Recovery of Satellite 1960 Iota 4: A Verification of Long-Range Orbit Prediction Techniques

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Details of the recovery of satellite 1960 Iota 4, a small faint satellite that had been lost for more than eight months, are presented to illustrate the practical application of a long-range orbit determination and prediction scheme. The validity of the orbit parameters determined for the Iota 4 search is substantiated through comparison with post-recovery orbital elements. Methods for effectively using small numbers of optical observations are developed, and an orbit improvement program that incorporates these methods is described. Practical use of prediction and search techniques designed to absorb reasonable fluctuations in a satellite's behavior is demonstrated.

Nomenclature

a = semimajor axis
e = eccentricity
E = eccentric anomaly
i = inclination
M = mean anomaly or anomalistic revolution number
$\mathbf{N}$ = unit vector directed toward ascending node
r = geocentric radius to satellite
$\mathbf{R}$ = geocentric position vector of satellite
t = time
t_0 = epoch of orbital elements
v = true anomaly
δN = angle between orbit plane and $\mathbf{R}$
θ = angle from the ascending node to $\mathbf{R}$
Ω = right ascension of the ascending node
ω = argument of perigee

Introduction

As the total number of orbiting objects increases, it becomes necessary to seek more economical methods for routine satellite tracking. For several years the author has sought to develop an orbit determination and prediction scheme with long-range capability as a possible solution to this problem. This scheme has been designed to operate effectively with a minimum number of observations and could reduce considerably the computational requirements of future space surveillance systems.

The successful reacquisition of satellite 1960 Iota 4 after it had been lost for more than eight months serves as an illustration of the current validity and usefulness of these methods. For this reason, this paper explores several aspects of the Iota 4 recovery problem, including orbit determination methods, the derivation of search elements from 32 initial observations, search techniques employed by Western Satellite Research Network teams, and the successful prediction of Iota 4's future behavior. Finally, the search elements are compared to post-recovery elements derived from more than 300 observations distributed over a period of two years. Agreement between these two sets of elements further establishes the validity of the original orbit determination.

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Iota 4 Recovery Problem

Satellite 1960 Iota 4 was an unexpected and unexplained fragment resulting from the Echo I balloon launching on August 12, 1960. The objects expected to have entered an approximately circular, 1000-mile orbit were to have been the Echo balloon (1960 Iota 1), the last stage rocket (Iota 2), and the two magnesium hemispheres that contained the balloon until injection into orbit (Iota 3 and Iota 5). Iota 4 first was observed following a few degrees behind Iota 1. For several weeks subsequent to launching, it was regularly observed. Then came a period of several months during which only a few sporadic observations were received. A search was initiated during the following period of over eight months which failed to produce any definite observations.

Observing Iota 4 was extremely difficult because it was seldom brighter than +8 magnitude and because it was visible as very short (less than $\frac{1}{10}$ sec) flashes of light occurring at 3-sec intervals. Soon after it was reported, and before any orbital data were available, it was suggested that Iota 4 was a piece of aluminized mylar that also had been placed in the magnesium container. However, recent acceleration determinations indicate that it is considerably more dense than an aluminized mylar model would suggest.

The best representative model to date describes Iota 4 as having the characteristics of a small metal ring (about 12 in. in diameter). As this object rotates, it reflects a small arc of light toward the earth's surface. If and when this arc of light crosses an observing station, a brief flash may be observed in a large telescope. Recently there have been periods of several weeks when Iota 4 was not visible at certain stations, even though it passed directly overhead during twilight hours.

Air drag damping and interaction with the earth's magnetic field caused Iota 4 gradually to slow its rotation. Since the number of flashes of light reflected was proportional to its rotation rate, Iota 4 was seen as fewer flashes separated by greater arc lengths in the sky. Figure 1 illustrates this effect and indicates that in the future Iota 4's rotation rate will be essentially zero. As fewer flashes were reflected, Iota 4 became increasingly difficult to track.

Recent observations indicated erratic flashes at unpredictable intervals with several instances of almost constant brightness for periods of several seconds. This seems to support the conclusion that Iota 4's rotation period has become extremely long. Tracking this illusive object therefore will become even more difficult in the future.

Iota 4's erratic optical characteristics make it an interesting target for any space surveillance system. The integrated

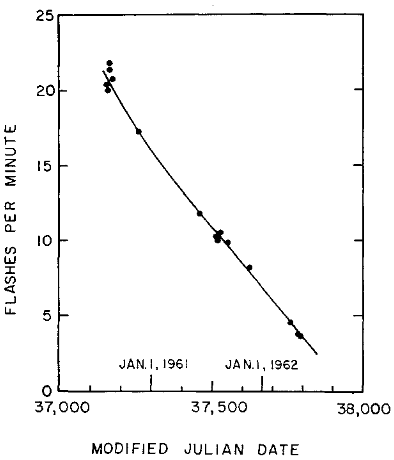

Fig. 1 Iota 4 flash rate decay

light it reflects usually is insufficient to photograph with a Baker-Nunn tracking camera. Additionally, its unusual physical characteristics make electronic tracking virtually impossible. Visual tracking of Iota 4 therefore will be necessary for a number of years. At present, its orbit is being maintained entirely with observations secured by teams of the Western Satellite Research Network, using elements and predictions derived from the techniques described in this paper. These methods may be used to predict accurately the position of Iota 4 at least several months or possibly more than a year in advance. There are a number of other orbiting objects, some equally as difficult to track as Iota 4, which could be tracked successfully with these methods.

Orbit Determination Techniques

Procedures described here are oriented principally toward handling faint satellites wherein one obtains sparse observations distributed over extended time intervals. However, they have been applied successfully to numerous additional problems in satellite mechanics. Similar procedures enabled Leonard[1–4] to effect recovery of satellites 1959 Alpha 2, 1958 Beta 1, 1958 Epsilon, and, more recently, 1961 Nu.

The following set of orbital element equations is employed in this discussion:

$$
\begin{aligned}
a &= a_0 + a_1(t - t_0) \\
e &= e_0 + e_1(t - t_0) + e_s \sin\omega \\
i &= i_0 \\
\Omega &= \Omega_0 + \Omega_1(t - t_0) + \Omega_2(t - t_0)^2 \\
\omega &= \omega_0 + \omega_1(t - t_0) + \omega_2(t - t_0)^2 \\
M &= M_0 + M_1(t - t_0) + M_2(t - t_0)^2
\end{aligned}
$$

The least predictable of these elements is M, the "timekeeping" parameter that must describe the satellite's position in orbit and ultimately its position in space. Gravitational anomalies, changes in air drag, solar radiation pressure, and similar effects continually are disturbing this equation. Any attempt to fit a precise M equation to observations occurring over a long time span therefore requires the introduction of several additional terms. Although these additional terms may prove useful for describing past history, experience has shown that they tend to impair long-range prediction accuracy.

In practice, a second-order polynomial for M has proved satisfactory for long-range prediction. Figure 2 shows the time residuals of Iota 4 observations relative to the post-recovery M equation. It is evident that Iota 4 is experiencing cyclical acceleration changes that are somewhat predictable. In the present scheme, no attempt is made to have the elements describe short-term fluctuations in the satellite's acceleration. Instead, prediction methods are designed to absorb large deviations from the satellite's expected behavior and are geared to using a "best fit" M equation that adequately defines long-range accelerations.

The effect of short-term fluctuations in acceleration also must be suppressed in long-range orbit improvement procedures. By distinguishing between the topocentric position of the *orbit* and the topocentric position of the *satellite,* one may effectively eliminate M and its relatively unpredictable behavior from the orbit determination scheme. An example wherein a satellite transits completely across a station's sky in several minutes illustrates this distinction. By contrast, the position of a point on the satellite's orbit changes only a few degrees relative to the local station during this time interval. The resulting observation utilization philosophy stipulates that observations should be employed primarily to define the position of the orbit and secondarily to define the satellite's position in the orbit.

The orbit determination procedure resulting from this philosophy may be described briefly as follows:†

1) Initially, the semimajor axis is determined either from the observed anomalistic period or from a previously computed value that has been modified slightly in accordance with previously observed accelerations. When observations are few, this procedure appears to yield greater accuracy than one that attempts to re-evaluate the semimajor axis before the other geometrical elements have been firmly established.

2) The geometrical orbit parameters (i, Ω, e, ω) are determined next. *Note that during this procedure the satellite's true position along the orbit is relatively unimportant.* Assuming e and ω to be correct, the satellite's geocentric radius at

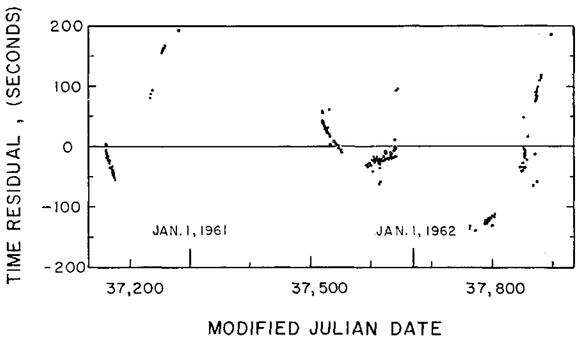

Fig. 2 Iota 4 time residuals

the observed azimuth may be computed. The observed altitude then may be employed to compute an approximate geocentric satellite position vector **R**. The angle δN between the orbit plane and **R** is determined next. For a given set j of observations that contain errors $\delta\Omega$ and δi, the $(\delta N)_j$ may be defined as follows:

$$(\delta N)_j \approx \delta i(\sin\theta)_j - \delta\Omega \sin i(\cos\theta)_j$$

where θ is the angle between a geocentric unit vector directed toward the ascending node **N** and the satellite's position vector **R**.

3) Corrected values of Ω and i now may be determined by a least-squares method. Usually only those observations having zenith angles of less than 40° are employed for correcting Ω and i.

4) Next a radius error δr is computed by assuming Ω and i to be correct. If Ω and i are correct, the intersection of the topocentric azimuth plane and the orbit plane defines the direction of the satellite's position vector. The observed altitude error then may be employed to compute δr. When errors δe and $\delta\omega$ are present in a given set of observations, an

† Theoretical expressions for the higher order terms of the element equations as developed in Ref. 7 are employed throughout the orbit determination procedure.

Table 1 Iota 4 observations (station 8517, Sacramento, Calif.: geodetic latitude = 38°.549, west longitude = 121°.7525, geocentric radius = 6370.1 km)

Date[a]	Right ascension	Declination	Azimuth	Altitude
226.29576	...	...	360.000	78.7830
226.38319	...	...	360.000	51.1670
226.47035	...	...	360.000	63.1670
226.47076	24.9077	62.2714	...	...
227.28048	294.3436	44.0060	...	...
227.28081	302.5697	47.5307	...	...
227.36826	...	...	360.000	51.5670
228.35334	...	...	360.000	51.7670
229.33841	...	...	360.000	52.1170
230.32348	...	...	360.000	52.5330
231.30854	...	...	360.000	52.9170
231.30890	339.8284	75.5522	...	...
232.20580	...	...	180.000	82.8330
232.20731	316.0480	43.1378	...	...
232.29362	...	...	360.000	53.5170
232.38109	5.0438	69.5877	...	...
232.46880	14.4605	21.2395	...	...
233.27868	...	...	360.000	54.1170
234.17578	...	...	180.000	75.4330
234.26376	...	...	360.000	54.7670
236.23388	...	...	360.000	56.3670
242.23131	...	...	360.000	50.4500
243.21639	...	...	360.000	50.2170
244.20146	...	...	360.000	50.1000
245.18654	...	...	360.000	50.0330
304.54671	...	...	360.000	54.4170
305.53162	...	...	360.000	54.0170
306.51652	...	...	360.000	53.5670
324.15690	...	...	180.000	75.1330
325.14173	...	...	180.000	71.4330
326.12657	...	...	180.000	67.5830
327.11140	...	...	180.000	63.7830

[a] Year days, 1960.

expression for the radius errors $(\delta r)_i$ may be written as follows:

$$(\delta r)_i \approx -[e/(1-e^2)^{1/2}]\delta\omega(r\sin E)_i - a\,\delta e(\cos E)_i$$

where E is eccentric anomaly.

5) A least-squares technique yields corrected values of e and ω. In general, only those observations near culmination and more than 30° from the zenith are employed for correcting e and ω.

6) When Ω, i, e, and ω have been determined with sufficient accuracy, the coefficients of the M equation may be extracted from the observed time residuals. This equation in turn yields a corrected value of the semimajor axis. Higher order terms of the element equations that depend upon air drag also may be re-evaluated.

The foregoing operations, combined with a systematic method of rejecting poor observations on the basis of altitude and mean anomaly errors, produce an effective orbit improvement scheme with good long-range capability.

Observation Utilization Philosophy

In the forementioned procedure, the orbital elements are divided into three groups (M and a, ω and e, Ω and i). The equations that relate one group with another are such that the "coupling" between groups is rather loose. Corrections are accomplished by isolating each group and making adjustments indicated by observations. An observation may be used in the adjustment of one, two, or even all three groups of parameters. Some observations may be poorly placed and, therefore, may not be employed.

In practice, the mean anomaly equation requires frequent adjustment. The argument of perigee and eccentricity will require less frequent adjustment. Right ascension of the ascending node, inclination, and semimajor axis are the most stable of the orbital elements and should be changed only when corrections are adequately defined by available observations. Finally, it should be noted that good orbital elements, acceleration data, and other information that has been obtained from continued observations over an extended period of time should not be discarded but should be employed in each new orbit determination.

Iota 4 Search Orbit

The previously discussed techniques were used to determine a search orbit based upon the 32 observations appearing in Table 1. These observations were made by A. S. Leonard and members of the Sacramento Moonwatch Team at a site near Sacramento, Calif. Although normally it is preferred to have observations from numerous geographical locations, the observations were spread over a large time interval and therefore were placed at an adequate number of different positions about the ellipse. The orbital elements derived for the search are listed below:

$$\begin{aligned}
t_0 &= 225.000\text{, August 12, 1960}\\
M &= -4.638095 + 12.1710254\,(t - t_0) + \\
&\quad 5.25 \times 10^{-6}\,(t - t_0)^2\\
\Omega &= 257°.877 - 3°.086\,(t - t_0)\\
\omega &= 10°.0 + 2°.963\,(t - t_0)\\
i &= 47°.20\\
e &= 0.01036 + 6.5 \times 10^{-4}\sin\omega\\
a &= 4960.15\text{ miles}
\end{aligned}$$

The acceleration term of the mean anomaly equation (M_2) was adjusted to reflect expected air drag and solar radiation pressure accelerations. The forementioned elements then were extrapolated more than eight months ahead from the last observation in order to generate search predictions.

Differential Search Predictions

A "differential prediction" system that has been designed to compensate for large errors in transit time allows one to predict the effects of reasonable but unexpected accelerations. Thus the expected altitude of the satellite's transit through a given azimuth plane may be plotted as a function of time (Fig. 3). Telescopes then are moved continuously to coincide with the predicted altitude. This "tracking on the orbit" technique has been adapted successfully to numerous phases of satellite observation. The predictions for this particular

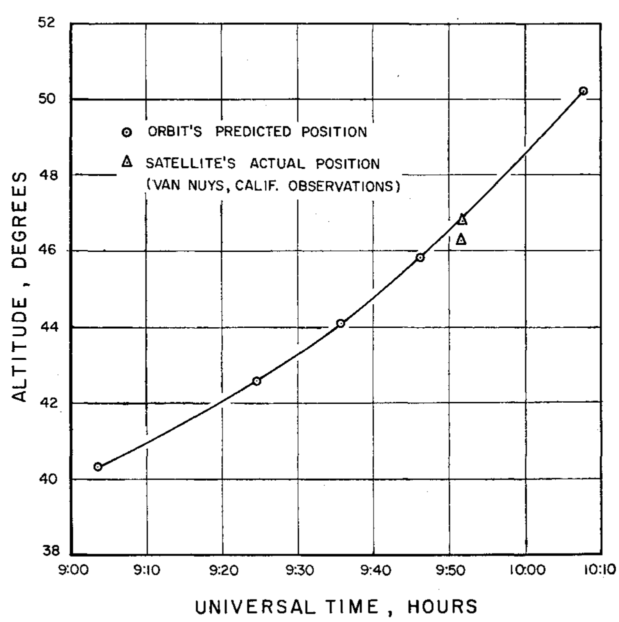

Fig. 3 "Orbit tracking" schedule

Table 2 Search orbit and final orbit compared

Parameter	Search orbit	Final orbit[a]
M_0	-4.638095	-4.634979
M_1	12.1710254	12.171440
M_2	5.25×10^{-6}	2.988×10^{-6}
Ω_0	$257°.877$	$257°.9346$
Ω_1	$-3°.086$	$-3°.085526$
Ω_2	...	-1.76×10^{-6}
ω_0	$10°.0$	$8°.797$
ω_1	$2°.963$	$2°.96933$
ω_2	...	1.70×10^{-6}
i_0	$47°.200$	$47°.2079$
e_0	0.01036	0.011437
e_s	6.5×10^{-4}	6.47×10^{-4}
a_0	4960.15	4960.200
a_1	...	-1.77×10^{-3}
t_0	225.000	225.000
No. of observations employed	32	230

[a] Rms altitude error = 0°.13.

search incorporated differential predictions sufficient to cover ±30 min time of transit error.

Station predictions were issued to teams comprising the Western Satellite Research Network (WSRN). This organization is composed of the following capable volunteer satellite observing teams, which are equipped with specialized telescopes and other observing equipment:[5,6]

Akron-Canton	Sacramento
Albuquerque	San Antonio
Aiken	San Jose
China Lake	Spokane
Denver	St. Petersburg
Madison	Terre Haute
Phoenix	Van Nuys
Rochester	Walnut Creek
	Whittier

Several weeks after the search commenced, the Van Nuys team reported sighting an object that later proved to be Iota 4. This observation, made during the morning of August 6, 1961, indicated that Iota 4 was about 16 min later than predicted (Fig. 3).

This time residual information was teletyped immediately to WSRN observers, and within a week 10 teams reported observing the newly acquired object. Since each team had differential predictions for all possible transits, it was a simple matter to make an accurate prediction for an object expected to transit 16 min late. New predictions, therefore, were not needed to assure the continued tracking of Iota 4.

Post-Recovery Analysis

Since recovery, Iota 4 has been observed regularly by WSRN teams, and over 300 observations have been analyzed. The orbit defined by these observations that occur over a two-year period is compared to the original search orbit in Table 2. The final orbit is based upon 230 observations that survived rejection during the orbit improvement procedure. The rms altitude error of the surviving observations was 0°.13, a value that is consistent with observational accuracy normally obtained by visual observing teams.

The comparison of elements presented in Table 1 illustrates the validity of the original orbit. The most serious error occurs in the M_2 coefficient of the mean anomaly equation. An error of this magnitude is reasonable, since available initial data were insufficient to define long-range accelerations. Figure 2 demonstrates that Iota 4 experienced large acceleration changes during its first few months in orbit. Therefore, it was difficult to predict future acceleration with a high degree of accuracy.

Comparisons of the initial and final values of a_0 and i_0 indicate very small errors. Since these parameters exert considerable influence upon the orbit's future behavior, additional effort was expended to assure their initial accuracy. The Ω_0 coefficient indicates a small error that reflects the accuracy with which an orbit plane may be determined using a few well-chosen observations. Larger errors are present in e_0 and ω_0, but they are not excessive. One would expect ω_0 to be poorly defined for a nearly circular orbit. The accuracy of the coefficients Ω_2, ω_2, and a_1 depend directly upon the accuracy of M_2. These terms were omitted from the original orbit, since their accuracy was in doubt and since their contribution to the extrapolated elements would have been rather insignificant.

Conclusion

An orbit determination and prediction scheme designed to allow long-range prediction of satellite positions has been developed and has been proved effective through a practical application involving the recovery of a lost satellite. The techniques described here may be applied to numerous other practical problems associated with tracking high faint satellites. In general, they are designed to allow effective utilization of minimal information.

References

[1] Whipple, F., "Artificial satellite 1959 Alpha 2 (rocket case)," Harvard College Observatory, Announcement Card 1430, Cambridge, Mass. (March 13, 1959).

[2] Leonard, A. S., "Determination of the orbit of satellite 1958 Beta One," Smithsonian Astrophysical Observatory, Special Rept. 27, Cambridge, Mass. (June 30, 1959).

[3] Smithsonian Astrophysical Observatory, "The recovery of satellite 1958 Beta One," Moonwatch Newsletter **III**, no. 10, 1–2, Smithsonian Astrophysical Observatory, Cambridge, Mass. (May 18, 1960).

[4] Smithsonian Astrophysical Observatory, "1958 Epsilon reacquired," Moonwatch Newsletter **IV**, no. 1, 1–3, Smithsonian Astrophysical Observatory, Cambridge, Mass. (July 21, 1959).

[5] McCue, G. A. and Rogers, M. C. (eds.), *Proceedings, Western Satellite Research Network, Sixth Conference* (Space & Information Systems Div., North American Aviation Inc., Downey, Calif., August 1961), p. 5.

[6] McCue, G. A. and Pierce, D. A., "Western Satellite Research Network," Space & Information Systems Div., North American Aviation Inc., Downey, Calif., Rept. MD 60-175 (May 8, 1960).

[7] Leonard, A. S., Bender, D. F., and McCue, G. A., "Orbit determination and analysis manual," Space & Information Systems Div., North American Aviation Inc., Downey, Calif., Rept. SID 61-391 (November 15, 1961).