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Engineering Notes

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HAMSAT-1 Precise Orbit Determination System and Performance

Narayanasetti Venkata Vighnesam,* Anatta Sonney,† and Promod K. Soni†
ISRO Satellite Center, Bangalore 560 017, India

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I. Introduction

HAMSAT is a microsatellite launched by the Indian Space Research Organization (ISRO), meant for providing satellite-based amateur radio services to the national and international communities of amateur radio operators (HAMs). The 42-kg HAMSAT satellite was launched onboard the PSLV-C6 mission as an auxiliary satellite, along with CARTOSAT-1 from the Satish Dhawan Space Centre, on 5 May 2005 at 05:02 Universal Time (UT). The satellite was put into an almost nominal 622-km circular orbit with an inclination of 97.91 deg. It will meet the long-felt need of the amateur radio operators in the South Asian region who possess the required paraphernalia and operate in the UHF/VHF-band-based satellite radio communication channel. It is configured as a spin-stabilized satellite with a spin rate of 4 ± 0.5 rpm and spin axis oriented toward positive orbit normal within a specification of ± 3 deg. No orbit maintenance is planned during its mission life.

Tracking of the spacecraft is by means of one-way VHF Doppler from the Bangalore and Lucknow ground stations. Orbit determination (OD) is required to facilitate spacecraft acquisition and tracking by telemetry, tracking, and commanding (TTC) ground stations in subsequent orbits. Orbital elements are to be provided in NORAD two-line-element (TLE) format for amateur radio operators.

Tracking data (range rate) contain the noise levels an order of magnitude more than the existing well-established ISRO's S-band network and variable biases (central-frequency offset). Because there is no algorithm enabling explicit solution of the orbit determination problem using the range rate exclusively, the Marquardt differential correction technique [1], which would allow both larger initial estimate error and larger measurement errors, was used for orbit estimate improvement. Coyle and Pernicka [2] demonstrated that the modified Marquardt technique applied to the least-squares solution provided the most desirable performance for Spartnik microsatellite orbit determination. HAMSAT orbit estimate improvement is based on the method given in [2]. Because tracking data are via one-way VHF Doppler, the orbit determination process requires stringent preprocessing. The description of preprocessing of the raw tracking data and the method of orbit improvement are explained. This paper describes the performance of the HAMSAT OD system during the first quarter of the mission. Achieved OD accuracy during the initial phase of the mission was studied in detail by theoretical definition. Orbit determination results were compared with orbital elements obtained from another source: NORAD two-line elements. This paper highlights the method of the orbit determination process, tracking data quality analysis, achieved orbit determination accuracy, and prediction accuracy to meet the HAMSAT mission requirements. Achievable orbit determination accuracy is found to be about 2 km in position and 2 m/s in velocity. Orbit prediction accuracy is studied and qualified enough for meeting the mission requirement of facilitating spacecraft acquisition and tracking by TTC ground stations in subsequent orbits.

II. Orbit Determination

Precise knowledge of orbital parameters is a prerequisite for the determination of the position of a satellite at any given time. The orbit determination process consists of obtaining the parameters, which completely describe the motion of the satellite within the specified accuracy over a period of time based on a set of observations. Determination of the satellite orbit means the refinement of the initial orbit parameters. The problem of OD consists of comparing measurements taken on a satellite trajectory with a model representing that trajectory. The model is generally represented by a system of differential equations or a set of analytical expressions for which the constants define the satellite trajectory as a function of time. Thus, given a priori estimate of these constants of integration (state parameters), the problem is to update or correct the a priori state parameters as a function of measurements. For Earth's artificial satellites, there are generally many more measurements than the number of state parameters to be estimated. Therefore, the comparison process or estimation process is one that satisfies some statistical principles such as least squares, maximum likelihood, or minimum variance. Thus, the OD system consists of the data system and data handling, dynamic models, and computational techniques, which include trajectory generation and estimation technique.

The general procedure for all definitive orbit computations is to set up some dynamical model of the orbit and use the observations to improve the orbit parameters of the model by the process of differential correction. The orbit is generated either by special perturbation technique (numerical integration of differential equations of motion) or by general perturbation theory (analytical integration of equations of motion). Observations are considered for some preselected time period, and by differential correction of parameters of the model, the sum of the squares of the residual is minimized. In this estimation process of weighted least squares, it is necessary to compute partial derivatives of observations with respect to model parameters.

ISRO's operational orbit determination program (ODP) derives the solution of equations of motion through numerical integration. The orbit generator is based on Cowell's method. For integrating the second-order differential equations of motion, the method based on the double-integration Gauss–Jackson–Merson second sum method

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*Head, Orbit Dynamics and Determination Section, Flight Dynamics Division.

†Engineer, Orbit Dynamics and Determination Section, Flight Dynamics Division.

is employed. The partial derivatives of measurements with respect to state parameters are computed using the increment method.

A. HAMSAT Orbit Determination

The solution of the spacecraft orbit determination problem is highly dependent upon the type of tracking data available at the ground station. Many algorithms exist for determining the orbit for different types and combinations of tracking data. The HAMSAT mission is supported by only one-way Doppler shift as a function of time, thereby providing the slant range rate as the single observation parameter. Low-Earth-orbit missions are typically able to supply two or more observed parameters simultaneously, enabling explicit solution of the orbit determination problem. An algorithm enabling explicit solution of the orbit determination problem using range-rate data exclusively was not found, but orbit estimate improvement is still possible via the Marquardt differential correction technique, which would allow both larger initial estimate error and larger measurement errors. This technique is an interpolation between the Newton method and the method of steepest descent. As described in [2], by using a differential correction scheme in conjunction with a batch least-squares estimator along with convergence improvements, the task of maintaining an acceptably accurate knowledge of the spacecraft orbit is made possible for a single ground station receiving a single measured parameter, even at higher levels of measurement noise and bias than those expected at the ground station.

HAMSAT orbit determination is carried out daily using 2.5 days of data arc with 1.5 days of overlap between data arcs in a routine operation. Tracking data are collected from the Bangalore and Lucknow ground stations. From each station, about two passes per day are taken for orbit determination.

B. Marquardt Technique for Convergence

The Marquardt technique for orbit estimation improvement would allow larger errors in both initial estimate and measurements. Consider the update of the state in the differential correction method:

$$X_i = X_{i-1} + \Delta X \tag{1}$$

where X_i and X_{i-1} are the consecutive six-dimensional states comprising position and velocity, and ΔX is the update of the state.

The Marquardt algorithm yields the normal equation as

$$[A^T A]'\{\Delta X\} = [A]^T [R] \tag{2}$$

where $[A]$ is the $(m \times 6)$ Jacobian matrix of the partials of measurements with respect to the initial state, $[A^T A]'$ is the matrix obtained by multiplying the diagonals of $[A^T A]$ by $(1 + \lambda)$, and $[R]$ is the observation residue matrix of $(m \times 1)$, where m is the total number of measurements and λ is a constant to be much larger than the magnitude of the elements of $[A^T A]$. When the root mean square (rms) residual decreases after each state estimate update, λ is replaced by λ/k, where k is typically $1 < \mathrm{k} \leq 10$ and where the rms residual increases, the previous state corrections are discarded and λ is replaced by $k\lambda$. This Marquardt algorithm was seen to exhibit more desirable convergence characteristics in the application of estimation.

C. Tracking System and Method of Processing

HAMSAT's tracking data are VHF one-way Doppler from ISRO's Bangalore and Lucknow ground stations. The one-way Doppler shift as a function of time provides the slant range rate as the single observation parameter. The TTC processor is ENERTEC. Raw tracking data are preprocessed through the tracking data preprocessing program (TDPP). In preprocessing, the raw tracking data acquired from different stations are edited, smoothed, and corrected for atmospheric refraction effects. The data are also corrected for onboard and ground-system delays, if any. The processed data are stored in a file, in a suitable format for orbit determination.

Range-rate measurements are obtained from the Doppler frequency shift. The Doppler frequency shift is converted into the slant range rate as

$$\dot{\rho}_i = -c \frac{\Delta f_i}{F_d}, \qquad 1 \leq i \leq m \tag{3}$$

where $\dot{\rho}_i$ is the range rate, c is the speed of light, Δf_i is the Doppler shift, F_d is the downlink frequency, and m is the total number of measurements. Because HAMSAT Doppler measurements Δf_i contain more noise and variable biases (central-frequency offset), these measurements are to be corrected by estimating the central frequency for each pass. Corrected Δf_i is obtained by removing estimated central-frequency offset from the measured Doppler shift. Central-frequency offset is computed by assuming that the Doppler curve is a third-degree polynomial:

$$f(t) = a + bt + ct^2 + dt^3 \tag{4}$$

where a, b, c, and d are constants, and f consists of points f_i, which are the sum of the observed Doppler shift and assumed central frequency. The radius of curvature R_c becomes

$$R_c = \frac{d^2 f/dt^2}{[1 + (df/dt)^2]^{3/2}} \tag{5}$$

Therefore, to get the inflection point, $d^2 f/dt^2$ should vanish at time $t = t_c$, where t_c is the time of closest approach of the object:

$$d^2 f/dt^2 = 0 \quad \text{for } t = t_c \tag{6}$$

Once t_c is known by solving Eq. (6), we can get the estimated central frequency f_c. The corrected Doppler shift Δf_i is obtained as

$$\Delta f_i = f_i - f_c, \qquad (i = 1, \ldots, m) \tag{7}$$

D. Dynamic Model

If the Earth were spherical, without atmosphere, and were isolated from other bodies in the solar system, the orbit of a satellite would be an ellipse of constant size and shape in a plane for which the direction remains fixed relative to the stars. The orbit will remain unchanged under such conditions. This situation would be changed by the effect of a variety of perturbed forces. The differential equations of motion of the orbit model adopted should include almost all perturbing forces, such that the predicted motion of the satellite should be as close as possible to the true motion of the satellite. The dominant perturbing forces that affect the motion of the satellite are the asphericity of Earth (central-body perturbation), aerodynamic drag, lunisolar gravitational attraction (third-body perturbation), and solar radiation pressure.

HAMSAT ODP software uses the EGM96 geopotential model (70X70) for central-body perturbation and the MSIS-90 model for atmospheric density computation. The JPL DE405 planetary ephemeris is used for lunar and solar gravitational attraction computation.

III. System Performance

The orbit determination system consists of tracking data preprocessing software and orbit determination software. Tracking-system performance and orbit determination performance can be studied through the orbit determination system. In the present study, the HAMSAT OD system performance during the first four months of the mission period is studied.

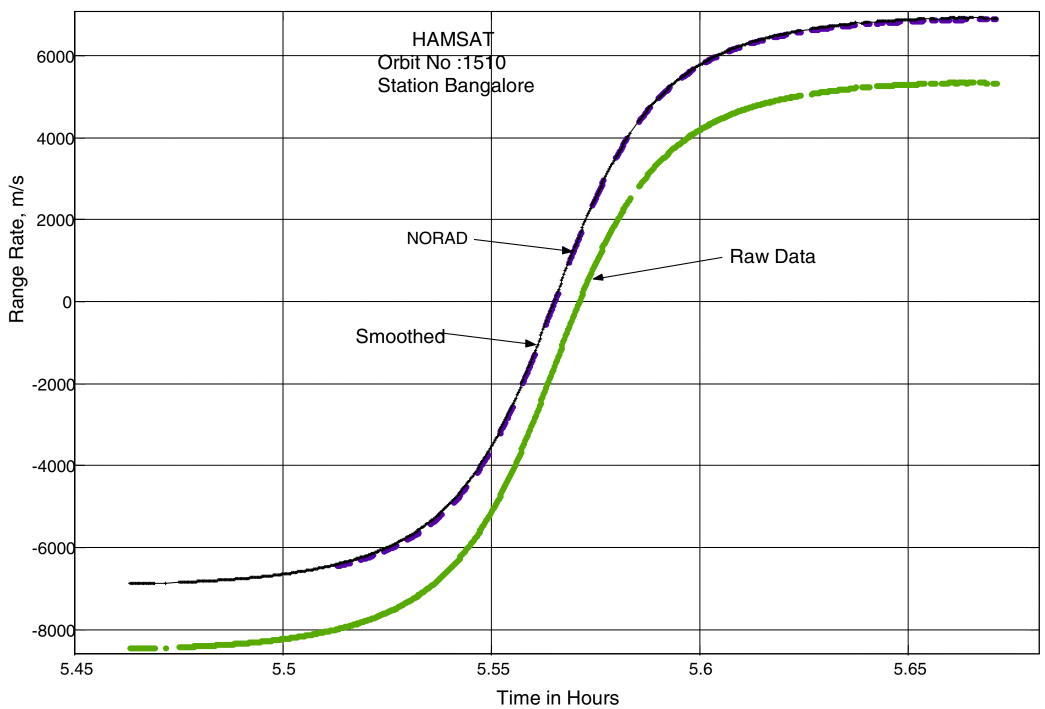
A. Tracking-System Performance

Tracking support is from ground stations in Bangalore and Lucknow, which have common visibility for HAMSAT. Measurements from both stations were used to carry out orbit determination.

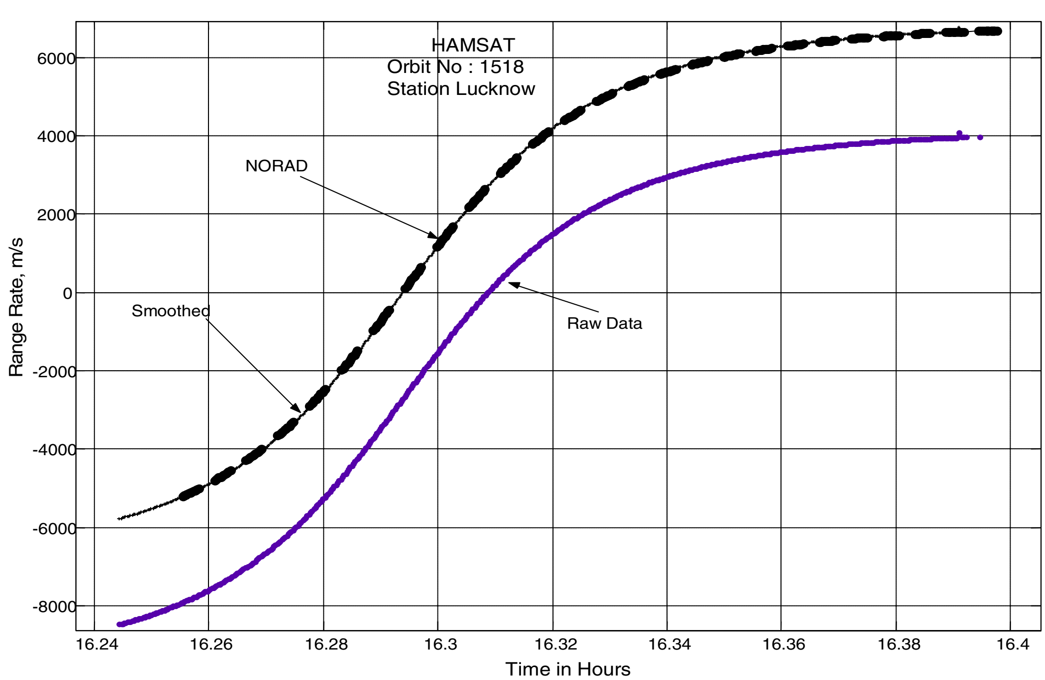
It was observed that the data contain a considerable amount of data breaks and invalid measurements due to frequency interference. The percentages of valid measurements are about 75 and 60% from the Bangalore and Lucknow ground stations, respectively. Data were preprocessed through the method described in Sec. II.C. The central-frequency offset was estimated and the range rate was computed. Typical passes representing data before and after smoothing are shown in Figs. 1a and 1b. Variable central-frequency biases are observed during this study period. Data contain a noise level of about 30 m/s, which was noticed from the orbit determination outputs.

B. Orbit Determination Performance/Achieved Orbit Accuracy

Orbit determination performance is studied for a number of cases during July and August 2005 data. The method adopted for accuracy estimation is *difference in position*, in which the orbit accuracy is measured as the difference between two consecutive definitive ephemerides over the period of overlapping tracking data. The rms values of position and velocity differences between these consecutive definite ephemerides are considered as position and velocity errors in OD. The method is the same that was applied for all Indian remote sensing missions [3,4]. The achieved orbit determination accuracy is shown in Table 1. Position error resolved



a) Raw verses expected range rate data for ground station Bangalore



b) Raw verses expected range rate data for ground station Lucknow

Fig. 1 Raw vs expected range-rate data for a) ground station Bangalore and b) ground station Lucknow.

Table 1 HAMSAT-1 orbit determination accuracy

Epoch Year	Month	Day	Position error km	Position error Radial, km	In-track, km	Cross-track, km	Velocity error km/s
2005	7	6	1.221802	0.024498	1.221542	0.005951	0.001314
2005	7	7	1.198449	0.035737	1.197052	0.045509	0.001287
2005	7	8	1.420152	0.059849	1.389138	0.289041	0.001526
2005	7	9	5.416899	0.709470	2.371137	4.818419	0.005690
2005	7	10	0.827774	0.169045	0.445791	0.676685	0.000835
2005	7	11	3.212414	0.455720	1.055217	2.999740	0.003337
2005	7	12	2.010504	0.170728	0.682339	1.883452	0.002146
2005	7	13	1.817871	0.297215	1.471369	1.025373	0.001869
2005	7	14	1.191703	0.106835	0.728050	0.937383	0.001265
2005	7	15	3.555365	0.054349	3.543196	0.288849	0.003826
2005	7	16	2.164817	0.435094	1.003712	1.868070	0.002182
2005	7	17	2.961310	0.037178	2.597101	1.422335	0.003190
2005	7	18	3.021870	0.094586	2.909426	0.811168	0.003249
2005	7	19	1.477899	0.171756	0.627034	1.327220	0.001558
2005	7	20	1.371327	0.021002	1.370654	0.037469	0.001476
2005	7	21	6.063979	1.061304	5.433220	2.474995	0.006212
2005	7	22	2.173946	0.023791	2.173058	0.057404	0.002340
2005	7	23	3.164496	0.361923	2.711492	1.590866	0.003343
2005	7	24	0.468897	0.007970	0.468439	0.019116	0.000504
2005	7	25	2.332547	0.276304	1.370364	1.867226	0.002461
2005	7	26	0.117375	0.017188	0.115731	0.009364	0.000122
2005	7	27	0.472339	0.023430	0.471676	0.008814	0.000507
2005	7	28	1.007673	0.177414	0.686079	0.716397	0.001033
2005	7	29	1.111768	0.172549	0.578387	0.933661	0.001155
2005	7	30	1.725776	0.451037	1.616154	0.403626	0.001647
2005	7	31	1.891384	0.019562	1.891245	0.011965	0.002036
2005	8	1	0.811677	0.021413	0.811360	0.007528	0.000873
2005	8	2	1.150589	0.018923	1.149624	0.043162	0.001238
2005	8	3	0.889625	0.048575	0.878913	0.128783	0.000954
2005	8	4	3.308261	0.582779	1.654617	2.804853	0.003376
2005	8	5	0.187305	0.029515	0.184319	0.015449	0.000193
2005	8	6	2.185855	0.625588	1.341326	1.608554	0.002048
2005	8	7	0.492714	0.094178	0.236182	0.422037	0.000498
2005	8	8	0.568731	0.021336	0.568258	0.009104	0.000611
2005	8	9	1.740031	0.333696	0.787280	1.515436	0.001757
2005	8	10	2.941618	0.676945	2.608125	1.180062	0.002893
2005	8	11	0.593060	0.018108	0.588296	0.072804	0.000637
2005	8	12	1.159244	0.020375	1.158674	0.030075	0.001248
2005	8	13	0.181298	0.007735	0.181103	0.003300	0.000194
2005	8	14	1.244971	0.298755	1.208362	0.023691	0.001227
2005	8	15	2.934844	0.401732	1.499360	2.490751	0.003069
2005	8	16	2.642347	0.819450	2.373836	0.821828	0.002392
2005	8	17	0.027400	0.008905	0.020334	0.016062	0.000024
2005	8	18	0.979768	0.309574	0.664652	0.649883	0.000888
2005	8	19	0.715486	0.151959	0.540340	0.443690	0.000715

in radial, along-track, and across-track was also studied. It was observed that the position and velocity accuracies based on most of the OD results are about 2 km and 2 m/s, respectively.

IV. Comparison with NORAD TLE

The two-line-element sets made available by NORAD (and redistributed by NASA) are mean orbital elements. The NORAD TLE is generated by their own orbit determination system using the observational data from the worldwide space-surveillance network. It has been widely used by members of the community who do not have their own orbit determination system. HAMSAT's estimated orbits through ODP were compared with NORAD two-line elements. Orbit comparisons were carried out for the estimated orbits from 4 July to 20 August 2005. It is noticed from this study that the mean difference in position and velocity are about 4.3 km and 4.1 m/s, respectively.

V. Prediction Accuracy

Prediction accuracy for HAMSAT was studied for its sustainability. No orbit maintenance is planned during its mission life. The mission requires the orbit to facilitate spacecraft acquisition and tracking by TTC ground stations in subsequent orbits. Prediction accuracy was studied for about 10 days and compared with NORAD prediction for acquisition-of-signal and loss-of-signal timings. Orbit solutions obtained through ODP were converted to the NORAD mean elements format. The simplified general perturbation satellite-orbit model 4 (SGP4) was used as an orbit propagator. A typical case is taken for this study, in which the difference between the NORAD and ODP estimated orbits is relatively more, and it is noticed that the maximum time difference for ten days is about 11 s in acquisition-of-signal and loss-of-signal times.

Each orbit determination output gives the determined orbit at the epoch and the expected orbit for the consecutive days within the tracking data period. The orbit prediction study was carried out by comparing the determined orbit with the expected orbit obtained from the consecutive days orbit determination. The study was carried out during the first quarter of the mission for the period during July and August 2005. It is observed that the mean prediction error during consecutive days in position and velocity are about 2 km and 2 m/s, respectively.

VI. Conclusions

The HAMSAT orbit determination system methodology and system performance were studied. Tracking data are the VHF one-way Doppler shift from the Bangalore and Lucknow ground stations.

Tracking data (range rate) contain noise of the order of about 30 m/s and variable biases (central-frequency offset). The low-Earth-orbit mission's operational orbit determination software was suitably updated to handle HAMSAT tracking data. Achievable orbit determination accuracy is found to be about 2 km in position and 2 m/s in velocity. Orbit prediction accuracy is studied and qualified enough for meeting the mission requirement of facilitating spacecraft acquisition and tracking by TTC ground stations in subsequent orbits. Because of the irregular periodicity of generation of the NORAD TLE, a new TLE that is independent of NORAD is required through ODP. Estimated orbital elements are being converted into NORAD–TLE format for subsequent use by amateur radio operators.

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References

[1] Wertz, J. R. (ed.), *Spacecraft Attitude Determination and Control*, D. Reidel, Dordecht, Holland, The Netherlands, 1978, Chap. 13, pp. 455–456.

[2] Daniel Coyle, and Henry J. Pernicka., "Orbit Determination at a Single Ground Station Using Range Rate Data," *Journal of the Astronautical Sciences*, Vol. 49, No. 2, 2001, pp. 327–344.

[3] Vighnesam, N. V., Anatta Sonney, and Subramanian, B., "IRS Orbit Determination Accuracy Improvement," *Journal of the Astronautical Sciences*, Vol. 50, No. 3, 2002, pp. 355–366.

[4] Vighnesam, N. V., Anatta Sonney, Boominathan Subramanian, and Pramod Kumar Soni, "IRS-P6 Orbit Determination and Achieved Accuracy During Early Phase," *Acta Astronautica*, Vol. 60, No. 2, 2007, pp. 79–87.

C. Kluever
Associate Editor