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Engineering Notes

Chandrayaan-1 Real-Time Orbit Determination

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Nomenclature

L_q	=	quaternion operator
q	=	quaternion matrix with components q_0, q_1, q_2, and q_3
q^*	=	complex conjugate of q
t_n, t_{n+1}	=	time instants, s
$\mathbf{V_b}$	=	incremental velocity vector in body frame, m/s
$\mathbf{V_i}$	=	incremental velocity vector in inertial frame, m/s
$\Delta\mathbf{V_{roll}}$, $\Delta\mathbf{V_{yaw}}$, $\Delta\mathbf{V_{pitch}}$	=	incremental velocity components in roll, pitch, and yaw directions, m/s
$\Delta\mathbf{V_x}$, $\Delta\mathbf{V_y}$, $\Delta\mathbf{V_z}$	=	inertial incremental velocity components in x, y, and z directions, m/s

I. Introduction

INDIA'S first satellite to the moon, Chandrayaan-1, carrying 11 scientific instruments for the purpose of expanding scientific knowledge about the moon was launched on 22 October 2008 from the Satish Dhawan Space Centre, Sriharikota, India, by the Indian Space Research Organization's (ISRO's) Polar Satellite Launch Vehicle PSLV-C11. The spacecraft was injected into a transfer orbit of (254.4×22932.7) km with an inclination of 17.9 deg on 22 October 2008 at 01 : 10 : 19.081 Coordinated Universal Time (UTC). The main objective of the mission is a simultaneous chemical, mineralogical, and photogeologic mapping of the whole moon with high spatial resolution using high-resolution state-of-the art sensors. The spacecraft was put into the moon's polar, circular orbit of about (100×100) km on 12 November 2008 by carrying out a sequence of five Earthbound maneuvers, a trajectory correction maneuver (TCM), a lunar orbit insertion (LOI) maneuver, and four lunarbound maneuvers. The orbit of the satellite had to be determined continuously at a brisk pace to meet the requirements of the mission operations.

This research addresses the performance of a satellite orbit restitution system based on the usage of onboard accelerometer data. The novel technique of obtaining precise orbit computation using accelerometer data that has been researched in this Note can be applied to the planetary missions for which the orbit perturbations are difficult to model when orbit reconstruction is required in real time. The possible shortcut to improve the orbit determination performance for such missions is the use of high-accuracy onboard accelerometers [1]. This Note presents the usage of onboard accelerometer data for quick orbit computation during spacecraft orbit maneuvers. An accelerometer is an instrument that measures the acceleration of the case of the sensor due to external forces. When properly configured and maintained at the spacecraft center of mass, an accelerometer, or a set of symmetrically placed accelerometers, measures all the nongravitational forces acting on the spacecraft.

Real-time orbit determination was demonstrated live for the Chandrayaan-1 mission. In all the maneuvers of the Chandrayaan-1 mission, the thrust cutoff, and thus the burn duration, was controlled by accelerometers autonomously. The Chandrayaan-1 mission carries four advanced accelerometers for burn calibration. A software named PROCAD (precise orbit computation using accelerometer data) was originated for the Chandrayaan-1 mission for determining the orbit using accelerometer data. Before the Chandrayaan-1 mission, PROCAD was tested using the realized flight data obtained from accelerometers onboard the Space Capsule Recovery Experiment-1 that was launched in the year 2007. PROCAD was made operational during all phases of Chandrayaan-1 to process the measurements of accumulated velocity from the accelerometer gathered from telemetry. The Chandrayaan-1 orbit was determined in real time even as the orbit maneuver was in progress. PROCAD gave the achieved orbit of Chandrayaan-1 immediately after the maneuver ended.

Comparison of the PROCAD orbit results with those determined with the tracking data of range and accumulated Doppler measurements showed close association between the state vectors during all phases of the Chandrayaan-1 missions. PROCAD showed a maximum position difference of 0.32% with respect to the determined state. The PROCAD program used in the mission operations center for the Chandrayaan-1 mission is an effective validation tool for an onboard accelerometer.

This Note describes the methodology of accelerometer data processing for computation of a precise orbit in real time, and it shows a comparison with the achieved orbit determination results using tracking data during all phases of the Chandrayaan-1 mission. An exploration of the feasibility of using an orbit determination program based on accelerometer data for future low-cost planetary missions, to have a close estimate of the satellite position during the progress of a maneuver when the satellite is not radio tracked, is made in this study.

II. Chandrayaan-1 Accelerometer

The maneuvers carried out during the initial phase of the Chandrayaan-1 mission were governed by the onboard accelerometer. The thrust stoppage during every maneuver was based on the accelerometer cutoff. The accelerometer package consisted of four advanced accelerometers in a tetrad configuration. The data processing software is part of the attitude and orbit control system bus management unit. The data processing software in the package carried out velocity channel error compensation, velocity channel failure detection and isolation, and reconfiguration of sensor channel.

The data processing software does important functions. The minor cycle count (64 ms) is incremented for time reference. The major cycle count is 512 ms. The sensor errors are compensated. The failure events are detected and isolated. The velocity increments along the satellite body axes are estimated. The estimated velocity increments are accumulated, and these measurements are stored and transmitted to the ground stations.

The sensor error is compensated for scale factor, bias, and misalignments. Bias and scale factors vary with temperature, and the software has the capability to effect temperature compensation. Whenever there is a significant change in temperature, a new scale

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factor and bias are computed at low periodicity. The compensation using the updated scale factor and bias is done at high periodicity. The bias in the accelerometer measurements is corrected for the day-to-day varying temperature effects. The operating temperature varies from 25 to 60°C. The temperature compensation is done by using a piecewise linear model. The net error in the velocity measurements of the accelerometers of Chandrayaan-1, after taking into account the scale factor, bias, and misalignment, is of the order of 50 mg.

III. Precise Orbit Computation Using Accelerometer Data

PROCAD is an orbit determination program that was specifically developed for the Chandrayaan-1 mission. PROCAD makes use of the accumulated velocity measurements to determine the spacecraft orbit.

An initial state vector of the satellite in the inertial frame at a given epoch, the accumulated velocity of the satellite in the satellite body frame at equally distributed intervals of time as measured by the accelerometer onboard and the quaternions at each measurement time for converting the velocity components from body to inertial frame, are input to this program. The inertial state vector of the satellite at equally distributed intervals of trajectory integration time starting from the epoch is the output of this program.

The accumulated velocity in the satellite body frame is received as the measurement at equal time intervals. The spacecraft attitude is obtained from telemetry in the form of quaternions:

$$q = [\,q_0 \quad q_1 \quad q_2 \quad q_3\,] \tag{1}$$

The incremental velocity vector in the body frame $\mathbf{V_b}$ along the roll, pitch, and yaw axes at each time instant is obtained by differencing the accumulated velocities between consecutive measurement times:

$$\mathbf{V_b} = [\,\Delta\mathbf{V_{roll}} \quad \Delta\mathbf{V_{pitch}} \quad \Delta\mathbf{V_{yaw}}\,] \tag{2}$$

The incremental velocity vector in the inertial frame $\mathbf{V_i}$ is represented as

$$\mathbf{V_i} = [\,\Delta\mathbf{V_x} \quad \Delta\mathbf{V_y} \quad \Delta\mathbf{V_z}\,] \tag{3}$$

$\mathbf{V_i}$ is computed using the incremental velocity in the body frame and the quaternions. The velocities in the body frame are transformed into velocities in the inertial frame by using quaternion rotation operators.

The quaternion rotation operator L_q associated with the quaternion q and applied to the velocity vector in the body frame $\mathbf{V_b}$ is defined as

$$L_q(\mathbf{V_b}) = q\mathbf{V_b}q^* \tag{4}$$

where, q^* is the complex conjugate of q.

Then,

$$\mathbf{V_i} = L_q(\mathbf{V_b}) \tag{5}$$

The rotation operator represents a rotation in the three-dimensional vector space with the axis of rotation given by the vector part of q, and the angle of rotation given by twice the angle associated with the quaternion q.

The velocity measurements were obtained from spacecraft telemetry at a sampling rate of 1.816 s and from a solid state recorder (SSR) onboard the spacecraft at a sampling rate of 512 ms.

The satellite trajectory generation is based on solving the equations of motion through numerical integration [2]. The orbit generator is based on Cowell's method. For integrating the second-order differential equations of motion, the Gauss–Jackson–Merson Second Sum method, based on double integration, is used. The differential equation of motion of the orbit model includes the significant perturbing forces [3]. Therefore, the predicted motion of the satellite is as close as possible to the true motion of the satellite.

The dominant perturbing forces that affect the motion of the satellite are the central body perturbation (Earth/moon), aerodynamic drag, third-body perturbation (moon, Earth, sun, and other planets), and solar radiation pressure. Since the accelerometer measures all the nongravitational forces acting on spacecraft, only the gravitational accelerations are considered in addition to the accelerations obtained from accelerometers to find the satellite's true position. EGM96 [4] and LP100 [5] are the gravity models that were used to calculate the central body perturbations with respect to the Earth and the moon in the Earth and moon orbits of Chandrayaan-1, respectively. DE405 is the Jet Propulsion Laboratory (JPL) planetary ephemeris file that was used to calculate the gravitational forces due to sun, moon, and the other planets for satellite trajectory generation.

PROCAD has a feature to run live, for the purpose of real-time orbit determination during the progress of a maneuver. Separate algorithms in PROCAD allow access, from telemetry, of the velocities of the spacecraft measured at each time instant by the accelerometer and the quaternions measured at the corresponding times, instantaneously integrating them with the initial state vector determined using tracking data. The accumulated velocity at a time instant t_n is subtracted from the next accumulated velocity measurement obtained at the succeeding time instant t_{n+1}. The velocity difference calculated in this way is added to the velocity component of the determined state vector at the time instant t_{n+1}, and the governing equations of motion including the accelerations due to Earth, moon, and sun are solved by numerical integration. The cycle is continued until the burn ends. The state vector of the spacecraft realized at the end of the burn is instantaneously displayed, also as a telemetry page.

IV. Real-Time Orbit Determination

The PROCAD program was put in a loop with the telemetry. Even as the maneuver was progressing and the telemetry was receiving the accumulated velocity measurements from the onboard accelerometer and the quaternions, PROCAD was integrating the instantaneous velocities of Chandrayaan-1 with the initial state vector at the start of the burn, determined by using range and Doppler data measured by a network of ground stations configured for the mission. At the very

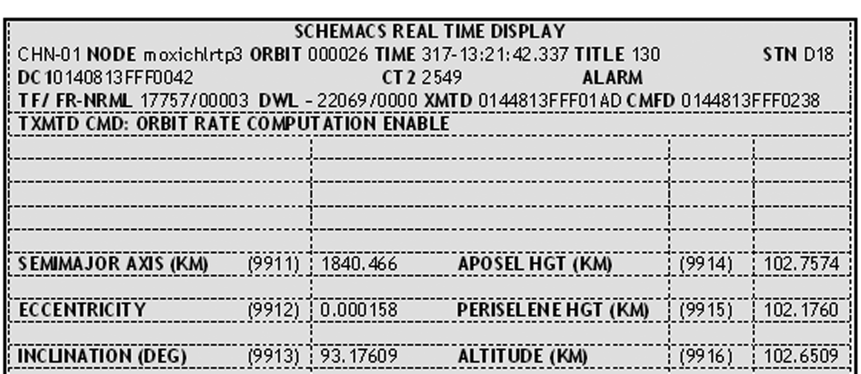

Fig. 1 Image of display of Chandrayaan-1 real-time orbit solutions during LBN-4.

Table 1 Position and velocity differences between Chandrayaan-1 orbit solutions: PROCAD vs postburn expected and postburn tracking data determined

		Position difference, km		Velocity difference, m/s	
Stage of Chandrayaan-1 mission	Burn duration, s	PROCAD vs postburn expected	PROCAD vs postburn determined	PROCAD vs postburn expected	PROCAD vs postburn determined
EBN-1	1046.88	1.862	10.31	4.166	18.28
EBN-3	559.04	1.037	2.085	2.124	2.738
EBN-4	189.00	0.135	23.09	0.613	19.10
EBN-5	147.66	0.111	0.729	0.734	1.142
TCM-1	5.59	6.547	6.432	0.580	0.595
LOI	816.70	2.606	3.727	2.885	7.104
LBN-1	56.00	0.023	1.125	0.181	0.487
LBN-2	868.00	2.062	1.229	3.340	3.346
LBN-3	30.62	0.172	0.957	0.241	0.867
LBN-4	58.60	0.014	0.187	0.244	0.708

Table 2 Chandrayaan-1 state vectors determined using range and Doppler tracking data

Stage of mission	Epoch, UTC[a]	Chandrayaan-1 state vectors in inertial frame, km, km/s					
EBN-1	2008-10-23 03:52:18.706	−5, 844.07	−5, 858.79	−2, 107.82	3.21	−7.85	−2.39
EBN-3	2008-10-26 01:48:10.031	−6.93	−1.301	−0.72	−0.0098	−0.00019	−0.0031
EBN-4	2008-10-29 02:11:34.259	−7, 024.30	−731.32	−557.32	−0.654	−9.93	−3.23
EBN-5	2008-11-03 23:28:40.010	−4, 891.45	−10, 833.82	−3, 756.05	3.630	−6.68	−2.027
TCM-1	2008-11-05 12:00:00.000	229,619.93	−105, 977.67	−24, 727.703	1.037	−0.16	−0.011
LOI	2008-11-08 11:34:24.037	−174.64	−2, 263.35	−309.21	−0.091	0.031	−1.84
LBN-1	2008-11-09 14:34:38.784	545.83	9,053.70	−1, 765.72	0.025	0.079	0.42
LBN-2	2008-11-10 16:42:32.050	−146.76	−1, 900.20	−280.41	−0.067	0.224	−1.59
LBN-3	2008-11-11 13:01:15.788	76.64	1,807.81	−836.00	0.116	0.638	1.39
LBN-4	2008-11-12 13:04:52.797	−63.07	−1, 676.15	757.99	−0.125	−0.666	−1.48

[a]The timelines are in year-month-day format.

instant the burn ended, the state vector at that instant was shown in the telemetry page. Figure 1 shows the telemetry page that was exhibited instantaneously at the end of the lunar burn (LBN)-4 when the spacecraft was maneuvered into the moon's polar, circular orbit of about (100×100) km on 12 November 2008.

The accumulated velocity measurements were obtained from either the telemetry or from the SSR during every maneuver between the start and end times of the burn. The corresponding quaternions for each of the measurement times were also obtained from telemetry. The state vector of Chandrayaan-1 at the start of the burn is known from the determined state using range and Doppler tracking data. Using these inputs, the PROCAD program gave the state vector at the instant of the burn end after numerical integration of the equation of motion.

The consolidated results of the differences between the PROCAD-determined state vectors, the orbit determination program (ODP)-determined state vectors, and the postburn predicted state vectors, are shown in Table 1.

The state vectors determined by PROCAD at the end of each burn during the initial phase of the mission are individually compared with the predicted state vectors at the end of the burn and the state vectors at the end of the burn determined by the Chandrayaan-1 operational ODP, using tracking data from the network of Earth stations configured for the mission.

The Chandrayaan-1 state vectors determined using range and Doppler data at each stage of the mission, against which the position and velocity differences have been calculated in Table 1, are shown in Table 2.

A comparison of the state vectors shown in Table 2 with those determined by JPL for the Chandrayaan-1 mission showed a maximum position difference of 500 m. Since the state vectors determined by ISRO and JPL were in consonance during all stages of the mission, the higher position and velocity differences seen in Earth burn (EBN)-1, EBN-4, TCM-1, and LOI phases could possibly be attributed to accelerometer measurement errors and larger burn times during EBN-1 and LOI.

V. Conclusions

A precise orbit computation program using accelerometer data, designed and developed for the Chandrayaan-1 mission, gave an alternative method of finding the orbit solutions throughout the launch and early phase of the mission. When there are two different sets of measurements obtained from entirely different sets of hardware, the mathematical and computational methods employed in two different software using each set of the measurements gave solutions that were favorably comparable on most occasions. The two sets of measurements were the range and Doppler data of a satellite from Earth station antennae, on the one hand, that were processed using a batch-weighted least-squares estimation technique and, on the other, the accumulated velocity measurements during a satellite maneuver measured by onboard accelerometers that were processed using a velocity integration method described in this Note. The import of time synchronization between receiving the measurements from a satellite in space, processing them on the ground using a software that computes orbit results that have to be available before the receipt of the next set of measurements from satellite telemetry within a few seconds, is spotlit by the favorable comparison of orbit solutions obtained through two different concepts. The method of orbit determination described in this Note gives a quicker awareness to the mission strategists about digressions that have major implications, like nonnominal injection of a satellite after launch, nonnominal progress of a maneuver, or the wrong orbit into which the satellite has cruised because of an emergency maneuver abort. The foremost advantage of having accelerometer payloads on a satellite was evidenced during the orbit raising phases of the satellite mission, as the accelerometer-based orbit determination program gave instantaneous orbital elements just as the maneuvers were progressing, thus giving the mission planners the live positional placement of the satellite in space. The demonstration of sequential execution of a program that demands outputs of correct computation that are fed as inputs to the succeeding iteration before the acquirement of the next set of measurements brought out the essence of real-time satellite orbit determination that would not have been possible without an adept hardware–software handshake.

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