Paper
Presentation
Next Topic
Table of Contents

A Monitoring and Warning System for Close Geostationary Satellite Encounters

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Abstract

In January 1997 Telstar 401 unexpectedly failed and began to oscillate indefinitely as a drifting satellite in the populous geopotential well between 97 to 113 degrees west longitude. This highlighted the fact that over 250 active satellites now exist in close proximity to a rich population of inactive (non-station kept) resident near-geosynchronous space objects. As a result of the Telstar 401 failure, MIT Lincoln Laboratory has joined a Cooperative Research and Development Agreement with a number of geostationary satellite operators to monitor close encounters of their satellites with Telstar 401 and any other potentially threatening objects. As part of this agreement, a Geosynchronous Monitoring and Warning System is being developed to provide the commercial operators access to information pertaining to potential threats to their satellites. This system will maintain the relevant component of the Deep Space Catalogue using high accuracy special perturbations orbit determination and all available data. It will provide a 60-day ALERT of a potential encounter followed by necessary tasking of Lincoln Laboratory sensors that will improve the encounter prediction in order to give users a final confirmation WARNING of the encounter 15 days in advance. Accuracy of the computed orbits and encounter predictions is the key component. Motivation, design, implementation, and preliminary operational results will be presented.

1. INTRODUCTION

On January 11, 1997, the Telstar 401 satellite failed on orbit at 97 degrees west longitude in the geosynchronous belt. This longitude is in the geopotential well centered at 105.3 degrees west. Since Telstar 401 was unable to be boosted out of the well, it consequently will oscillate indefinitely from its failure longitude to 113 degrees west with a complete period of about 800 days. As the geostationary satellites exist in a narrow band about the geosynchronous radius of 42164 km, Telstar 401 poses a potential threat to all satellites in the well.

MIT Lincoln Laboratory has both the resource of operating the Millstone Hill Radar (MHR) at Westford, Massachusetts, which has coverage of all satellites in the geopotential well, and a very high precision orbit determination program DYNAMO. It also operates the Space Based Visible telescope (SBV), which has complete coverage of the geosynchronous belt. With this capability MIT Lincoln Laboratory became involved in a Geosynchronous Encounter Analysis Cooperative Research and Development Agreement (GEA CRDA) with a number of commercial owner/operators of geostationary satellites that exist in the well. These currently consist of four companies: GE Americom, Loral Skynet, SATMEX, and Telesat Canada with 34 active satellites. The primary purpose of this CRDA is to monitor encounter distances of Telstar 401 and other drifters with the active CRDA partner satellites. This is accomplished by obtaining adequate tracking and performing the appropriate analysis and research to provide the most accurate encounter distance estimates possible.

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14. ABSTRACT

In January 1997 Telstar 401 unexpectedly failed and began to oscillate indefinitely as a drifting satellite in the populous geopotential well between 97 to 113 degrees west longitude. This highlighted the fact that over 250 active satellites now exist in close proximity to a rich population of inactive (non-station kept) resident near-geosynchronous space objects. As a result of the Telstar 401 failure, MIT Lincoln Laboratory has joined a Cooperative Research and Development Agreement with a number of geostationary satellite operators to monitor close encounters of their satellites with Telstar 401 and any other potentially threatening objects. As part of this agreement, a Geosynchronous Monitoring and Warning System is being developed to provide the commercial operators access to information pertaining to potential threats to their satellites. This system will maintain the relevant component of the Deep Space Catalogue using high accuracy special perturbations orbit determination and all available data. It will provide a 60-day ALERT of a potential encounter followed by necessary tasking of Lincoln Laboratory sensors that will improve the encounter prediction in order to give users a final confirmation WARNING of the encounter 15 days in advance. Accuracy of the computed orbits and encounter predictions is the key component. Motivation, design, implementation, and preliminary operational results will be presented.

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Since the failure of Telstar 401, MIT/LL has monitored over 100 encounters with CRDA partner satellites, as well as a number of encounters with government satellites. The closest of these have been on the order of 2 km with a 2 km uncertainty (Abbot and Thornton, private communication). Typical distributions of encounter distances will be shown below. As Figure 1-a shows, by the end of 2001, Telstar 401 will pass by 27 satellites, 18 of these being CRDA partner satellites and 9 being non-commercial.

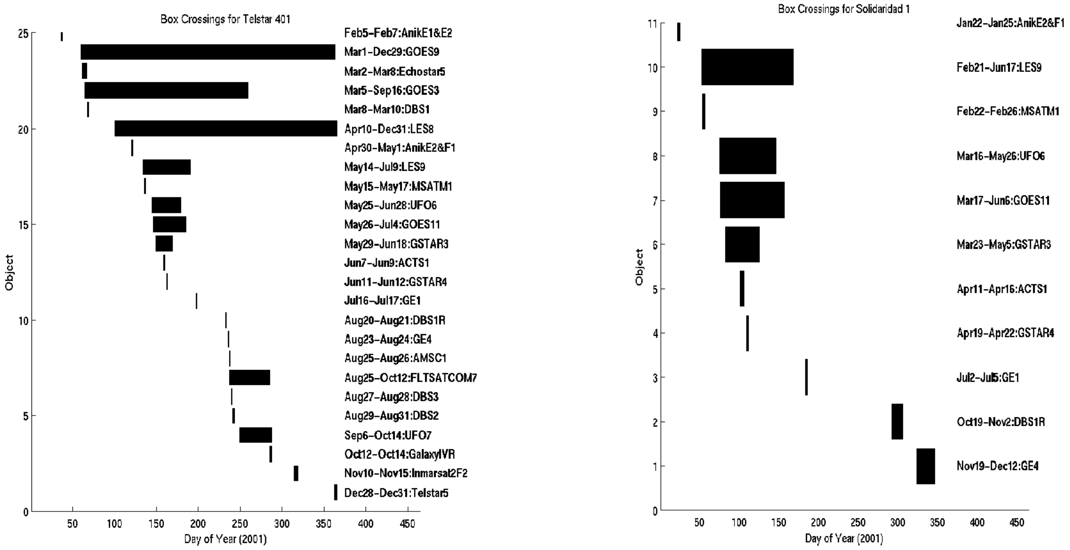

Figure 1 a-b. Predicted encounters of Telstar 401 and Solidaridad 1. The larger horizontal box indicates a larger longitude box for the target satellite.

On August 29, 2000, Solidaridad 1 failed at 109 degrees west longitude. It will oscillate indefinitely in the well from 109 to 101 degrees due to its inability to thrust and boost itself above the well. The predicted encounters for 2001 will be those of Figure 1-b.

Yet another failure occurred with Galaxy 7 on November 24, 2000 at 125 degrees west longitude. It would have drifted indefinitely in the well between 85 and 125 degrees, threatening a large number of satellites. Galaxy 7 is not completely dead, as some thrusting capability exists. Its owners therefore performed maneuvers in late November to boost it into an orbit with a perigee and apogee above the geosynchronous distance of about 74 and 286 km respectively. It also is now circulating west at about two degrees per day. There are still currently 26 satellites within 50 km of its perigee to apogee range, although the threat to these is small.

The following four histograms (Figures 2a-d) show predicted encounters distances of the four CRDA partner's satellites against the relevant inactive geosynchronous satellites for a period of one year. The histograms all peak at encounter distances of around 20 to 30 km. One can see from these distributions that high-accuracy orbit determination at the few km level is required to confidently predict a significant proportion of the encounter distances.

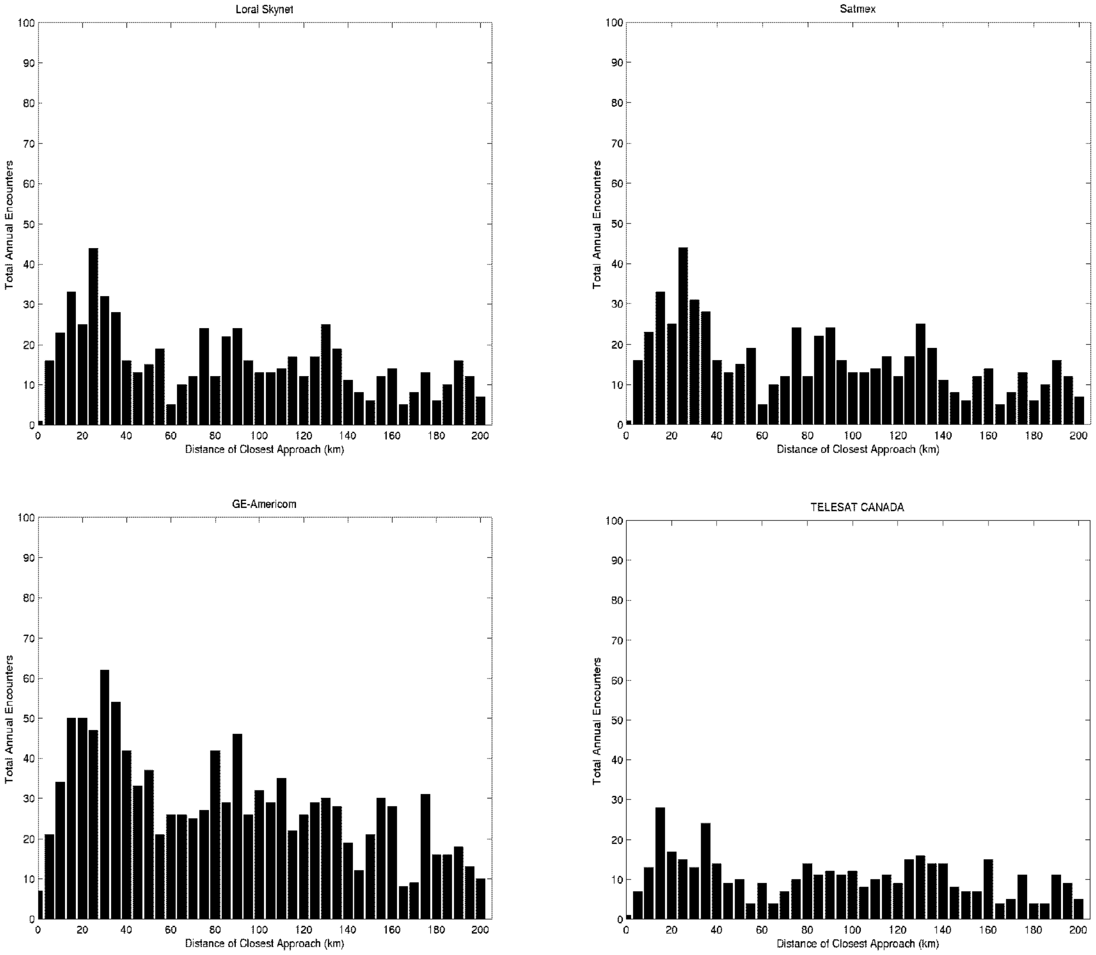

Figure 2a-d. Encounter histograms for a one-year period for the four CRDA partners (a: Loral-Skynet, b: Satmex, c: GE-Americom, and d: Telesat-Canada).

To handle the extensive encounter monitoring activity for the CRDA, a Geosynchronous Monitoring and Warning System (GMWS) is under development. This system will automatically estimate future encounters of CRDA partner satellites against the relevant threatening inactive population and provide the appropriate analysis for the significantly close encounters.

2. CONCEPT OF OPERATIONS AND OVERVIEW OF GMWS

The Geosynchronous Monitoring and Warning System begins by maintaining a catalogue of deep-space resident space objects (RSOs) on a daily basis using an automated orbit determination system. This catalogue currently maintains orbits of the CRDA partner satellites and the inactive satellites near the geostationary belt between 6.2 and 7.1 earth radii and with eccentricity less than 0.1. This currently totals approximately 500 objects. It will eventually include the entire threat population of both non-

CRDA active geostationary satellites and those inactive objects currently excluded from the GMWS catalogue but with semimajor axis and eccentricity that permits them to cross the geosynchronous belt.

Using the GMWS catalogue, the system generates ALERTS approximately 60 days in advance of an encounter and WARNINGS 15 days before the encounter. The ALERT prediction from 60 to 15 days is based on the current position of the active station kept CRDA partner satellite, which is assumed to be in the center of its station-keeping box. The satellite will of course drift inside that box and will maneuver to maintain its position near the center of the box. If maneuver information is not routinely received from the partner, it is generally requested at this point if a potentially threatening encounter is predicted. The 15-day WARNING is based on the actual position of the CRDA satellite in its station-kept box, since by this time the maneuver information should be added. The ALERT and WARNING period provides time to obtain some additional tracking to improve the accuracy of the encounter prediction. The WARNING period allows the CRDA partner to monitor the encounter and consider any avoidance maneuvers, which can often be included in nominal station keeping.

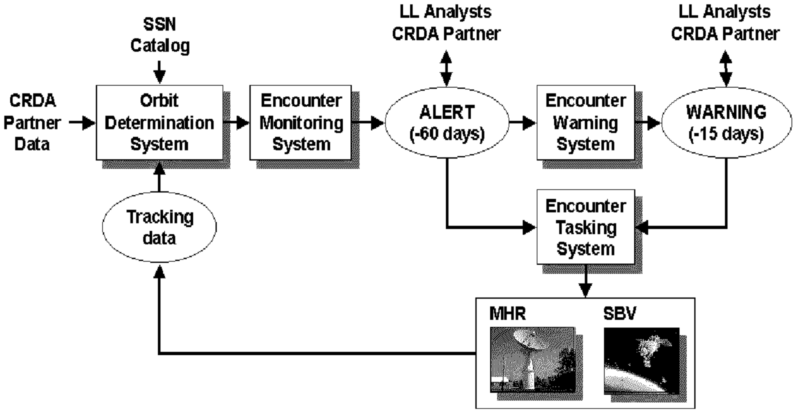

Figure 3. This diagram shows the important functional components of the GMWS.

The functional components of the GMWS consist of an Orbit Determination System, Monitoring and Warning System, and Tasking System. These are shown schematically in Figure 3 and described in more detail in the following sections.

The orbit determination system seeks to maintain high precision element sets with minimal analyst intervention using MIT Lincoln Laboratory analytical orbit determination code ANODER and numerical code DYNAMO. DYNAMO is a general-purpose special perturbations orbit determination and ephemeris generation program based strictly on numerical methods to solve the equations of motion with state of the art force models. Inputs to the system include MHR and SBV observations resulting from automated GMWS tasking, as well as all Space Surveillance Network (SSN) observations. The system is also being interfaced with CRDA partner ranging data, which arrive via electronic mail. The system uses ANODER to update an initial element set and then DYNAMO to produce a final, precision element set.

The monitoring and warning system predicts close approaches between geosynchronous catalogued, threatening RSOs and CRDA partner satellites. The system propagates all threat element sets over a 60-day interval to determine encounters based on CRDA partner satellite station-keeping box size. The system issues encounter ALERTS for all encounters occurring during the next 60 days. Subsequently, the system monitors the distance of closest approach and orbit uncertainties and sends WARNINGS for close approaches 15 days prior to the encounter.

A WWW interface will make the ALERTS and WARNINGS generated by GMWS available to the CRDA partners. The list of ALERTS and WARNINGS generated by GMWS will be displayed on a password protected, CRDA partner specific, web page. These ALERTS and WARNINGS will be hyper-linked to element sets, and any other information considered useful by the CRDA partners.

The tasking system ensures that adequate observations on threat RSOs and CRDA partner satellites are provided to the orbit determination system in order to improve the encounter distance uncertainty, which, along with the date of the encounter, determines tasking priority. The system tasks MHR and, if available, SBV. Once an encounter ALERT has been issued, the system schedules data collection on prioritized objects to ensure that sufficiently precise orbits are determined. Once a close approach WARNING has been issued, the system further requests observations on the encountering objects. The system monitors the performance of the tasked sensors and the orbit determination system, and predicts orbit uncertainty using the overlap of propagated positions from successive element sets as discussed below. It terminates special data collection once tasking limits have been reached or orbit uncertainties are adequate, and alerts an MIT Lincoln Laboratory analyst when needed. The tasking system also issues a request for data collection through close approaches to allow assessment of the prediction accuracy after the encounter.

The GMWS prototype uses MATLAB for computational power and ease of development and Perl for robust and straightforward process and file handling. It relies on the MIT Lincoln Laboratory metric database that receives all SSN observations.

3. ORBIT DETERMINATION and ENCOUNTER PREDICTION

This section will discuss in more detail the orbital aspects of GMWS. Included will be the methodology of computing the geosynchronous orbits, the orbit and encounter estimate accuracy determination, and the method of determining and validating satellite encounters.

3.1 Orbit Determination

The analytical orbit theory of ANODER provides a good initial element set for the high precision orbit determination of DYNAMO. This generally insures convergence with DYNAMO, especially with low-density tracking data sets or those with tracks with large errors.

DYNAMO uses the JGM3 gravity field model, includes direct lunar and solar effects, models body tides, solar radiation pressure, earth-reflected radiation and atmospheric drag, and models thrust forces and is capable of generating one-meter orbits given suitable observations.

The DYNAMO theory is used to predict the encounter distances. Currently, GMWS is maintaining a catalogue of roughly 450 inactive objects (based on the criterion 6.2 < semimajor axis < 7.1 earth radii and eccentricity < 0.1). Given sufficient tracking, these orbits are generally easy to compute. The rule for defining the fit span for the DYNAMO fits is 11 days minimum per fit, or as long as necessary to have six tracks of optical data, radar data, or a mix of the two. (A track is defined as a group of observations separated 15 minutes in time from its neighbors.) For the active CRDA satellites, the minimum fit span is 3-5 days or as long as necessary to have six tracks. This shorter span is to account for the CRDA satellites maneuvering to maintain station keeping. Maneuver detection and estimation has not yet been included in GMWS. Maneuver information is routinely provided by some CRDA partners and otherwise provided on request near the close encounter of one of their satellites. This information is also incorporated automatically into GMWS. Given the start time of the maneuver and sufficient data, DYNAMO can model the parameters of the maneuver, generally recovering them to 5%. Additional information of duration, delta-velocity and direction of the thrust is used to confirm the parameters determined by DYNAMO or to predict the effect of a maneuver on an encounter. Maneuver detection and modeling is a difficult problem especially in a data-poor orbit determination. There are various approaches to this that will be discussed below as ongoing research.

3.2 Orbit and Encounter Distance Accuracy

Estimates of both orbit fit and orbit prediction accuracy are necessary to assign errors for the predicted encounter distances. There are but a few geosynchronous orbits for which there are highly accurate reference orbits; for example the TDRS satellites that have orbits generated with typical accuracies of 25 m [1] generated by NASA GODDARD. These reference orbits are useful for some of the research related components of GMWS. But in general, orbit accuracy must be measured internally by using orbit overlap and by analysis of Keplerian elements and data residuals.

In GMWS there are two methods of estimating orbit uncertainty. One computes the orbit fit accuracy and the other the orbit prediction accuracy. These methods are based on comparing satellite positions predicted by different element sets over a certain common time period. If all forces are correctly modeled and observations are perfect, element sets computed from different (preferably independent) data sets for an object should be identical. The methods differ in which element sets are selected for comparison.

The orbit fit overlap method finds two fit spans for an object that overlap by one day. (GMWS fit spans are typically 11 days long so the overlap interval is less than 10% of the data fitting span.) On the day of overlap, satellite positions are computed from both element sets and compared. The resulting position differences are decomposed into radial, along-track, and cross-track components. This decomposition provides information about the source or cause of the error. The overlap method is statistically meaningful, since it uses two element sets generated from semi-independent observation sets. Experience with the overlap assessment of accuracy has shown it to be a valid measure; for example, orbits have been computed for the TDRS satellites and overlapped and also compared with the high accuracy NASA GODDARD trajectories and the accuracies assessed by both methods agree well (Abbot, private communication).

It is also necessary to measure how well a given element set predicts the position of an object into the future. It does this by predicting the object's position into the past and comparing this position with the position predicted by an averaged element set for the day of the prediction. This averaged element set is an un-weighted average of all osculating element sets computed by the system for that object for that day. For example, for N-day fit spans with a new orbit computed every day, after N days there will be element sets from, at most, N separate fits spans. These averaged element sets are thus statistically robust, though they are susceptible to biasing by a bad orbit or potentially by a bad track. For this reason, a weighted average will most likely be used in the future, perhaps using weights equivalent to the reciprocal of the overlap error (to weight poor orbits less).

3.3 Validation

The methods described above provide a fair measure of the encounter distance uncertainty although, in fact, it is not a completely independent error assessment. The only way to independently validate the predictions is to directly observe the encounters with radar. The goal is to verify that the predicted encounter time and close-approach distance agree with that derived directly from radar observations to within the uncertainty measure for the predicted encounter distance.

Millstone and Haystack radars are employed in a joint tracking procedure. After selecting an encounter to validate, both radars ensure that they can track the objects (often one of the objects is a low-radar cross section, non-coherent target). About ten minutes prior to the predicted encounter time, both radars begin tracking the same object (say, object A) as a check on joint calibration. After about 5 minutes, Millstone switches to the other target (say, object B). In case it has to search, Millstone performs the switching because it has a wider beam. Both radars track their respective targets through the predicted encounter time. About five minutes after the encounter time, Millstone switches back to object A, providing final closure on the joint track. During the track, observations are taken on both objects, and precision pointing data (range, azimuth, and elevation) are collected from both antennas for rapid analysis. Millstone also collects range-time-intensity (RTI) data for display. Afterwards, the data are compared with the predictions, taking the known uncertainties into account.

Because the encounters often involve a small object passing very close to a large, active object (with large solar panels), the radars have difficulty keeping the small object in track around the time of closest approach due to side-lobe interference from the larger object. One possibility to avoid this is to not track the smaller object through the closest approach, interpolating later to fill in the missing data.

When Haystack is not available for a joint track, Millstone simply tracks both objects before and after the encounter, tracking one of them through the closest approach. Missing data from the other object are supplied later by interpolation.

3.4 Encounter Determination

The distance r from the earth center to an object in an elliptical orbit is

$$r = a(1 - e\cos E), \tag{1}$$

where E is the eccentric anomaly, a is the semimajor axis, and e is the eccentricity. The geocentric radius r at apogee is given by $a(1+e)$ and that at perigee by $a(1-e)$. Two objects will always miss one another if they can have no common radial distance. The requirement for this is that the perigee of one be greater than the apogee of the other, in other words, either of the conditions

$$\begin{gathered} a_1 - a_1 e_1 \le a_2 - a_2 e_2, \text{ or} \\ a_2 - a_2 e_2 \le a_1 - a_1 e_1, \end{gathered} \tag{2}$$

that simplify to

$$|a_1 - a_2| \le a_1 e_1 + a_2 e_2 . \tag{3}$$

Two objects typically will differ by some inclination. As a result, the only possible intersection of the orbits is near the intersection of the orbital planes. One can show that even for small inclinations that for typical satellite and orbit dimensions the encounter is localized to the point at which the orbital planes intersect.

The intersection $\hat{I}$ of the orbital planes for two objects 1 and 2 is given by

$$\hat{I} = \hat{W}_1 \times \hat{W}_2 / \left|\hat{W}_1 \times \hat{W}_2\right|, \tag{4}$$

where $\hat{W}$ is the normal of the orbital plane. If $\hat{P}$ is the direction from the earth center to the perigee of an object, the direction cosine for $\hat{I}$ in the orbital plane of an object is given by

$$\cos v_I = \hat{I} \bullet \hat{P}, \tag{5}$$

where v is the true anomaly and subscript "I" denotes intersection. Expressions for $\hat{I}$ and $\hat{P}$ can be found, for example, in Reference [2]. Since

$$\cos E = \frac{\cos v + e}{1 + e\cos v}, \tag{6}$$

the distance from the earth center to this object at one point of orbital closest approach can be estimated using Eq. (1). Repeating the same calculation for the second object allows the distance at the point of orbital closest approach to be calculated. Of course, the process must be repeated for the value of true anomaly corresponding to $-\hat{I}$ and it still remains to be answered whether or not the objects reside at these points at the same time. In practice, this is accomplished as follows. The CRDA partner satellite is assumed to be station kept and the orbital elements and longitude that GMWS currently computes is defined to be its orbit and longitude for the next 60 days. On each of the next 60 days for each of the other satellites for which the threat is to be monitored, the two lines of intersection are computed. The corresponding distances from the earth center and the true anomalies are computed from equations (1) and (5). This yields the mean anomaly and the times the CRDA satellite is at the two lines of intersection. Based on the time that the CRDA satellite is at the intersection, the longitudes of the other encountering satellites are computed. For each pair, for each of the two intersections per day, the test is made $|L_2 - L_1| \leq L_{threshold}$; $|r_2 - r_1| \leq r_{threshold}$. This provides a tabulation of ALERTS over the next 60 days for which the longitudes and geocentric radii are within the encounters thresholds. Currently $L_{threshold}$ = 0.05 degrees (which is the typical longitude box size for a commercial geostationary satellite) and $r_{threshold}$ = 50 km.

As a potential encounter is approached 15 days ahead, the encounter distance is computed in a different manner. At this point the latest orbits for both encountering objects are computed from GMWS and propagated 15 days ahead in Earth-centered-inertial coordinates at 60 s spacing. These are used to compute the distance between the two satellites at each of the 60 s epochs (sometimes the encounter occurs so quickly that a finer time spacing is required to find the absolute closest distance). The relevant close encounters are tabulated along with the orbit predictions errors for each satellite that are added in a quadratic sum to represent the error of that predicted encounter distance.

4. PRELIMINARY RESULTS

A baseline version of GMWS has been developed and is continuing to be validated. A beta version with web page should be accessible to the CRDA partners in April 2001. There are still some issues determining optimal fit spans that will provide the most accurate orbits. This will be discussed more below. The accuracies of the orbit fitting and the predicted encounter distances are key components of the GMWS and are continually assessed.

A number of performance evaluators have been developed to monitor GMWS. One of these measures the frequency that GMWS cycles through computing new orbits for all its objects. To do this, histograms are generated of the age of the most recently determined orbits of the GMWS catalogue objects. A typical such histogram is shown in Figure 4. This should and does correlate with the age of the last observations, verifying that the orbits are being updated with new tracking. The GMWS catalogue of orbits is generally completely updated every 7 days. Objects with the older element sets that are near or at the WARNING stage would be given priority for additional tasking by the Millstone Hill Radar or SBV.

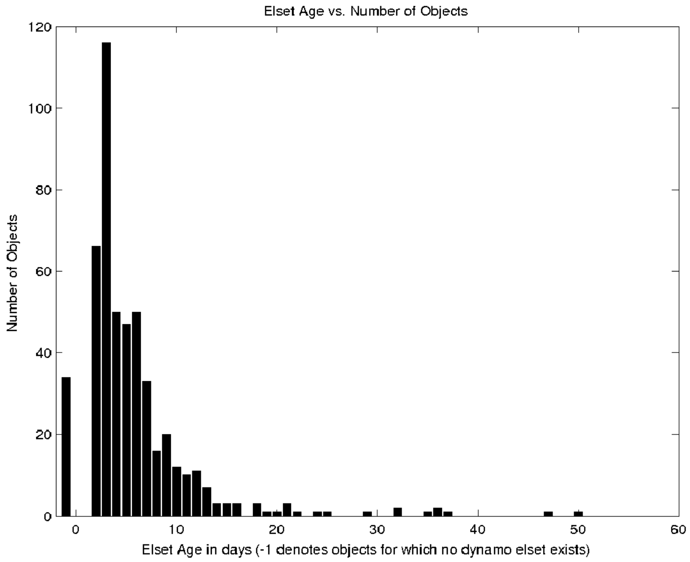

Figure 4. This histogram shows the distribution of element set ages for objects in the GMWS catalogue. The bar less than 0 shows the number of objects that did not fit during the period, mostly due to lack of observations.

The accuracy of the orbit fits on all objects is also monitored. Figure 5 shows a histogram of the accuracy assessment as based on overlap for the objects in the GMWS catalogue.

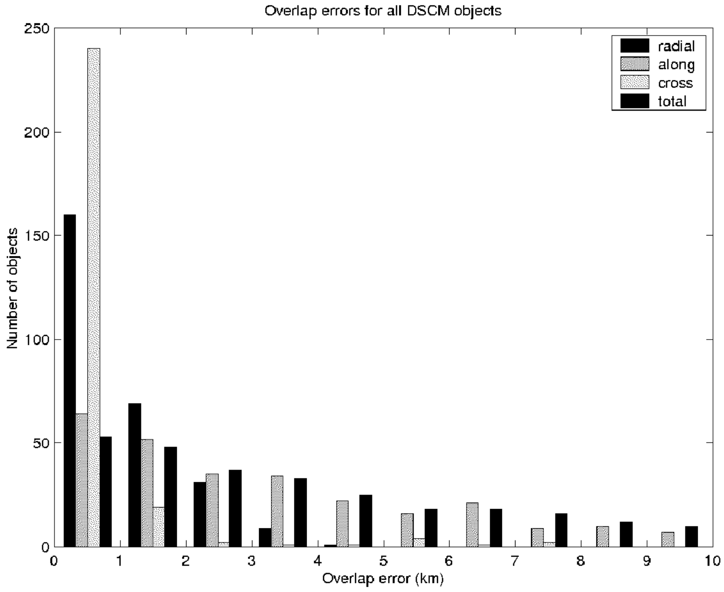

Figure 5. This histogram shows the distribution of overlap orbit errors (grouped by radial, along-track, and cross-track components and the total error) for objects in the GMWS catalogue. Notice that the radial and cross-track errors are 2 km or less for most objects, but the along-track errors are more evenly distributed.

Most of the GMWS orbits have radial and cross-track errors below 4 km, which is consistent with the amount of nominal optical tracks for a typical orbit. The along-track errors are more evenly distributed, dominating the total error beyond 3 km. This is probably because of the relative shortage of radar tracks. To confirm this, Figure 6 shows along-track error histograms for orbits grouped by the number of radar tracks that went into the fit. Most of the GMWS orbits have no radar tracks, but for those that do, even just one, the along-track error distribution is concentrated below 4 km. Therefore, the radar tracks are invaluable in constraining the orbits. This is consistent with a study of tracking distribution on the orbit accuracy of a TDRS [1]. Unfortunately, radar tracks are scarce unless they are specifically tasked. When the radars are tasked, the radial error is usually on the order of 100 m, the along track on the order of 500 m, and the cross track is now the dominate error due to angle precision and is on the order of 1.5 km.

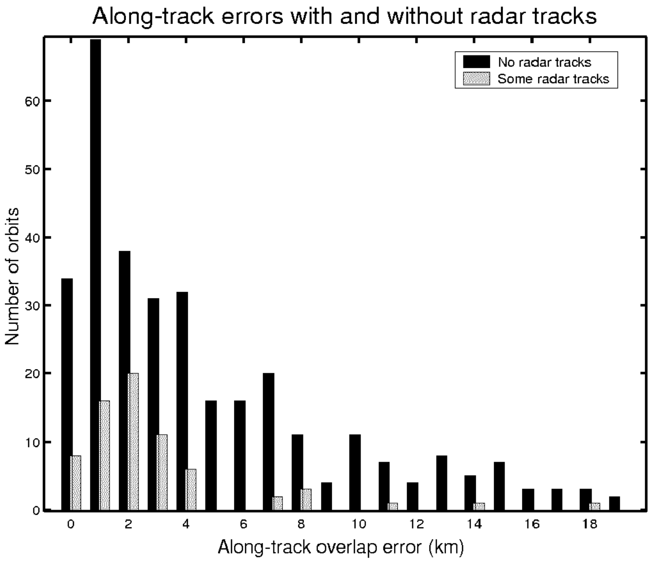

Figure 6. This plot shows along-track overlap errors for all inactive objects in the catalogue versus number of radar tracks that went into the fit. With even one radar track in the fit, along-track overlap errors are generally below 4 km, but with optical data only (no radar tracks), along-track errors are more distributed.

Finally, Figure 7 presents a histogram of WARNINGS for all partners for a 15-day span beginning on January 18, 2001. It is interesting to compare this with Figures 2a-d, which show total encounters over a whole year. With the current GMWS catalogue accuracy of 4 km or less, encounters of 12 km or less (which are statistically at the 3-σ limit) are the general concern.

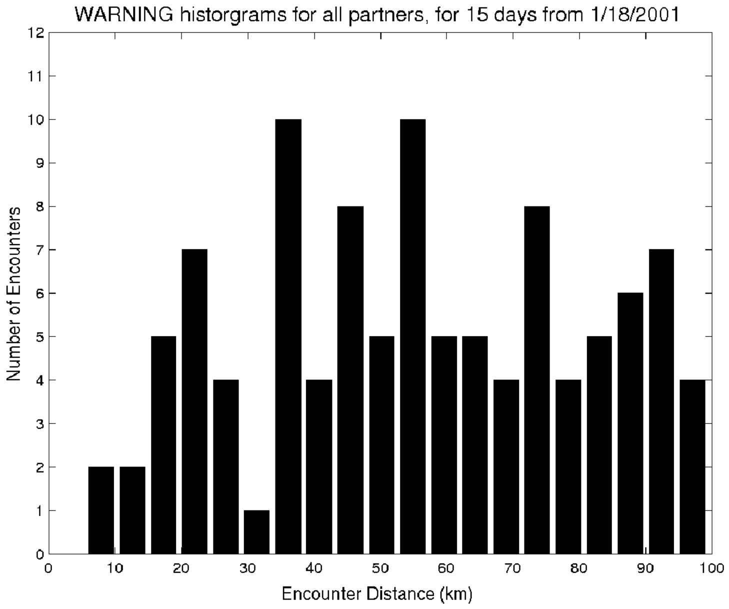

Figure 7. Histogram of WARNINGS produced by the system on January 18, 2001 for all partners. This included all encounters for 15 days from the date of computation. With a GMWS catalogue accuracy of 4 km, encounters of 12 km or less (3σ) are of a concern.

5. SUMMARY and FUTURE WORK

The GMWS is currently maintaining a catalogue of about 450 inactive objects and 34 CRDA objects. It is producing encounter ALERTS 60 days in advance for the CRDA partner satellites against the inactive geosynchronous belt. This provides time to obtain additional tracking to refine the encounter accuracy as well as to obtain upcoming maneuver information from CRDA partners that may not be routinely provided. It also generates WARNINGS 15 days in advance and at this point efforts are made to obtain the best encounter estimate possible as well as working with CRDA partners if a significantly close encounter is predicted typically less than 12 km. To help obtain the desired encounter accuracy, tasking is requested of the Millstone Hill Radar and the Space Based Visible telescope, both operated by MIT Lincoln Laboratory.

Accuracy measures of the fitted orbit as well as the predicted encounter are made with various overlaps of orbits. Generally, the tracking at the geosynchronous orbits comes from optical sensors and as a result, the along-track component of the orbit has the largest error. This has been validated with experiments using different tracking scenarios of TDRS and compared with the NASA Goddard high accuracy trajectory [1]. The reference also has shown that even just a few radar tracks can improve the along track determination since the radar range helps determine the size and shape of the orbit (semimajor axis and eccentricity). An important parameter for determining orbits of geosynchronous satellites is a scale factor for the solar radiation pressure. This considers that one does not always know the effective

Paper
Presentation
Next Topic
Table of Contents

surface area of the object to the sun or the object's mass. The ability to determine this parameter depends on the type and quantity of the tracking data. This is a parameter that is determined best when even just a few radar tracks are available, but it can also be determined given long enough spans of optical data [1]. For this reason, the GMWS is experimenting with data spans of considerably longer that the current nominal 11 days for the inactive satellites.

Range data from the CRDA partners are an important component. Not only can they improve the orbit accuracy to the 100-meter level (Abbot and Thornton, private communication), they also help confirm the data calibration determined by the CRDA partner. Currently, some CRDA partner range data are being routinely provided and requests have been made to obtain this data from all the CRDA partners. This data is automatically included into GMWS. Finally, maneuver detection and modeling is the biggest research component for GMWS. The CRDA partners routinely provide a considerable amount of maneuver information, and it is specifically requested if a significantly close encounter is predicted. Besides protecting the CRDA satellites against all inactive satellites, there are issues with the other active satellites and, for these, the maneuver information may not be available in a timely manner. Maneuver detection is a difficult problem, especially if the tracking density is low. The orbit determination can model the maneuver quite well once the start time of the maneuver is known and enough tracking on either side is available. Various approaches are being examined for maneuver detection which include: examining the data residuals to look for discontinuities; monitoring the longitude, longitude drift rate and inclination and knowing the bounds for these angles; predicting a maneuver based on historical maneuver frequency for a particular satellite as derived from a historical catalogue of the element sets or any other information of previous maneuvers, and as based on theoretical considerations for geosynchronous station-keeping.

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