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DYNAMIC CALIBRATION OF SPACE OBJECT TRACKING SYSTEMS

by

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Summary

It is generally recognized that proper calibration is a necessary ingredient in the effective utilization of a tracking system. This paper presents a method of calibrating space object tracking systems under dynamic conditions which closely approximate those of the operational environment. Briefly, this calibration scheme involves the tracking of a reference satellite whose position in space is very accurately known as a function of time. By means of a set of digital computer programs, the unknown error model coefficients of the tracking system are extracted by operating upon the differences between the track observations and the reference satellite positions.

This calibration method has been successfully applied to a number of systems, particularly the AN/FPS-49 trackers of the BMEWS and Spacetrack systems of the USAF Air Defense Command. The essential results of this calibration activity are presented to illustrate the application of the technique.

Introduction

In this paper the term calibration will refer to a two-step process in which (1) a description of the non-random or systematic errors present in the tracking measurements is obtained and (2) appropriate actions are taken, based upon the description, to eliminate the systematic errors. In the more elementary methods of calibration the systematic errors are simply characterized by a constant or bias error. The bias is determined by taking track measurements on some earth bound reference target or a celestial object and the system is adjusted to "zero out" the bias. For many tracking systems this rather elementary approach is entirely adequate.

There exists, however, a class of space object tracking systems for which a more comprehensive calibration is desirable. Here, the systematic error must be considered to be a function of the target's motion and position. If a quantitative description of the tracker's systematic error

behavior can be obtained, then the error may be subsequently corrected either by system adjustment or in the data processing. In this case a reference target possessing dynamic characteristics approximating those of the operational targets is required. Examples of those types of tracking systems that can derive benefit from dynamic calibration include: (1) systems for which a complete elimination of all significant systematic errors would be economically or technically difficult or (2) systems for which it is desired to upgrade the track data quality beyond the original design specifications.

Error Model Concept

The central concept in this dynamic calibration scheme is the systematic error description or error model. Consider the total tracker measurement error to be composed of two components: (1) a random or individually unpredictable component and (2) a systematic component which is functionally related to one or more observable target parameters. In general, the systematic error component may be expressed by the linear equation

$$\triangle Y = a_0 + a_1 X_1 + \ldots + a_n X_n \qquad (1)$$

where $\triangle Y$ is the systematic error component of the target parameter Y, the X's are measurable independent variables, and the a's are constant coefficients, initially unknown. A complete description of the tracker's error behavior is, therefore, afforded by a set of equations (one for each of the basic measured parameters) each having the form of equation (1).

Utilizing the error model concept, calibration of a tracking system reduces to formulating an appropriate error model, estimating the coefficient values, and taking appropriate action to eliminate the errors thus described. The error model may be derived by considering all those system factors which could produce a systematic error component and expressing them in the form of equation (1). Typical factors might include leveling error, servo lag errors, site survey errors, etc.

The error model coefficient values are determined by collecting a sample of observations on a reference object whose position is accurately known at all times during the sample tracks. Since the random error component is always superimposed upon the systematic component, determination of coefficient values is essentially a statistical estimation process.

It should be mentioned that the coefficients of some of the model terms may be known a priori. Examples of this class of systematic error might include atmospheric errors and signal processing errors. The coefficients of these terms would of course be fixed and not be subject to statistical estimation.

Given the error model coefficient values, the systematic error removal is a rather straightforward step. For some of the model terms, removal by maintenance adjustment may be appropriate; here, the coefficient values indicate the amount of the adjustment. For other terms, it may be most convenient to remove their effect in the processing of the tracker data. In order that the error removal be effective, it is important that the coefficient values remain relatively stable over the interval between calibrations.

The Calibration Method

The subject calibration procedure is shown in flow diagram form in Figures 1 and 2. Figure 1 depicts the error model coefficient estimation process while the systematic error removal is shown in Figure 2. The coefficient estimation step is carried out with the aid of a set of digital computer programs shown enclosed within the large dotted box in Figure 1. At the present time the process is fully operable as demonstrated by its successful application to a number of space tracking systems. The details of the various steps in the calibration process are presented in the following paragraphs.

The Reference System

The error model coefficient estimation process begins with the collection of a sample of calibration track data on a reference satellite by the system under calibration. The reference satellite is also tracked by a reference tracking system from which the "true" positions of the reference satellite are established in the form of orbital elements. In general, the system under calibration and the reference need not track simultaneously.

In choosing a reference satellite and reference tracking system, several considerations must be kept in mind. First, the reference satellite must be conveniently trackable by both the system under calibration and the reference system. In addition, the motion of the reference satellite should cover nearly the same parameter space as the operational objects. The reference system must be capable of determining orbital elements from which the "true" positions of the reference satellite during the calibration tracks can be recovered. Since "true" positional errors are superimposed upon the calibration observation errors, the "true" positions must be considerably more accurate than the calibration observations. Finally, the time delay in receiving reference orbital elements must be sufficiently short to allow for timely calibration.

For those very accurate tracking systems for which a suitable reference system is not available, the application of this calibration method is not possible. For these systems an Error Model Best Estimate of Trajectory (EMBET) approach must be taken.[1]

Residual Computation

The calibration observations and the reference orbital elements are next operated upon by a computer program which computes the "true" reference satellite positions at the calibration observation times and compares these with the observed positions. The differences between the observed and "true" positions are termed residuals and are subsequently used as estimates of the error in the observed positions. The program used in this step is the Spiral Decay Orbit Determination Program.[2]

Data Processor

The calibration observations and corresponding residuals are accepted by a data processor program which has several primary functions. These include: (1) removing the fixed systematic errors from the data, (2) filtering the residuals, (3) computing the error model independent variables (the X's in equation 1), and (4) formatting the residuals and independent variables.

The residual filtering function (2) was found to be a very critical step in obtaining good error model coefficient estimates and, therefore, should be expanded upon somewhat. It was found that "bad" residuals or residuals having non-typical magnitudes occur occasionally. These "bad" residuals might arise from unusual phenomena such as signal drop-outs and temporary electronic

malfunctions. Since these "bad" residuals have an adverse effect upon the outcome of the multiple regression, they must be removed from the data sample. To accomplish this filtering function, a statistical test based upon the Chebyshev inequality is employed to determine candidates for removal.

Multiple Regression

The final step in the error model coefficient estimation step is the multiple regression. Here, the filtered residuals and error model independent variables (X's) are operated upon resulting in the selection of the "best" set of error coefficient values. This "best" set is chosen such that the sum of the squares of the model adjusted residuals (residual minus the systematic model component) is minimized.

The multiple regression is carried out with a general purpose stepwise multiple regression program. This program is listed in the IBM Share Library (No. 3145); the mathematical details of the program are covered in Reference 3.

It should be recognized that an experienced analyst is required to interpret the statistical significance of the final regression result. Some of the factors that must be considered are the residual sample size, the ranges of the independent variable values, and the correlation matrix of the independent variables.

Systematic Error Removal

The removal of the systematic errors from the system's tracking data is illustrated in Figure 2. Here, the effects of some of the systematic error terms are removed by a maintenance adjustment while others are eliminated mathematically. This mathematical error correction is shown as an additional step in the tracker's data processing.

An Application of the Method

As was mentioned previously, it is highly desirable to calibrate a tracking system under its dynamic operating environment in order to identify and remove, or suppress, systematic errors present in the observations. In striving to develop methods for improving the accuracy of the observed positions of targets, the Radio Corporation of America (RCA), Systems Engineering Department at the Missile and Surface Radar Division (M&SR), located at Moorestown, New Jersey, performed a study which involved the utilization of a near earth satellite as a calibration target. This calibration technique was initially applied in May 1965, to the

AN/FPS-49 Tracking Radar located at Moorestown. The favorable results of this study led to the application of this technique to other radar installations where the AN/FPS-49 and other radars are deployed.

Description of the System Under Calibration

The AN/FPS-49 Radar System is a key portion of the Ballistic Missile Early Warning System (BMEWS). The system was designed and developed by RCA at its M&SR Division in Moorestown. The system installed at the Moorestown Tracking Facility operates as a full time Spacetrack Sensor, providing position data on orbiting objects. The primary requirement of the radar systems deployed at the BMEWS radar sites is to reliably identify a missile raid and to provide maximum warning time of such a raid. However, the BMEWS sites perform secondary mission functions among which includes providing satellite position information to the immense satellite cataloging facility of the Spacetrack Center located at Colorado Springs, Colorado.

The AN/FPS-49 Tracking Radar is a pulsed radar that has long range track and scan capability. Estimation of the target coordinates are provided in range, range rate, azimuth and elevation. The antenna is an 84 foot parabolic reflector; the antenna pedestal can be rotated through 180° in elevation and with the proper manipulation of radar controls, 360° in azimuth.

The Error Model

The error model presented below describes the systematic error components of the AN/FPS-49 radar. These errors are a mathematical representation of some adverse physical effect upon the radar observation. Some terms of the initially postulated error model were found to be superfluous and nonsignificant while the latest error model included terms which were initially, not readily identifiable. These terms were determined with the aid of statistical techniques, an understanding of the system hardware and the physical environment preponderating the measurement process. In some cases, the terms of the error model were verified by independent tests in addition to the subject calibration method. Nonetheless, all terms of the error model were substantiated by the relative consistency of the test results.

Once the systematic error model has been defined, it is simply a matter of determining coefficients of the error terms by means of the calibration method described in the section above. An example of the error model utilized in the error model coefficient determination for the AN/FPS-49

Tracking Radar is described below. The error model is characterized by a set of four equations, one for each parameter measurement in range (R), range rate (Ṙ), azimuth (A), and elevation (E). Under each term is a brief description of the physical connotation. The $\triangle$'s represent the error in each measured parameter.

$$\triangle R = a_0 \qquad + a_1 \dot{R}$$
$$\qquad \text{CONSTANT} \quad \text{TIME LAG}$$

$$\triangle \dot{R} = b_0 \qquad + b_1 \ddot{R} \qquad + b_2 R$$
$$\qquad \text{CONSTANT} \quad \text{TIME LAG} \quad \text{FREQUENCY}$$
$$\qquad\qquad\qquad\qquad\qquad\qquad \text{ERROR}$$

$$\triangle A = c_0 \qquad + c_1 \dot{A} \qquad + \frac{c_2}{\cos E}$$
$$\qquad \text{CONSTANT} \quad \text{TIME LAG} \quad \text{AXIS}$$

$$+ c_3 \tan E \sin A + c_4 \tan E \cos A$$
$$\text{-----------LEVEL-----------}$$

$$+ c_5 \sin 64 A + c_6 \cos 64 A$$
$$\text{------------SYNCHRO-----}$$

$$\triangle E = d_0 \qquad + d_1 \dot{E}$$
$$\qquad \text{CONSTANT} \quad \text{TIME LAG}$$

$$+ d_2 \cos E + d_3 \cos^3 E + d_4 \cos^5 E$$
$$\text{--------------SAG--------------}$$

$$+ d_5 \sin A + d_6 \cos A$$
$$\text{------LEVEL-------}$$

The Reference System

In order to demonstrate the utility of this method to calibrate a space object tracking system, a Tranet/Transit type satellite was selected to serve as a calibration target. The selection was made on the following basis:

1. The position of these satellites are very accurately known.

2. The ephemerides (orbital elements) are readily available.

3. The high altitude characteristic of the satellite lends itself to long tracks. This effectively results in adequate coverage of radar data space which closely resembles the normal operating environment.

4. The inclination of the orbit typical to these satellites exploits the reference target for calibration of the northern tracking systems.

The reference object which was selected had the following orbital characteristics.

OBJECT: 1966-67A
CATALOG NO.: 2401
PERIOD (MIN.): 106.8
INCLINATION (DEG.): 88.86
APOGEE (KM): 1106
PERIGEE (KM): 1052

The ephemerides were received from the Naval Weapons Laboratory and were derived from the Tranet Doppler Tracking System. The ephemeris points are spaced at 2 minute intervals and are considered to be accurate to 70 meters.

Calibration Data Sample

A basic ingredient of this calibration technique is the collection of sufficient data from the system under calibration. The calibration data must form an adequate data base, traversing the radar data space covered in the operating environment. In order to ensure that these requirements were met, the tracking system was tasked to track the reference satellite from horizon to horizon for all orbit passes during a 48 hour calibration period. It should be noted that the tracking requirements were not completely complied with because of maintenance functions and pre-emption of tracking assignments. However, the data samples utilized in the calibration examples presented in this paper represent for the most part, the efforts of controlled tracking of the reference satellite.

Calibration results for the AN/FPS-49 radar at Moorestown, New Jersey, and Thule, Greenland, have been selected to illustrate applications of this calibration technique. Many calibration exercises (via this technique) have been performed at these radar sites in the past few years. Two examples of such exercises are presented in this paper. A summary of the data collected during the example calibration exercises are presented below in Table 1. For analysis purposes, each 48 hour calibration exercise was considered to comprise a data group since the trackers' systematic error behavior would be expected to remain constant over this period.

Error Model Coefficient Estimates Results

Typical results of this calibration technique are presented in Tables 2 through 9. In these tables coefficient estimates for the error model terms of the AN/FPS-49 radars at Moorestown and Thule are given for various calibration exercises. Tables 2 through 5 present coefficient estimates of the Moorestown radar error model on a parameter basis while similar parametric coefficient estimates of the Thule radar error model are given in Tables 6 through 9.

It should be mentioned that the error model coefficient estimates presented have been normalized with respect to the standard error estimate for the respective parameters. The estimates then, do not reflect the true error characteristics of the system under calibration. This was done in order to preserve the performance characteristics of the AN/FPS-49 radars which are of a classified nature. However, it is felt that the relative estimates presented do illustrate the ability of the technique to determine the tracking error behavior of a space object tracking system.

As can be seen from the tables, the error model terms differ slightly for each radar. This is largely due to the slight equipment differences and the differences in the sample data collected by each site. Calibration exercises in the past, have at times, indicated the possible presence of other terms in the general AN/FPS-49 Radar Error Model which was previously described. However, for the examples considered, only those terms of the error model are presented which are known to exist and which were estimated with statistical significance.

A fair amount of consistency can be seen from the tabulated results of the error model coefficient estimates. However, there are some deviations that can be accounted for or explained. In evaluating these coefficients, several factors must be kept in mind. For instance, the tabulated coefficient estimates tend to be statistically distributed about the true value due to random errors in the residuals. Therefore, a statistical deviation from the true value of the coefficient must be accounted for. Also many of the error model terms are sensitive to the sample data space. That is, the radar data space for each calibration exercise may not be similar and therefore differences in the coefficient estimates for these sensitive terms can be expected.

Typical examples of error terms sensitive to radar space are the axis error term in the azimuth error model and the sag error terms in the elevation error model. Coefficients for these error terms

were found to be highly influenced by elevation data space. The magnitude of the azimuth axis error term presents another problem to the estimation process. This term is small compared to the other model terms thereby making it difficult to obtain good estimates of the coefficient.

It may appear in evaluating the tabulated results that there is an excessive variation in the range rate constant error terms for both the Moorestown and Thule radars. It should be noted that these values are within the tolerances that could be expected from design specifications of the range rate measuring circuitry.

The coefficient estimates of the synchro error terms of the Moorestown azimuth error model also exhibit some variation. The synchro error terms, like the azimuth axis error term, in general are small and are difficult to estimate. However, the estimate variations are within expected statistical deviations.

A few other noteworthy comments should be made with regard to the variability in some of the error model coefficient estimates. For example, it can be seen from the tables that the constant error coefficient for the Thule radar error model in azimuth and elevation exhibits a large variation from group to group. It was substantiated through an independent source that corrective maintenance was being performed on the angle encoder gear boxes during this exercise period. It can also be observed that rather large coefficients were estimated for the time lag errors terms of the Moorestown radar elevation error model and for all parametric error models of the Thule radar. The reason for these excessive coefficients have been potentially verified as servo adjustment problems. Thus it can be seen that this technique can also be utilized as indicator of faulty sensor performance.

Performance Improvement with Calibration

One of the functions of the tracking systems discussed here is the determination of space object orbits. Hence, a measure of the value of this sensor calibration scheme lies in the improvement in the accuracy of orbit determinations.

It has been verified experimentally that orbit determination accuracy is improved by this calibration method. As an illustration, the accuracy of a typical orbit determination is given in Figure 3, both with and without calibration.

In this experiment approximately 300 smoothed observations (10-second smoothing was employed)

were collected over a 12 hour period on a Tranet
System satellite. Two orbital fits using the Spiral
Decay Orbit Determination Program[2] were per-
formed. The first used the observational data with
only nominal measurement biases removed (average
systematic error) to represent the "without calibra-
tion case." For the second orbital fit the systematic
errors were removed from the observations using
previously determined coefficient values; this repre-
sents the "with calibration" case.

The errors in both orbital fits were estimated
by subtracting the true object positions, which are
known by virtue of the Tranet tracking network, from
the "fitted" positions. The magnitudes of the posi-
tional difference vectors are shown plotted as a func-
tion of time on Figure 3. Inspection of this figure
shows that calibration produced a significant improve-
ment in the orbit determination. The average im-
provement for each revolution of the satellite is
indicated at the top of the plot.

The results contained in Figure 3 demonstrate
conclusively that the application of this dynamic
calibration method can significantly improve track-
ing system performance.

<u>Conclusion</u>

The foregoing discussion has presented the
salient features of the dynamic calibration scheme.
The scheme has been successfully applied to
several space object tracking systems and has pro-
vided an effective method for improving their per-
formance. This calibration procedure should be
generally applicable to any tracking system for
which a sufficiently accurate reference target is
available.

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TABLE 1. SUMMARY OF SAMPLE CALIBRATION EXERCISE DATA

DATE OF EXERCISE		MOORESTOWN DATA		THULE DATA	
Day of Year	Day/Month/Year	No. Tracks*	No. Observations**	No. Tracks*	No. Observations**
87-88	28-29 Mar. 1967	7	474		
93-94	3- 4 Apr. 1967	7	396	10	649
101-102	11-12 Apr. 1967			9	409

*A track is considered to be the tracking of the satellite on each orbit pass.
**An observation is an estimate of the target position and velocity based on 10-second smoothing of track data.

TABLE 2. MOORESTOWN ERROR MODEL COEFFICIENT ESTIMATES–RANGE

Data Group (Day of Year)	Coefficient Estimates	
	a_0 Constant	a_1 Time Lag
87-88	-0.131	-0.088
93-94	0.077	-0.076

TABLE 3. MOORESTOWN ERROR MODEL COEFFICIENT ESTIMATES – RANGE RATE

Data Group (Day of Year)	Coefficient Estimates		
	b_0 Constant	b_1 Time Lag	b_2 Frequency Error
87-88	-0.088	-1.284	-0.0415
93-94	0.088	-1.716	-0.0453

TABLE 4. MOORESTOWN ERROR MODEL COEFFICIENT ESTIMATES – AZIMUTH

Data Group (Day of Year)	Coefficient Estimates				
	c_0 Constant	c_1 Time Lag	c_2 Axis	c_5 Synchro sin 64 A	c_6 Synchro cos 64 A
87-88	0.194	-0.720	0.026	0.077	0.043
93-94	0.400	-1.078	0.143	0.006	0.002

TABLE 5. MOORESTOWN ERROR MODEL COEFFICIENT ESTIMATES – ELEVATION

Data Group (Day of Year)	Coefficient Estimates			
	d_0 Constant	d_1 Time Lag	d_2 Sag	d_3 Sag
87-88	1.089	-8.210	1.002	-0.019
93-94	0.998	-9.855	1.477	-1.125

TABLE 6.   THULE ERROR MODEL COEFFICIENT ESTIMATES – RANGE

| Data Group (Day of Year) | Coefficient Estimates | |
	a_0 Constant	a_1 Time Lag
93–94	–7.656	–1.673
101–102	–7.289	–1.610

TABLE 7.   THULE ERROR MODEL COEFFICIENT ESTIMATES – RANGE RATE

| Data Group (Day of Year) | Coefficient Estimates | | |
	b_0 Constant	b_1 Time Lag	b_2 Frequency Error
93–94	0.891	2.309	–0.234
101–102	–0.611	3.406	–0.337

TABLE 8.   THULE ERROR MODEL COEFFICIENT ESTIMATES – AZIMUTH

| Data Group (Day of Year) | Coefficient Estimates | | | | |
	c_0 Constant	c_1 Time Lag	c_4 Level	c_5 Synchro	c_6 Synchro
93–94	–0.984	–3.645	–1.295	–0.218	–0.139
101–102	2.512	–4.245	–1.525	–0.184	–0.101

TABLE 9.   THULE ERROR MODEL COEFFICIENT ESTIMATES – ELEVATION

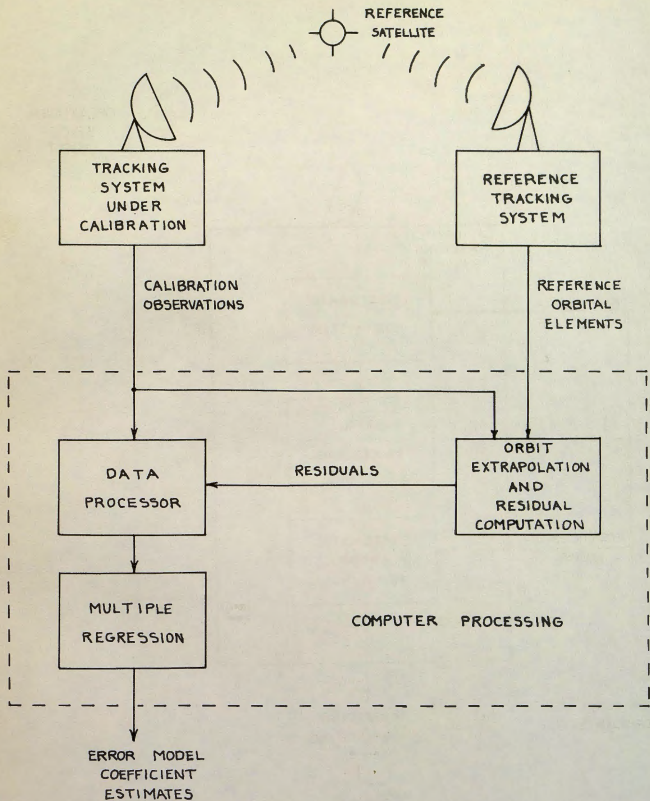| Data Group (Day of Year) | Coefficient Estimates | | |
	d_0 Constant	d_1 Time Lag	d_6 Level
93–94	5.029	–7.821	–0.120
101–102	–0.379	–6.188	–0.135

FIGURE 1

THE CALIBRATION METHOD – ERROR MODEL COEFFICIENT ESTIMATION
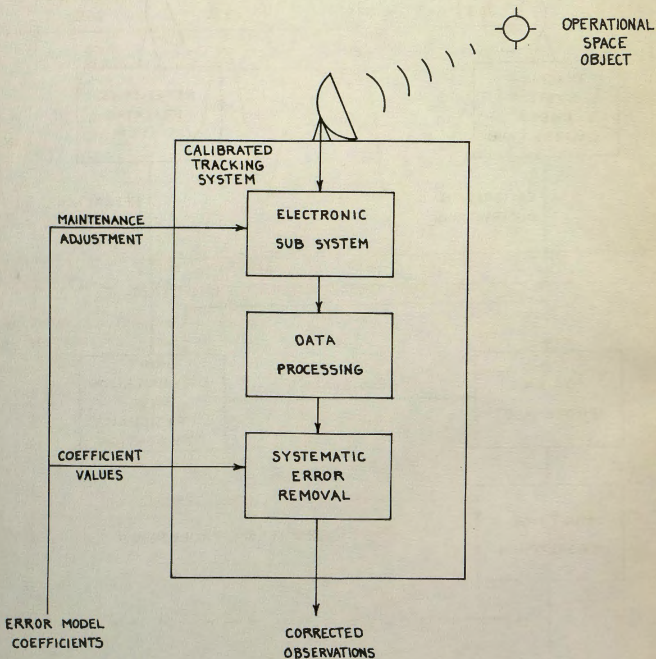
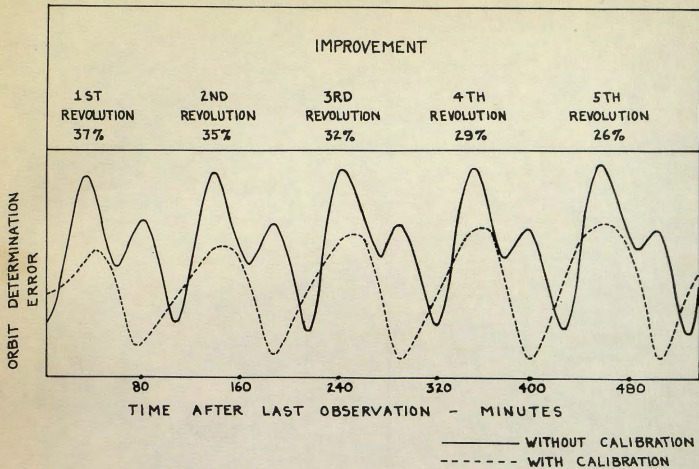FIGURE 2

THE CALIBRATION METHOD - SYSTEMATIC ERROR REMOVAL

FIGURE 3

ORBIT DETERMINATION IMPROVEMENT WITH CALIBRATION