux in the UK, Gibraltar and the Troodos Mountains, Cyprus. The sensors are controlled by automatic tasking scripts downloaded each day from the central control point in the UK. Observations are automatically reduced and the data are returned to the UK for post processing and analysis shortly after the end of the night's observing run.

2. INTRODUCTION

The geostationary orbit region is a narrow region of space containing a relatively large number of objects. Unlike other orbital regimes the choice of orbital parameters in GEO is, by definition, limited by the requirements of remaining stationary over a fixed surface longitude. The popularity of the region has led to a high population density which places tight constraints on the accuracy with which satellites must be maintained within the bounds of their designated ITU orbital "slots". Satellite operators rely on accurate knowledge of the orbits of their own payloads, derived from their own telemetry information, to keep each satellite within its slot, thereby keeping their satellite safe from interaction with neighbouring objects which are expected to be maintained within their own slots. The analysis of satellite orbits in this paper suggests that the sense of security that this strategy engenders can be illusory. Without collaborative action between satellite operators to co-operatively manage manoeuvres there exists a real danger of collision between neighbouring controlled payloads. Co-operation between satellite operators can mitigate the risks of payload-payload interaction. However, there are also significant numbers of objects that no-one controls—space debris in its various forms. Space debris needs to be constantly monitored to ensure that high quality orbits are available to allow satellite operators to know and, if necessary, to minimise the risks that debris poses to active payloads.

For general space surveillance requirements a high degree of accuracy in the predicted positions of a satellite or piece of space debris is rarely required for the purposes of catalogue maintenance. The primary requirement is that the object should appear within the field of view of the sensor on the timescale demanded by the requirements of the catalogue maintenance; this timescale, and hence the degree of required accuracy, is set by the limitations on observing and analysis time available for the task. One exception to this limitation on the requirement for accuracy occurs when a close approach is predicted. In the case of close approaches the accuracy of the prediction is critical; where likely errors are small, the false alarm rate is also small, allowing an operator to make an informed choice whether to take action to mitigate the potential threat to a payload; if the errors are large, false alarm rates will also be large, making informed decisions impossible.

3. CLOSE APPROACHES IN GEO

Observatory Sciences collected a set of copies of the public domain NASA catalogue of unclassified deep space TLEs covering the years 2002 and 2004. The longest gap between the copies of the catalogue was 6 days at the beginning and end of each of the years; for the rest of each year updated copies were obtained at least three times each week. These catalogues were then used to make predictions of satellite positions to investigate the frequency of close approaches. The histogram plot of the number of approaches within miss distance bands for the results of the calculations for 2002 is shown in Fig. 1.

Objects with TLEs older than 15 days were not used in the calculations. Wherever possible, close approaches between two co-controlled or clustered satellites have been excluded.

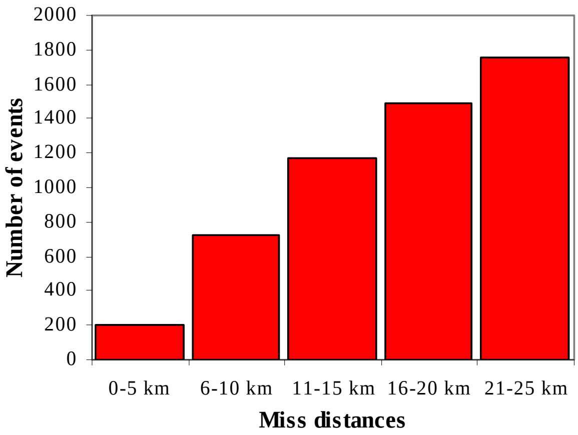

Figure 1. Histogram plot of frequency of close approach miss distances during 2002.

A very similar frequency distribution of events was observed in the results of the calculations for 2004. As can be seen from the histogram a significant number of approaches takes place each year.

The bin representing the closest approaches, those with a miss distance of 5 km or less, contains over 200 events, involving 116 different objects, in the 2002 data; similarly, over 200 events, involving 140 different objects, were found in the 2004 data. These events fall into a regime where the calculated miss distance is similar to the expected propagation accuracy of the TLEs, which are often quoted to have a propagation error of around 3 km.

Analysis of the list of events in the bin of approaches with a miss distance of 5 km or less shows that these totals include a number of temporary associations where one satellite replaced another in an orbit slot and pairs of satellites for which an association was not recognised in the histogram analysis. It is estimated that these residual co-controlled pairs only represent around 10% of the total of near misses displayed in the histogram. Over 25% involve at least one uncontrolled object. At least 10% of the approaches involve two clearly defunct satellites. Only a small number of the approaches (a little over 2%) involve rocket bodies or other pieces of space debris. The remaining near misses are between two apparently unassociated neighbouring active payloads.

4. TESTING THE ACCURACY OF THE PREDICTIONS

Having established that the NASA TLEs predict that there may be significant numbers of close approaches in GEO it is necessary to establish that these events are real, not just an artefact of the TLEs themselves. For example, it is possible that these events are the result of observations taken either side of a manoeuvre being used to calculate the TLE, the inclusion of observations of mis-identified objects, or some other source of errors in the TLEs. Observatory Sciences, therefore, set out to undertake observations of predicted close approaches to determine the level of agreement between the predictions and the real on-orbit situation.

4.1. The procedure

Observatory Sciences observes the environment surrounding UK geosynchronous satellites so it was decided to watch for possible close approaches involving a selection of these objects. Each day a programme was run to make predictions of the positions of the target satellites covering the next sixteen days; these predicted positions were compared with the positions of the rest of the GEO objects to look for close approaches. A close approach was defined as any object passing within 25 km of one of the target satellites.

In common with most schemes to predict close approaches, objects that could not possibly come close to the target were eliminated from the list of potential approaching objects. A closer examination was then undertaken of the remaining objects from the catalogue of TLEs. This allowed the list of potential approaching objects to be further refined by eliminating objects which would not approach closely during the prediction period. Finally, any object for which there was any possibility of a close approach with one of the target satellites during the prediction period had its position calculated with increasing frequency around the time of closest approach to obtain a distance of closest approach, the "miss distance", between the two objects.

Once such an approach had been predicted the PIMS network of sensors was tasked to obtain observations of both objects in advance of the date of the anticipated event. The scheduling system was tasked to obtain observations of each object every two hours throughout the night. These observations were then fed into an orbit improver to create refined orbits which were used to make further predictions as the time of the forthcoming approach came nearer.

Sometimes these updated orbits demonstrated that no event would occur. In general this was the result of a manoeuvre of one of the objects which moved its track away from the original predictions. An alternative cause was an error in one or other of the original TLEs, possibly due to the TLE having been created from data spanning a manoeuvre or including mis-tagged observations. Around 50% of the predictions made 16 days in advance do not result in an approach. This kind of false alarm rate is to be expected given the typical payload manoeuvre cycle. However a number of false negatives, where the predictions 16 days in advance have not predicted an approach, have also been observed. Often a new TLE, issued closer to the date of the approach, results in a new approach being added but also some events which were not predicted at all have been serendipitously seen during routine observing.

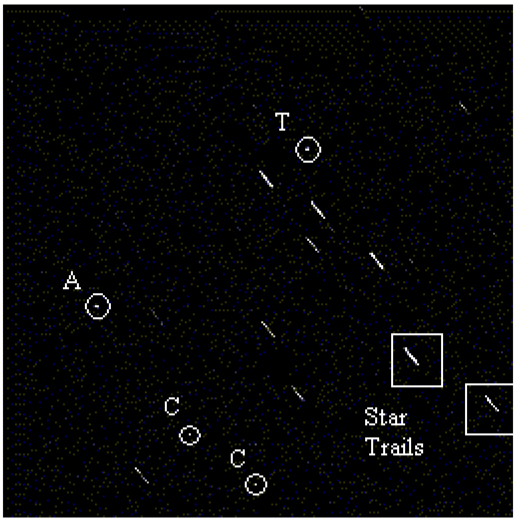

Figure 3.1. 20 minutes prior to closest approach.

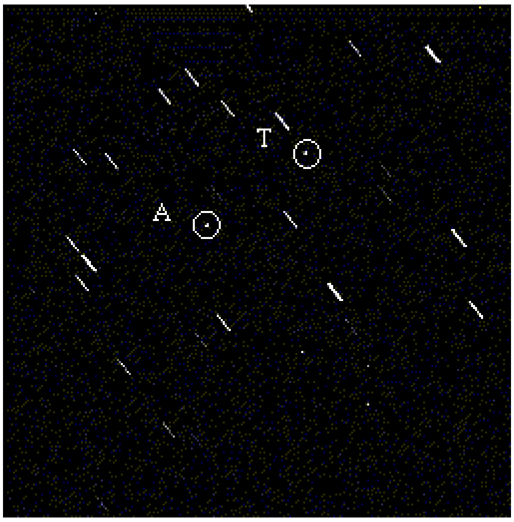

Figure 3.2. 10 minutes prior to closest approach.

Figs. 3.1 to 3.4 show some of the PIMS images taken of an approach. The images are stationary with respect to the target satellite T; the approaching satellite A is seen to cross the frame from the lower left to upper right. A nearby group of satellites C can be seen to move with the approaching satellite. Stars are seen as short trails as the sensor is nearly stationary in altitude and azimuth. Where our updated orbits continued to indicate the likelihood of a close approach all of the PIMS sensors were tasked, in addition to the observations of each object every two hours, to obtain continuous observations during the period of the anticipated approach. Continuous observations of the target object were scheduled from twenty minutes prior to the predicted moment of the approach until twenty minutes following the approach. The observations covering the approach were then analyzed to verify the predictions.

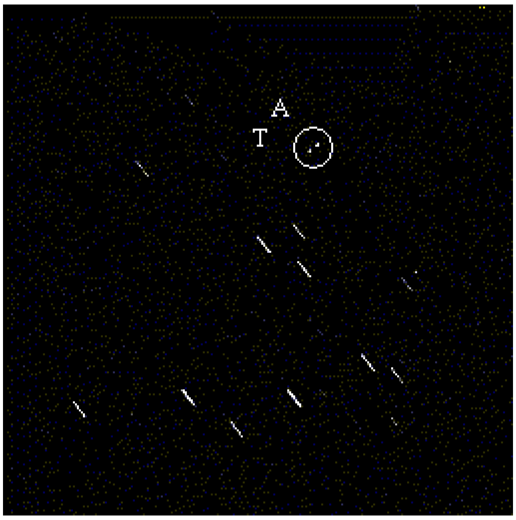

Figure 3.3. Closest approach.

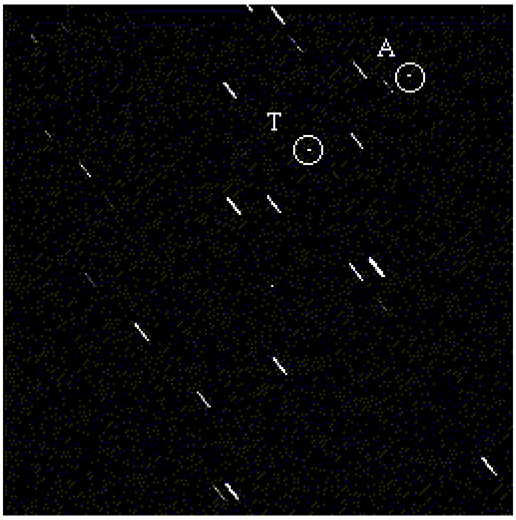

Figure 3.4. 8 minutes after closest approach.

Two modes of observations were obtained of close approaches: those where two geographically separated sensors managed to obtain simultaneous observations of the approach, and those where only a single sensor obtained data. In the first mode the simultaneous observations from two sites are combined to obtain three dimensional positions of the objects at any given moment during the event by triangulation. We refer to this use of triangulation to generate positions purely geometrically as the parallax method. In the second mode the data were used to calculate new improved orbits that fitted the observations as closely as possible during the period of the approach. The improved orbits were then used to calculate the three dimensional positions of the objects throughout the event. We refer to this mode as the dynamical method. Examples of both methods are presented below.

4.2. Parallax method

With observations from more than one site it is possible to use triangulation to get {x,y,z} positions of the objects. Miss distances can be calculated using standard trigonometric methods. The miss distance and time of closest approach calculated by this method are then independent of any dynamical considerations. Each sensor provides RA and declination positions which can be combined to give three dimensional {x,y,z} positions on each object at each instant.

In practice the observations are not exactly simultaneous, so polynomials are fitted through the RA and declination data points from each sensor for each satellite. The polynomials for each satellite are then used with an estimated range to give approximate {x,y,z} positions for that satellite. The ranges to the satellite from the two sensors are iterated to minimize the differences in the {x,y,z} positions calculated from each sensor.

4.2.1. Multi site observations of an approach between 1990-079A and 1996-015A at 23:45 GMT on 27th May 2004.

Both 1990-079A and 1996-015A are active station-kept payloads. Both satellites are in near circular orbits; 1996-015A is a low inclination object with an inclination close to zero degrees; 1990-079A has an inclination of around 5º.

Initial predictions of this event were made using a TLE for 1990-079A dated 18th May 2004 and 20th May 2004 for 1996-015A. The predictions indicated that this was the closest of a series of approaches starting on 26th May 2004, occurring every 12 hours, when the orbital planes of the two objects intersected as 1990-079A ascended and descended through the zero inclination GEO belt. In the days prior to 25th May 2004 the prediction calculations indicated that no close approaches were expected. The absence of any approaches in the predictions made before the inclusion of the new TLEs used for the predictions made on 25th May 2004 was due to a change in the orbital elements of 1996-015A whose right ascension of the ascending node changed from 356º in the TLE of 16th May 2004 to 92º in the TLE of 20th May 2004.

The close approach on 27th May 2004 took place in the middle of the observing period for all the sensors in the network. The GEO longitude of 1990-079A and 1996-015A was such that it was possible to observe the conjunction using all the sensors in the PIMS network throughout the period of the approach.

The RA and declination positions of the satellites as derived from the observations taken during the approach are plotted in Fig 4.

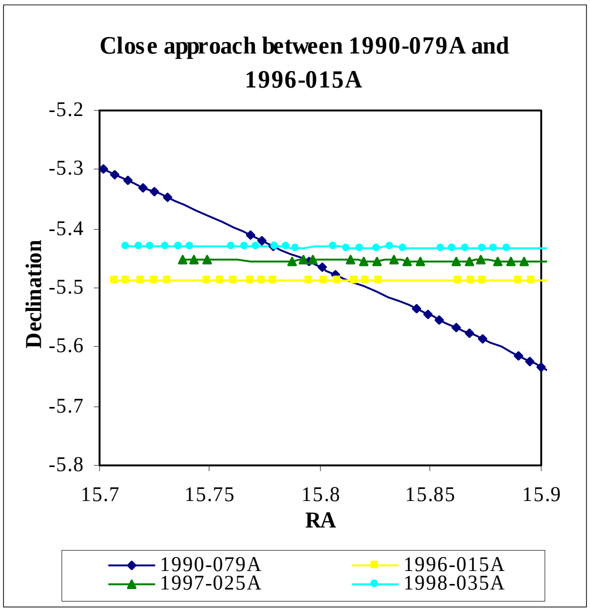

Figure 4. RA – Dec plot of PIMS observations of the close approach between 1990-079A and 1996-015A.

4.2.2 Post conjunction analysis

Observations from four sensor were combined in five pairs to obtain triangulated {x,y,z} positions for the satellites during the approach. Fresh orbits were also calculated for each satellite using observations taken during the nights before the approach and on the night of the approach itself. These orbits were used to calculate dynamical {x,y,z} positions throughout the period of the approach. Miss distances and close approach times were calculated using the {x,y,z} positions calculated by each method. These miss distances and time were compared to each other and to the pre-event prediction.

The minimum angular separation can be used to give an approximate verification of the values of the calculations as this gives the minimum possible miss distance of the objects assuming there is no difference in the radial distances of the objects from the observing site. The minimum angular separation between 1990-079A and 1996-015A was approximately 0.005º. This equates to a minimum possible miss distance of approximately 3 km. The angular separation is equivalent to around 10 pixels on a PIMS CCD detector.

The pre-event prediction from the NASA TLEs for this approach was:

23:45 GMT 21 km

The recalculated orbits using observations taken prior to and during the approach gave a post-event dynamically calculated approach distance and time of

23:47 GMT 6 km

The mean geometric approach distance and time from multi site observations were

23:47.2 GMT 7.4 km

The approximate error in this geometrically derived distance is 1.5 km.

It can be seen that the post-event dynamically calculated and the geometrically derived miss distances and approach times agree well. However there is significant disagreement between the values derived from the observations of the approach and the values predicted from the NASA TLE.

Since the pre-event predictions do not agree well with the observed miss distance, the cause of the difference was investigated. The routine pre-event observations of the two satellites in the nights prior to the approach indicate that both satellites underwent manoeuvres in the days leading up to the event that were not reflected in the TLEs used for the pre-event prediction. There is clear evidence in the observations for a manoeuvre of 1996-015A between 22:00 on 23rd May and 18:00 on 24th May and a manoeuvre of 1990-079A between 01:00 and 19:00 on 25th May 2004.

In the preceding discussion no errors have been given for distances calculated from TLEs. It is assumed that the errors in the {x,y,z} positions calculated from the TLEs are as frequently quoted, around 3 km.

The miss distance and times from triangulated observations and those calculated from updated orbits agree within the limits of accuracy of each method, confirming the validity of the two methods.

4.3. The dynamical method - Single site observations of an approach between 2001-005B and 1991-079A at 04:43 GMT on 7th March 2005

This approach took place in the early morning of 7th March 2005; it was only observed from Herstmonceux.

Initial predictions of this event were made using a TLE with an epoch date of 13th February 2005 for 1991-079A, and 17th February 2005 for 2001-005B; the more up-to-date of the TLEs was thus dated 18 days prior to the approach, the other was dated 22 days prior to the approach. Further predictions were made from the NASA TLEs as updated versions of the catalogue became available.

There was no change in the predicted time of approach between the initial predictions, based on the NASA TLEs dated 18 and 22 days prior to the event and the predictions based on the NASA TLEs dated 2 and 3 days prior to the event (released after the date of the approach). However the NASA TLEs dated 2 and 3 days prior to the approach do show a change in the miss distance, although the two values of the miss distance can be deemed to agree at the limit of the expected accuracy of the TLEs. There was no difference between the predictions based on the initial NASA TLEs and the final predictions made on the day of the event based on the updated orbital elements created from observations taken in the interim period. It was from the updated orbital elements that the observations of the conjunction itself were scheduled.

2001-005B is in a nearly circular stationary low inclination orbit. 1991-079A is believed to be no longer active. Although its orbit indicates that it is drifting westwards it remains close to GEO distance with an inclination of about 8.5°. The observations between the initial prediction and the date of the approach indicated that 2001-005B was not manoeuvred.

The RA and declination positions of 2001-005B and 1991-079A obtained from observations of the approach are plotted in Fig. 5.

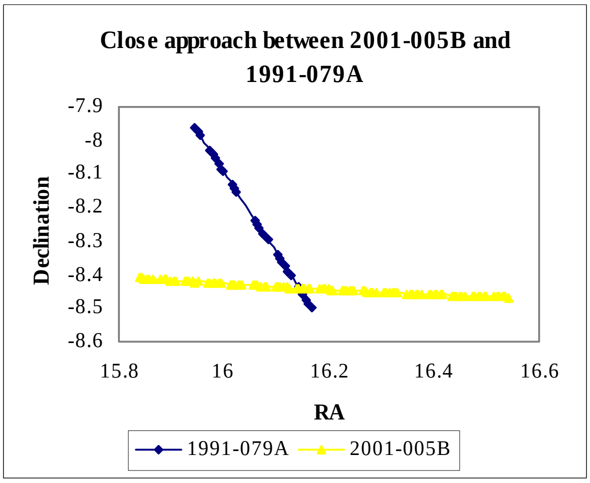

Figure 5. RA – Dec plot of PIMS observations of the close approach between 2001-005B and 1991-079A.

4.3.1 Post conjunction analysis

Fresh orbits for each satellite were calculated using the observational data obtained up to and including the approach. These calculated orbits were then used to obtain {x,y,z} positions of the satellites throughout the period of the approach. These {x,y,z} positions were used to recalculate the approach miss distance and time. The miss distance and time thus obtained were then compared with the pre-event prediction.

As in the multi-site example the minimum angular separation can be used to give a minimum possible miss distance. In this instance the minimum angular separation was ~ 0.03º, indicating a minimum possible miss distance of around 19 km.

The initial pre-event prediction from the NASA TLEs for this approach was:

04:43 GMT 25 km

The last TLEs available with epoch dates prior to the date of closest approach gave a time of closest approach and miss distance of:

04:43 GMT 19 km

The recalculated orbits using observations taken prior to and during the approach gave a post-event dynamically calculated approach distance and time of

04:43 GMT 26 km

The close agreement between the initial pre-event predictions and the calculated miss distance constrain the magnitude of propagation errors for these objects over a period of 18 days and suggest that they are not time dependent over a short propagation period. It is not clear whether the later predictions from updated TLEs, which only agree at the limit of the expected propagation accuracy, indicate a small error in one of the TLEs or are indicative of a scatter in the propagation predictions.

5. CONCLUSIONS

In order for any forecast of close approaches to have any value it is necessary to be able to quantify the success rate and false alarm rate of the predictions. To do this the accuracy of the information on which the predictions are based needs to be well established. For most purposes in space surveillance the source of the information is the NASA TLEs and, in the case of deep space, the SDP4 propagator used with them.

Multi site observations of a close approach give a means to undertake an independent check on the validity of calculations based on NASA TLEs, and hence test the accuracy of the TLEs. The positions of the objects involved in the approach can be calculated both by dynamical means from the TLEs and directly through trigonometric parallax. These geometrically derived positions allow positions predicted from the TLE to be compared with those from an independent source.

In the multi site case presented here it can be seen that both methods give consistent results within their expected accuracies.

The multi site case also gives confidence that the miss distances of close approaches calculated by the dynamical method will produce results of acceptable accuracy.

However the quality of the prediction is, at best, only as good as the quality of the TLE. As has been seen, errors do exist in the TLEs themselves resulting in an initial false negative in the predictions of approaches involving 1990-079A. Furthermore the difference between the miss distance derived from the TLE and that derived from the observations indicate that the NASA TLEs are unable to account for the effects of orbital manoeuvres.

As can be seen from the single site example, when the TLEs of the objects concerned are accurate the predictability of close approaches is good. The errors introduced by propagation of the TLE over a period of 18 days or more do not appear to have a significant impact on the predicted miss distance and time of closest approach. However the variability in the predicted miss distance remains problematic. In this case the predictions remain valid over the kind of period that would be useful to a satellite operator when evaluating the cost to loss ratios involved in responding to a potential risk to a payload. With a miss distance of around 25 km an operator can be confident in deciding that the likely risk does not warrant the use of fuel that an additional avoiding manoeuvre would entail. The risk factor for a predicted approach of less than 6 km is not as well quantified due to the possible scatter in the propagation errors of the TLEs.

NASA TLEs are well suited to the task of space surveillance where their accuracy is well matched to the requirements of the task. However, the use of NASA TLEs for close approach forecasting in deep space can be seen to contain a number of problems that limit the quality and usefulness of the predictions. In particular, from the perspective of any planned forecasting service, evaluating the frequency of false negatives resulting from errors in the NASA TLEs is likely to be the most problematic issue. Without 24 hour monitoring of a large number of payloads it is impossible to estimate the number of false negative forecasts.