"Procedures for Minimizing the Effects of High Solar Activity
on Satellite Tracking and Ephemeris Generation"

by

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ABSTRACT

We are currently experiencing a period of high solar radiation combined with wide short-term fluctuations in the radiation. The short-term fluctuations, especially when combined with highly energetic solar flares, can adversely affect the mission of U.S. Space Command's Space Surveillance Center (SSC) which catalogs and tracks the satellites in orbit around the earth.

Rapidly increasing levels of solar electromagnetic and/or particle radiation (solar wind) causes atmospheric warming, which, in turn, causes the upper-most portions of the atmosphere to expand outward, into the regime of low altitude satellites. The increased drag on satellites from this expansion can cause large, unmodeled, in-track displacements, thus undermining the SSC's ability to track and predict satellite position.

On 13 March 1989, high solar radiation levels, combined with a high-energy solar flare, caused an exceptional amount of short-term atmospheric warming. The SSC temporarily lost track of over 1300 low altitude satellites--nearly half of the low altitude satellite population. Observational data on satellites that became lost during the days following the 13 March "solar event" was analyzed and compared with the satellites' last element set prior to the event (referred to as a geomagnetic storm because of the large increase in magnetic flux in the upper atmosphere). The analysis led to a set of procedures for reducing the impact of future geomagnetic storms. These procedures adjust selected software limit parameters in the differential correction of element sets and in the observation association process and must be manually initiated at the onset of a geomagnetic storm. Sensor tasking procedures must be adjusted to ensure that a minimum of four observations per day are received for low altitude satellites. These procedures have been implemented and, thus far, appear to be successful in minimizing the effect of subsequent geomagnetic storms on satellite tracking and ephemeris computation.

Introduction

On 13 March 1989, one of the stations which report three-hourly values of geomagnetic flux (Ap), Fredricksburg, Virginia, reported a level of flux averaged over all eight three-hourly measurements which was the highest recorded value since 1960 (Reference 3). This major geomagnetic storm was believed to be linked to a very

strong solar flare observed on the surface of the sun three days earlier, on 10 March, which was pointed almost directly at Earth. Also on 13 March, another strong flare occurred; the x-ray radiation from this flare, classified as an x-level, or highest energy-level flare, undoubtedly contributed to the intensity of the geomagnetic storm already in progress. Additional x-level flares occurring on the 14th, 16th, and 17th of March extended the duration and effects of the storm, which included dramatic displays of the aurora borealis as far south as the Caribbean (Reference 1). Other, much publicized effects of the storm included disruption of shortwave radio communications, power outages such as the one which blacked out parts of Montreal and the province of Quebec for as long as nine hours, and the spurious opening and closing of automatic garage doors (Reference 2). The storm had an even more dramatic effect on US SPACECOM's Space Surveillance Center (SSC), which lost track of over 1300 low altitude satellites--over half of the low altitude satellite population. Several days of intensive around-the-clock manual analysis effort was required to "catch-up" with the lost satellites and reduce the "lost list" to a marginal level. Several more weeks of manual effort was required to reduce the list back to nominal levels.

Rapid changes in solar radiation, such as occurred on 13-17 March, 1989, produce large unmodeled drag effects on low altitude satellites and can defeat automatic observation processing and element set maintenance. Prediction accuracy is thereby degraded, thus causing problems in identifying and tracking low altitude satellites.

Analysis of satellite observations and the SSC's observation processing during and after the March Event led to a set of software procedures for minimizing the effects of future such events (large changes in solar radiation) on the SSC. A summary of the analysis and a description of the procedures themselves follows, preceded by a brief discussion of the effects of changes in solar radiation on the orbits of low altitude satellites.

Effects of Solar Radiation on Earth's Atmosphere and Low Altitude Satellites

Solar radiation warms the Earth's upper (tenuous) atmosphere through two primary effects: photoionization, caused by electromagnetic radiation, and ionization caused by collisions between solar wind particles (mostly electrons and protons), and air molecules. Increases in solar radiation increase atmospheric warming, which in turn causes the tenuous atmosphere to expand outward. This expansion increases atmospheric density in the realm of low altitude satellites, producing increased drag. Conversely, reductions in solar radiation cause the tenuous atmosphere to contract, thus reducing drag on low altitude satellites.

The SSC measures the amount of drag recently encountered by low altitude satellites and assumes this value remains constant as it predicts future satellite positions. (There are exceptions to this rule, such as when high interest satellites are maintained using special perturbations theory. For these special cases, measurements of solar radiation are incorporated in ephemeris prediction). If changes in drag are gradual and drag measurements are taken frequently enough, the assumption of constant drag provides satisfactory accuracy. However, when large, rapid changes in solar radiation produce similarly large, rapid changes in atmospheric drag, measurement of drag can lag significantly behind what is actually being experienced, and orbit prediction accuracy can deteriorate.

There are both long and short-term variations in solar radiation. The 11-year solar cycle is an example of long-term variation. A solar flare, which can last from minutes to hours, is an example of a short-term variation. Another example of short term variation is the fluctuation in total solar radiation that occurs during the peaks in the eleven-year cycle; these fluctuations can run their course in as little as a few days. The SSC's method of satellite drag prediction easily accommodates long-term fluctuations in solar radiation. However, solar conditions such as those which occurred 10-17 March, 1989, in which the solar wind from a major flare arrived at the earth at the same time that a peak in the short-term fluctuation in total radiation was occurring, can cause drag to change significantly in a matter of half a day or less. For example, a spike in Ap, such as occurred in 10-17 March 1989, can cause a 45 nm displacement in a near earth satellite's predicted position in just 12 hours (perigee = 185 km). It was this rapid increase in drag on low altitude satellites (generally, satellites with periods less than 110 minutes) which caused the SSC to temporarily lose track of over 1300 satellites.

Overview of the SSC's Satellite Observation Processing and Satellite Element Set Maintenance Segments

The SSC maintains the element sets of nearly 7000 satellites in a file called the SATF. The element sets are updated each time observations are received through a process called differential correction, similar to a Kalman filter or, in effect, a seven dimensional least squares fit. A complete differential correction (DC) is not performed each time an observation is received; instead, a simpler "sequential" DC is performed until a preset period of time expires, at which time a full DC is performed using all of the observations received during a period of time referred to as the Length of Update Interval (LUPI). The LUPI varies from 5 to 14 days for low altitude satellites, depending on the apogee and perigee heights of their orbits. The sequential DC permits only relatively small changes to the satellite's element set but has the advantage that it is much faster than a full DC, since it does not attempt to do a "least squares" fit of all LUPI

observations (it performs a simple "update" of the covariance matrix) and thus requires only one "pass". Once the update interval for a given satellite expires, or the sequential DC fails, or the element set accuracy declines past a given point, a full DC is performed for that satellite's element set. A full DC requires a minimum of seven observations.

Element sets from the SATF are periodically transmitted to spacetrack sensors in the Space Surveillance Network. The sensors use the latest element set received from the SSC to predict look angles for satellites for which they are tasked to provide observations. The sensors compare their observations against the predicted positions of the satellites using the latest element set received from the SSC. If the comparison is within established association criteria, the sensor will tag the observation with the requested satellite number and send it to the SSC as a routine observation. If it does not meet the association criteria, the sensor will tag it as an Unknown Object (UO) and send it to the SSC tagged with a 9XXXX number in place of the satellite number. The processing of UO observations within the SSC is much more tedious and time consuming because they have to be compared against every satellite in the SATF file.

Deterioration in the Observation Processing and Element Set Maintenance Segments during the March 1989 Solar Event

Prior to the Solar Event of March 13-17, 1989, Air Force Space Command (AFSPACECOM) had anticipated that problems might be encountered during the upcoming peak in the solar cycle and had tasked Kaman Sciences (on contract to maintain the SSC software) to examine ways to minimize the effects of changing solar radiation on the SSC's mission of satellite tracking and ephemeris prediction. Thus, at Kaman's request, satellite observation data taken before, during, and after the March Solar Event was saved for analysis. Using this data, Kaman recreated the March Solar Event scenario in AFSPACECOM's Off-Site Test Facility using computers and software similar to the SSC's. The analysis showed that deterioration occurred in three chronological phases.

> Phase 1. During the initial phase, low altitude satellites began reflecting the effects of the increased drag, caused by the solar flare-induced geomagnetic storm, through relatively large differences between their observed and predicted positions. Although still within SSC and sensor association limits, the magnitude of the difference caused the satellites to fail sequential DC updates or fail the SSC's internal accuracy check; they were then scheduled for a full DC update. During normal periods, this process is able to "catch" and update delinquent element sets before they degrade further. However, during this solar event, the full DC typically either rejected the latest observations because they were too far from "nominal", or, when too many recent observations were

available to ignore, the full DC simply failed. In either case, the element set was not updated with the new observations. When the full DC failed, it failed either because it could not accept the large change in drag and mean motion suggested by the newest observations, or the full DC could not meet convergence criteria, or both. The convergence criteria could not be met because the disparity between the old (before flare) and new (post flare) observations prevented an acceptable "fit".

Phase 1 - Suggested Fixes. To correct the problems in this phase, the following steps suggested themselves.

o   Reduce LUPI. If the Length of Update Interval (LUPI) were reduced to the point where most or all of the observations to be used in the DC update were new (post flare), then the DC would not be permitted to ignore the post flare observations. Further, convergence criteria could be achieved since the preponderance of the observations were post flare. Testing showed that convergence could be achieved with a LUPI of three days in nearly every case. Any further reduction greatly increased the likelihood that less than the minimum number of observations (seven) would be available for the full DC.

o   Increase Parameter Change Limits for Full DC. To prevent full DCs from failing because drag and mean motion changes exceeded normal limits, these limits were increased. Typically, the effects of the increase or decrease in satellite drag caused by changes in solar radiation are in-track. For example, the effect of increased drag is to drop the satellite to a lower orbit, thus reducing the semi-major axis of the orbit and increasing mean motion. Other orbit parameters will remain largely unchanged. The orbit plane will remain the same, and only very slight changes in altitude and eccentricity will occur. To the spacetrack sensor, the orbit will appear the same, except the satellite will be ahead of its predicted position (case of increased drag), or behind its predicted position (case of decreased drag).

Thus, during periods of high solar activity, the full DC should be permitted to accept wider changes in drag and the parameter which describes in-track motion, mean motion (n, revolutions per day). Testing indicated that the limit to changes in drag should be increased by a factor of ten and the limit for changes in mean motion increased by a factor of six.

o   <u>Increase Observation Flow Rate</u>. If the daily observation flow rate is not increased when the LUPI is decreased to three days, the number of observations available for the full DC will be drastically reduced, close to, or even below the minimum of seven. To prevent the full DC from failing because of a lack of the minimum number of observations, and to maintain an acceptable level of accuracy in the full DC, sensor tasking must be increased to ensure that a minimum of four observations per day are received for all low altitude satellites. If a still higher number of observations were received, accuracy could approach that of normal solar conditions with normal LUPI values.

<u>Phase 2</u>. During Phase 2, the satellite element sets were so inaccurate that the SSC could no longer associate routine observations with their element sets. During this phase, many of the sensors were still able to associate the observations with the drag-displaced satellites because the sensors have considerably wider association criteria than the SSC. In this phase, the SSC typically detags properly tagged routine observations and places them in an Unassociated Observations File as unknown observations.

<u>Phase 2 - Suggested Fix: Increase In-Track Multiplier</u>. This problem can be corrected by increasing the association criteria of the SSC to equal that of the sensors in the in-track direction. Analysis showed that if the in-track association multiplier were doubled, i.e. increased from 3 to 6 for low altitude satellites, the SSC's in-track association criteria would approximate that of the Eglin phased array sensor. (Association criteria is not the same for every spacetrack sensor. Eglin was selected because, as a dedicated spacetrack sensor, it provides more observations than any other phased array sensor).

<u>Phase 3</u>. During Phase 3, the element sets are so old that neither the SSC nor the spacetrack sensors can associate the observations with the drag-displaced satellites. Thus, all of the observations on these satellites are tagged as Unknown Objects by the sensors. When they arrive at the SSC, they eventually wind up in the Unassociated Observations File. At this point, trained Orbital Analysts must manually retrieve the observations from this file and attempt to associate them with element sets in the SATF using various software tools currently available. This process is very tedious and time consuming and greatly increases CPU usage. However, this intensive manual interaction was necessary 24 hours a day for several days after the March Solar Event. Once this phase is reached, there is no known method for enhancing the manual recovery processes already known to SSC analysts and crew personnel. The objective of the fixes recommended in the two

previous phases is to prevent Phase 3 from ever being reached.

Summary of SSC Performance Parameters During the March 1989 Solar Event

During the three phases described above, post-event analysis revealed that the percentage of observations that were tagged as Unknown Objects increased from 18% to over 40%; satellite catalog accuracy dropped drastically; the success rate for full DCs dropped sharply; total observation flow rate increased dramatically; CPU usage rose to the point of saturation; and, as was previously mentioned, the satellite "lost list" increased to over 1300 satellites. The normal level for this list is below 100 satellites.

Summary of Recommended Software Procedures

The following procedures were recommended for implementation in the SSC. They apply to low altitude satellites (non-payloads) with periods less than 110 minutes:

1. Increase spacetrack sensor tasking to ensure a minimum flow of four observations per day. Maintain this tasking until solar maximum subsides in late 1994.

2. When Ap rises over 100, or a sharp change in F_{10} (solar radiation measured at 10.7 cm wavelength, in units of 10^{-22} watts/M^2/Hertz) occurs, implement the following steps:

    a) Decrease LUPI to three days;

    b) Increase the in-track multiplier for each satellite to 6;

    c) Increase DC change limit multiplier for drag to 10;

    d) Increase the DC change limit multiplier for mean motion to 6.

    Return the above parameters to normal approximately three days after solar activity returns to normal.

Conclusion

The software procedures described in this paper have been adopted by USSPACECOM's Space Surveillance Center (SSC) as standard operating procedures during periods of high solar activity since late June, 1989. Their objectives are to maintain the satellite "lost list", the Unknown Object (UO) rate, and CPU (Central Processing Unit) usage at near normal levels during such periods. Thus far, these objectives have been achieved.

REFERENCES

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