①

AFIT/GSO/ENS/91D-11

AN ANALYSIS OF TRACKING AND IMPACT PREDICTIONS

THESIS

Susanne V. Lefebvre

Captain, USAF

AFIT/GSO/ENS/91D-11

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*	**2 REPORT DATE** December 1991	**3. REPORT TYPE AND DATES COVERED** Master's Thesis

4. TITLE AND SUBTITLE

An Analysis of Tracking and Impact Predictions

5. FUNDING NUMBERS

6. AUTHOR(S)

Susanne V. Lefebvre, Captain, USAF

7 PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Institute of Technology,
WPAFB OH 45433-6583

8. PERFORMING ORGANIZATION REPORT NUMBER

AFIT/GSO/ENS/91D-11

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release;
distribution unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The accuracy of the United States Space Command's early Tracking and Impact Predictions and its OPREP-3 report initiation procedure are analyzed. The study involves satellites which decayed between 1987 and 1990. Each of the early decay predictions are compared to the final prediction with the resulting time error compared to the accuracy level asserted by the Space Surveillance Center.

The results of this study indicate that the accuracy of the decay predictions is usually, but not always, within the asserted accuracy level. The results also suggest the existence of a positive bias indicating that the early decay predictions are routinely late relative to the final decay prediction.

Six multiple linear regression models were then developed in an attempt to improve the prediction process. It was determined that incorporating the developed regression models into the prediction process would substantially improve the decay predictions.

It was also determined that the OPREP-3 report initiation decision should continue to be made six hours before decay, but that it should also incorporate the developed regression models and widen its error window.

14 SUBJECT TERMS

Artificial Satellites, Satellite Decay, Tracking and Impact, Orbiting Satellites, Tracking, Low Orbit Trajectories

15. NUMBER OF PAGES

54

16. PRICE CODE

17 SECURITY CLASSIFICATION OF REPORT Unclassified	**18 SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT** UL

NSN 7540-01-280-5500

Standard Form 298 (Rev 2-89)
Prescribed by ANSI Std Z39-18
298-102

(A)

THESIS APPROVAL

STUDENT: Susanne V. Lefebvre, Captain, USAF CLASS: GSO-91D

THESIS TITLE: AN ANALYSIS OF TRACKING AND IMPACT PREDICTIONS

DEFENSE DATE: November 15, 1991

GRADE:

COMMITTEE	NAME/DEPARTMENT	SIGNATURE
Advisor:	Major Thomas S. Kelso/ENS	Thomas Sean Kelso
Reader:	Dr. William E. Wiesel/ENY	William E. Wiesel
Reader:	Prof. Daniel E. Reynolds/ENC	Daniel E. Reynolds

AFIT/GSO/ENS/91D-11

AN ANALYSIS OF TRACKING AND IMPACT PREDICTIONS

THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
Air University
In partial Fulfillment of the
Requirements for the Degree of
Master of Science in Space Operations

Susanne V. Lefebvre, B.S.
Captain, USAF

December, 1991

Approved for public release; distribution unlimited

Preface

The purpose of this study is to analyze the predictions made by the Space Surveillance Center (SSC) concerning the impact time and location of decaying satellites. Because of my prior experience in the SSC and because I believe there to be a general lack of confidence by the public in these predictions, I was very interested in determining how accurate these predictions really are.

There are two specific goals for this thesis. The first goal is to directly compare the accuracy of the Tracking and Impact Predictions (TIPs) made by the SSC during the four years from 1987 to 1990 to the accuracy level asserted by the SSC. The second goal is to determine if, based on these findings, it would be advantageous for the SSC to prepare its OPREP-3 report earlier than is currently being done. The OPREP-3 report is used to notify the proper authorities of possible impact by a decaying object near or within the Soviet border.

In my attempt to perform the analysis, I received a great deal of help from several people to whom I would like to express my sincere gratitude. I would first like to state that I am deeply indebted to my thesis advisor, Professor T. S. Kelso, for his constant patience, insight, and direction. Second, I would like to thank Dr. William E. Wiesel for sharing his knowledge of the programs used by the SSC. Third, I would like to thank Professor Daniel E. Reynolds for his undying enthusiasm and encouragement as well as his statistical expertise. He has that precious ability to make what can sometimes seem very difficult and time consuming actually *fun*. Finally, I would like to thank my fiancé Charles J. Martin, Jr., the most important person in my life, for his constant support and understanding during those many months when I was glued to either the microfiche reader or the computer screen.

Susanne V. Lefebvre

Table of Contents

List of Figures

Figure Page

List of Tables

Abstract

This study analyzed the accuracy of the early Tracking and Impact Predictions (TIPs) made by the United States Space Command's Space Surveillance Center (SSC) during the 1987-1990 time period. The final prediction data was first compared to visual observation data (Vis Obs) for those objects for which Vis Ob data was available. The early TIP decay predictions which include the 7-day through 3-hour predictions were then compared to the final prediction for each TIP object. For each TIP run, the time error was then calculated as a percentage of the time until decay. The results were then compared to the accuracy level asserted by the SSC

The results of this study indicate that the accuracy of the decay predictions is usually, but not always, within the ±20 percent accuracy level asserted by the SSC. The results also suggest the existence of a positive bias indicating that the early TIP decay predictions are routinely late relative to the final decay prediction.

An attempt was then made to model out some of the positive bias found in the TIP decay prediction data using multiple linear regression. Six regression models were found which, if incorporated into the current SSC TIP decay procedures, would allow the SSC to predict the final decay prediction time with substantially less error.

This study also analyzed the current SSC OPREP-3 report initiation procedure. It was determined that the decision to initiate the report should remain at the 6-hour point but that one of the regression models mentioned above, namely Model 6, should be used in conjunction with the TIP decay prediction data to obtain a better estimate of the final decay time. It was also determined that the ±15 minute error window currently used as a guide for determining the necessity of the OPREP-3 report should be widened to approximately ±40 minutes to more accurately account for error extremes in the TIP decay prediction calculations.

AN ASSESSMENT OF TRACKING AND IMPACT PREDICTIONS

I. *Introduction*

Background

The main mission of the Space Surveillance Center (SSC), located at Cheyenne Mountain Air Force Base, Colorado, is to detect, track, identify, and catalog all man-made space objects in support of the United States Space Command (USSPACECOM). One of the responsibilities of the SSC is to provide Tracking and Impact Prediction (TIP) for those objects that are within fifteen days of decay and which have a high probability of impacting the earth. The purpose of TIP processing is to ensure "that the Missile Warning Center and the USSR (when applicable) will not mistake a TIP object for an incoming RV (re-entry vehicle)" (6 Sec 9,13) and "to determine which country is liable for damages resulting from a satellite's impact" (6 Sec 9,13). TIP processing uses special perturbations theory to predict the decay time and location of all payloads, rocket bodies, platforms, and debris with a greater than five percent chance of surviving re-entry.

The impact predictions are updated at specific time intervals throughout the TIP object's decay. Each new prediction, called a *TIP run*, includes a decay time, a decay location, and a ground trace. The ground trace is a map upon which the decaying satellite's flight path is drawn and is used to determine whether the USSR should be notified. If deemed necessary, the information will be passed up-channel to the proper authorities in an OPREP-3 report. The more accurate the early predictions, the sooner the proper authorities can be notified. The author, having worked as an orbital analyst in the SSC, has noted a general lack of confidence in the accuracy of the earlier predictions and the use, therefore, of the later predictions for such decisions as the necessity of OPREP-3 report initiation.

Research Objective

The purpose of this research project is two-fold: (1) to compare the accuracy of the TIP decay predictions for the 1987-1990 time period to the accuracy level asserted by the Space Surveillance Center and (2) to determine if it would be advantageous for the SSC to initiate the OPREP-3 report earlier than is currently done.

Overview

The remainder of this study includes a literature review of orbital mechanics, perturbative forces, differential corrections, SSC satellite decay processing, and multiple linear regression (Chapter II), data collection and description (Chapter III), methodology used to conduct the study (Chapter IV), results of the analysis (Chapter V), and finally, conclusions and recommendations (Chapter VI).

II. *Review of Literature and Background Development*

Introduction

The following pages will review literature on five topics pertinent to this research proposal. The intent of this section is to expand the background information presented earlier. The specific topics discussed are orbital mechanics, perturbative forces, differential corrections, satellite decay processing as performed by the Space Surveillance Center (SSC), and multiple linear regression.

Orbital Mechanics

This section discusses the concepts and definitions of orbital mechanics necessary for a basic understanding of the orbital motion of an artificial satellite about the earth. Five independent parameters, called *orbital elements*, are required to completely describe the size, shape, and orientation of an orbit. To further pinpoint the position of a satellite along its orbit at a particular time, a sixth parameter is required. Together, these six parameters form an *orbital element set* and allow one satellite to be distinguished from thousands of other satellites in earth orbit. One type of orbital element set is the Keplerian element set. It includes the semi-major axis, eccentricity, inclination, right ascension of the ascending node, argument of perigee, true anomaly, and epoch time (3:58, 6:Sec 2,5) (see Figure 1). The semi-major axis (a) is one-half the longest diameter of a satellite's orbit and is used to describe the size of the orbit. The longer the semi-major axis, the larger the orbit. The semi-major axis can also be used to determine the time required for the satellite to complete one revolution. This quantity is known as the satellite's orbital period. For convenience, the SSC has classified artificial earth satellites into three general categories: deep-space satellites, near-earth satellites, and decaying satellites. Deep-space satellites are those satellites with orbital periods greater than or equal to 225 minutes. Near-earth satellites are those satellites with orbital periods between 87.5 minutes and 225 minutes. Decaying satellites are those satellites with orbital periods equal to or less than 87.5 minutes (10).

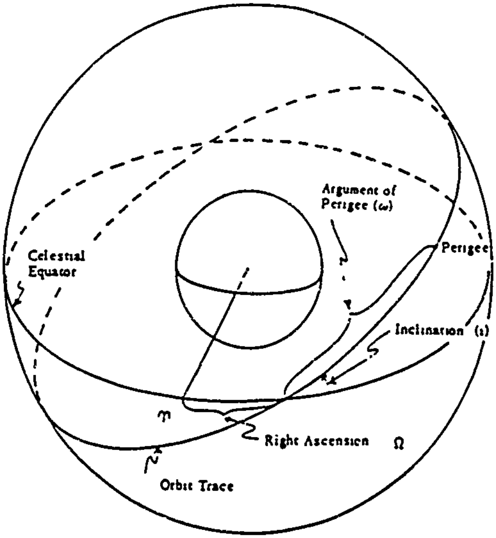


Figure 1. Orbital Elements (Reprinted from 7:Sec 2,28)

Eccentricity (e) is a parameter used to describe the shape of a satellite's orbit. Earth satellites can have only circular or elliptical orbits. The eccentricity of a perfectly circular orbit is equal to zero, while that of an elliptical orbit is between zero and one. The closer the eccentricity is to one, the more elongated the orbit.

Inclination (i) is one of two parameters used to locate the orbital plane in space. It is the angular measurement between the equatorial plane and the orbital plane and is measured in a counterclockwise direction at the ascending node. Simply put, the inclination is the angle between the orbit's angular momentum vector and the earth's. The inclination determines whether an orbit is prograde or retrograde, polar or equatorial. If the inclination is greater than or equal to 0° but less than 90°, the orbit is prograde. If the inclination is greater than 90° but less than or equal to 180°, the orbit is retrograde. If the inclination is near 90°, the orbit is polar. If the inclination is equal to 0°, the orbit is equatorial (6:Sec 2,6).

Right ascension of the ascending node (Ω) is the second parameter used to locate the orbital plane in space. It is an angular measurement in the equatorial plane from the vernal equinox to the ascending node. The vernal equinox is an imaginary line drawn in inertial space from the center of the earth, through the equator, towards the sun at the beginning of spring. This direction is routinely referred to as the first point of Aries (♈) (see Figure 2). "The ascending node is the point at which a satellite's ground trace intersects the equator as the satellite travels from the southern hemisphere into the northern hemisphere" (6:Sec 2,6).

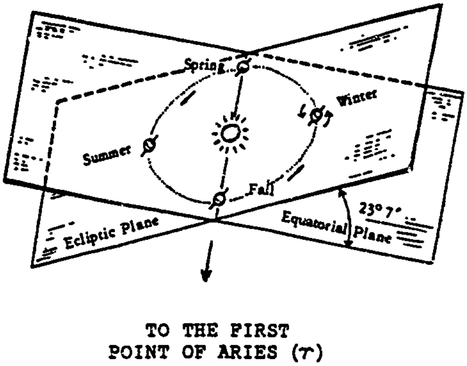


Figure 2. The Vernal Equinox (Reprinted from 7:Sec 2,28)

Argument of perigee (ω) is an angle used to orient the orbit within the orbital plane. It is the angle that is swept out by the satellite as it travels from the ascending node to the perigee point. Perigee is the position in an earth satellite's orbit that is closest to the center of the earth. It should be noted that perigee is not defined for a perfectly circular orbit, since all points in a circular orbit are an equal distance from the center of the earth. It should also be noted that in practice, there is no such thing as a perfectly circular orbit.

"True Anomaly (v) is the angular measurement in the direction of the satellite's motion along its orbital plane from perigee to the satellite's position at epoch time" (6:Sect 2,8). Epoch time can be any arbitrary moment in time and is used as a reference point. In the Space Surveillance Center, the epoch time is usually set to the time the object was last observed (1). True anomaly and epoch time go together. One is of no use without the other. The SSC does not directly use true anomaly, however. Instead, it uses a parameter known as *mean anomaly*, (M). To derive mean anomaly, another angle, *eccentric anomaly*, (E) is first determined using the geometric relationship shown in Figure 3 The eccentric anomaly is then used to derive the mean anomaly using Equation 1 (3:183-184, 6:2,8-9).

$$M = E - e\sin(E) \tag{1}$$

where

E is the eccentric anomaly

e is the eccentricity

It should be noted that unlike true and eccentric anomaly, mean anomaly is not an angle but a mathematical relationship. The use of mean anomaly instead of true anomaly allows a satellite's orbital path to be modeled on a circle instead of an ellipse. In this way, the satellite is modeled as moving at a constant velocity. If an elliptical model were used, a more complicated mathematical model would be needed to account for the gradual increase in velocity of a satellite as it approaches perigee and the gradual decrease in velocity as it approaches apogee. Mean anomaly is used, therefore, to simplify the problem of predicting where a satellite will be in the future (6:2,8).

Perturbative Forces

There are three major perturbative forces that affect the orbit of most artificial earth satellites. The magnitude of these forces depends on the satellite's size, shape, mass, and orbit. The three

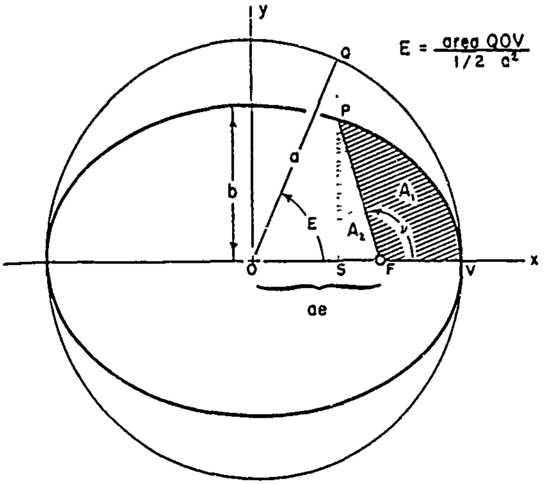


Figure 3. Eccentric Anomaly (Reprinted from 3:183)

forces are the direct result of atmospheric drag, the nonspherical shape of the earth, and third-body gravitational attraction Together, these perturbations not only change a satellite's orbit, but can also cause the satellite to plummet to earth or *decay* (16:165).

Atmospheric drag is caused by the friction between the molecules in the earth's upper atmosphere and the surface of the satellite. Atmospheric drag acts in a direction opposite to the velocity of the satellite relative to the atmosphere. Because the near-earth environment is characterized by a higher atmospheric density than the deep-space environment, near-earth satellites experience greater atmospheric drag than do deep-space satellites. When referring to the atmospheric drag on a satellite, a dimensionless quantity (C_d), called the drag coefficient, is used. The drag coefficient is related to the shape of the satellite (3:423–424).

The remaining two perturbative forces, those resulting from the nonspherical shape of the earth and third-body attractions, are less significant for near-earth satellites than for deep-space satellites

The nonspherical shape of the earth is the result of the fact that the earth has a nonuniform shape and density. This phenomenon results in an asymmetrical mass distribution that causes the earth's gravitational force on the satellite to be directed slightly away from the center of the earth. The third-body gravitational effects are due to the fact that the earth is not the only gravitational force acting on a satellite's orbit. Other planetary bodies also exert a gravitational pull on the satellite. These third-body effects are stronger for closer bodies such as the sun and moon (6:Sec 6,5).

Differential Corrections

The Space Surveillance Center (SSC) uses differential corrections to update its element sets. Element sets, or *elsets*, change daily, mainly due to perturbations such as those previously discussed. These daily changes must be incorporated into the element sets and are done so through the use of differential corrections. Satellite observations sent by the Space Sensor Network (SSN) and received by the SSC do not exactly fit the position predicted by the element sets. These deviations are caused by changes in a satellite's orbital elements due to perturbations which were not accounted for by the model, by the fact that the element set and the associated perturbation modeling cannot predict the exact position of the satellite, and by "each sensor's error (bias) in measuring the exact position of a satellite" (6:6,6). Differential corrections are used to update element sets by attempting to eliminate any residuals caused by changes to orbital elements. To minimize errors, a least squares fit is used. Simply put, "differential corrections attempt to mathematically fit the best ellipse (with associated perturbations) to the observations of a particular satellite" (6:6,6).

The two main perturbation models used by the SSC when performing its differential corrections are the *General Perturbations (GP)* model and the *Special Perturbations (SP)* model. For both GP and SP elsets, an elliptical orbit is found such that when the respective perturbations are added on, the result will represent the true path of the satellite as closely as possible. Because SP modeling accounts for more perturbations than does GP modeling, the final path described by an SP elset will fit the satellite's true path better than that described by a GP elset.

General Perturbations Modeling. The GP model uses analytical equations to incorporate latitude-dependent perturbations. These perturbations include the imbalanced mass distribution of the earth due to its nonspherical shape, the greater mass present in the southern hemisphere of the earth, and other observed mass anomalies. Atmospheric effects are accounted for by using the BSTAR drag term (6.Sec 6,9). BSTAR is derived from the atmospheric model and is a ballistic coefficient for atmospheric drag (20 5). The units of BSTAR are 1/ER, where ER is the earth's average equatorial radius (19:123).

Special Perturbations Modeling The SP model employs numerical methods, rather than analytical methods, to incorporate latitude-dependent perturbations (zonal), longitude-dependent perturbations (sectoral), and both latitude and longitude-dependent perturbations (tesseral). Gravitational effects are accounted for by breaking the surface of the earth down into small grids to allow for better resolution. Gravitational effects of the sun, moon, and planets can also be modeled.

Occasionally, satellites will pass through the same area and experience the same perturbative forces. When this occurs, the satellites encounter resonance effects. The SP model is also capable of accounting for this phenomenon.

To model atmospheric effects, SP modeling uses the Jacchia-Nicolet model, which is more sophisticated than the atmospheric model used for GP updates. The Jacchia-Nicolet model accounts for the earth's diurnal bulge, solar activity, geomagnetic activity, and semiannual variation. The diurnal bulge is due to the fact that the sunlit side of the earth is warmer than the dark side, causing the atmosphere on the sunlit side to expand into space. This expansion results in a varying atmospheric density based on altitude and sun angle. The level of solar activity is also incorporated into the model to account for the increase in the number of charged particles ejected from the sun at higher levels of solar activity. Geomagnetic activity is accounted for by incorporating the earth's magnetic field strength, measured in A_p levels, which is also affected by solar activity. Semiannual variation refers to measured harmonic variations in the atmosphere due to seasonal changes (6:Sec 6,9-10). It should also be noted, however, that there are limits to the predictive ability of the atmospheric model. One major source of TIP prediction error, for example, is related to our current inability to accurately predict future solar activity and its subsequent effects on our atmosphere. Currently, the best we can do is predict changes in the atmosphere which would occur about two days after an observed solar event. Because the atmospheric model cannot accurately account for future solar activity, errors in the predicted decay times can be substantial.

Satellite Decay Processing

This section discusses the methods used by the Space Surveillance Center to predict the time and location of decaying satellites The SSC processes two types of satellite decays. The first type, *Normal Decays*, refers to all objects except payloads, rocket bodies, platforms, and significant debris (those with radar cross sections greater than one square meter) which have a predicted decay date within thirty days. These objects have less than a five percent chance of surviving re-entry. The second type of satellite decay is known as *Tracking and Impact Prediction* (TIP). TIP decays include all payloads, rocket bodies, platforms, and significant debris which have a predicted decay date within fifteen days. These objects have a greater than five percent chance of surviving re-entry and, therefore, a greater likelihood of causing damage upon impact. For both types of decays, the SSC will manually update the orbital elements of the decaying objects before a decay prediction is made. The processing of these two types of decays differs in the sophistication of the perturbative model used for the element set updates, the frequency of updates, and the programs used to compute the predicted decay parameters.

Normal Decay Processing. The SSC runs a program called DECAYX to identify new normal decays and compute the predicted decay dates of all normal decays. The program is run daily. The element sets of these objects are then updated using general perturbations techniques. DECAYX is rerun once all the element sets of the normal decays have been updated. The new decay dates are then logged for future reference. If a normal decay is no longer tracked by the Space Sensor Network, and it is past its most current predicted decay date, it is assumed to have burned in and is *decayed* from the SSC's active satellite database.

TIP Decay Processing. Because TIP decays have a higher probability of surviving re-entry, their element sets are updated using special perturbations techniques. TIP processing is more rigorous than normal decay processing due to the higher probability of a TIP object surviving re-entry. Once a satellite has been identified as a TIP object, SP element set updates and decay predictions are performed at specific points in time: seven-to-ten days before re-entry, four days before re-entry, two days before re-entry, one day before re-entry, twelve hours before re-entry, six hours before re-entry, two-to-three hours before re-entry, and just after re-entry. The programs used by the SSC to update the orbital element sets and then compute the decay parameters for TIP objects are called MANDC and TIPX, respectively. Each updated decay prediction includes a decay latitude and longitude, a decay time, and a decay time error window. A ground trace is also produced for all but the seven-to-ten day run.

The difference between one TIP run and the next successive TIP run essentially lies in the *obspan* used for the SP MANDC update. The obspan is the time period from which the observations (which are used to update the SP element set) are chosen. The obspans used for the various TIP runs are shown below in Table 1. The seven-to-ten day TIP run, for example, uses a two-day obspan which means that the SP MANDC will use the last two days of observations in

TABLE 1

TIP RUN OBSPANS (5:Atch 1,2)

TIP RUN	OBSPAN (days)
7-10 day	2.00
4 day	1.40
2 day	1.25
1 day	1.00
12 hr	0.80
6 hr	0.67
2-3 hr	0.50
Final	0.50

its update. The number of observations within a particular obspan will vary from one object to another.

As a TIP object approaches its impact point, the Space Sensor Network is periodically instructed to increase the *tasking* for the object. The tasking is a means by which observational requirements are set for each satellite. The tasking procedure is necessary because there are only a few sensors with which to track the large number of orbiting satellites. Tasking ensures that the proper number and dispersion of observations will be obtained on each satellite and that observations on high-interest satellites will be obtained and forwarded to the SSC on a priority basis. Tasking codes include a category and a suffix. The category sets the priority (or importance) of obtaining and transmitting the observations. The categories range from CAT 1 to CAT 3 with CAT 1 being used for events of highest priority and CAT 3 for routine near-earth satellites (6:Sec 3,11). The suffix defines the amount of observational data required for the satellites. The suffixes used and their meanings are listed in Table 2. The tasking requirements for TIP decay processing is shown in Table 3.

TABLE 2

TASKING SUFFIXES (6:Sec 3,11-12)

SUFFIX	AMOUNT OF OBSERVATIONAL DATA
A	Maximum data on all available passes.
B	1-1/2 minutes of data on all available passes.
D	Three observations evenly spaced throughout the track on all available passes. (Phased Arrays)
H	Three observations evenly spaced throughout the track on all available passes. (Mechanical Trackers)
M	Used for deep-space maneuverable satellites. Up to 20 observations are required for a suspected or detected orbit deviation.
S	As specified in a message by the SSC for near-earth satellites. Requires an in-track or cross-track search for deep-space satellites.
T	Maximum data on all available passes (used for later stages of TIP decay).

Note that each successive TIP run uses a smaller obspan. Although the obspan is smaller, the number of observations in that obspan will not necessarily be less due to the change in tasking requirements. The observations will also become closer in time to the actual decay time and will, therefore, more accurately reflect the current decay path of the object.

It should also be noted that intermediate updates are often run on most of the TIP objects. The extra updates are mostly run between the 7-day run and the 1-day run, but can occur anywhere in the update cycle. These *monitors* as they are called, use the same obspan as the previous run. They are routinely accomplished when time permits and serve to improve the prediction process as a whole. Due to the fact that monitor runs are and will continue to be an integral part of the TIP decay process, the results of this research project will not be based solely on the main TIP decay updates, but rather, will reflect a more realistic update process in which periodic monitor runs may serve as intermediate updates. The existence of monitor runs should not pose a problem and is mentioned only for completeness.

TABLE 3

TIP TASKING (5:Atch 1,1)

DAYS FROM DECAY	TASKING
> 2	2B
> 1 and ≤ 2	2T
≤ 1	1T

As previously mentioned, one of the purposes of TIP processing is to ensure that the USSR does not mistake a TIP object for an incoming re-entry vehicle. Consequently, the SSC is required to prepare an OPREP-3 report for release up-channel if a TIP object's 6-hour or 3-hour ground trace indicates that its impact point (with a ±15 minute window) is within 100 nautical miles of the Soviet border (8,11,12,15). Higher authorities will release the information to the Soviets upon their request.

Multiple Linear Regression

Multiple linear regression is a method used to describe the relationship between several independent variables and a dependent variable. It can also be used to predict the outcome of the dependent variable when the independent variables are varied (4:213,18:27-31).

If the independent and dependent variables can be fit to a model of the form shown in Equation 2, we can say that we have a linear statistical model for the expected value of the dependent variable, E(Y), where Y is the dependent variable. Note that this, in turn, means that E(Y) is a linear function of the unknown parameters β_i (see Equation 2) and not necessarily a linear function of the independent variables themselves (X_i) (17 495-497). This, in turn, means that the independent variables could be used to predict the dependent variable.

$$E(Y) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + \beta_7 X_7 \qquad (2)$$

where

X_i are the independent variables

E(Y) is the expected value of the dependent variable, Y

β_i are the y-intercept and coefficients to be determined

For this research project, the independent variables will correspond to the early TIP decay predictions (e.g., 7-day run, 4-day run), and the dependent variable will correspond to the final decay prediction.

III. *Data Collection and Description*

Data Collection

The satellite decay data used in this study was obtained from the Space Control Operations Division (J3SOS) at Cheyenne Mountain Air Force Base which oversees the day-to-day processing of satellite data by the Space Surveillance Center (SSC). As previously mentioned, one of the responsibilities of the SSC is to provide Tracking and Impact Prediction (TIP) for those objects that are within fifteen days of decay and which have a high probability of impacting the earth. As SSC personnel process each TIP object, they meticulously log the results in a *TIP Folder* After the object has decayed, the folders are reviewed by other SSC crew members and then by J3SOS personnel to ensure their accuracy. Several items from each TIP folder are then transferred to microfiche for historical purposes. The items transferred include the TIP Required Items Checklist, the Decay History, the Final TIP Message, the Final Element Set, the Pre-/Post-Ephemerides, and the Final Ground Trace.

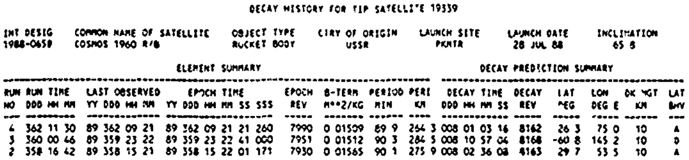
Data Description

The data relative to this study was extracted from the TIP Required Items Checklist, the Decay History, and the Final Element Set for each TIP object studied.

TIP Required Items Checklist. The TIP Required Items Checklist is a manually-kept, chronological account of each TIP's processing. Each TIP run is recorded to include the time it was completed, the crew member responsible, the resulting decay prediction, and any unusual circumstances.

Decay History. The Decay History is a computer-generated log of each special perturbations update and includes the run time, time of last observation, epoch time, epoch revolution number, B-term value, period, and resulting decay prediction. An example is provided at Figure 4.

B-Term. As a decaying object enters the atmosphere, its outer surface interacts with the molecules in the atmosphere. This interaction produces a drag on the object which can alter the



```
                                        DECAY HISTORY FOR TIP SATELLITE 19339

INT DESIG     COMMON NAME OF SATELLITE    OBJECT TYPE    CTRY OF ORIGIN    LAUNCH SITE     LAUNCH DATE     INCLINATION
1988-065B     COSMOS 1960 R/B             ROCKET BODY         USSR             PKMTR         28 JUL 88         65 8

                                ELEMENT SUMMARY                                             DECAY PREDICTION SUMMARY
---------------------------------------------------------------------------------  --------------------------------------------------------
RUN RUN TIME    LAST OBSERVED        EPOCH TIME          EPOCH   B-TERM   PERIOD PERI   DECAY TIME   DECAY    LAT     LON    DK HGT  LAT
NO  DDD HH MM  YY DDD HH MM   YY DDD HH MM SS SSS     REV   M**2/KG   MIN    KM   DDD HH MM SS   REV    DEG    DEG E    KM    DRV
--- ---------  -------------  -------------------   -----  -------  ------ ----  ------------  -----  -----  -----  ------  ---
 4  362 11 30  89 362 09 21   89 362 09 21 21 260    7990  0 01509   89 9  264 3 008 01 03 16   8162   26 3    75 0    10     A
 3  360 00 46  89 359 23 22   89 359 23 22 41 000    7951  0 01512   90 3  284 5 008 10 57 04   8168  -60 8   145 2    10     D
 2  358 16 42  89 358 15 21   89 358 15 22 01 171    7930  0 01565   90 1  275 9 008 02 36 08   8163   29 7    53 5    10     A
```

Figure 4. Example Decay History (Reproduced from 14)

object's speed and direction as it descends through the atmosphere. The predicted decay times and locations, therefore, will change according to its descent parameters. The drag on an object becomes more and more pronounced as it descends due to the increase in thickness of the atmosphere. The size, shape, and orientation of an object will determine its drag which in turn will affect its impact point. As each object is updated with an SP MANDC, a term known as its *B-term* is also updated (see Equation 3).

$$B\text{-}term = \frac{C_d A}{m} \qquad \left(\frac{meters^2}{kilogram}\right) \tag{3}$$

where

C_d is the coefficient of drag

A is the relevant surface area

m is the mass.

The B-term is measured in meters squared per kilogram and is essentially the effective surface area per unit mass affected by atmospheric interaction. The B-term is determined by fitting C_dA/m and the velocity vector to the observational data. Because a decaying object's orientation or rotational state can suddenly change, and because it may also break apart and lose pieces, the B-term values can change dramatically throughout the decay process.

Decay Date and Time. The decay date and time is logged on the decay history in the Greenwich Mean Time format. It includes the year, day, hour, minutes, and seconds (see Figure 4).

Latitude and Longitude. The latitudes are recorded as positive degrees for north latitudes and negative degrees for south latitudes. The longitudes are recorded as degrees east longitude.

Final Element Set. The Final Element Set is a listing of the parameters which describe the final orbit of the TIP object (see Figure 5). The data used in this study included both the final eccentricity value (ECC) and the final mean motion (XNO), where the mean motion is defined as the number of orbital revolutions that the satellite completes in one day.

```
           ELEMENT TRANSMISSION PROGRAM - OPS ELEMENT DISPLAY

LN SATNO   NAME     EPOCH            XNDO2       XNDDO6   BSTAR       ELNO
LN SATNO I         NODE      ECC     OMEGA     M          XNO         REVNO
 1 17051U           90  5 82342055  .17094580    35103-4  20946-3 0   9823
 2 17051   65.7946  73 9501  0006718 297 5603   63.0542 16 49494053   1211
```

Figure 5. Example Final Element Set (Reproduced from 14)

Only those TIP objects which underwent the entire update cycle (7-day run through final run) were used. This was necessary in order to accurately analyze the effects of each successive update and prediction. In the cases where the TIP Required Items Checklist and the Decay History disagreed, the results from the Decay History were used. The data includes TIP objects which decayed during the years 1987 through 1990.

IV. *Methodology*

Final Prediction

The first objective of this research project was to compare the accuracy of the TIP decay predictions made during 1987-1990 to the accuracy level asserted by the Space Surveillance Center. To achieve this, the data from the final decay predictions was used as the control by which to compare the earlier predictions. This was necessary because only a relatively few TIP objects are actually sighted as they enter the lower atmosphere or impact the surface of the earth. Therefore, a comprehensive comparison to actual impact data was not possible.

The final prediction was chosen as the control because it uses observations which are closest to the actual impact point and is considered to be the most accurate prediction available. In order to further justify the use of the final prediction as the control, a statistical analysis was also performed to directly compare the few sighted re-entry points, called *Vis Obs*, with the corresponding final predictions made by the Space Surveillance Center. The Vis Ob data, when available, was taken from the Decay History printout where it was recorded in the same format as the TIP prediction data. The specific results of the analysis can be found in Chapter V.

Time Error Calculation

In order to assess the accuracy of the decay predictions, it was necessary to determine the *time error* for each separate TIP run, where the time error is calculated as the difference between the predicted decay time for that TIP run and the final run. To achieve this, it was first necessary to convert the decay dates and times (two separate values) to a single value. Here, the hours, minutes, and seconds were converted to their fractional values of 24 hours. The appropriate day of the year was then added to this number to create a unique value representing the predicted decay date and time. These values were then used to calculate a time error for each run by subtracting the final predicted decay time from that run's predicted decay time. Note that predicted decay times earlier than the final predicted decay time yield a negative time error. The results of the time error calculations and corresponding graphs can be found in Chapter V.

Location Error Calculation

It was decided that it would be of interest to also calculate the difference between the predicted location point for each run and the final predicted location point (*location error*). To achieve this, three different methods were explored.

Method I. The first method explored attempted to use the predicted latitude and longitude values in conjunction with their predicted revolution numbers to calculate the location error. For those TIP runs in which the revolution number differed from the final revolution number, the location error was calculated based solely on the difference in revolution number and the distance traveled in a typical decay orbit. Any difference in location within the same revolution was considered insignificant when compared to the large location error incurred by differing revolution numbers. It was then assumed that the satellite's altitude would not significantly add to the size of the orbit and, thus, that the satellite's orbit could be considered to be essentially at the surface of the earth. Therefore, the distance from the center of the earth to the satellite (r) was taken to equal the mean radius of the earth (R). The satellite would then travel a distance equal to the circumference of the earth during each revolution. A mean earth radius (R) of 6,370.949 kilometers was used for a calculated earth circumference of 40029.853 kilometers. (23:F-155).

For those TIP runs in which the revolution number did not differ from the final revolution number, the location error was calculated based on the great circle distance between two points on the earth. Equation 4 was used to calculate the distance from one latitude and longitude position to another.

$$D = 111.12 * [Sin(L_1)Sin(L_2) + Cos(L_1)Cos(L_2)Cos(\lambda_2-\lambda_1)] \qquad (kilometers) \qquad (4)$$

where

D is the distance

L is the latitude

λ is the longitude

Equation 4 assumes a spherical earth and calculates the number of degrees along an arc length between the two points as measured from the center of the earth. The resulting value is then multiplied by 111.12 kilometers per degree. Note that southern latitudes and eastern longitudes must be entered as negative numbers (13:72).

This method was ultimately rejected because the relative positions of the predicted location points and the direction of the satellite's motion could not be accurately determined. Thus, because a positive location error would always result from the use of the above equation, an unacceptable bias was introduced into the data.

Method II. A second method was then used in an attempt to obtain a first approximation for the location error. First, each TIP object was assumed to be in a perfectly circular orbit again at the surface of the earth. Thus, the semi-major axis distance (a) was taken to equal the mean radius of the earth (R). Second, each TIP object's orbit was assumed to have an 88-minute period. Again, using a mean earth radius (R) of 6370.949 kilometers and an earth circumference of 40029.853 kilometers, a satellite velocity of 7.518 kilometers per second was calculated (23:F-155). This velocity was then multiplied by the previously calculated time error (converted to seconds) to determine the distance the satellite would travel during that time period.

Method III. The actual method used was a refinement of Method II. First, in order to more accurately determine the velocity of each TIP object, the satellite's mean motion (n) was used. Because data on the mean motion for each TIP run was unavailable, an approximation had to be made. The only data available was the final mean motion (XNO) recorded in the Final Element Set printout included in the TIP folder. In using this value as the mean motion for each run, an error was introduced into the calculation of the location error. Because the final mean motion value will be higher than earlier values (the object is traveling faster), the calculated location error will be larger than the actual location error. In this way, the calculated location errors will serve as upper bound error values. Also, because calculated location error values are again very large (thousands of kilometers), the error introduced by using the final mean motion instead of the actual mean motion should be insignificant when compared to the location error values themselves. Any trends, therefore, that may exist in actuality should still be visible with the small additional error introduced by strictly using the final mean motion.

To calculate the location error, the final mean motion was first converted to radians per second and then used to solve for the semi-major axis distance (a) using Equation 5 and a value of 3.986012 x 10^5 km^3/sec^2 for μ (3:185,429).

$$c = \sqrt[3]{\frac{\mu}{n^2}} \qquad \textit{(kilometers)} \qquad (5)$$

where

a is the semi-major axis

μ is the earth's gravitational parameter

n is the mean motion

The satellite's velocity (v) was then calculated from the semi-major axis using Equation 6 and the assumption of a circular orbit (i.e., $r = a$) (3:16,28). A circular orbit was assumed based on the mean eccentricity value of the TIP objects as obtained from the final element set. It should also be noted that this equation assumes a two-body motion which is essentially the case for decaying objects in low-earth orbit.

Each satellite's velocity was then multiplied by the time error previously calculated (again converted to seconds) to determine the location error from the distance each TIP object traveled during that time period. The results of the location error calculations and the corresponding graphs can be found in Chapter V.

$$v^2 = \mu\left(\frac{2}{r} - \frac{1}{a}\right) \qquad \left(\frac{kilometers^2}{second^2}\right) \tag{6}$$

where

μ is the earth's gravitational parameter

r is the distance from the center of the earth to the satellite

a is the semi-major axis

Accuracy Comparison

To compare the accuracy of the 1987-1990 decay predictions to the accuracy level reported by the Space Surveillance Center, it was decided to use the same accuracy assessment method employed by the SSC. This would allow for a direct comparison. The SSC asserts an accuracy of ±20 percent of the amount of time until the object decays. The "time until decay" is calculated as the time between that TIP run's epoch time (obtained from the decay history) and the predicted decay time (1,9). For example, if the amount of time until decay for a particular TIP run were exactly 10 days and the time error calculated was exactly +1 day, then the decay prediction would be +10 percent of the time until decay. The results of the analysis for time error can be found in Chapter V.

OPREP-3 Report Initiation

The second objective of this research project was to determine if it would be advantageous for the SSC to initiate its OPREP-3 report earlier than is currently done.

The current procedure for initiation of the OPREP-3 report is to use the satellite ground trace produced during the 6-hour TIP run. The ground trace shows the predicted impact point as well as a ±15 minute decay window. The SSC crew commander will initiate the OPREP-3 report if any portion of that ground trace within the decay window falls within 100 nautical miles of the Soviet border. Then, at the 3-hour TIP run, the OPREP-3 report is either initiated, updated, or cancelled according to the updated information given in the 3-hour ground trace (8,11,15).

To determine whether it would be advantageous to initiate the report earlier than at the 6-hour point, the mean time error for the 1987-1990 time period was analyzed. The specific results can be found in Chapter V. Based on these results, it was decided that it would be inappropriate to base the initiation decision on data generated by earlier TIP runs. It was then decided that multiple linear regression would be used to determine if a linear model could be developed which would eliminate biases found in the prediction data and predict the final decay time with a better accuracy than is currently obtained by the 6-hour TIP run. It was surmised that if a better accuracy could be obtained earlier in the prediction process by using a linear model to approximate the final decay prediction, the OPREP-3 report could be initiated earlier. It was also conjectured that the existence of such a model might provide some insight into the decay process itself and suggest an avenue of study in the event that there is a future attempt to improve the decay prediction program.

The first step was to determine if a model of the form shown in Equation 7 could be found such that the early decay prediction data could be used to approximate the final decay prediction time. The results are given in Chapter V.

$$E(t_f) = \beta_0 + \beta_1 t_1 + \beta_2 t_2 + \beta_3 t_3 + \beta_4 t_4 + \beta_5 t_5 + \beta_6 t_6 + \beta_7 t_7 \qquad (7)$$

where

t_i are the early TIP decay predictions

$E(t_f)$ is the expected value of the final decay prediction time

t_f is the final decay prediction time

β_i are the y-intercept and coefficients to be determined

Assuming that such a linear regression model could be found, the next step would be to determine which of the independent variables could be eliminated from the regression model and still approximate the final decay prediction time with an accuracy similar to (or better than) that obtained currently at the 6-hour TIP run.

To achieve this, a total of six linear models, $E_1(t_f)$ through $E_6(t_f)$, were developed to calculate the expected value of the final decay prediction time, $E(t_f)$, where each subsequent model systematically incorporated more of the early prediction data into the model.

The six models were then used to calculate $E(t_f)$ for all 180 TIP objects. The difference between these approximations to the final prediction and the actual final predictions, or *approximation error* was then calculated. The results can be found in Chapter V.

V. *Results of the Analysis*

Analysis of Final TIP Decay Predictions

Of the total 180 TIP objects from 1987-1990 studied in this research project, 93 were visibly spotted during reentry. The data obtained from these sightings is recorded on the decay history for these objects and is referred to as *Vis Obs*.

The Final TIP decay predictions made by the Space Surveillance Center (SSC) for these 93 objects were compared to the Vis Ob data. The mean time error calculated was -0.87 minutes with a standard deviation of 12.27 minutes. Using Method III described in Chapter IV, a location error of -301.89 kilometers with a standard deviation of 5864.47 kilometers was calculated. Note that there is a tendency for the final predicted decay time to be slightly earlier than the Vis Ob decay time. The final prediction time error calculations were then broken down by year and are shown in Figures 6 and 7.

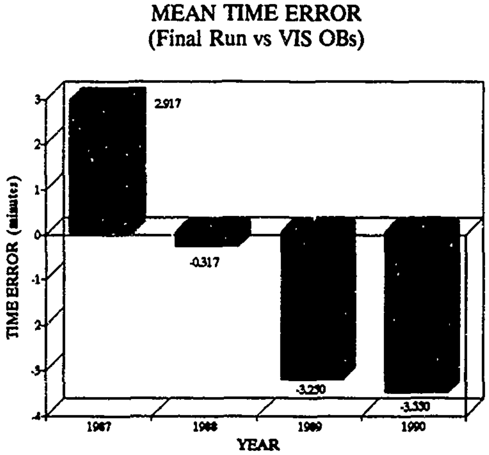


Figure 6. Mean Time Error for Final Prediction

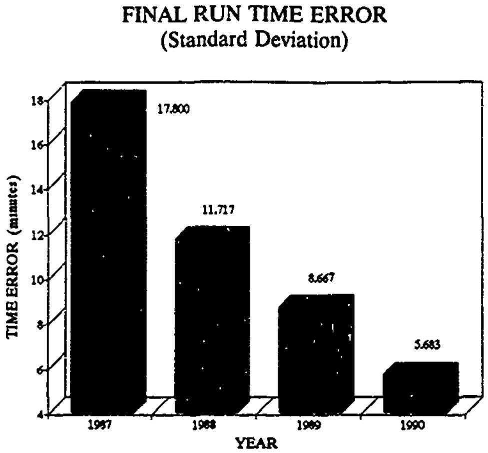


Figure 7. Final Time Error Standard Deviation

As seen in Figure 6, the mean time error becomes more and more negative from 1987 to 1990. This seems to indicate a growing tendency for the final decay prediction time to be slightly earlier than the Vis Ob decay time. There is no clear explanation for this trend. It may, however, be related to how the Vis Ob decay point data is chosen. Figure 7 indicates that the size of the time error deviation decreases from 1987 to 1990. A search for a possible explanation led to an analysis of the level of solar activity during the 1987-1990 time period.

It was found that the level of solar activity began to increase dramatically in 1987 and continued to increase through the solar maximum which is believed to have occurred around March of 1990 (21:3201). Figures 8 and 9 depict the sunspot number and 10.7 centimeter solar flux levels during the 1987-1990 time period where the data was first smoothed using a simple averaging technique (22). At first, this information would seem to suggest that the mean time error and standard deviation should have increased steadily throughout the 1987-1990 period. A closer look at the level of sunspot activity and solar flux during that period, however, revealed that although there was an overall increase in both parameters from 1987 to 1990, there was a much more dramatic increase in

SUNSPOT NUMBER
(1987-1990)

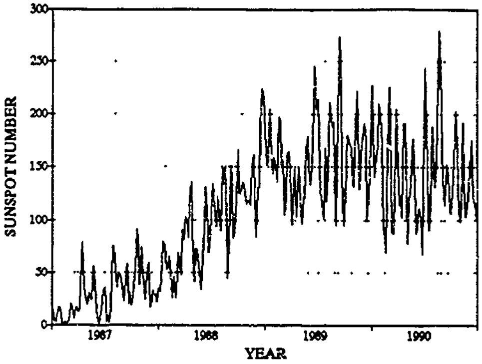


Figure 8. Sunspot Number (1987-1990)

10.7 cm SOLAR FLUX
(1987-1990)

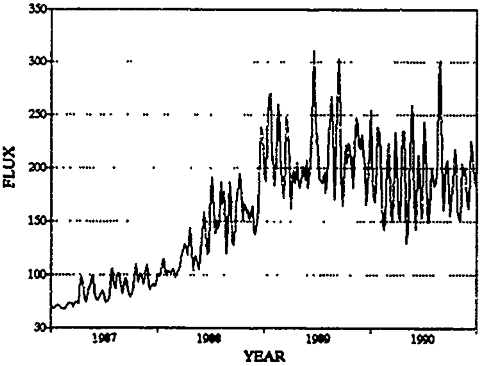


Figure 9. 10.7 cm Solar Flux (1987-1990)

those levels during 1987 and 1988 than during 1989 and 1990 (see Figures 8 and 9). The trend seen in Figure 7 may be related to this apparent leveling-off of solar activity in 1989 and 1990.

Again, because Vis Ob data is not available for all TIP objects, and because the above mean and standard deviation time error values were small, it was decided that the final TIP decay prediction could be used as the control against which to compare the earlier TIP decay predictions.

Analysis of Early TIP Decay Predictions

Time Error. The difference between each of the early predicted decay times and the corresponding final predicted decay time was then calculated and plotted for the 1987-1990 time frame. The results are listed in Table 4 and plotted in Figures 10 and 11.

TABLE 4

TIME ERROR RESULTS FOR 1987-1990

TIP RUN	MEAN TIME ERROR (minutes)	STANDARD DEVIATION (minutes)
7-Day	402.350	1288.800
4-Day	161.150	636.767
2-Day	93.700	283.967
1-Day	51.217	141.500
12-Hour	21.133	84.483
6-Hour	9.133	42.233
3-Hour	-0.267	22.767

As can be seen in Figure 10, there is a definite tendency for predicting the decay time late relative to the final prediction for all but the 3-hour run. A possible explanation for this may be that the atmospheric effects on the TIP objects are not being accurately modeled and that the overall drag on the object may actually be higher than the current values calculated by the SSC. Whether or not a sufficient explanation for this positive bias is found, however, it may be possible to incorporate an algorithm into the software used by the SSC to model out the above bias and, thus, improve the overall decay prediction. Figure 11 shows a general decrease in the time error deviation from the 7-day run to the 3-hour run. As expected, this decrease indicates that the decay predictions improve as the object approaches its reentry time.

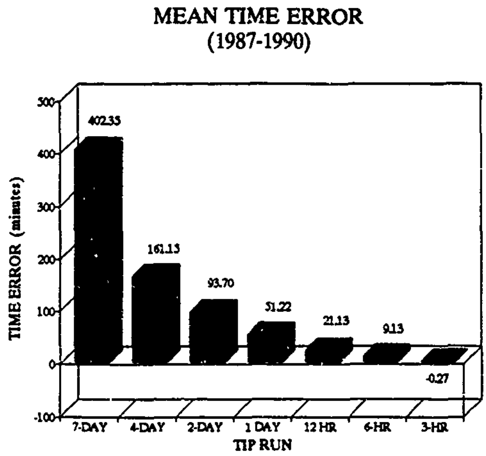


Figure 10. Mean Time Error (1987-1990)

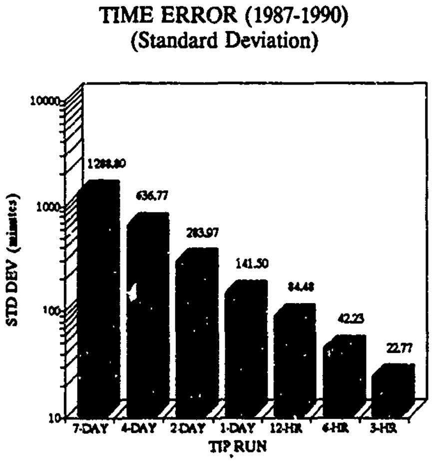


Figure 11. Time Error Standard Deviation (1987-1990)

The predicted decay time errors were then broken down by year. The results are shown in Figures 12 and 13. Figure 12 again shows that a positive error bias exists for the decay time predictions. Figures 12 and 13 also show that the mean time error for 1988 is consistently better than for any other year, but that its standard deviation is consistently higher than for any other year.

A second look at Figures 8 and 9 suggest a possible explanation for the higher standard deviation. As seen in the graphs, the level of solar activity began to gradually increase in 1987. There was, however, a sharper increase in those levels in 1988 and then a leveling-off of those levels in 1989 and 1990. It is possible that the larger deviations associated with the 1988 TIP decay data (as indicated by the larger standard deviation) may be associated with the sharper increase in solar activity during that year than for the other years.

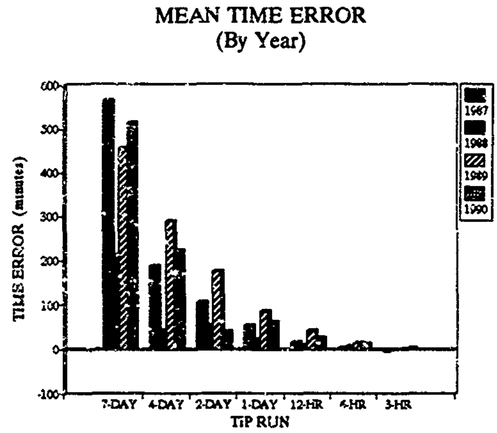


Figure 12. Mean Time Error (By Year)

In an attempt to explain the better mean time error found for 1988, it was postulated that perhaps a software fix was incorporated by the SSC to temporarily adjust for the increasing level of solar activity. However, it was determined that no such software fix was implemented (2). It was

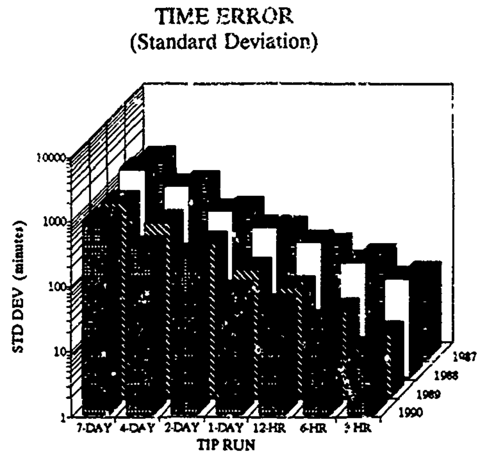


Figure 13. Time Error Standard Deviation (By Year)

also surmised that perhaps a procedural change was implemented by the SSC crews. This, too, was found to not be the case (10). It is not clear why the mean time error for 1988 is consistently better than for any other year.

Location Error. Similarly, the location error for the 1987-1990 time period was calculated using Method III as described in Chapter IV. The results are listed in Table 5 and graphed in Figures 14 and 15 Note that a similar positive error bias is seen in Figure 14 for location error as in Figure 10 for time error. Again, this may be related to an underestimated drag term resulting from high levels of solar activity. As with the time error calculations, the location error calculations were then broken down by year. The results are shown in Figures 16 and 17. As in Figure 13 for the time error, it can be seen in Figure 17 that the standard deviation for the location error is also highest for the year 1988. Again, this may be related to a sharper increase in solar activity during 1988 than for the other years.

TABLE 5

LOCATION ERROR RESULTS FOR 1987-1990

TIP RUN	MEAN LOCATION ERROR (kilometers)	STANDARD DEVIATION (kilometers)
7-Day	196,580	581,701.10
4-Day	76,160	300,133.37
2-Day	42,960	133,471.22
1-Day	23,730	66,672.89
12-Hour	10,120	39,812.62
6-Hour	4,420	19,533.66
3-Hour	-170	10,690.66

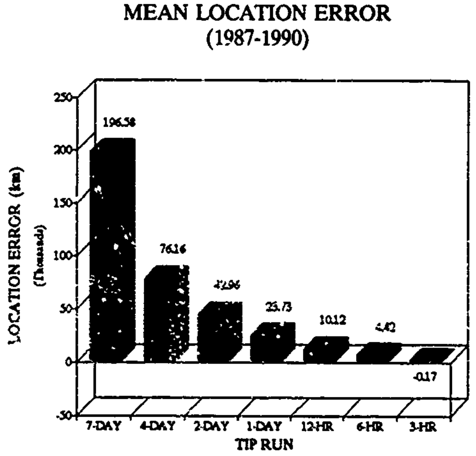


Figure 14. Mean Location Error (1987-1990)

Accuracy Comparison

As mentioned in the previous chapter, the Space Surveillance Center reports a decay prediction accuracy of ±20 percent of the amount of time left until the TIP object decays. Accordingly, the time error for each decay prediction was calculated as a percent of the time left until decay for that

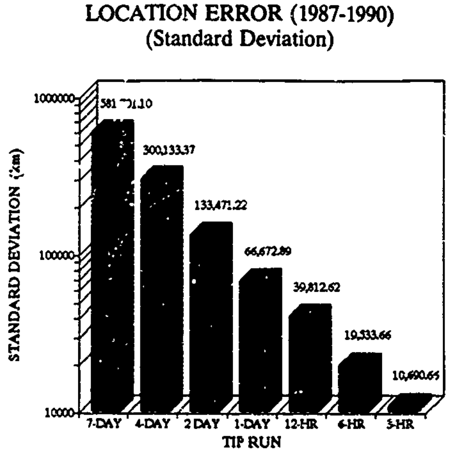


Figure 15. Location Error Standard Deviation (1987-1990)

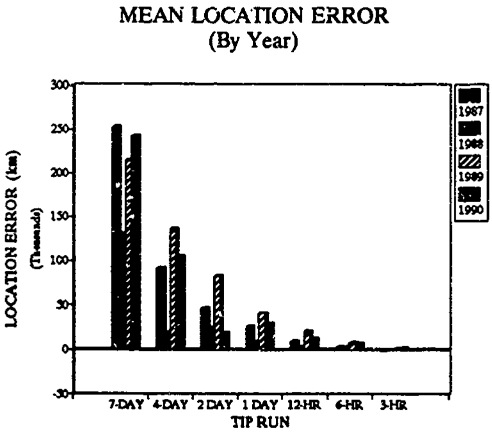


Figure 16. Mean Location Error (By Year)

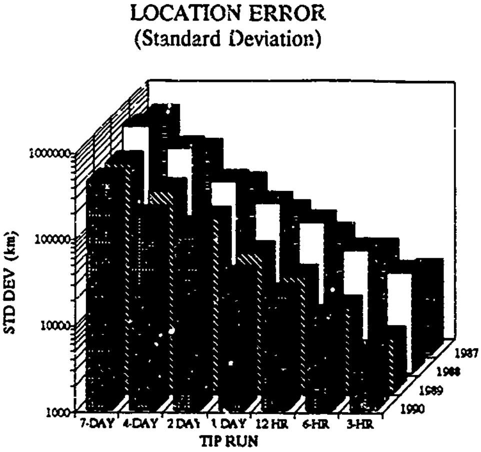


Figure 17. Location Error Standard Deviation (By Year)

TIP run. Plots were created showing the time error as a percent of the time until decay for each TIP run. The results for the 7-day, 1-day, and 3-hour runs are depicted in Figures 18-20.

The percentage of those TIP objects which actually fell outside the reported ±20 percent accuracy standard were then calculated and plotted. The results for the entire 1987-1990 time period are shown in Figure 21. Figure 22 shows the results broken down by year.

As can be seen in Figure 22, the year with the largest percentage of its decay predictions outside the reported ±20 percent accuracy standard is 1988. 1990, on the other hand, had decay predictions outside the reported ±20 percent accuracy standard for only the 2-day and 6-hour runs. All other decay predictions were better than the reported ±20 percent accuracy standard. Again, the results for 1988 may be related to the sharper increase in solar activity during that year than in the other years (see Figures 8 and 9).

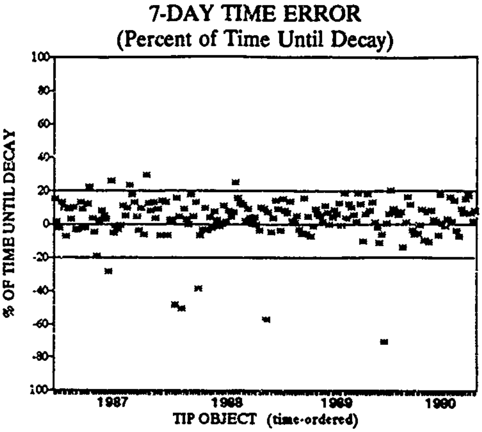


Figure 18. 7-Day Time Error

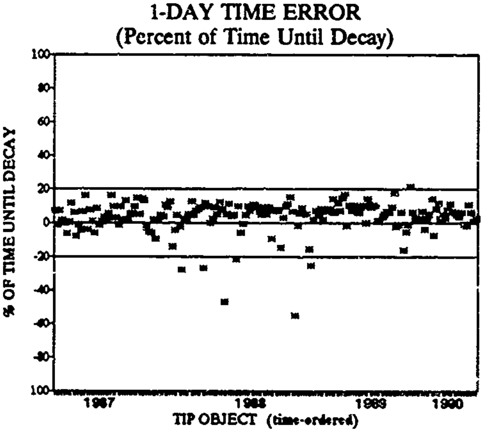


Figure 19. 1-Day Time Error

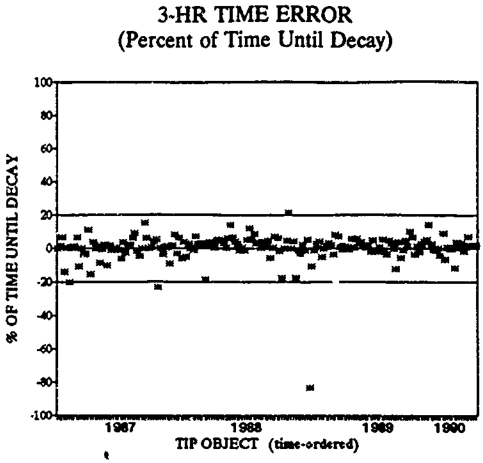


Figure 20. 3-Hour Time Error

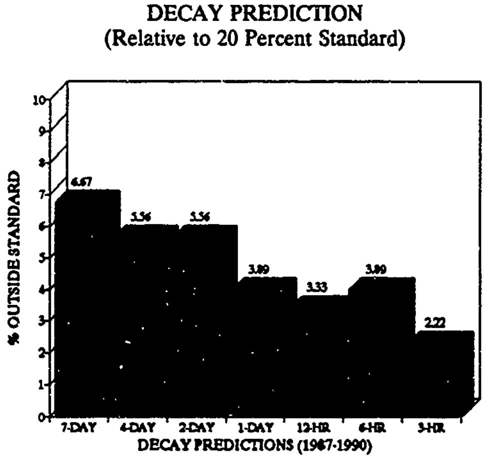
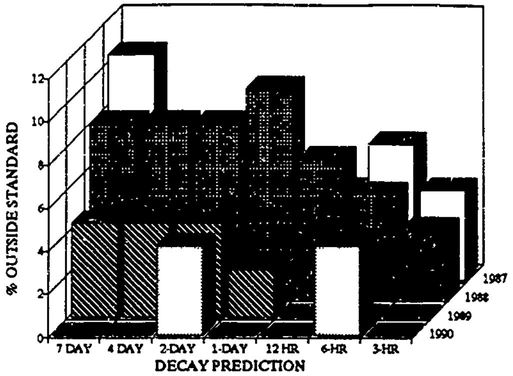


Figure 21. Decay Prediction Accuracy (1987-1990)



DECAY PREDICTION
(Relative to 20 Percent Standard)

Figure 22. Decay Prediction Accuracy (By Year)

OPREP-3 Report Initiation

As discussed in Chapter IV, the results of the accuracy calculations for time error were analyzed to determine how far back in the TIP decay process one could go without significantly lowering the prediction accuracy used to initiate the report.

Figure 10 suggests that if the current TIP prediction process were employed, it would be detrimental to use the prediction data generated earlier than at the 6-hour point to initiate the OPREP-3 report. Use of the 12-hour prediction data, for example, would incur an average increase in time error of 12 minutes. Such an increase in time error would be unacceptable.

As discussed in Chapter IV, multiple linear regression was then used to first determine if a model of the form shown in Equation 7 could be found to predict the final decay time. The results were an R-square value of 1 0000 and a p-value of .0001. This means that at a significance level of 05 there exists a perfect linear relation between some of the independent variables and the dependent variable where at least two of the β terms are not zero. The variance inflation values were all extremely large, indicating the independent variables were all highly correlated and that a great deal of redundancy exists in the data.

Because it was found that a perfect linear relationship existed between the early decay predictions and the final decay prediction, six separate linear models, $E_1(t_f)$ - $E_6(t_f)$, were developed in an attempt to approximate the final decay prediction with a greater accuracy than that obtained by the current TIP decay process alone. It was surmised that the resulting regression model might be used to eliminate some of the positive bias found in the prediction data and, therefore, improve the decay prediction accuracy.

Accordingly, six models were developed. They are given in Equations 8 through 13. The first model uses only the 7-day prediction data to calculate the expected value of the final decay prediction time, $E(t_f)$. Each subsequent model incorporates one additional decay prediction data point to calculate $E(t_f)$. The six models were then used to calculate $E(t_f)$ for all 180 TIP objects. The difference between these approximations to the final prediction and the actual final predictions (approximation error) was then calculated for each model.

$$E_1(t_f) = -0.116442 + 0.999064(t_1) \tag{8}$$

$$E_2(t_f) = -0.155478 + 0.49007(t_1) + 0.951197(t_2) \tag{9}$$

$$E_3(t_f) = -0.082444 + 0.41692(t_1) + 0.050001(t_2) + 0.908343(t_3) \tag{10}$$

$$\begin{aligned} E_4(t_f) = {} & -0.053030 + 0.007471(t_1) - 0.014395(t_2) + 0.196518(t_3) \\ & + 0.810492(t_4) \end{aligned} \tag{11}$$

$$\begin{aligned} E_5(t_f) = {} & -0.022322 - 0.004222(t_1) - 0.005502(t_2) + 0.046458(t_3) \\ & - 0.049000(t_4) + 1.012311(t_5) \end{aligned} \tag{12}$$

$$E_6(t_f) = -0.008370 + 0.000553(t_1) - 0.002944(t_2) + 0.014541(t_3) - 0.009096(t_4) - 0.183413(t_5) + 1.180378(t_6) \tag{13}$$

where

$E_i(t_f)$ is the expected value of the final decay prediction time

t_f is the final decay prediction time

t_1 is the 7-day prediction time

t_2 is the 4-day prediction time

t_3 is the 2-day prediction time

t_4 is the 1-day prediction time

t_5 is the 12-hour prediction time

t_6 is the 6-hour prediction time

By comparing Figure 23 to Figure 10, it can be seen that every model yielded a better mean approximation error than the TIP runs themselves. For example, at the 6-hour point, Figure 10 shows that by strictly using the current decay prediction procedure, a mean time error of 9.13 minutes is incurred. Figure 23, however, shows that this mean time error could be reduced to only 19 seconds if Model 6, $E_6(t_6)$, were incorporated into the prediction process.

Figure 23 also shows that the best approximation for the final decay time was achieved using Model 4, $E_4(t_f)$, where the estimate of the mean approximation error for the 1987-1990 TIP decay objects was zero. Since Model 4 uses the decay predictions generated by the 7-day through 1-day TIP runs, this would suggest that Model 4 could possibly be used to predict the final decay time and decide the necessity of OPREP-3 report initiation at the 1-day point rather than at the 6-hour point. This in turn would give the proper authorities an additional 18 hours notice of possible satellite impact near or within the Soviet border. Further comparison of Figure 24 with Figure 11, however, shows that a greater error deviation would be incurred if the decision were moved up to the 1-day point (i.e., 172.92 minutes instead of 42.23 minutes). Assuming an error limit of one standard deviation, it would be necessary to keep the decision at the 6-hour point in order to maintain approximately the same error limits (i.e., 40.23 minutes instead of 42.23 minutes).

Because Figures 11 and 24 both represent the amount of error deviation from a mean, they could be used to estimate an error window. This led to a further analysis of the procedure involved in OPREP-3 report initiation. As mentioned previously, the current procedure is to look at a ±15 minute window on the 6-hour or 3-hour ground trace to determine the necessity of the report. It is assumed that this window was intended to allow for some error in the predicted decay time calculations. If this is actually the case, then based on the standard deviation results for the 6-hour point and using one standard deviation as an error margin, the current ±15 minute error window is too small. A more reasonable error window might be ±42.23 minutes for the current procedure (see Figure 11, 6-hour point) or ±40.25 minutes if Model 6 is incorporated into the procedure (see Figure 24).

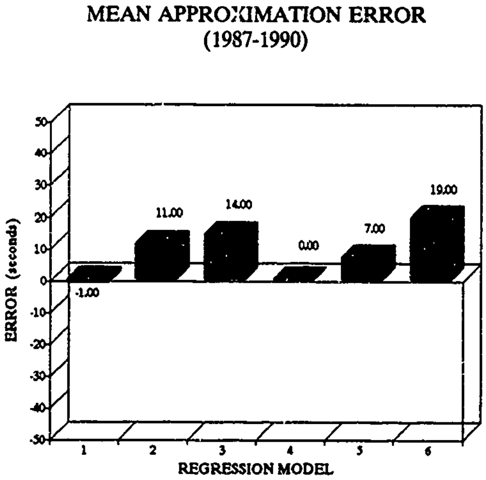


Figure 23. Mean Approximation Error (1987-1990)

VI. *Conclusions and Recommendations*

TIP Decay Accuracy

According to the results of the data used in this research project, the accuracy of the TIP decay predictions is pretty much as reported by the Space Surveillance Center (i.e., within ±20 percent of the time until decay). Except for the relatively few predictions which fell outside of this margin (which might be attributed to noise within the data itself), the decay predictions in general were much better than the reported ±20 percent as can be seen in Figures 18-20.

It should be noted, however, that a positive bias seems to exist indicating that the early TIP decay predictions are routinely late relative to the final decay prediction. It may be possible to develop an algorithm to completely model this bias out and, thus, temporarily improve the decay predictions until a reasonable explanation and fix can be found for this bias. The existence of such a bias may be due to an increase in solar activity from 1987 to 1990 which would cause an expansion of the atmosphere and a subsequent increase in atmospheric drag on decaying satellites.

Based on the multiple linear regression analysis findings of this research project, the use of linear models such as those given in Chapter V in conjunction with the data generated by the current TIP decay process would allow the SSC to better predict the final decay time by eliminating some of the positive bias found in the data.

It may also be beneficial to pursue a study of the current Special Perturbations model used by the Space Surveillance Center and attempt to better account for the level of solar activity which affects the earth's atmosphere and its orbiting satellites.

OPREP-3 Report Initiation

With regard to OPREP-3 report initiation, it is first recommended that the initiation decision continue to be made at the 6-hour point, rather than any earlier. It is also recommended, however, that a linear regression model, such as Model 6, be used in conjunction with the 7-day through 6-

VI. *Conclusions and Recommendations*

TIP Decay Accuracy

According to the results of the data used in this research project, the accuracy of the TIP decay predictions is pretty much as reported by the Space Surveillance Center (i.e., within ±20 percent of the time until decay). Except for the relatively few predictions which fell outside of this margin (which might be attributed to noise within the data itself), the decay predictions in general were much better than the reported ±20 percent as can be seen in Figures 18-20.

It should be noted, however, that a positive bias seems to exist indicating that the early TIP decay predictions are routinely late relative to the final decay prediction. It may be possible to develop an algorithm to completely model this bias out and, thus, temporarily improve the decay predictions until a reasonable explanation and fix can be found for this bias. The existence of such a bias may be due to an increase in solar activity from 1987 to 1990 which would cause an expansion of the atmosphere and a subsequent increase in atmospheric drag on decaying satellites.

Based on the multiple linear regression analysis findings of this research project, the use of linear models such as those given in Chapter V in conjunction with the data generated by the current TIP decay process would allow the SSC to better predict the final decay time by eliminating some of the positive bias found in the data.

It may also be beneficial to pursue a study of the current Special Perturbations model used by the Space Surveillance Center and attempt to better account for the level of solar activity which affects the earth's atmosphere and its orbiting satellites.

OPREP-3 Report Initiation

With regard to OPREP-3 report initiation, it is first recommended that the initiation decision continue to be made at the 6-hour point, rather than any earlier. It is also recommended, however, that a linear regression model, such as Model 6, be used in conjunction with the 7-day through 6-

hour data to improve the final decay prediction time. By implementing such a change in SSC procedures, there would be an average improvement in the 6-hour decay prediction time error of 528.8 seconds. Lastly, it is also recommended that the ±15 minute error window currently used as a guide to initiate the OPREP-3 report be widened to approximately ±40 minutes to better account for possible error in the decay prediction calculations.

Bibliography

1. Barker, Bill, Deputy Astrodynamics Project Manager. Personal Interview. KAMAN Sciences Corporation, Colorado Springs, CO, 13 September 1991.

2. Barker, Bill, Deputy Astrodynamics Project Manager. Personal Interview. KAMAN Sciences Corporation, Colorado Springs, CO, 8 October 1991.

3. Bate, Roger R. et al. *Fundamentals of Astrodynamics*. New York: Dover Publications, Inc., 1971.

4. Cody, Ronald P. and Jeffrey K. Smith. *Applied Statistics and the SAS Programming Language* (Third Edition). Amsterdam: Elsevier Science Publishing Co., Inc., 1991.

5. Department of the Air Force. *Operational Checklist.* USSPACECOM/J3 Form 76. TIP Support: Intermediate Runs. OPR J3SOS, 23 October 1989.

6. Department of the Air Force. *Orbital Analyst Handbook*. Colorado Springs, Colorado: HQ AFSPACECOM, March 1989.

7. Department of the Air Force. *Space Handbook*. Maxwell, Alabama: Air University, January 1985.

8. Giani, Major Vincent C., Commander, Space Surveillance Center. Personal interview. HQ USSPACECOM/J3SO, Cheyenne Mountain AFB CO, 1 May 1991.

9. Hall, Gary L., Chief Orbital Analyst, Space Control Operations Branch. Personal interview. HQ USSPACECOM/J3SOS, Cheyenne Mountain AFB CO, 9 September 1991.

10. Hall, Gary L., Chief Orbital Analyst, Space Control Operations Branch. Personal interview. HQ USSPACECOM/J3SOS, Cheyenne Mountain AFB CO, 8 October 1991.

11. Halpin, Lt Col Michael P., Former Commander, Space Surveillance Center. Personal interview. HQ USSPACECOM/J3SS, Peterson AFB CO, 1 May 1991.

12. Halpin, Lt Col Michael P., Former Commander, Space Surveillance Center. Personal interview. HQ USSPACECOM/J3SS, Peterson AFB CO, 23 May 1991.

13. Hewlett-Packard. *HP-25 Applications Programs*. 00025-90011, Rev. C 8/75, 1975.

14. HQ USSPACECOM/J3SOS. Historical Tracking and Impact Prediction Data. Microfiche. January 1987 - December 1990.

15. Koch, Lt Col Fred H., Former Commander, Space Surveillance Center. Personal interview. HQ USSPACECOM/J3SS, Peterson AFB CO, 1 May 1991.

16. Liu, J.J.F. "Advances in Orbit Theory for an Artificial Satellite with Drag," *Journal of the Astronautical Sciences, 31:* 165-188 (April-June 1983).

17. Mendenhall, William et al. *Mathematical Statistics with Applications* (Fourth Edition). Boston: PWS-KENT Publishing Company, 1990.

18. Neter, John et al. *Applied Linear Statistical Models: Regression, Analysis of Variance, and Experimental Designs* (Third Edition). Boston: Richard D. Irwin, Inc., 1990.

19. North American Aerospace Defense Command. *NORAD Technical Publication.* TP SCC 008. Colorado Springs: HQ NORAD, 6 April 1982.

20. Roehrich, Michelle. *Orbit Propagator Types.* J3SOT-TN-91-1. Colorado Springs: USSPACECOM/J3SOT, 29 August 1991.

21. Sawyer, Kathy. "Solar Tantrum Erupting," *Applied Optics, 29:* 3201-3202 (1 August 1990).

22. USAFETAC. *USAFETAC Project 910809,SESS Data for Satellite Orbits.* USAFETAC/DNE Letter with two Attachments, 15 August 1991.

23. Weast, Robert C. (editor) *CRC Handbook of Chemistry and Physics* (Sixty-Third Edition). Boca Raton: CRC Press, 1982.

Vita

Captain Susanne V. Lefebvre was born on 26 June 1963 in Landstuhl, Germany. She graduated from Fort Walton Beach High School in May 1981 and received a four-year ROTC scholarship. She attended the University of Florida, graduating with high honors and receiving a Bachelor of Science in Mathematics in May of 1986. While at the University of Florida, she was a member of the Air Force ROTC Detachment 150, received the AFROTC Commandant's Award in May 1983, was chosen as the first female wing commander in 1984, was a distinguished graduate, and was awarded a regular commission upon graduation. Her first assignment was at Lowry AFB, Colorado where she graduated as the Top Graduate of the first Undergraduate Space Training Class in February 1987. Upon graduation, she was then assigned to the United States Space Command from February 1987 to May 1990. During this period, she worked as an Orbital Analyst in the Space Surveillance Center, as the Near-Earth Analyst in J3SOS, and as Deputy Launch Officer in J3SOS. Her responsibilities included performing timely processing of all tracking data from a worldwide network of 26 spacetrack sensors, maintaining all procedures concerning near-earth processing, and developing, coordinating, and disseminating all information concerned with domestic and cooperative space launches. In May 1990, she entered the School of Engineering, Air Force Institute of Technology at Wright-Patterson Air Force Base, Ohio.

Permanent address: 315 Cecelia Dr.
Fort Walton Beach, Florida 32548