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ESD-TDR-65-155

OPTICAL OBSERVATION OF FAINT SATELLITES
(Final Report)

Technical Documentary Report No. ESD-TDR-65-155
July 1964

496L SPO
Electronic Systems Division
Air Force Systems Command
Laurence G. Hanscom Field, Bedford, Massachusetts

Project No. 1770, Task No. 17701

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The Space and Information Systems Division
North American Aviation, Incorporated, Downey, California;
G. A. McCue, D. F. Bender, J. G. Williams, A. S. Leonard, authors)

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FOREWORD

This document constitutes the final effort in support of the contract entitled "Research to Improve Techniques for Systematic Optical Observation of Faint Satellites and Observation of Special Satellites." This 38-1/2-month study was sponsored by the 496L-SPO, Electronics Systems Division, under contract AF 19(604)-8427.

The contractor's designation of this report is SID 64-1490.

ABSTRACT

Significant accomplishments under this study are summarized and enumerated. Direct operational support of the Space Detection and Tracking System (SPADATS) by a group of volunteer observers, the Western Satellite Research Network (WSRN), was the most important achievement resulting from this contract. Technical groundwork that will permit the future direct support of SPADATS by WSRN is described.

CONTENTS

INTRODUCTION

Numerous tasks, ranging from orbit analysis to observation of satellites invisible to radar, were accomplished during the course of this 38-1/2 month contract. In addition to these contributions to Space Track and SPADATS, major contract effort was devoted to strengthening and expanding WSRN. This active, responsible network will benefit SPADATS directly in the years ahead.

Today, an improved and expanded WSRN, which responds directly to SPADATS' needs and priorities, is a reality. Since 1960, the network has grown from a group of 8 teams (5 located in California), which reported their occasional important observations by airmail, to 25 teams and 82 observing sites including stations in Australia, South America, and South Africa, which continually submit telegraphic reports concerning a number of "difficult" satellites, in addition to responding to various priority operations (e.g., decays, lost satellites, new launchings, optical signature data).

During July 1964, teams were participating actively in WSRN at the following locations:

Adelaide, Australia
Akron-Canton, Ohio
Albuquerque, New Mexico
China Lake, California
Cleveland, Ohio
Denver, Colorado
Durban, South Africa
Kansas City, Kansas
Madison, Wisconsin
Milwaukee, Wisconsin
Newberg, Oregon
Pasadena, California
Pendleton, Oregon
Phoenix, Arizona
Rochester, New York
Sacramento, California
San Antonio, Texas
San Jose, California
Sao Paulo, Brazil
St. Petersburg, Florida
Townsville, Australia
Van Nuys, California
Walnut Creek, California
Whiteman, Missouri
Whittier, California
Wichita, Kansas

TECHNICAL EFFORT

Most technical effort performed under the contract was completed during the first year of the study. Routine technical progress was reported in each of twelve quarterly progress reports (References 1 through 12). Significant analyses and the formulation of practical space mechanics techniques for use by volunteer observers were reported in an "Orbit Determination and Analysis Manual" (Reference 13). The development of an observer-oriented, orbit-improvement program was reported in Reference 14, entitled "Recovery of Satellite 1960 Iota 4—A Verification of Long-Range Orbit Prediction Techniques." WSRN's observer-oriented methodology for solving practical satellite mechanics problems also was discussed in this paper.

The remaining significant technical efforts were devoted to developing computer programs that will be available for future WSRN operational support to SPADATS. Several of the most important programs are discussed in the following text.

PREDICTION PROGRAM

The existing WSRN prediction program may use any of three types of orbital elements: (1) SPADATS, (2) WSRN (mean anomaly format), or (3) Leonard (nodal revolutions format). Because of the many different types of satellite orbits, and the different observing practices of the teams, the program was written so as to be versatile.

The operator may elect to predict the culmination point of the satellite transit, a meridian transit, a transit of the east-west plane, or transits of points at particular angles from the node. Any or all of these modes could be used for any one of the stations in a single run. Differential corrections for any time difference (up to 12 different times) or additional positions on the same pass may be computed. The differential correction procedure has proven its worth in numerous searches for lost satellites, and in the subsequent post-recovery operations. During typical operations, the program is capable of generating up to 1500 predictions per minute on the IBM 7094.

OBSERVATION REDUCTION AND ORBITAL ELEMENT IMPROVEMENT PROGRAM

This program uses the following system of orbital elements:

$$a = a_o + a_1 (t - t_o)$$

$$e = e_o + e_1 (t - t_o) + e_s \sin \omega$$

$$i = i_o + i_s \sin\omega$$

$$\Omega = \Omega_o + \Omega_1 (t - t_o) + \Omega_2 (t - t_o)^2 + \Omega_c \cos\omega$$

$$\omega = \omega_o + \omega_1 (t - t_o) + \omega_2 (t - t_o)^2 + \omega_c \cos\omega$$

$$M = M_o + M_1 (t - t_o) + M_2 (t - t_o)^2 + M_3 (t - t_o)^3 + M_c \cos\omega$$

The least predictable of these elements is M, the time-keeping parameter. By distinguishing between the position of the orbit and the position of the satellite in the orbit, the influence of M may be eliminated effectively. This philosophy is carried out in the following procedure:

1. Initial values of all of the orbital parameters are guessed.

2. First to be determined are the geometrical parameters (i, e, Ω, ω). The true position of the satellite along the orbit has little effect on the determination of these parameters. The observed position of the satellite is converted to a unit vector. This observation vector is then compared with the predicted path of the orbit through the observer's sky; the difference between the two is the position residual. The position residual takes the form of a small vector which is projected into vertical and horizontal components.

3. The horizontal projection of the jth residual, δN_j, depends on δi and $\delta\Omega$ as follows:

$$\delta N_j = \sin\theta_j \, \delta i - \sin i \cos\theta_j \, \delta\Omega$$

   where θ_j is the angle between the ascending node and the observed position of the satellite. A least-squares routine fits the best coefficients δi and $\delta\Omega$ to those observations with small zenith angles.

4. The vertical component of the jth residual, δr_j, depends on δe and $\delta\omega$ in the following manner:

$$\delta r_j = \frac{-e\, r_j \sin E_j}{(1-e^2)^{1/2}} \delta\omega - a \cos E_j \, \delta e$$

   where E_j is the eccentric anomaly corresponding to θ_j. A least-squares routine then is used to determine the best values of $\delta\omega$ and δe for those observations not near the zenith (the limit being at the discretion of the program user).

5. When i, e, Ω, and ω have been determined, a new equation for M is calculated from observed time residuals. Then a_0, a_1, e_s, i_s, Ω_1, Ω_2, Ω_c, ω_1, ω_2, ω_c, and M_c may be evaluated analytically. Note that the sinusoidal terms due to the third harmonic of the earth's gravitational potential can cause radius vector variations of ±5 miles, an effect not compensated for in the SPADATS system but included here.

6. Inaccurate observations are rejected systematically and the process is repeated until the precise orbit is found. Both mean anomaly and SPADATS-type elements are output. The time residuals are automatically plotted against data and the various residuals are printed out for the analyst's inspection.

This procedure has yielded long-term reductions (during one year) with an accuracy of better than 3 minutes of arc (root mean square) with respect to the observed positions.

Because WSRN is asked to track those satellites which are difficult for radar, it is necessary to perform many orbit analyses. Typically, the SPADATS element sets on an object which is lost or very nearly lost are inaccurate. Observations made one or two years earlier may be used to produce very accurate elements by using the long-term element reduction methods. An example of the application of long-term reduction methods to satellite orbit-keeping was published in Reference 14.

OPTICAL CHARACTERISTICS REDUCTION PROGRAM

This program converts the observations of satellites to an absolute basis. The observed maximum and minimum brightness is corrected for range by conversion to brightness (in magnitudes) at 1000 miles. The phase-angle is calculated in order to determine the phase-angle dependence of brightness.

A WSRN listing of satellite sightings is issued periodically. Factors such as the time, position, range, maximum and minimum brightness, tumble rate, flash duration, observer identification, and comments are tabulated. Six thousand observations of 221 different satellites are tabulated at present (Reference 15).

SUPPORT OF WSRN TEAMS

The network teams regularly receive predictions on satellites for which positional data or optical appearance data are desired. Satellite lists and bulletins giving observing information are issued periodically.

Each team has copies of the "Orbit Determination and Analysis Manual" (Reference 13), which provides reference material. Each team has been given a "Satellite Orbit Calculator" as an aid to visualization and calculations. Several nomograms also have been distributed as aids to calculation and for making predictions.

Those teams that make frequent use of orbital elements receive weekly reproductions of the updated SPADATS element sets. A summary of team information (Reference 16) is issued annually. Included in this summary are the locations and sensor numbers for all of the active sites, the names, addresses, and telephone numbers of the team leaders and their alternates, and a description of the type and number of observing instruments.

Each year a WSRN team conference has been held near one of the team sites. At the conferences team members have a chance to discuss observation methods and to give reports on individual studies. All network teams receive copies of the conference proceedings (References 17 through 20).

DIRECT SUPPORT OF SPADATS

The following objects were recovered and tracked optically for SPADATS after being lost by electronic sensors:

1960 Iota 4 (052)

1961 Nu 1 (107)

1962 Beta-Upsilon 2 (515)

1963 13 B (575)

The following are faint objects which are now tracked routinely by WSRN:

1962 Kappa 3 (273)

1962 Alpha-Epsilon 2 (341)

1962 Beta-Upsilon 2 (515)

1963 13 B (575)

1964 3 A (737)

1964 3 B (738)

Objects previously tracked for SPADATS but which were given up after improvements in the electronic system are:

1958 Beta 1 (016)

1959 Alpha 2 (012)

1960 Iota 3 (051)

1960 Iota 5 (053)

1960 Nu 1 (058)

1960 Nu 2 (059)

1961 Nu 1 (107)

Two objects in exceptionally eccentric orbits (300 miles at perigee to 41,000 miles at apogee) also are being tracked. They are:

1964 6 B (748)

1964 6 D (751)

A number of objects which had an increase in tumble rate because of either a leak or a rupture of some pressurized container have been noted. Some of these objects showed a corresponding change in the orbital elements at the time of spin-up. These objects are:

1960 Eta 3 (047)

1960 Nu 2 (059)

1961 Zeta 1 (084)

1962 Beta-Alpha 2 (426)

1962 Beta-Kappa 1 (444) (on three separate occasions)

1963 33 B (633)

1964 2 A (733)

1964 5 A (744)

One decaying satellite has been observed. The Madison team observed 1963 50 A (707) during its reentry on March 27, 1964. A number of objects have been observed shortly before decay. The pre-reentry observations were made on the following objects:

1961 Delta 1 (081)

1961 Phi 2 (174)

1962 Theta 2 (267)

1962 Iota 1 (269)

1962 Iota 2 (270)

1962 Alpha-Xi 1 (367)

1962 Beta-Theta 1 (441)

1963 10 A (567)

1963 10 B (568)

1963 11 B (570)

1963 18 B (587)

1963 50 A (707)

1964 13 B (767)

1964 34 B (823)

On several occasions WSRN has been used to help track objects from launchings in which many objects were orbited. Seven of the eight objects orbited in the 1963 47 launch have been tracked optically. All five of the objects tracked by radar from the 1964 4 (Echo 2) launch have been tracked optically by WSRN. In addition, one other object from this launch, a Mylar strip, was tracked through the first visibility period. This Mylar strip is not being tracked electronically.

The orbit reduction program was applied to 15 radar observations of 1961 Omicron 43 (158) when the SPADATS program did not converge and the object became lost. The resulting elements allowed this object to be recovered electronically. In a similar effort, analysis of 12,000 observations of the 1960 Epsilon pieces was carried out and the negative results were forwarded to SPADATS.

Several changes in reporting were made recently to ensure better utilization of observations forwarded to SPADATS. During the past year positional data have been telegraphed to SPADATS in the same format employed for electronic data. The teletype tapes now go directly into the SPADATS system without further modification. Optical data on foreign objects of interest have been telegraphed recently in a form that reduces brightness data to a standard range and phase angle.

CONCLUSION

A network of experienced, responsible volunteer observers, which contributes directly to SPADATS, has been organized under this contract. These visual observers have been able to supply SPADATS with observational data (positions and optical signatures) which otherwise would have been unobtainable. The support WSRN has been able to supply to SPADATS covers many facets of satellite tracking and owes a great deal of its worth to its versatility.

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1. Optical observations
2. Western Satellite Research Network (WSRN)
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V. Secondary Report No. SID 64-1490
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