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Application of High-Precision Two-Way Ranging to Galileo Earth-1 Encounter Navigation

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Navigation Systems Section

The application of precision two-way ranging to orbit determination with relatively short data arcs is investigated for the Galileo spacecraft's approach to its first Earth encounter (December 8, 1990). Analysis of previous S-band (2.3-GHz) ranging data acquired from Galileo indicated that under good signal conditions submeter precision and 10-m ranging accuracy were achieved. It is shown that ranging data of sufficient accuracy, when acquired from multiple stations, can sense the geocentric angular position of a distant spacecraft. A range data filtering technique, in which explicit modeling of range measurement bias parameters for each station pass is utilized, is shown to largely remove systematic ground system calibration errors and transmission media effects from the Galileo range measurements, which would otherwise corrupt the angle-finding capabilities of the data. The accuracy of the Galileo orbit solutions obtained with S-band Doppler and precision ranging were found to be consistent with simple theoretical calculations, which predicted that angular accuracies of 0.26–0.34 μrad were achievable. In addition, the navigation accuracy achieved with precision ranging was marginally better than that obtained using delta-differenced one-way range (ΔDOR), the principal data type that was previously used to obtain spacecraft angular position measurements operationally.

I. Introduction

The approach phase leading up to the Galileo spacecraft's first Earth encounter (designated Earth-1) provided a good opportunity to test the viability of high-precision two-way ranging as an operational radio metric data type. Two-way ranging data acquired by Deep Space Network (DSN) stations have been accurate to 15 m or better for nearly 20 years, depending upon the frequency band and station–spacecraft radio link characteristics. Such data have typically been utilized for orbit determination at assumed accuracies of 100–1000 m, due to the effects of station delay and transmission media calibration errors, and the influence of small, poorly modeled spacecraft nongravitational forces. Since the early 1970s, evolutionary improvements in the accuracy and stability of timing systems, station delay calibration procedures, and transmission media calibration techniques, coupled with more sophisticated orbit determination software, now make it possible to reconsider the use of precision ranging for interplanetary spacecraft navigation.

In a recent experiment conducted with radio metric data acquired from the Ulysses spacecraft, two-way ranging data were processed with a new range data-filtering technique that made it possible to successfully utilize the data at an assumed accuracy of 10 m for the first time [1]. This filtering technique utilized estimated parameters to explicitly account for and remove residual ground system calibration errors and solar plasma–induced delays from the ranging data. Other factors that contributed to the success of the Ulysses experiment were the accuracy and consistency of the DSN station delay calibrations and the utilization of a new DSN station location set developed by Folkner and Dewey.[1]

The use of Galileo ranging for a second test of the range data–filtering technique used to process the Ulysses data was motivated by the earlier results of the Galileo Venus encounter orbit solutions. During Galileo's approach to Venus and its subsequent flyby, good signal strength was obtained from the spacecraft's two low-gain S-band (2.3-GHz) antennas, yielding point-to-point two-way range noise (indicative of the precision of the data) of under 1 m and an apparent accuracy of 10 m or better [2]. In addition, the station delay calibrations during this time period appeared to be of good consistency, showing little variation over the month prior to the encounter. This article describes an investigation which reexamined the orbit determination that was utilized for the design of the last targeting maneuver prior to the Earth-1 encounter. A brief discussion of the theoretical basis for the ability of high-accuracy ranging data to sense spacecraft angular position is presented, as well as comparisons of different solutions obtained using combinations of various data types, including two-way Doppler and ranging, and ΔDOR.

II. Theoretical Background

A simple investigation of the ability of ranging and Doppler data to determine the trajectory of a distant spacecraft can be conducted by analyzing the theoretical precision with which the geocentric spacecraft motion can be sensed from one or two passes of data. Similar analyses have been performed previously for range and Doppler data separately [1,3,4]. The station–spacecraft tracking geometry is illustrated in Fig. 1. The topocentric range, ρ, and range-rate, $\dot{\rho}$, can be accurately approximated over short periods of time (up to roughly 24 hr) in terms of the geocentric spacecraft range (r), range rate ($\dot{r}$), declination (δ), and right ascension (α), as follows:

$$\rho \approx r - (r_s \cos\delta \cos H + z_s \sin\delta) \tag{1}$$

$$\dot{\rho} \approx \dot{r} + w r_s \cos\delta \sin H \tag{2}$$

where

r_s = station distance from Earth's spin axis (spin radius)

z_s = station height above Earth's equator (z-height)

w = Earth rotation rate (7.3×10^{-5} rad/sec)

$H = \alpha_g + \lambda - \alpha$

and

α_g = right ascension of Greenwich meridian

λ = station east longitude

From Eqs. (1) and (2), it can be seen that four of the six components of the geocentric spacecraft trajectory (r, $\dot{r}$, δ, and α) can be sensed by range and range-rate measurements. Over the time period of interest, $\dot{r}$, δ, and α are nearly constant. A determination of the remaining two coordinates, $\dot{\delta}$ and $\dot{\alpha}$, and hence the complete trajectory, normally requires the acquisition of multiple passes of data over a period of several days. The accumulated information in each ranging and Doppler pass can be thought of as a multidimensional measurement of the spacecraft trajectory, with the statistical combination of several such measurements yielding a complete determination of the trajectory.

A simple least-squares error analysis of estimates of r, $\dot{r}$, δ, and α, derived from a single pass of range and Doppler data, can be formulated analytically (refer to the paper by Hamilton and Melbourne [3] for more details). For the purposes of this analysis, it is assumed that $\dot{r}$, δ, and α are constants, and that r varies linearly with time. The information matrix, J, for these coordinates, assuming a tracking pass in which the station–spacecraft hour angle H varies as $-\psi \leq H \leq +\psi$, can be expressed as

$$\begin{aligned} J \approx & \left(\frac{1}{\sigma_\rho^2 \omega \Delta t}\right) \int_{-\psi}^{+\psi} [\partial\rho/\partial(r,\dot{r},\delta,\alpha)]^T \\ & \times [\partial\rho/\partial(r,\dot{r},\delta,\alpha)]\, dH \\ & + \left(\frac{1}{\sigma_{\dot{\rho}}^2 \omega \Delta t}\right) \int_{-\psi}^{+\psi} [\partial\dot{\rho}/\partial(r,\dot{r},\delta,\alpha)]^T \\ & \times [\partial\dot{\rho}/\partial(r,\dot{r},\delta,\alpha)]\, dH \end{aligned} \tag{3}$$

[1] W. M. Folkner and R. J. Dewey, "Radio Source Catalog and Station Location Set for Ulysses," JPL Interoffice Memorandum 335.1-90-048, Jet Propulsion Laboratory, Pasadena, California, September 13, 1990.

where

σ_ρ = range measurement noise one-sigma uncertainty

$\sigma_{\dot\rho}$ = range-rate (Doppler) measurement noise one-sigma uncertainty

Δt = time interval between measurements

In Eq. (3), it is assumed that the time between measurements, Δt, is the same for both the range and Doppler measurements. The partial derivatives appearing in Eq. (3) at some time t, with respect to the geocentric coordinates at time t_o, where t_o is assumed to be the time at which the spacecraft crosses the local meridian of the tracking station, are as follows:

$$\frac{\partial\rho}{\partial(r,\dot r,\delta,\alpha)} \approx [1, t-t_o, r_s\sin\delta\cos H - z_s\cos\delta, - r_s\cos\delta\sin H] \tag{4}$$

$$\frac{\partial\dot\rho}{\partial(r,\dot r,\delta,\alpha)} \approx [0, 1, -wr_s\sin\delta\sin H, -wr_s\cos\delta\cos H] \tag{5}$$

The error covariance, Λ, for r, $\dot r$, δ, and α at time t_o is simply

$$\Lambda = J^{-1} = \begin{bmatrix} \sigma_r^2 & 0 & \sigma_{r\delta}^2 & 0 \\ 0 & \sigma_{\dot r}^2 & 0 & \sigma_{\dot r\alpha}^2 \\ \sigma_{r\delta}^2 & 0 & \sigma_\delta^2 & 0 \\ 0 & \sigma_{\dot r\alpha}^2 & 0 & \sigma_\alpha^2 \end{bmatrix} \tag{6}$$

where

$$\sigma_\delta^2 = \frac{\omega\Delta t}{(r_s\sin\delta)^2} f_1\left(\psi, \sigma_\rho^2, \sigma_{\dot\rho}^2\right) \tag{7}$$

$$\sigma_\alpha^2 = \frac{\omega\Delta t}{(r_s\cos\delta)^2} f_2\left(\psi, \sigma_\rho^2, \sigma_{\dot\rho}^2\right) \tag{8}$$

Equations (7) and (8) are similar to expressions derived by Anderson [4] in an earlier analysis of this same problem (the functions f_1 and f_2 are not shown explicitly, as they are rather complex). As noted by Anderson, σ_δ is proportional to $1/\sin\delta$, and will theoretically become infinite for spacecraft located on the celestial equator ($\delta = 0$). Hamilton and Melbourne [3] found an equivalent result for a single pass of Doppler data only. In contrast, σ_α is seen from Eq. (8) to be proportional to $1/\cos\delta$, which has little (±10 percent) variation over the declination range spanned by the ecliptic plane (±24 deg), in which most interplanetary spacecraft trajectories lie. Although formulas for σ_r and $\sigma_{\dot r}$ are not explicitly given, Eq. (6) predicts that these quantities are determined with a precision limited only by the precision of the range and Doppler measurements and the number of measurements acquired. Thus, for the case of single-station tracking, the ability of ranging and Doppler data to determine the spacecraft declination depends heavily on the tracking geometry.

The situation described above changes dramatically when an additional pass of ranging and Doppler data from a properly chosen second station is added into the information matrix. Consider a scenario in which a tracking pass is acquired from a station with z-height, z_s, and spin radius, r_s, followed immediately by another pass from a second station, with z-height, $-z_s$, and spin radius, r_s. This choice of station coordinates is not arbitrary; stations located at the DSN complexes at Goldstone and near Canberra have spin radii that are nearly equal (to within about 5 km) and z-heights that are nearly equal in magnitude but have opposite signs. Applying the assumptions used in the single-pass analysis to this case yields an error covariance matrix, Λ, that incorporates the information matrix obtained from the first pass, designated J_1, and the information matrix from the second pass, J_2:

$$\Lambda = [J_1 + J_2]^{-1} \tag{9}$$

For the case of $\delta = 0$, the formula for σ_δ obtained from Eq. (9) reduces to a simple form

$$\sigma_\delta = \frac{\sigma_\rho}{2z_s}\sqrt{\frac{\omega\Delta t}{\psi}} \tag{10}$$

From Eq. (10), it can be seen that the z-height component of the baseline formed by the two stations enables a determination of δ, and that this determination is provided solely by the ranging data. The result for σ_α obtained in Eq. (10) is simply equal to the expression for σ_α from Eq. (8) multiplied by a factor of $1/\sqrt{2}$.

A simplified illustration of the result obtained in Eq. (10) is shown in Fig. 2, for a spacecraft at near-zero declination (i.e., $\sin\delta \approx \delta$) being tracked by two stations located on a two-dimensional Earth. In Fig. 2, the two stations shown have z-heights equal in magnitude but opposite in sign, as was assumed in developing Eqs. (9) and

(10). The spacecraft declination is sensed through the difference between the range measured from the two different stations. As explained by Taylor et al. [5], the greatest accuracy in determining this range difference is achieved by explicitly differencing simultaneous or near-simultaneous range measurements obtained during periods of mutual visibility. If the spacecraft dynamics and the range measurements can be modeled with sufficient accuracy, though, this explicit differencing is not required; the two-way ranging data from the different station passes implicitly contain the information needed to determine δ, as shown in Eq. (10) above.

Using Eq. (10), the angular precision that can theoretically be achieved by using two passes of S-band (2.3-GHz) ranging and Doppler data for $\delta = 0$ was computed and plotted in Fig. 3, as a function of the combined tracking time from the two stations, which were assumed to have r_s and z_s coordinates corresponding to the DSN Goldstone and Canberra complexes. The assumed ranging and Doppler measurement accuracies used to construct Fig. 3 ($\sigma_\rho = 10$ m and $\sigma_{\dot{\rho}} = 1$ mm/sec) are based on previous experience with Galileo S-band ranging and Doppler data [2]. In Fig. 3, the total tracking time is assumed to be divided equally between the two participating stations. During the Galileo spacecraft's approach to the Earth-1 encounter, typical tracking pass lengths were 9 to 10 hr; Fig. 3 indicates that for two 10-hr passes, the theoretical angular precision achieved is about 0.26 μrad in declination and about 0.34 μrad in right ascension. Subsequent calculations using Eq. (10) for nonzero values of δ ranging from -24 to $+24$ deg (not shown here) yielded results that were within 10 percent of the data shown in Fig. 3. In comparison, the angular precision of Galileo S-band ΔDOR, the principal data type used to obtain angular measurements during actual Earth-1 encounter navigation operations, was about 0.04–0.08 μrad, depending upon the tracking geometry [6].

Although not as accurate as ΔDOR in this experiment, two-way ranging is a much simpler data type to employ operationally, in that the data are easier to acquire and process. In addition, it will be shown subsequently that the superior angular precision of ΔDOR does not always translate into an equivalent level of navigation accuracy. In a typical mission operations environment, the scheduling and postprocessing requirements associated with ΔDOR result in data acquisitions every 1 to 2 days at best, and more often at intervals of 3 to 7 days instead (e.g., 19 ΔDOR measurements were acquired over the 44-day data arc used in this experiment; 2750 two-way range measurements were acquired during the same period). This sparsity of ΔDOR data sometimes leads to navigation accuracies that are, in an angular sense, poorer than the theoretical angle-finding capability of the data.

While the theoretical results above show that ranging can overcome the dependence of Doppler-based angle determination on the tracking geometry, it must be recognized that the effects of systematic range measurement errors, principally station delay calibration errors, will not necessarily be reduced through statistical averaging, as will the effects of random errors. These systematic errors must be accounted for in some way, or reduced a priori through the use of very accurate calibrations.

III. Station Delay Calibrations

To account for the effects of systematic bias errors on the ranging data, pass-specific bias parameters were estimated for each Deep Space Station (DSS) used to acquire ranging from Galileo. In addition to station delay calibration errors, which generally do not change very much over the duration of a single pass, these bias parameters were intended to represent slowly varying range delays due to the solar plasma, which are often the largest nongeometric component of range measurements acquired with S-band uplink and downlink frequencies [1]. The data were divided into batches so that no two ranging passes from the same station were included in a single batch. Stochastic range bias parameters were then estimated for each station during each successive batch by using a batch-sequential filter algorithm.

An examination of the station delay calibration data obtained during the Earth-1 approach phase indicated that for the 60 days prior to the encounter, the values of station delay calibrations for the DSN 70-meter subnet (most of the Galileo Earth-1 approach radio metric data were acquired from this subnet) were very consistent and showed little day-to-day variation. Great effort was made on the part of DSN station personnel to maintain the consistency of the 70-m station configurations during this phase of the mission. The standard deviation of the station delay calibrations was observed to be just 55 cm, with the largest variations being on the order of 1.5 m. Since tracking passes were obtained infrequently from the 34-m standard (STD) subnet, the sparsity of station delay calibration data from this subnet prevented any similar analysis. The Sun–Earth–spacecraft angle was quite large within the data arc (greater than 150 deg); therefore, the anticipated magnitude of solar plasma–induced delays in the S-band range measurements was 1 m or less, assuming an average level of solar activity [7]. Based on these considerations, the stochastic range biases associated with the 70-m stations were assigned a priori uncertainties of 2 m, and the range biases associated with the 34-m STD stations were assigned a priori uncertainties of 10 m.

IV. Analysis

The Earth-1 orbit determination analysis for this experiment consisted of recomputing the orbit determination delivery that was used for the design of the final Earth-targeting maneuver and used several different data sets and assumed data accuracies. The data arc used for the solutions extended from October 10, 1990 (59 days prior to encounter) to November 23, 1990 (15 days prior to encounter). This time period corresponds to Earth–spacecraft distances ranging from 50–12.5 million km, and a geocentric spacecraft declination of 15–13 deg. The radio metric data acquired included 3740 Doppler points (600-sec count time) and 2750 range points. Additionally, 19 ΔDOR observations were obtained, including 11 observations from the DSN Goldstone–Canberra baseline, and 8 observations from the Goldstone–Madrid baseline. Table 1 summarizes the parameters and assumptions that were used in the orbit determination filter model. In Table 1, the estimated parameters are those that were explicitly solved for in the estimation process; the consider parameters were not estimated, but the effects of uncertainty in these quantities was accounted for (i.e., "considered") when calculating the error covariance associated with the solution for the estimated parameters. Also in Table 1, the radial and transverse components of the solar radiation pressure model refer to the direction parallel to the Sun–spacecraft line, and the two directions orthogonal to that line, respectively.

For the set of solutions that was computed, several different choices of data set and data weighting (i.e., specification of the assumed measurement noise level for each data type) were exercised in order to determine the effect of each variation on the predicted aim point for the encounter. These solutions were then compared with a highly accurate (50-m) post-flyby reconstruction of the trajectory that was computed using both pre- and post-encounter radio metric data. For the precision ranging analysis, a range data weight of 10 meters was used. Although the noise level previously observed in Galileo ranging data was at the submeter level, a weight of 10 m was chosen in light of the presence of 1- to 2-meter-level systematic ionospheric calibration errors that could affect data acquired at S-band frequencies. For comparison purposes, a range data weight of 1 km was used in several solutions, as this value is representative of more traditional methods of utilizing ranging (1 km was, in fact, the range weight used operationally for the Earth-1 encounter). Two sets of solutions were calculated; in the first set a Doppler weight of 1 mm/sec (60-sec count time) was used for all solutions, and in the second set a Doppler weight of 2 mm/sec (60-sec count time) was employed. The Doppler data weight used during actual Earth-1 encounter operations was 1 mm/sec, which is commensurate with the inherent accuracy of the data. In each set, solutions were constructed using Doppler data only; Doppler plus 1-km range; Doppler, 1-km range and 50-cm ΔDOR; and Doppler plus 10-m range. A final solution was constructed using only 10-m range for comparison purposes. The stochastic range bias filter model was employed in all cases involving 10-m range.

V. Results

The results of the analysis are shown in Figs. 4 and 5, and are summarized in Table 2. Figures 4 and 5 portray the two sets of solutions obtained with Doppler weights of 1 mm/sec and 2 mm/sec, respectively, in an Earth-centered aiming plane coordinate system.[2] The one-sigma dispersion ellipses associated with each solution (representing a 39-percent confidence interval) are also shown in Figs. 4 and 5. For the Earth-1 encounter, the aiming plane was nearly coincident with the plane of the sky, that plane which is normal to the Earth–spacecraft line-of-sight, over the entire data arc. Therefore, the ability of different radio metric data types to determine the aim point for the encounter was very closely related to their ability to measure the geocentric spacecraft angular position over the time span of the data arc. Thus, this encounter represents a fairly direct test of the angle-finding capability of S-band precision ranging data.

The solution utilizing 1-mm/sec Doppler and high-precision ranging, shown in Fig. 4, resulted in the closest agreement with the post-flyby reconstruction of all the solutions performed, with an error of 4.2 km in the aiming plane. This error translates into an angular error of 0.34 μrad, a value that is in good agreement with the theoretical precision of two Northern and Southern Hemisphere 9- or 10-hr DSN tracking passes, shown in Fig. 3. This precision range result compares quite favorably with the 1-mm/sec Doppler, 1-km range, 50-cm ΔDOR solution (also shown in Fig. 4), which had an error of 7.8 km

[2] The aiming plane or "B-plane" coordinates system is defined by three unit vectors, **S**, **T**, and **R**; **S** is parallel to the incoming asymptotic velocity vector, **T** is parallel to the ecliptic plane (mean plane of the Earth's orbit), and **R** completes an orthogonal triad with **S** and **T**. The aim point for a planetary flyby is defined by the miss vector, **B**, which lies in the **T**–**R** plane, and can be thought of as specifying where the point of closest approach would be if the target planet had no mass and did not deflect the flight path.

(equivalent to 0.62 μrad); this solution was the best solution obtained during actual Earth-1 encounter operations. The relatively poor performance of ΔDOR is attributed to the number of velocity changes (due to attitude update maneuvers and propellant line flushings) that had to be estimated by the orbit determination filter, and the sparsity of the ΔDOR data set (19 ΔDOR points versus 2750 range points). Operational complexities associated with the scheduling of ΔDOR and the sequencing procedures used by Galileo made it difficult to acquire a large data set for the Earth-1 encounter. In addition, ΔDOR scheduling difficulties during the Earth-1 approach resulted in a somewhat irregular distribution of ΔDOR points over the data arc, which is also believed to have contributed to the relatively poor performance that was obtained. This aspect of Earth-1 navigation operations is described in greater detail by Gray [6]. As is evident in both Figs. 4 and 5, the ranging data, when utilized at a 1-km weight, have little effect on the Doppler-plus-range solutions versus the Doppler-only solutions, indicating that at 1 kilometer most of the information content of the ranging data is being effectively discarded, except for the direct measurement of the Earth–spacecraft distance, r.

In the solutions obtained with a 2-mm/sec Doppler weight (Fig. 5), the Doppler-only and Doppler/1-km range solutions improved noticeably in terms of the error relative to the post-flyby reconstruction. Additionally, the dispersion ellipses for these two cases were more commensurate with the actual orbit determination errors than in the 1-mm/sec Doppler cases. This indicates that with a weight of 1 mm/sec, the Doppler data were being affected by some modeling error that was not adequately accounted for by either the assumed level of random measurement noise or with the estimated and consider parameter set described in Table 1. It is believed that the principal error source causing this behavior was the solar plasma effect (larger than expected ionospheric calibration errors may have also been a contributing factor), which was not explicitly accounted for by the Doppler measurement error model used in the orbit determination filter, but was accounted for in the precision range error model by the stochastic bias parameters (hence, the good agreement between the aiming plane error for the 10-m range-only solution and the dispersion ellipse associated with this solution). As in the solution set with 1-mm/sec Doppler, the accuracy of the Doppler/1-km range/ΔDOR solution with 2-mm/sec Doppler was found to be poor (0.43 Δrad) relative to the theoretical angle-finding capability of the ΔDOR data (0.04–0.08 μrad). It should be noted here that theoretical studies have indicated that navigation accuracies of 0.08–0.10 μrad may be achieved with two-way X-band (8.4-GHz) ranging and Doppler data, provided that accurate (1 m or better) station delay and transmission media calibrations are available [1].

VI. Conclusions

The results of the analysis indicate that for Galileo Earth-1 approach navigation, precision ranging data yielded orbit solutions which, although not in theory as accurate as those obtainable with ΔDOR data, were in fact somewhat better in this particular case. The relatively poor navigation performance of ΔDOR is primarily attributed to the sparsity of the ΔDOR data set and the irregular distribution of these measurements within the data arc. In addition, it was found that the orbit determination errors obtained in the Doppler and precision ranging solutions were consistent with simple theoretical predictions of the angle-finding capability of S-band ranging and Doppler data. The relative ease of ranging data scheduling and processing procedures makes ranging an attractive alternative to ΔDOR, when the nominally higher performance of ΔDOR is not required. Further improvements (factors of 3 to 5) in the navigation accuracy obtainable with precision ranging may be achieved through the use of X-band (8.4-GHz) frequencies, as opposed to S-band (2.3-GHz) frequencies, and through improved station delay and transmission media calibration accuracies.

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Table 1. Galileo orbit determination model assumptions.

Model parameters	A priori uncertainty, 1σ	Remarks
Estimated		
Spacecraft state vector		
Epoch position	10^8 km	No information
Velocity	10^8 km/sec	
Solar radiation pressure		
Radial	5 percent of nominal	
Transverse	1 percent of nominal	
Attitude update maneuvers	0.5 mm/sec	About 1 every 2 weeks
Propellant line flushings		
Magnitude	0.5 mm/sec	About 1 every 3 weeks
Direction	15 mrad	
Quasar location, for ΔDOR	100 nrad	Conservative
Range bias parameters (1 per station-pass)		
DSN 70 m	2.0 m	
DSN 34 m STD	10.0 m	Conservative
Consider		
DSN station locations (correlated covariance), m		
Spin radius	0.24	Relative uncertainty between stations is approximately 5 cm
Longitude	0.24	
z-height	0.30	
Troposphere zenith delay calibration error, cm		
Wet	4.0	
Dry	1.0	
Ionosphere zenith delay calibration error, cm		S-band values (conservative)
Daytime	75.0	
Nighttime	15.0	
Acceleration biases, km/sec^2		
Radial (spacecraft spin axis)	3×10^{-12}	
Transverse	1×10^{-12}	
Earth ephemeris (heliocentric), km		
Radial	0.2	A priori covariance, JPL ephemeris DE 125
Along track	30.0	
Out-of-plane	15.0	
Earth mass, GM	0.15 km^3/sec^2	DE 125

Table 2. Comparison of orbit solutions and reconstructed trajectory.

Case	Aiming plane error, km	Equivalent angular error, μrad
1-mm/sec Doppler (no range) (no ΔDOR)	27.7	2.22
1-mm/sec Doppler, 1-km range (no ΔDOR)	27.8	2.22
1-mm/sec Doppler, 10-m range (no ΔDOR)	4.2[a]	0.34[a]
1-mm/sec Doppler, 1-km range, 50-cm ΔDOR	7.8	0.62
2-mm/sec Doppler (no range) (no ΔDOR)	15.1	1.21
2-mm/sec Doppler, 1-km range (no ΔDOR)	12.1	0.97
2-mm/sec Doppler, 10-m range (no ΔDOR)	6.5[a]	0.52[a]
2-mm/sec Doppler, 1-km range, 50-cm ΔDOR	5.4	0.43
10-m range (no Doppler) (no ΔDOR)	7.3[a]	0.58[a]

[a]Precision ranging solutions.

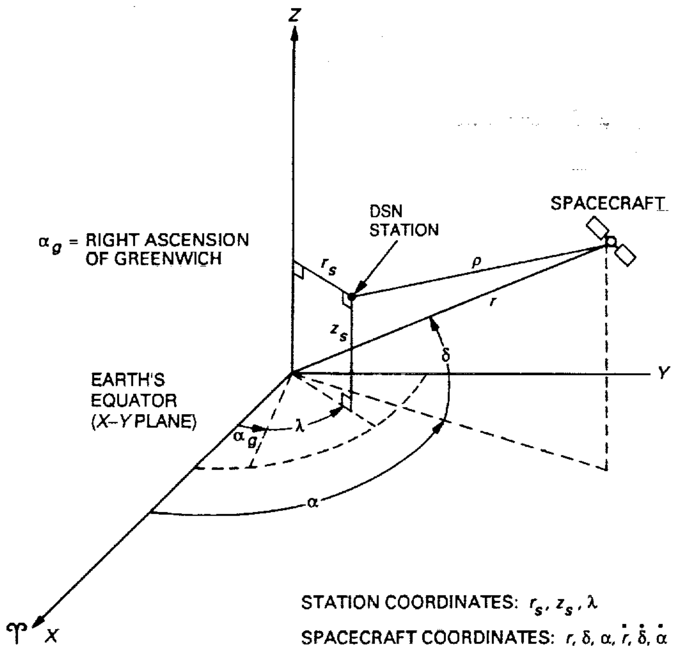

Fig. 1. Station–spacecraft tracking geometry.

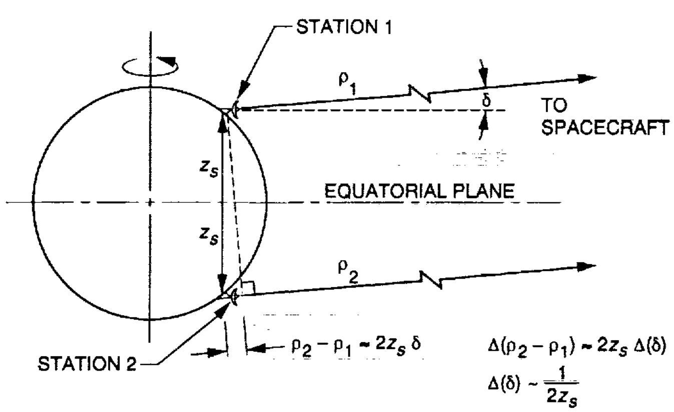

Fig. 2. S-band ranging and Doppler theoretical angular precision.

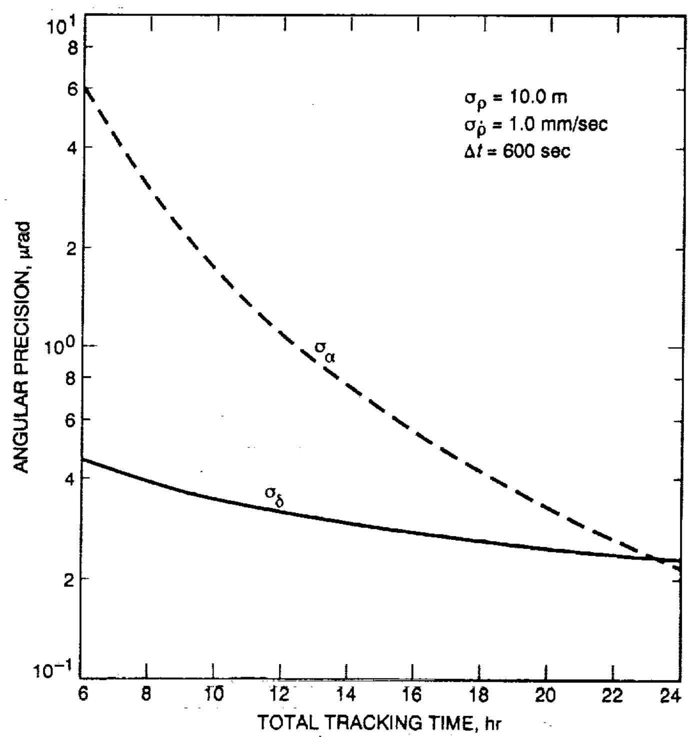

Fig. 3. Declination determination using range measurements from two widely separated stations.

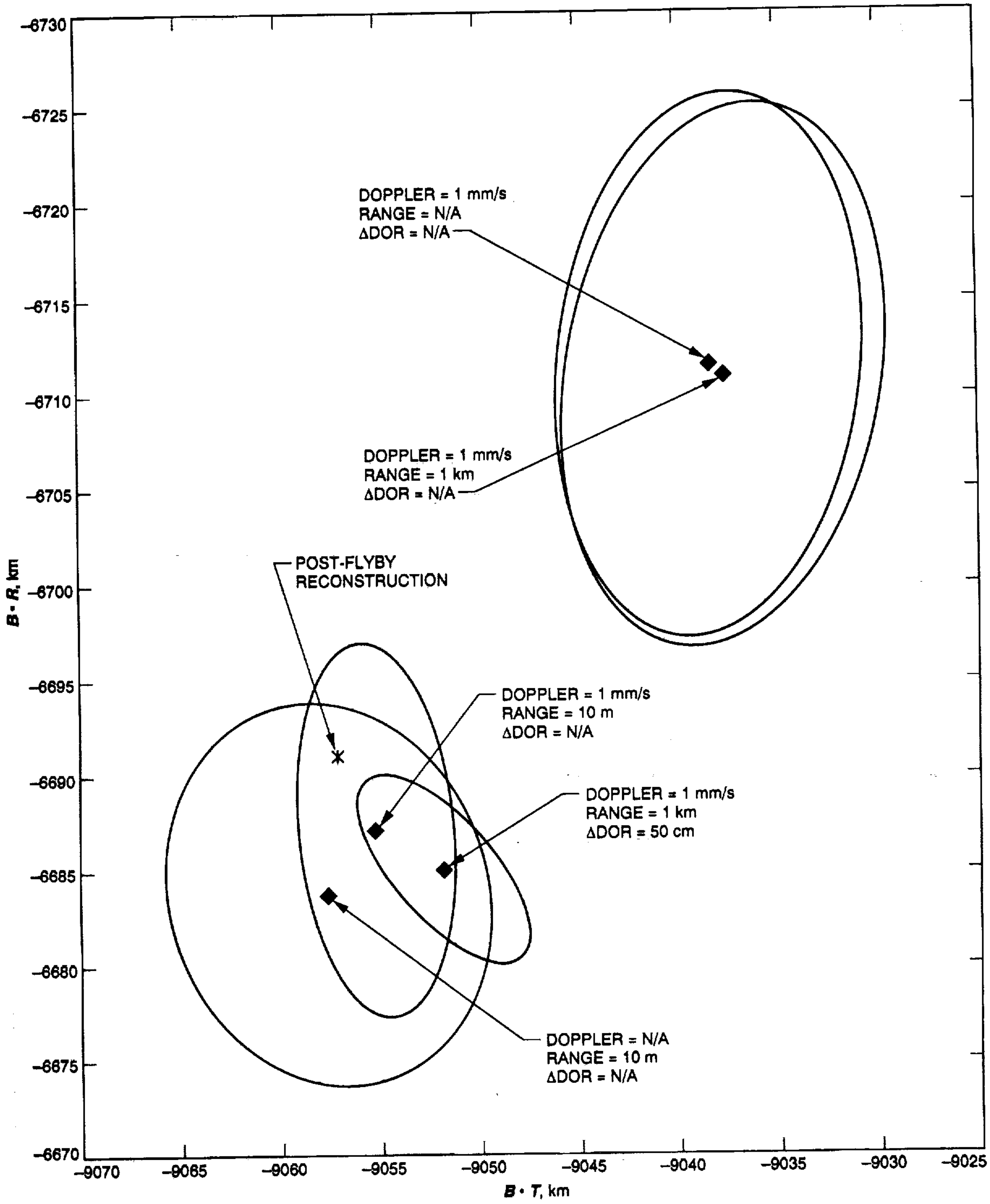

Fig. 4. Earth-1 aiming plane (solutions with 1-mm/sec Doppler weight).

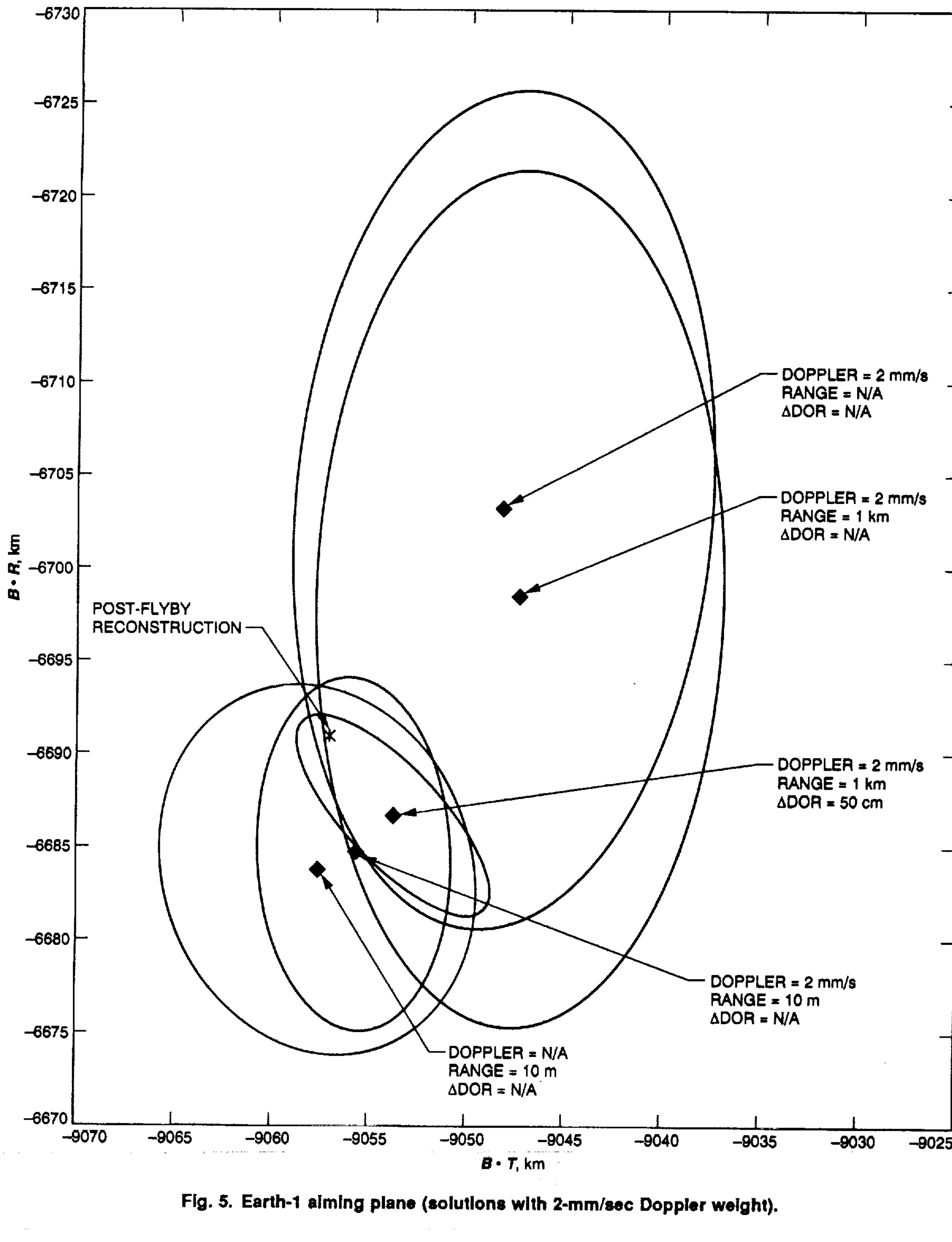

Fig. 5. Earth-1 aiming plane (solutions with 2-mm/sec Doppler weight).