ΔVLBI Data Performance in the Galileo Spacecraft Earth Flyby of December 1990

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The performance of the delta very long baseline interferometry (ΔVLBI) data type during the recent Earth flyby of the Galileo spacecraft is presented. First, the data are given significance by showing why the mission design requires an accurate flyby. Then, the data's performance is analyzed, including its operational features, as well as its accuracy. Finally, the effectiveness of these data in improving the accuracy of the flyby is shown. Comparisons are made between the expected and actual performances of the data. The processing time, reliability, and accuracy of these data were very good, and a solid gain was made in the encounter accuracy.

I. Introduction

Delta very long baseline interferometry (ΔVLBI) has been used as an operational data type on each of the recent deep space projects, e.g., Voyager, Magellan, Ulysses, and Galileo. (An alternative name that is often used is ΔDOR, which stands for delta differential one-way range.) Recently, a number of hardware and software improvements have been made to improve the reliability, accuracy, and turnaround processing time required for this data type. A short history of the VLBI system and its improvements is given in Appendix A. A diagram of the data flow is shown in Fig. 1. It would be useful to have a report on the operational performance of the ΔVLBI data since these improvements have been made available.

The various deep space projects differ widely in their need for the ΔVLBI data type. Fortunately, the December 1990 Galileo flyby of the Earth provides an example where the recent improvements were used and the ΔVLBI data promised to be extremely useful for the Earth flyby. A study of the expected benefit of including ΔVLBI data during this encounter was performed earlier,[1] and a study of the effect of using connected-element interferometry data was reported in this publication [1]. This was the first of two Galileo flybys of the Earth, labelled Earth gravity assist 1 (EGA 1), which occurred on December 8, 1990, at a 960-km altitude. It yielded an unusual opportunity to assess the value of Earth-based radio data on the approach to Earth (i.e., the radio data became an encounter-relative data type). A series of ΔVLBI's was performed on the approach, and the purpose of this article is to assess the performance and usefulness of those ΔVLBI's in supporting the encounter. Where appropriate, the figures reproduce the original Galileo Navigation Team presentation material.

ΔVLBI data complement the basic radio Doppler data nicely because they are purely angular measurements (as seen from the Earth), while the Doppler data are most

[1] D. W. Murrow, "S-Band ΔDOR Data for Earth One Flyby," JPL Interoffice Memorandum GLL-NAV-89-60 (internal document), Jet Propulsion Laboratory, Pasadena, California, June 8, 1989.

accurate in the radial direction. Since this article concerns ΔVLBI performance, only the two angular dimensions will be reported. For large distances out on an Earth encounter trajectory, these angular dimensions correspond to the classical B-plane[2] coordinates. Keep in mind that the high-gain antenna was not opened, and that the ΔVLBI's were of the single-frequency-band type at 2.3-GHz (S-band) frequency, rather than the dual-frequency-band type at 8.4 GHz/2.3 GHz (X-band/S-band), for which the spacecraft was designed. The 2.3-GHz data type is of additional interest given the recent problem in unfurling Galileo's high-gain antenna, since the same type of ΔVLBI data may be needed for later portions of the mission (especially given the likelihood that there would be little or no optical navigation data).

II. Mission Design

Because of the radioisotope thermoelectric generator (plutonium loaded) used to generate power for the spacecraft, an extra margin of safety was required against any chance of impinging on the Earth's substantial atmosphere. A typical mission requirement at each event on the encounter trajectory would be to keep the probability of impacting the encounter body to ≤ 0.01 (or equivalently ≤ 1.0 percent). Even this number is often relaxed somewhat if there would still be time (if necessary) to design and perform an emergency corrective maneuver before the encounter. However, for the two Galileo–Earth encounters, a requirement that the probability of impact always be $\leq 10^{-6}$ was levied, and the consequences were analyzed in the *Galileo Navigation Plan*[3]. This very conservative requirement led to a sequence of three intermediate-biased aimpoints and six trajectory correction maneuvers (TCM's) on the approach trajectory. The resulting maneuver spacings and altitudes are shown in Fig. 2, and the sequence of B-plane aimpoints is shown in Fig. 3.

Since the Earth flyby was used to shape the spacecraft's trajectory, any spatial miss in the encounter would require a significant propellant penalty to correct later. Propellant penalty has been defined for Galileo as the increase in propellant required to complete the mission with 90-percent confidence. The propellant penalty for any miss was calculated, given the maneuvers planned after the Earth flyby, to produce contours of constant propellant penalty in the Earth B-plane. The constant propellant penalty contours are very flattened in the radial direction, due primarily to the high cost of correcting the resulting timing errors. As a rough estimate of the cost, in the radial direction a 10-km miss in the B-plane requires a 10 m/sec penalty in propellant to correct after the flyby, while in the tangential direction a 10-km miss only requires a 2 m/sec penalty to correct. Since the Galileo propellant budget is very tight, even a 10 m/sec fuel savings will increase the confidence level of completion of the nominal Jupiter tour or, alternately, increase the length of a possible extended mission.

A timeline of the ΔVLBI's scheduled and performed is given in Fig. 4. Note that the ΔVLBI data in support of a given maneuver stop well before the date of the maneuver, to allow time for design and implementation.

III. ΔVLBI Performance

A. Processing Time

There are several measures to be used in assessing ΔVLBI performance as an operational data type. The simplest of these is the processing delay time. Twelve hours were allocated, following the completion of acquisition, for delivery of processed data to the Project navigation computer. This total allocation was broken down as follows: 2.5 hr for playback, 5 hr for correlation, 1 hr for conditioning and delivery to the Navigation Team, and 3.5 hr for internal margin. Actual delay times were about 2 hr for the playback, 4 hr for the correlation, and 10 min for the conditioning and delivery—well within the requirement. Actually, processing time of about this length was demonstrated in 1982, but was not a requirement until the Magellan Project. The Voyager Project ΔVLBI data-processing time was typically several days, in order to save money.

B. Scheduling Requirements

A second measure of performance is the difficulty of scheduling a ΔVLBI observation, as judged by the requirements the scheduling places on the Deep Space Network. One factor is the amount of Deep Space Station time required. Table 1 shows the steps and time intervals required to perform a single ΔVLBI observation, which, even if no other data are to be taken, adds up to nearly two hours of dedicated time for each of two antennas. Note that, for most of this time, it is either impossible or impractical to be receiving data from the spacecraft. (By comparison, when Doppler and ranging data are taken, similar pre- and post-calibration times are required, but other

[2] The B-plane is perpendicular to the direction of the incoming spacecraft trajectory asymptote. Its origin is at the center of the encounter body, and the B-plane coordinates of the spacecraft encounter are computed on the trajectory asymptote (as though the encounter body did not cause any bending).

[3] *Galileo Navigation Plan*, Project Document 625-566, Revision A (internal document), Jet Propulsion Laboratory, Pasadena, California, October 1989.

downlink data are normally received while the navigation data are obtained.) Another requirement is to perform the observation during the relatively short period of station overlap, which makes it impossible to adjust the start time by any large amount when scheduling conflicts occur. To make matters worse, with the Galileo high-gain antenna unavailable, it has been necessary to use the large antennas of the 70-m subnet for these observations. Finally, the Galileo sequence command charging algorithm is such that nine commands are charged to the navigation total for each ΔVLBI carried out (or five commands for the later observations, which were performed without turning off the telemetry).

Since DSN antenna time is severely oversubscribed, it is necessary to justify that these data are needed in spite of the relatively difficult requirements for scheduling the time. Often the basis for the need is not readily apparent and must be defended in detail. An example of this is a request for a specific pair of observations by P. Kallemeyn and V. Pollmeier,[4] the text of which is included as Appendix B. Even after the schedule has been agreed to, there are likely to be unexpected cancellations. On the timeline of Fig. 4, each cancelled ΔVLBI observation is indicated. The six cancelled observations were lost to the high-priority needs of other projects, which means these observations did not have a high enough priority to survive, given the competition for deep-space antenna time. The scheduling is done in an interactive, iterative fashion, so to some extent early cancellations were replaced by using requests for later data. However, as discussed later, an important result of using ΔVLBI data may have been weakened by these cancellations. Fortunately, the desirability of some ΔVLBI observations was clear in this case, otherwise even more might have been cancelled.

C. Reliability

The reliability of the ΔVLBI data has an indirect effect on the ease of scheduling, since extra observations have to be scheduled to make up for any expected loss rate. Figure 4 also indicates the four or five[5] ΔVLBI observations that failed, out of 27 attempts. Probably the fairest assessment of reliability would be to assume four failures out of the 27 attempts, or 85-percent reliability. This 85-percent reliability is quite good, and it will be interesting to see whether future ΔVLBI's will maintain such a rate.

D. Accuracy

Achieved accuracy of the data is the best known measurement of performance. First, a detailed orbit estimate is made, estimating the spacecraft's initial state, its accelerations, and any other parameters that may affect the values of the observables (which are Doppler, range, and ΔVLBI measurements). When this is done, a test of the quality of the result is obtained by comparing the actual measurements taken with those measurements that would be predicted by using the fitted parameter values. The differences among these predicted and actual measurements are called residuals. These are plotted for the earlier ΔVLBI observations in Fig. 5, resulting in a standard deviation of 0.20 m.[6] Since Doppler data were also fitted in the computer run used to obtain Fig. 4, the ΔVLBI scatter is somewhat conservative as a measure of its precision, but does not include any bias error. In order to discuss the performance of these ΔVLBI observations, it would be useful at this point to have an analytic estimate of the expected accuracy.

Three analytic estimates of the expected ΔVLBI accuracy for Galileo have been made. The first is from the *Galileo Navigation Plan*, assuming the system as designed (with a high-gain antenna and dual frequency with 8.4 GHz), and it results in an expected scatter of 0.14 m with a total accuracy of 0.30 m. After it was realized that some observations would be made with the present spacecraft configuration, a second estimate was made in May 1990[7] for this EGA 1 approach under a variety of possible conditions. For the most likely conditions, with a conservative assumption of 0.60 m on the expected ionospheric error, the component uncertainties are shown in Table 2, and the result was an expected total error of 0.74 m. An ongoing general effort is made to improve the ΔVLBI data type (see e.g., [2]), and after this accuracy estimate was published, a specific effort was made to refine and im-

[4] P. Kallemeyn and V. Pollmeier, "Rationale for a ΔDOR Pair Two Days After TCM7," JPL Interoffice Memorandum GLL-NAV-90-051 (internal document), Jet Propulsion Laboratory, Pasadena, California, June 7, 1990.

[5] The last east–west baseline observation was delayed and about to fail when J. Border supplied, in real time, an alternate quasar with later viewing available. This observation was not used in the time-pressured orbit estimate that immediately followed (due to setup time and additional analysis needed to verify use of the new quasar), but was used in later reconstruction operations.

[6] A short explanation is needed here since ΔVLBI errors may be expressed in any of three related dimensions: nanoseconds, meters, or nanoradians, as diagrammed in Fig. 6. The measurement is the spacecraft delay (difference in signal arrival time between the two antennas) minus the quasar delay, so the most direct units are nsec. However, using an approximate conversion of 6×10^6 m for the projected length of the baseline and 0.3 m/nsec for the speed of light makes a typical accuracy of 1.0 nsec equivalent to 0.3 m or 50 nrad.

[7] J. S. Border, "ΔDOR Observation Parameters for 1990 Galileo Earth Approach," JPL Interoffice Memorandum 335.1-90-025 (internal document), Jet Propulsion Laboratory, Pasadena, California, May 10, 1990.

prove the calculation of the dominant ionospheric delay effects [3].[8,9] The new analysis predicted an ionospheric error of only 0.09 m. This change alone would reduce the expected total error to 0.45 m, but a better understanding of instrumental effects, plus the use of 70-m (rather than 34-m) antennas further reduced the expected error. After the encounter, a third analytic estimate of the expected errors was made,[10] with the component uncertainties also included in Table 2, for a total expected error of 0.21 m.

The third analytic estimate (of 0.21-m uncertainty) is very close to the observed scatter (of a 0.20-m standard deviation). Note that these both omit the bias uncertainty due to the quasar position error. Taking these factors into account, the observed scatter of 0.20 m and the *Galileo Navigation Plan* estimate of a 0.30-m total uncertainty will be used as best estimates of the achieved single-observation uncertainty. The resulting single-observation uncertainties (along the baseline) of the ΔVLBI data arc are shown in Table 3.

With a pair of observations (one N–S plus one E–W observation), one can estimate the spacecraft position in two dimensions. Since the two baselines are not orthogonal, the resulting two-dimensional accuracy is a function of the direction in the B-plane, as shown in Fig. 7.[11] The intent of Fig. 7 is to supply multipliers for use in extending the single-dimension scatter and uncertainty accuracies given above (or the corresponding encounter accuracies from Table 3) to two dimensions. A pair of observations will have an uncertainty ranging from 0.77 times the single-observation uncertainty (in the most favorable direction) to 1.85 times the single-observation uncertainty (in the direction of maximum uncertainty). For example, at the end of the usable data arc, Table 3 gives the accuracy of an observation as equivalent to 0.85 km mapped to encounter. A pair of these observations has a maximum uncertainty of 1.85×0.85 km, or 1.6 km. Unfortunately, the direction of maximum uncertainty corresponds approximately to the radial direction for the EGA 1 flyby aimpoint, which is bad for both propellant cost and safety. However, a radial spacecraft delivery error of 1.6 km would result in no noticeable increase in impact danger and a 1.0-m/sec propellant penalty. For comparison, a study from the *Galileo Navigation Plan* of the effectiveness of the Doppler data is shown in Fig. 8. For the same data cutoff time, the worst direction ($B \cdot R$) Doppler uncertainty is 12.9 km, more than eight times that of a ΔVLBI pair. Next, the effect on encounter accuracy must be discussed.

IV. Effect on Encounter

The a posteriori reconstructed delivery error of 8.4 km is plotted in Fig. 9, together with the computed (solid line) and adjusted (dashed line) delivery uncertainty ellipses. (Due to known difficulties in fitting the orbit data, an adjustment factor of 1.5 was used to enlarge the computed uncertainty ellipse.) An attempt was also made to construct what would have happened if no ΔVLBI data had been available, and the resulting Doppler-only error and uncertainty ellipses have also been plotted in Fig. 9. First, note that the size of the reconstructed delivery error is much larger than the ΔVLBI maximum final position uncertainty of 1.6 km, although its direction is near to the maximum ΔVLBI uncertainty direction shown in Fig. 7. Thus, there would appear to be a significant growth in error due to propagating the trajectory from the last ΔVLBI observations to the encounter. The size of the delivery error was also larger than the computed encounter uncertainty ellipse. This behavior suggests the possibility of an inadequately modelled error source, which is thought to be primarily the sum of small errors in modelling solar pressure effects plus Trajectory Correction Maneuver 7 (TCM7) modelling errors. A discussion of this topic is given below.

A. Estimating Acceleration and Velocity Changes

Both Doppler and ΔVLBI data can be affected by many possible error sources, but there is an important difference between the two. While ΔVLBI is a direct measure of angle, Doppler depends on its time history to infer position in the B-plane. Since a time history is also needed to estimate any accelerations or velocity changes acting on the spacecraft, it is difficult to estimate any velocity changes or accelerations in the B-plane by using Doppler data alone. In fact, an inadequate modelling of the solar pressure and other nongravitational accelerations led to a similar problem with the orbit determination delivery 27 (OD 27) estimate, just before the Earth encounter ΔVLBI data were initiated, as shown in Fig. 10.

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[8] A. J. Mannucci, "Checking Faraday Ionosphere Calibration Using TEMPO Passes," JPL Interoffice Memorandum 335.1-90-025 (internal document), Jet Propulsion Laboratory, Pasadena, California, October 16, 1990.

[9] A. J. Mannucci, "Temporal Statistics of the Ionosphere," JPL Interoffice Memorandum 335.1-90-056 (internal document), Jet Propulsion Laboratory, Pasadena, California, October 25, 1990.

[10] J. S. Border, "Galileo S-Band ΔDOR Measurement Accuracy for First Earth Approach, October–November 1990," JPL Interoffice Memorandum 335.1-91-012 (internal document), Jet Propulsion Laboratory, Pasadena, California, April 23, 1991.

[11] For an Earth encounter asymptote, the angles made by the baselines (as seen from the spacecraft) correspond to B-plane angles. These baseline angles are not constant, but only vary by a few degrees over the course of any observation and also over the period of the ΔVLBI data arc.

One of the things it was hoped the ΔVLBI data would do was to better estimate these accelerations, so it is fair to ask why a better job was not done. An answer can be seen from an analysis of Fig. 4. The original planning for ΔVLBI scheduling provided a time interval of 70 days before the orbit data cutoff for TCM7 (with an increased amount of data in the last 23 days). This was the only opportunity to use ΔVLBI data to estimate the nongravitational accelerations with a minimum of other perturbations (such as TCM's, science turns, and momentum corrections) in the data arc. Failure of the first two observations reduced the available time interval to 55 days, which is only a small loss. However, the cancellation of six sequential E–W baseline observations reduced the available time interval with pairs of observations to just 11 days. When the last N–S observation in this group failed, the effective time interval was reduced to just 8 days.

A sample calculation is shown in Appendix C to illustrate how drastically the short effective time interval reduces accuracy when estimating an acceleration. Using realistic times and ΔVLBI measurement accuracies leads to a resulting encounter uncertainty of 13.7 km due to the poorly estimated uncertainty—similar to the size of the actual encounter error. This is a rather simplistic example. In reality, the encounter error is thought to be a combination of several velocity and acceleration estimate errors. However the example does show how drastically the ability to estimate the solar pressure effect can be reduced by shortening the measurement arc.

The importance of the cancelled E–W ΔVLBI observations can also be seen by comparing the encounter error and covariance ellipse in Fig. 9 with the ΔVLBI uncertainty plot in Fig. 7. The encounter covariance ellipse is narrower than the ΔVLBI uncertainty plot, due to the shortage of E–W observations relative to N–S observations. Furthermore, the ellipse's semimajor axis (and also the encounter error itself) points much closer to the anti-N–S baseline direction than to the maximum ΔVLBI uncertainty direction. Thus, the trajectory was well resolved along the N–S baseline, but much less well resolved in the direction perpendicular to it. That this should be true in spite of an even distribution of N–S and E–W observations in the latter portion (where the observations are most accurate) attests to the predominance of velocity and acceleration estimation errors in this encounter.

B. Comparison With Doppler Solution

In June 1990, when this campaign of ΔVLBI data was recommended, it was calculated that the expected increase in propellant margin would be 10 m/sec (10 m/sec is equal to 9.4 kg of propellant). By comparison, based on the actual delivery, the increase in propellant margin reported by the Navigation Team was 5 m/sec. While smaller than the expected value, this increase is within the range of results that would be expected in drawing one sample from the distribution of likely encounter deliveries. To show how this encounter might have fared without the ΔVLBI data, the effect of using the best Doppler-only orbit solution was plotted in Fig. 9. Even though the Doppler-only delivery error was almost three times as large (at 22 km), it was in a direction where corrections would have a low propellant cost. Thus, the savings would have been only about 5 m/sec. However, if the ΔVLBI data had been about three times as effective in estimating the spacecraft orbit in a direction perpendicular to the N–S baseline, then a 10-m/sec propellant savings would have been realized.

A final insight into the orbit estimation process can be gained by analyzing the ΔVLBI residuals at the second (TCM8) orbit cutoff, as shown in Figs. 11 and 12. Figure 11 shows the result when only the Doppler data are used to estimate the orbit. In this case, the ΔVLBI residuals drift off rather badly, reaching values of about 15 m by the end of the data arc. This shows that the Doppler data are not very good for estimating the changes in velocity in the B-plane. Notice that the drifting becomes especially bad after TCM7. By contrast, after adding in the ΔVLBI observations to the fitting process, the residuals are much smaller, as shown in Fig. 12. However, these residuals are still noticeably larger than the set obtained for the earlier cutoff, as shown in Fig. 5, indicating some difficulty in fitting the additional changes in velocity now included in the data arc. It is apparent that the E–W baseline residuals show some remaining trend after the fitting process, but it was not obvious at the time how to eliminate this trend. Keep in mind that a very limited time period was available for the orbit determination processing so that the design of TCM8 could proceed on time. After the fact, it soon began to appear that a better solution could have been made by restricting any variation in the reconstruction of the TCM7 ΔV, and forcing an additional adjustment to be made in either the solar pressure terms or some other nongravitational acceleration term.

V. Conclusions

A mostly successful ΔVLBI campaign was carried out in support of the Galileo EGA 1 encounter. The processing time, reliability, and accuracy of these data were very good, and a solid gain was made in the encounter accuracy. The final result would probably have been even better if it were not for the cancellation of all the early observations on the E–W baseline.

Acknowledgments

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References

[1] S. W. Thurman, "Galileo Earth Approach Navigation Using Connected Element Interferometer Phase-Delay Tracking," *TDA Progress Report 42-100*, vol. October–December 1989, Jet Propulsion Laboratory, Pasadena, California, pp. 34–47, February 15, 1990.

[2] J. S. Ulvestad, O. J. Sovers, and C. S. Jacobs, "A Higher Density VLBI Catalog for Navigating Magellan and Galileo," *TDA Progress Report 42-100*, vol. October–December 1989, Jet Propulsion Laboratory, Pasadena, California, pp. 274–300, February 15, 1990.

[3] J. S. Border, W. M. Folkner, R. D. Kahn, and K. S. Zukor, *Precise Tracking of the Magellan and Pioneer Venus Orbiters by Same-Beam Interferometry*, paper AAS 91-191, AAS/AIAA Spaceflight Mechanics Meeting, Houston, Texas, February 11, 1991.

Table 1. DSS time requirement for ΔVLBI support

1. Load MDA and station-pointing predictions	45 min
2. DSP pre-calibration	30 min
3. Ranging pre-calibration	30 min[a]
4. ΔVLBI collection	
Spacecraft observation	5 min[b]
Slew	3 min[c]
Quasar observation	10 min[b]
Slew	3 min[c]
Spacecraft observation	5 min[b]
5. Post-calibration	15 min
Total	~2 hr (2.5 hr if with ranging)

[a] Only if Doppler and ranging data are to be taken. Not needed if this is a stand-alone pass.

[b] Minimum observation time is determined by accuracy requirement and signal power level.

[c] Required slew time depends on the separation between the spacecraft and quasar.

Table 2. Galileo S-band ΔDOR error budget for first Earth approach: original and revised (1σ)

Error Source	May 1990 Prediction, cm	Revised, cm
Spacecraft signal-to-noise ratio (SNR)	14	6
Quasar SNR	26	9
Phase ripple	31	15
Baseline	2	2
Troposphere[a]	9	4
Ionosphere[a]	60	9
Solar plasma[a]	1	1
Root sum square	74	21

[a] Sometimes combined and called media.

Table 3. ΔVLBI data characteristics

	Days to Encounter	Range to Earth, 10^6 km	Scatter,[a] km	Accuracy,[b] km
Data Start	90	87	2.90	4.35
	48	43	1.43	2.14
	40	35	1.17	1.76
Data End	20	17	0.57	0.85

[a] Scatter = 0.20 m × range/baseline, where baseline = 6×10^6 m.

[b] Accuracy = 0.30 m × range/baseline.

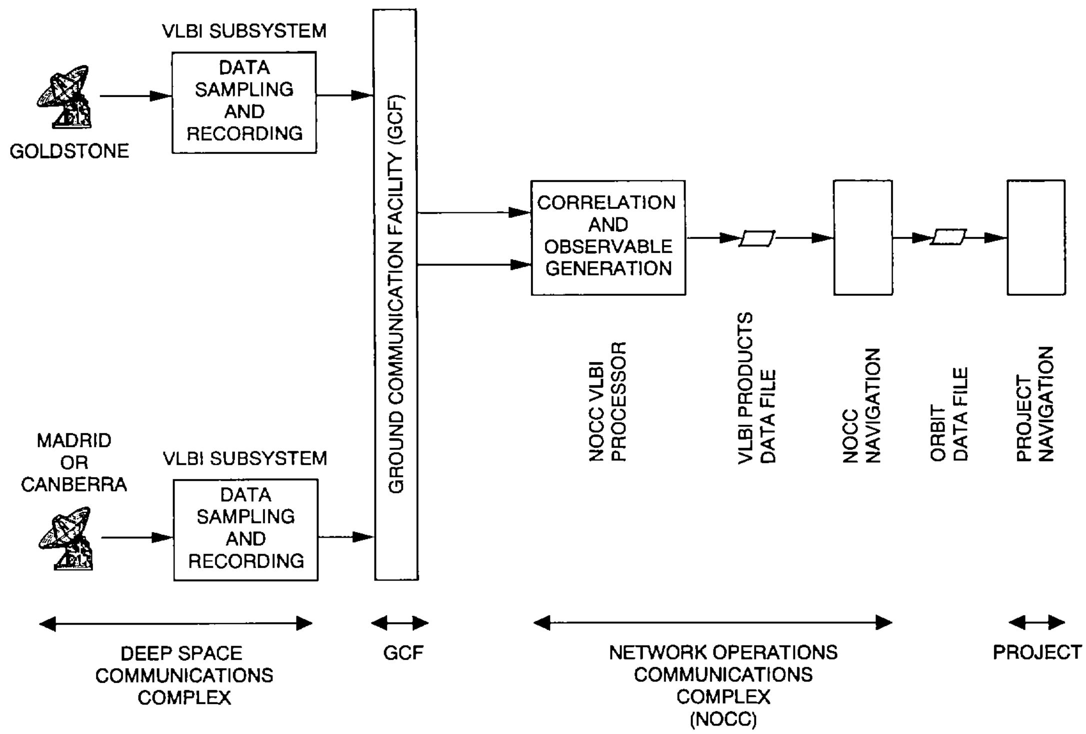


Fig. 1. ΔVLBI data flow.

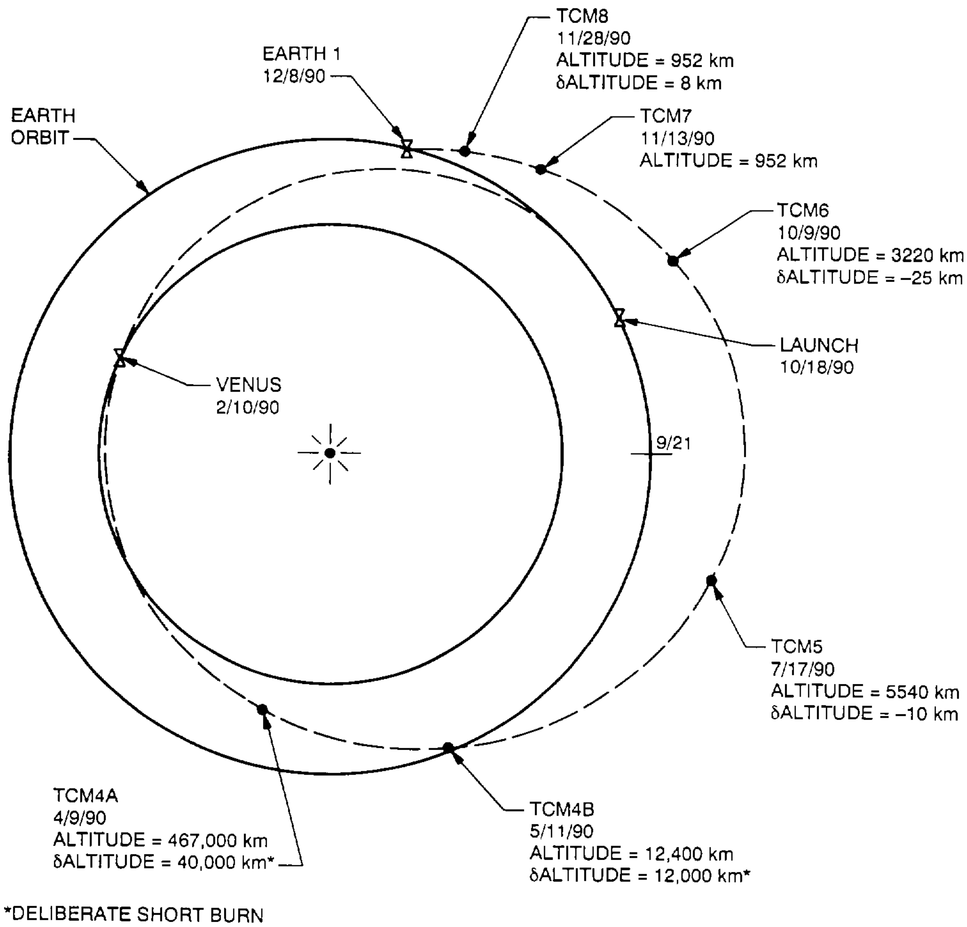


Fig. 2. Galileo EGA 1 approach trajectory.

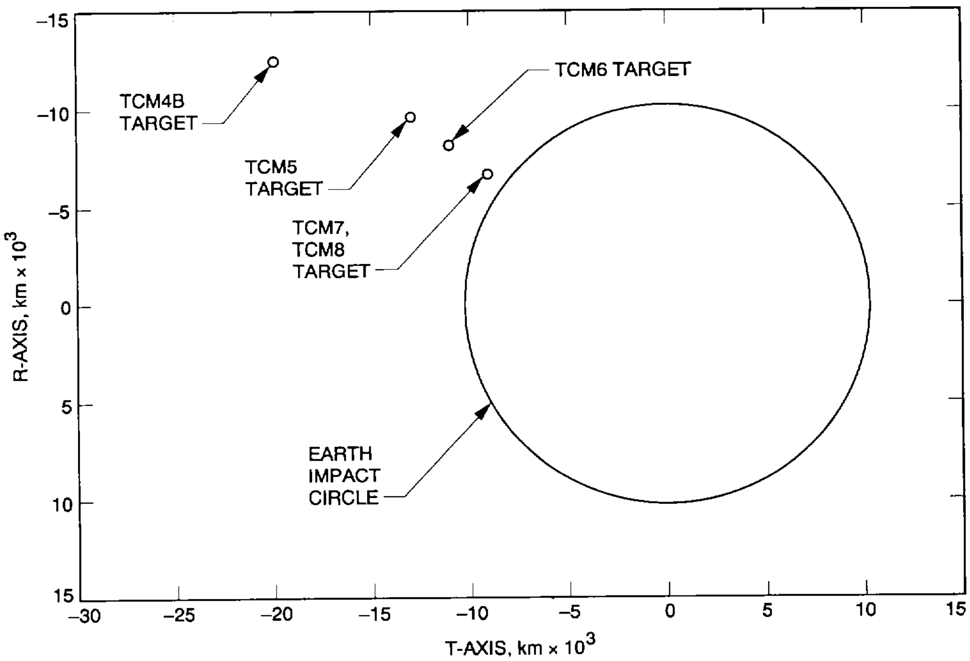


Fig. 3. B-plane aimpoints.

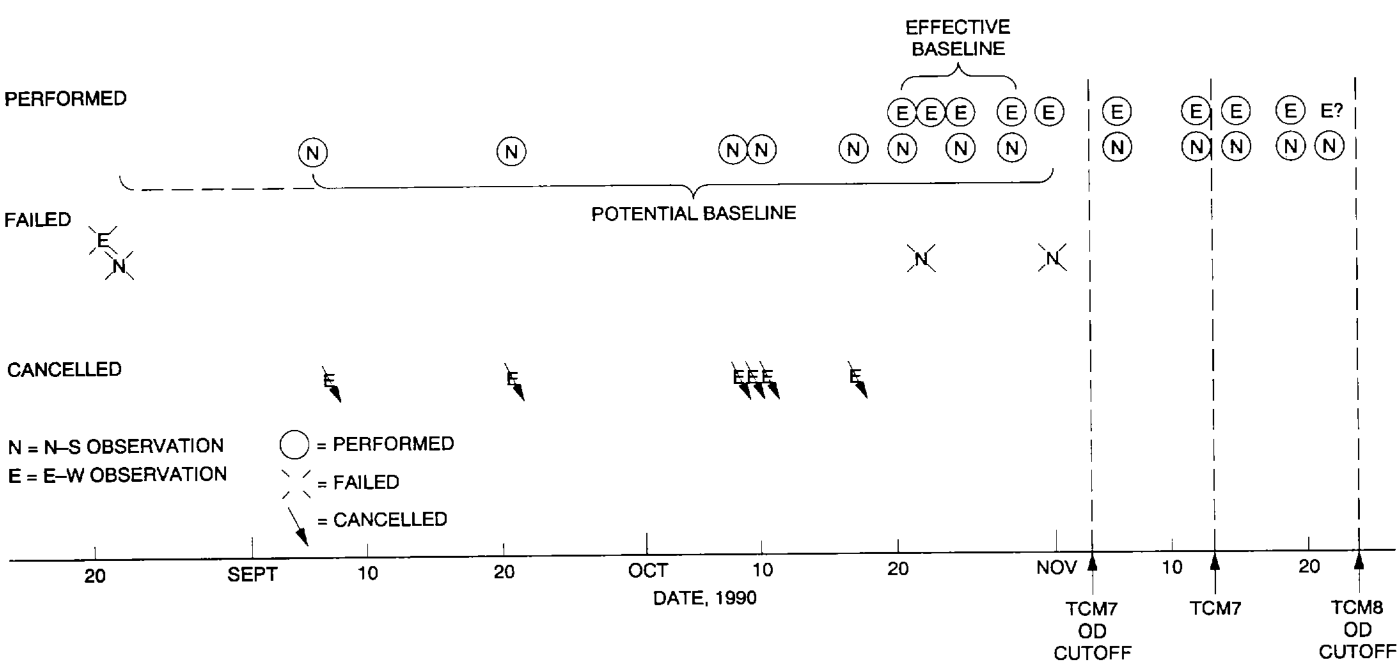


Fig. 4. ΔVLBI schedule.

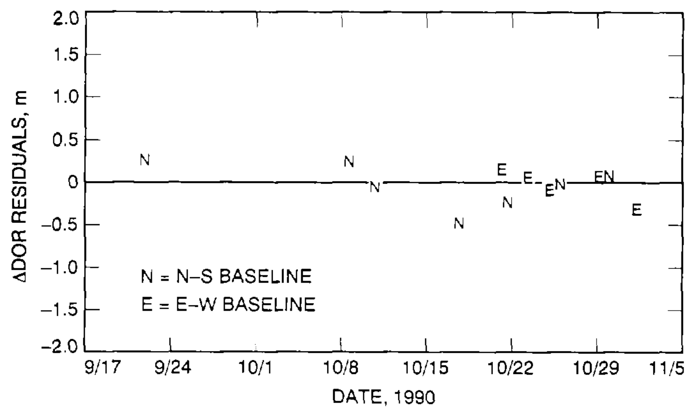


Fig. 5. ΔVLBI residuals for first cutoff.

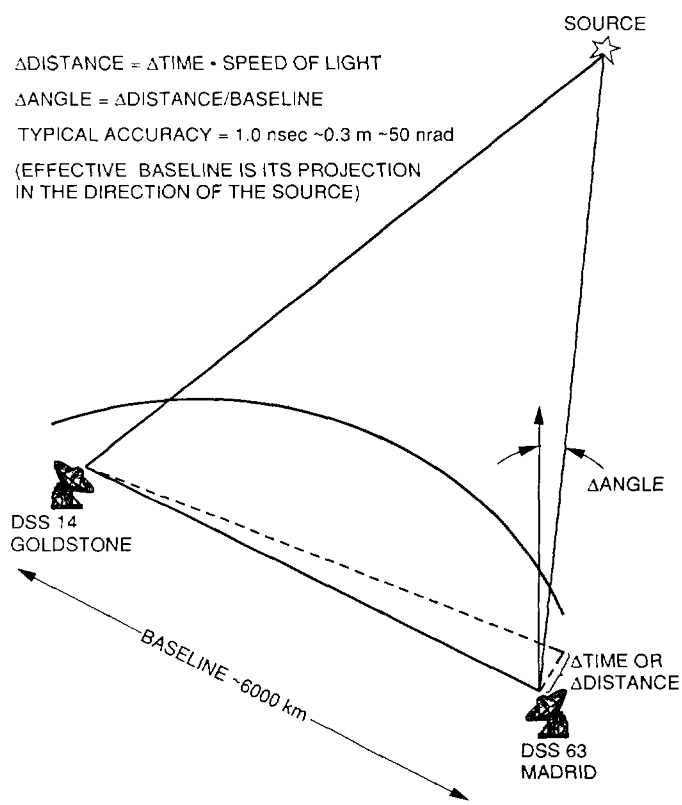


Fig. 6. Equivalent measures of ΔVLBI error.

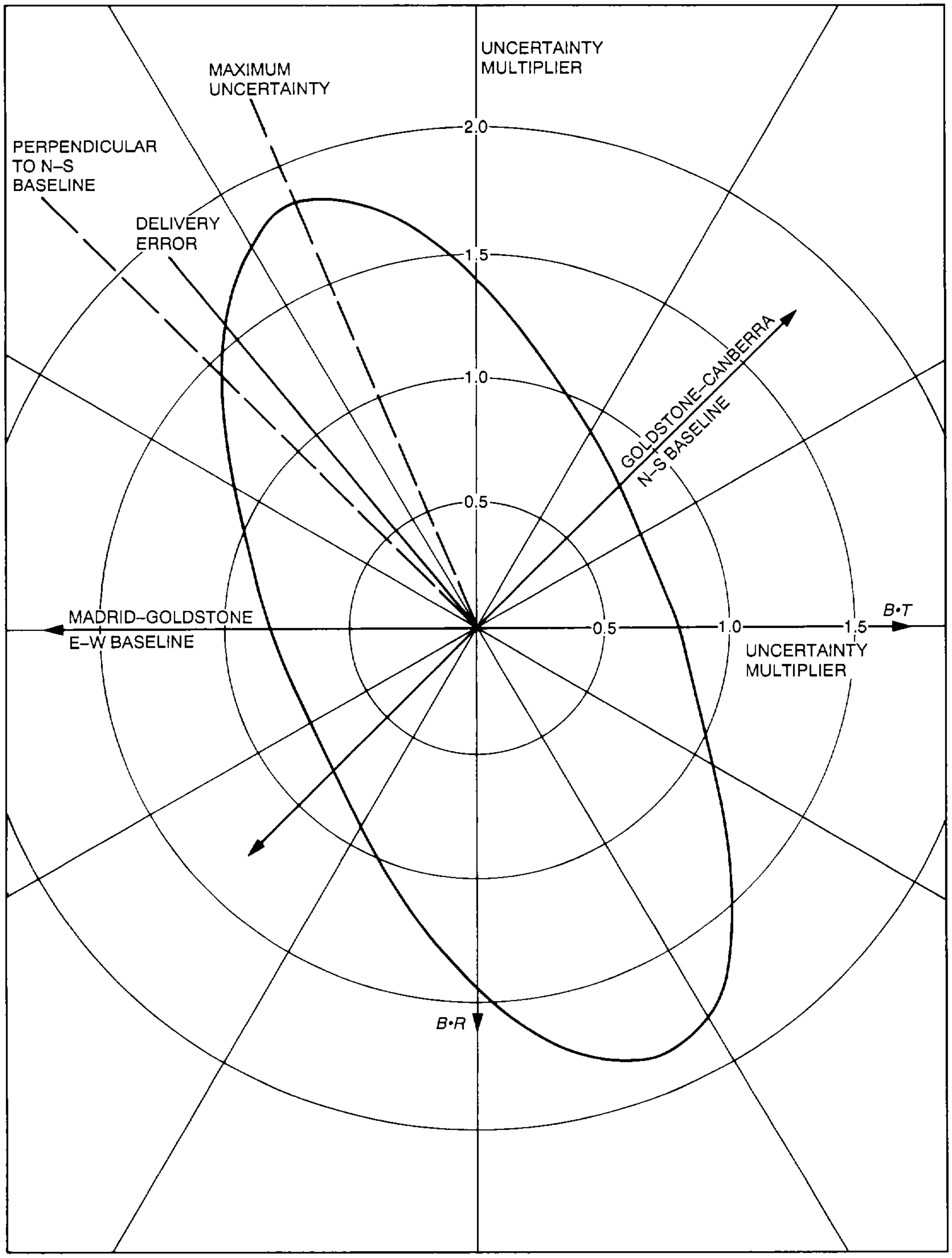


Fig. 7. Uncertainty multiplier for a ΔVLBI pair.

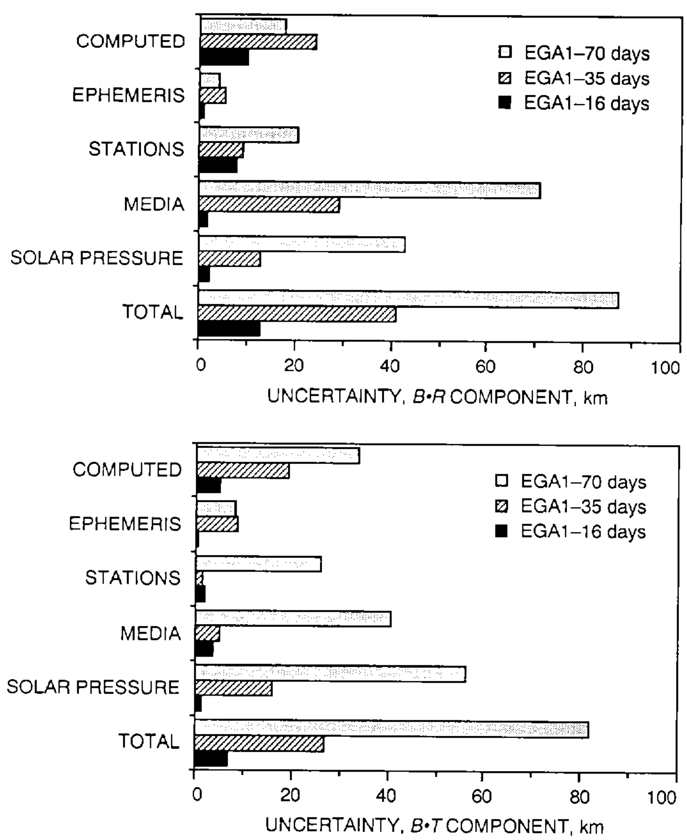


Fig. 8. Doppler data uncertainty (in the B-plane).

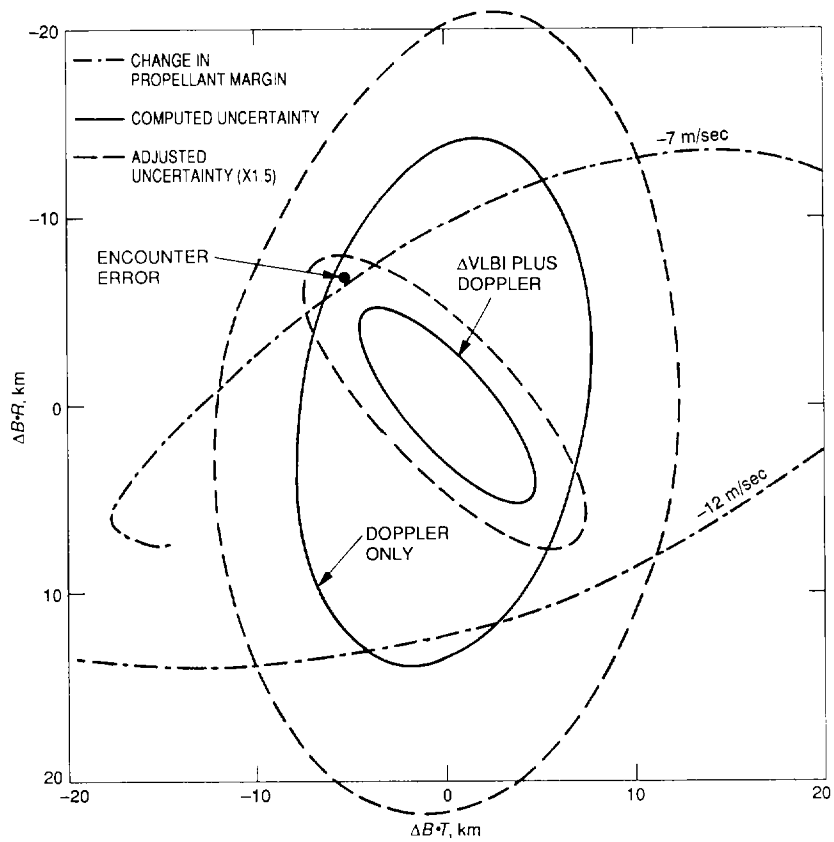
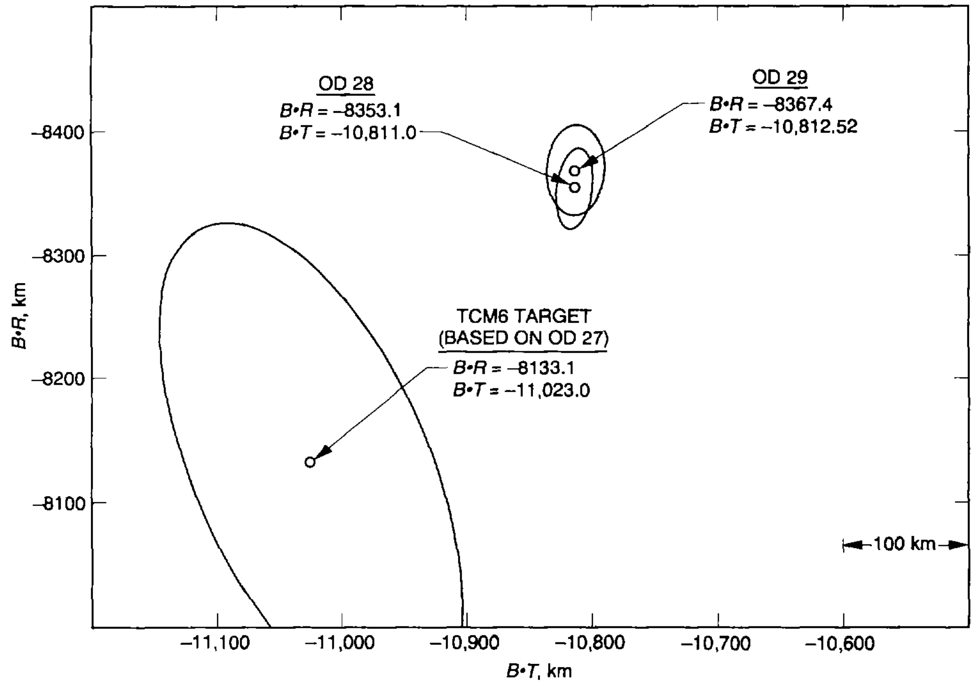


Fig. 9. B-plane delivery uncertainty and error.



DISCUSSION

- THE CURRENT B-PLANE SOLUTION IS ABOUT 300 km FROM OD 27 MAPPED USING THE BEST TCM6 ESTIMATE. WITH RESPECT TO STATISTICS DELIVERED WITH OD 27, THIS REPRESENTS A 3σ ERROR.
- SOLUTIONS BASED ON DOPPLER AND RANGE DATA ARE VERY SENSITIVE TO ERRORS IN NONGRAVITATIONAL FORCE MODELLING, ESPECIALLY SOLAR PRESSURE.
- REVISING THE EFFECTIVE SPACECRAFT AREA DOWNWARD, AND SOLVING FOR AN AXIAL ACCELERATION, REDUCES THE ERROR IN THE OD 27 SOLUTION.
- INCLUSION OF ΔDOR DATA IN THE OD SOLUTIONS REDUCES SENSITIVITY OF ESTIMATES TO NONGRAVITATIONAL MISMODELLING.

Fig. 10. Example and discussion of the Earth B-plane drift.

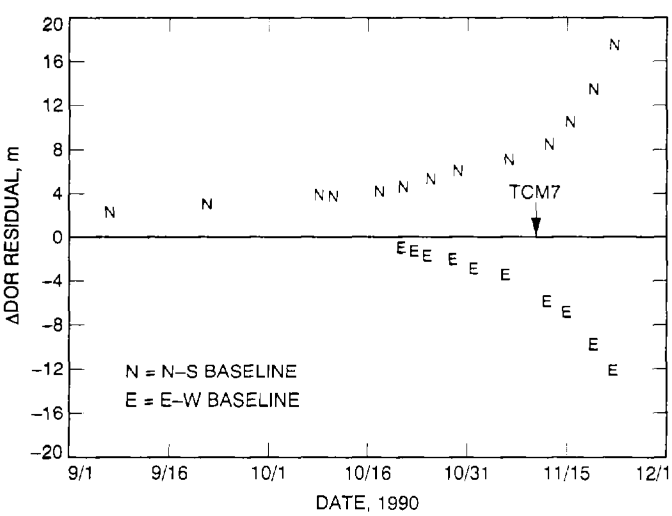


Fig. 11. ΔVLBI residuals for second cutoff of the Doppler-only solution.

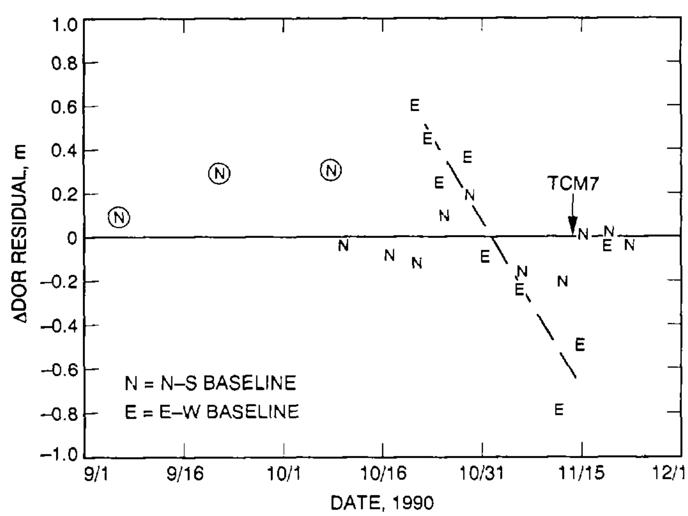


Fig. 12. ΔVLBI residuals for second cutoff of the Doppler-plus-ΔVLBI solution.

Appendix A

A Short History of the VLBI System and Its Improvements

The first ΔVLBI measurements of interplanetary spacecraft were made in the late 1970's by using radio astronomy equipment referred to as the Block 0 VLBI System. Data were recorded on videotape and shipped to a correlator facility for processing. The facility was located on the campus of the California Institute of Technology. Typical throughput time was four weeks. In 1981, the interim Block I VLBI System was developed by the DSN. This system consisted of computer-controlled data recording at the stations on nine-track tape, a satellite link to transmit the recorded data to the Jet Propulsion Laboratory, and a correlator at the Network Operations Control Center for data processing. Turnaround time as short as six hours was demonstrated, but constraints on scheduling data playbacks yielded a typical throughput time of 72 hours.

In 1986, the Narrow-Channel Bandwidth VLBI System replaced the interim Block I VLBI System to provide operational support for spacecraft navigation. Analog filters were replaced by digital filters. This change reduced key instrumental errors by a factor of two and improved overall system accuracy. The system configuration was automated and driven by station predicts (a computer data set consisting of the predicted antenna-pointing directions as a function of time). The option to record data on disk or tape was provided. The reliability of the system was improved in 1988 by developing a station-predicts–driven system for antenna pointing during ΔVLBI activities and by automating a procedure to detect and swap faulty channel downconverters. In 1989, the data playback rate was increased by a factor of two, reducing throughput time to less than 12 hours.

Appendix B

Example of a Detailed ΔVLBI Justification

Subject: Rationale for a ΔDOR Pair Two Days After TCM7

The Galileo Project Navigation Team has requested the Mission Control Team to negotiate tracking coverage to provide two ΔDOR activities after TCM7. If this negotiation is successful, it will mean TCM7 is "bracketed" by two pairs of baselines—the first one day before and another two days after. There are three reasons for this request.

First, the limited amount of time between the end of TCM7 and the TCM8 data cutoff (9 days) allows little time to develop a solution for plane-of-sky components for the maneuver. Since ΔDOR provides immediate information in the plane-of-sky, it follows that a pair of ΔDOR's after the maneuver will result in a better solution for TCM7 than can be obtained by Doppler.

Second, one may ask, Won't the ΔDOR pair scheduled on DOY 323 provide this plane-of-sky information? The answer is yes, it will, but this DOY 323 pair occurs three days after a SITURN (science turn) and retropropulsion module flushing. Any residual ΔV from the SITURN may appear as errors in TCM7. With no plane-of-sky measurement between TCM7 and the SITURN, the solution for TCM7 may become corrupted and that, in turn, will lead to a degraded B-plane solution.

A third reason for this request deals with redundancy for post-maneuver ΔDOR's. A ΔDOR activity is a complicated affair, involving spacecraft and ground configurations to be coordinated to the minute. The Navigation Team requires at least two successful baseline pairs following the TCM for any of the ΔDOR to be of use. With no baseline pair on DOY 319, a single point failure after TCM7 will endanger the success of the entire ΔDOR campaign.

In short, placement of a ΔDOR baseline pair two days after TCM7 will not only provide for a better OD solution, but will reduce the risk of suffering from the loss of one post-TCM7 ΔDOR.

Appendix C

Sample Calculation—Uncertainty of Estimation of Acceleration

To estimate an acceleration a by differencing two position measurements Δx_1 taken over a time interval Δt_1, one has

$$a = \frac{2(\Delta x_1)}{(\Delta t_1)^2}$$

The effect of that acceleration on a position at encounter Δx_e, propagated forward for a time interval Δt_2 from the last measurement, would be

$$\Delta x_e = \frac{(\Delta x_1)(\Delta t_2)^2}{(\Delta t_1)^2}$$

To obtain the effective uncertainty in Δx_1 requires taking the root sum square of the uncertainties at the ends of the time interval. In addition, the worst-case multiplier 1.85 from Fig. 7 will be used to obtain an upper bound (i.e., assuming an estimate is to be made in the most uncertain direction). Thus, using sig to denote the uncertainty,

$$\mathrm{sig}(\Delta x_1) = 1.85\sqrt{(\mathrm{sig}x_1)^2 + (\mathrm{sig}x_2)^2}$$

Then, the resulting uncertainty in the encounter conditions is given by

$$\mathrm{sig}(\Delta x_e) = \frac{\mathrm{sig}(\Delta x_1)(\Delta t_2)^2}{(\Delta t_1)^2}$$

For the first example, consider ΔVLBI measurements taken at 90 days and 40 days before encounter, with the resulting acceleration estimate propagated the last 16 days to encounter. The inputs are

$$\Delta t_1 = 50 \text{ days},\ \Delta t_2 = 16 \text{ days}$$

the measurement uncertainty is

$$\mathrm{sig}(\Delta x_1) = 1.85\sqrt{1.17^2 + 2.90^2}$$

and the resulting encounter uncertainty is

$$\mathrm{sig}(\Delta x_e) = 0.59 \text{ km}$$

Now, for comparison, let the first measurement be taken 48 days before encounter. The inputs are

$$\Delta t_1 = 8 \text{ days},\ \Delta t_2 = 16 \text{ days}$$

the measurement uncertainty is

$$\mathrm{sig}(\Delta x_1) = 1.85\sqrt{1.17^2 + 1.43^2}$$

and the resulting encounter uncertainty is

$$\mathrm{sig}(x_e) = 13.7 \text{ km}$$

which is similar to the size of the actual encounter error in the B-plane. Thus, the accuracy is seen to be very dependent on the size of the effective measurement interval.