ESTIMATION OF SYSTEMATIC ERRORS IN ANGLES OF TRACKING ANTENNAE

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ABSTRACT

ISTRAC provides Telemetry Tracking and Command (TTC) support in S-Band for Launch Vehicle and spacecraft missions from a network of ground stations. All the TTC stations employ tracking antennae with a elevation over azimuth mount with pointing accuracies of 0.03 deg. During the Launch Vehicle phase, these antennae are designated towards the Launch Vehicle using real time tracking data from RANGE complex in computer designate mode. Target tracking is also achieved in program track mode using predicted antenna pointing angles. Antenna angles data is an important input for Preliminary Orbit Determination immediately after satellite injection and also orbit determination during the LEO phase. This requires that the systematic errors in the antenna look angles are estimated and corrected appropriately for proper target pointing and also for the use of angles data in orbit determination.

After a detailed sensitivity analysis, an error model that characterizes the systematic errors in azimuth and elevation angles was evolved. A software package to estimate the error coefficients using Linear Least Squares in batch processing mode was developed and operationalised. The error coefficients are estimated with IRS satellite tracking and operational orbit determination results with an established position accuracy of better than 200 m as reference. Systematic errors of each of the ground station antennae are computed by conducting tracking campaigns designed to collect data spread evenly in the Azimuth - Elevation domain.

This paper presents the details of the error model employed, software package developed and the results obtained. Improvements in the orbit determination results, using corrected angles data are reported.

1. INTRODUCTION

ISTRAC provides Telemetry, Tracking and Command (TTC) support in S-band for Launch Vehicle and Spacecraft missions from a network of ground stations. Precision Coherent Monopulse C-band (PCMC) radars are also used for tracking purposes. TTC stations employ tracking antennae with elevation over azimuth mount with pointing accuracies of 0.03 deg. These antennae are driven by servo system which operate in several modes such as manual, auto track, program track, computer designate and slew. Pointing accuracy of PCMC radar is 0.0057deg. During Launch phase these antennae are designated towards the Launch Vehicle using Real Time tracking data in computer designate mode. Target tracking is also achieved in program track mode using predicted antenna tracking angles. Azimuth and Elevation data is an important input for Preliminary Orbit Determination (POD) immediately after satellite injection and also Regular Orbit Determination (ROD) during Launch and Early Orbit phase. Antenna calibration is carried out to estimate the systematic errors in the look angles and the corrected angles are used for proper target pointing and Orbit Determination.

To estimate the fixed biases in the angle data many methods such as boresight tracking, Sun tracking, Radio stars tracking were employed and fixed biases in angles data were estimated. Even after correcting for these fixed biases, second order errors were observed in OD. This lead to graphical analysis of data and study the error behaviour at various elevations. This study indicated that there exist systematic errors in the angle data. To characterize these errors, different models of systematic errors are studied and an appropriate error model was developed.

A software (SATCAL) was developed to estimate the systematic error components viz., collimation, non-orthogonality, mislevel, azimuth and elevation encoder non-linearities, droop, azimuth and elevation encoder offsets, and velocity and acceleration lags. Using IRS-P2 tracking data, the systematic error coefficients were estimated for the tracking antenna at ISTRAC down range station in Maurtius. These coefficients were used for correcting the angles data used in POD.

A detailed mathematical formulation and the procedure of calibration are discussed in this paper. The estimated error coefficients for the Mauritius ground station, and the improvement after correction in preliminary orbit estimate of IRS-P3 satellite are presented. IRS-P3 satellite carried a C-band transponder and PCMC radars tracked the transponder during payload commissioning tests. The results obtained from calibration of PCMC radars using limited data are also presented.

2. MATHEMATICAL FORMULATION

2.1 ERROR MODEL

The radar coordinate system is defined in range, azimuth and elevation topocentric frame. The tangent plane is oriented normal to the local gravity vector. During the installation and operation of an instrumentation radar / tracking antenna many errors can occur. The predominant errors are azimuth axis tilt, elevation axis skew, collimation, and deflection caused by gravitational force. Following are the error sources for angles data.

Azimuth encoder offset : The radar train axis is adjusted to zero with the pedestal pointing axis referenced to true astronomic north. The pointing axis or line of sight (LOS) mechanical axis is perpendicular to the elevation axis. The residual pointing axis misorientation when projected into the roller path plane and compared to true north at exact zero encoder angle, is called azimuth encoder offset.

Elevation encoder offset : The instrumented pedestal elevation axis is zero adjusted at a pointing axis line of sight orientation parallel to the roller path plane. The residual primary RF axis misorientation from a direction parallel to the roller path plane at the pedestal position which results in exact zero encoder angle output is called elevation encoder zero reference.

Non-orthogonality : By definition, the pointing axis of a two axis gimbaled pedestal is perpendicular to the elevation axis. The deviation from squareness of the azimuth axis to that of the elevation axis causes a significant pointing axis orientation error which projects into the roller path plane.

Collimation : RF axis orthogonality error is a measure of the nonperpendicularity of the instrumented RF axis with respect to the elevation axis. Whenever the instrumented RF sensing axis is oriented other than parallel to the pedestal pointing axis, as projected into the roller path plane collimation error exists.

Mislevel : The roller path plane is defined as a plane normal to a mean pedestal axis of rotation which is very close to vertical or parallel to the local gravity vector. The pedestal roller path plane orientation relationship to the local gravity vector is mislevel. The error effect is caused by pedestal fabrication, assembly and tooling misalignments.

Droop : The antenna pedestal, dish, feed and strut components are acted upon by the force of gravity which produces relative movement of the instrument boresight axis in elevation as a function of elevation angle. This RF axis shift is called the RF droop.

Azimuth and Elevation encoder linearity : Encoder is a device which translates the mechanical rotation of a shaft into an incremental electrical digital representation. The inaccuracies of these devices are the result of effective deviations from the straight line correlation of the input shaft rotation and the incremental output electrical digital representation due to various factors such as environmental conditions, inherent system errors, loading, and misalignment effects.

The error equations are written as :

$$\begin{aligned} Az_o = {} & Az_t + x_1 + x_2 \tan El + x_3 \sec El + x_4 \sin Az + x_5 \cos Az + \\ & + x_6\, dAz/dt + x_7\, d^2Az/dt^2 + x_8 \sin Az \tan El - x_9 \cos Az \tan El \end{aligned} \quad (1)$$

$$El_o = El_t + x_8 \cos Az + x_9 \sin Az + x_{10} + x_{11} \cos El + x_{12} \sin El + x_{13}\, dEl/dt + x_{14}\, d^2El/dt^2 \quad (2)$$

where x_1 = Azimuth encoder offset
x_2 = Non-orthogonality
x_3 = Collimation
x_4 & x_5 = Azimuth encoder non-linearity components
x_6 & x_7 = Azimuth Velocity and acceleration lags
x_8 = Mislevel about East
x_9 = Mislevel about North
x_{10} = Elevation encoder offset
x_{11} = Droop
x_{12} = Elevation encoder nonlinearity
x_{13} & x_{14} = Elevation velocity and acceleration lags

suffix 'o' indicates the observation, and suffix 't' indicates true value.

Various methods used for calibration of antenna are by star tacking, balloon tracking, aircraft tracking and satellite tracking. Satellite tracking is preferred because of all weather capability, coverage over entire horizon and dynamic tracking.

2.2 ORBIT DETERMINATION

Regular Orbit Determination is done for Indian Remote Sensing Satellites (IRS series) using range and range rate tracking data from ISTRAC network ground stations. Two and half days of tracking data on a sliding basis is used. The force model for orbit computation comprises of

• Earth Gravity model	GEM T3 (50 x 50 harmonics)
• Atmospheric density	MSIS-86
• Luni-Solar forces	JPL-DE-2000
• Solar radiation pressure	

Special perturbation theory by Cowell is used for the trajectory generation. Numerical integration adopted is Gauss-Jackson-Merson eighth order method. The state parameters are refined by differential correction using weighted least squares method. The position accuracies of the operational orbit determination is better than 200m. In terms of antenna angles it is better than 0.0140 deg.

2.3 ESTIMATION METHOD

With the true azimuth and elevation obtained from the orbit determination process, each observation gives two equations (1) and (2). The equations may be represented in matrix form as follows.

$$A\,X = B \qquad (3)$$

For the ith observation these equations can be written as

$$b_k = (Az_o - Az_t)_i \quad \text{and} \quad b_{k+1} = (El_o - El_t)_i \quad \text{for} \quad i = 1,2,...,n \quad \text{and } k = 2i - 1 \qquad (4)$$

$$X = \{x_1, x_2, \dots, x_{14}\} \qquad (5)$$

$$a_k = \{\ 1 \ \ TE \ \ CE^{-1} \ \ SA \ \ CA \ \ dAz/dt \ \ d^2Az/dt^2 \ \ SA*TE \ \ -CA*TE \ \ 0 \ \ 0 \ \ 0 \ \ 0 \ \ 0\ \} \qquad (6)$$

$$a_{k+1} = \{\ 0 \ \ 0 \ \ 0 \ \ 0 \ \ 0 \ \ 0 \ \ 0 \ \ CA \ \ SA \ \ 1 \ \ CE \ \ SE \ \ dE/dt \ \ d^2E/dt^2\ \} \qquad (7)$$

where CA = cos Az, SA= sin Az, CE = cos El, SE = sin El, TE = tan El

Based on the theory of Least squares the best estimate of equation (3), X* is given by

$$X^* = (A^TA)^{-1} A^T B \qquad (8)$$

The coefficients thus estimated are updated iteratively.

3. CALIBRATION SCHEME

The sky of observations is divided into 36 sectors (twelve 30^0 segments in azimuth and three segments in elevation 10^o-30^o, 30^o-60^o and 60^o-80^o). Observations in the lower elevation upto 10 deg are not considered because of large refraction errors. As the collimation and non-orthogonality errors increase infinitely in elevations 80-90 deg observations in this range are also omitted. The geometry of passes is studied and those passes which satisfy these conditions are selected and scheduled for tracking. These scheduled passes are tracked by the ground station and the data is transmitted to mission computers.

The raw tracking data consists of range, range rate and angles at the rate of 8 samples/sec This data is received from ground stations on mission computers in real time and is archived. The archived data is used for processing of the observations. In the first level of processing, the data is validated for time errors, data transmission errors and quality and then measurements are converted to engineering units. In the second level, observations are compared with computed values from ephemeris and outliers of 3σ are removed. Ground and transponder delays are corrected in range measurements. Using the least squares fit, tracking data is 'thinned' to 1 sample/sec. This thinned data is smoothed piecewise by considering 30 sec piece and 3 points are selected from each piece. Light travel corrections and troposphere and ionosphere refraction corrections are then applied to the selected data. The preprocessed data at an interval of 10 sec are selected and the angles data from all the scheduled passes are grouped together. In the second level of selection, 25 to 30 angle data points per sector are selected and it is ensured that all the sectors are filled.

Reference azimuth and elevation values and their rates are obtained from the regular orbit determination results. Figure 1 shows the calibration scheme.

4. RESULTS AND DISCUSSIONS

4.1 CALIBRATION OF S-BAND ANTENNA AT MAURTIUS

The main aim of the calibration exercise is to obtain accurate angles data for POD immediately after a satellite injection and also for computer designate mode of tracking of launch vehicles. POD is orbit determination by classical methods using single station and limited (100-200 sec) range and angles data. POD results are used for tracking the spacecraft until the orbit is established.

TTC station at Mauritius is the Downrange station for Polar Satellite Launch Vehicle (PSLV) mission and helps in monitoring the spacecraft separation and collecting tracking data immediately after injection. Prior to the launch of PSLV-D3 / IRS-P3 on March 21, 1996, calibration exercise for Mauritius antenna was conducted. The estimated systematic errors derived from this exercise are shown in Table-1. The observations of IRS-P3 satellite from Mauritius were used for POD. The tracking data available was for 160 sec. and the accuracies required from POD are 10 km in semi-major axis and 0.03 deg in inclination. POD results using corrected / uncorrected angles and range data are compared with the ROD results in Table-2. It is seen that, with ROD as reference, the differences in semi major axis and inclination are 15.719 km and -0.091 deg respectively before correction and 0.918 km and -0.02 deg after correcting for systematic errors.

4.2 PCMC RADAR CALIBRATION

ISRO Launch Vehicle Range complex uses C-band radars (PCMC) with an angular accuracy of 0.0057 deg for launch vehicle tracking. A C-band transponder was flown on IRS-P3 for the purpose of calibrating these radars. The transponder was switched ON (on a test basis) and the satellite was tracked in four passes by PCMC radars. The tracking data was preprocessed and was used to estimate a reduced set of systematic error coefficients. The estimated error coefficients for PCMC radars are shown in Table-3. It can be seen that azimuth and elevation encoder offset values compare well with boresight measurements given in Table-4.

The uncorrected / corrected PCMC angles data was combined with range and range rate data from S-band network and orbit was estimated. Angle residual statistics are shown in Table-5 and converged state vectors are presented in Table-6. The following observations are made from this analysis.

i. As compared with ROD, the position error has improved from 23.5m to 8m and velocity error has improved from 16.1 cm/sec to 0.6 cm/sec.

ii. It is seen from theseresults that the residual mean of corrected data is better than the specified accuracy 0.0057 deg. The RMS values indicate that there are second order terms to be corrected. The second order errors can be estimated by scheduling the high elevation passes and conducting calibration campaign.

It is proposed to improve the reference orbit with onboard GPS receiver and improve the calibration accuracies.

5. REFERENCES

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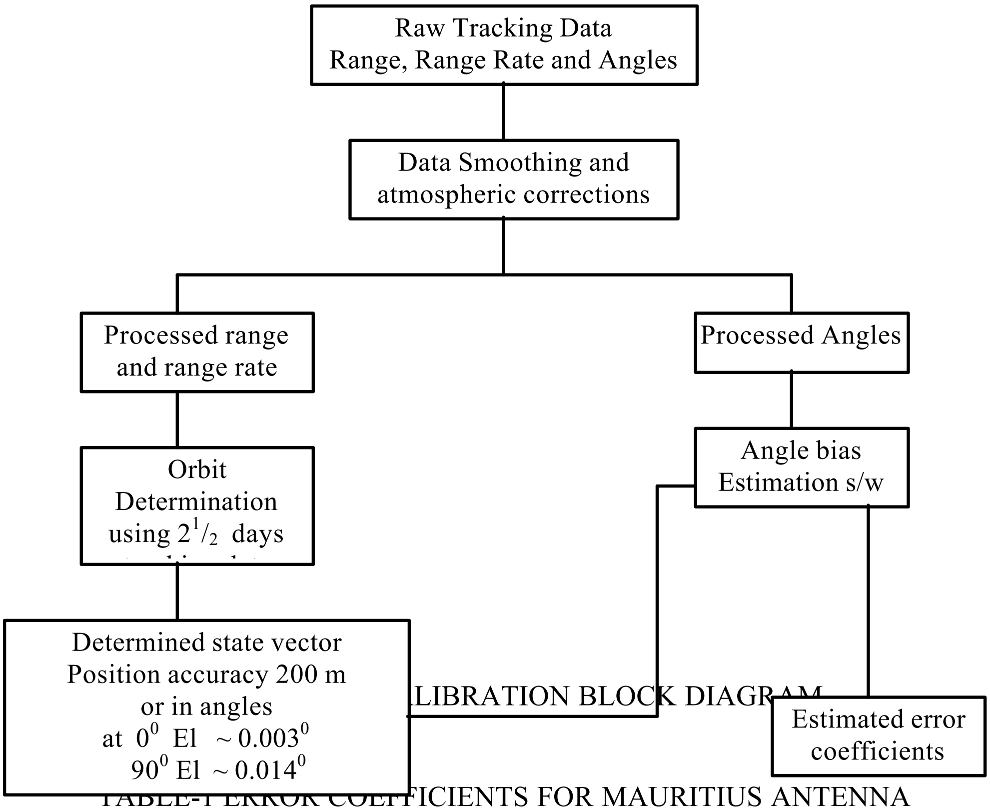

LIBRATION BLOCK DIAGRAM

TABLE-1 ERROR COEFFICIENTS FOR MAURITIUS ANTENNA

Error coefficient		MAURTIUS
Azimuth bias (deg)	x_1	0.178
Non-orthogonality (deg)	x_2	0.062
Collimation (deg)	x_3	-0.010
Az. encoder nonlinearity (deg)	x_4	-0.194
Az. encoder nonlinearity (deg)	x_5	-0.048
Az. velocity lag (sec)	x_6	-1.022
Mislevel (deg)	x_8	0.039
Mislevel (deg)	x_9	-0.007
Elevation bias (deg)	x_{10}	-0.202
Droop (deg)	x_{11}	-0.089
El. encoder nonlinearity (deg)	x_{12}	-0.009
El. velocity lag (sec)	x_{13}	-1.907

TABLE-2 POD RESULTS AND COMPARISON WITH ROD

EPOCH : 1996-03-21-05-11-02-07

Parameter	PRELIMINARY ORBIT DETERMINATION		Regular Orbit Determination
	Uncorrected angles range and range rate	Corrected angles range and range rate	Range and range rate
a (km)	7189.777	7204.579	7205.497854
e	0.000641	0.002124	0.002332
i (deg)	98.881	98.809	98.789565
Ω (deg)	156.677	156.610	156.612388
w (deg)	250.709	245.611	243.5181
M (deg)	318.206	323.370	325.4653
h_p (km)	803.125	811.132	806.803
h_a (km)	810.453	841.738	838.198

TABLE - 3 ESTIMATED ERROR COEFFICIENTS OF PCMC RADARS

Error coefficient		PCMC-1	PCMC-2
Azimuth Bias (deg)	x_1	-0.435	0.766
Non-orthogonality (deg)	x_2	-0.095	0.101
Az. Enc. nonlinearity (deg)	x_4	-0.052	0.094
Az. Enc. nonlinearity (deg)	x_5	0.038	-0.010
Azimuth velocity lag (sec)	x_6	0.470	-0.696
Mislevel East (deg)	x_8	-0.080	0.039
Mislevel North (deg)	x_9	-0.023	0.005
Elevation Bias (deg)	x_{10}	0.223	0.051
El. velocity lag (sec)	x_{13}	0.350	-0.699

TABLE - 4 MEASURED BORESIGHT ERRORS

RADAR	ΔAz (deg)	ΔEl(deg)
PCMC-1	-0.4722	0.1900
PCMC-2	0.6187	-0.0489

TABLE-5 RESIDUAL STATISTICS FROM IRS-P3 ROD

	UNCORRECTED ANGLES				CORRECTED ANGLES			
RADAR	Azimuth (deg)		Elevation (deg)		Azimuth (deg)		Elevation (deg)	
	Mean	RMS	Mean	RMS	Mean	RMS	Mean	RMS
PCMC-1	-0.49	0.49	0.17	0.17	-0.0022	0.023	-0.0016	0.016
PCMC-2	0.73	0.74	0.05	0.06	-0.0011	0.033	-0.0037	0.011

TABLE - 6 IRS-P3 ORBIT DETERMINATION RESULTS

EPOCH 1996 04 02 00 00 00 000

PARAMETER	UNCORRECTED DATA		CORRECTED DATA	
	REFINED	S.D.	REFINED	S.D.
a (met)	7202736.017754	0.282503	7202735.995244	0.025135
e	0.001356	0.000002	0.001357	0.000000
i (deg)	98.802338	0.000004	98.802323	0.000000
ω (deg)	139.783241	0.001448	139.794369	0.000128
Ω (deg)	168.301081	0.000003	168.301110	0.000000
M (deg)	103.774438	0.001446	103.763373	0.000128
Pos Err (met)	23.517		8.237	
Vel Err (cm/s)	16.090		0.587	