Deep Space Navigation with Noncoherent Tracking Data

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Navigation capabilities of noncoherent tracking data are evaluated for interplanetary cruise phase and planetary (Venus) flyby orbit determination. Results of a formal covariance analysis are presented which show that a combination of one-way doppler and ΔDOR yields orbit accuracies comparable to conventional two-way doppler tracking. For the interplanetary cruise phase, a tracking cycle consisting of a 3-hour doppler pass and ΔDOR (differential one-way range) from two baselines (one observation per overlap) acquired 3 times a month results in 100-km orbit determination accuracy. For reconstruction of a Venus flyby orbit, 10 days tracking at encounter consisting of continuous one-way doppler and ΔDOR sampled at one observation per overlap is sufficient to satisfy the accuracy requirements.

I. Introduction

The success of the ΔDOR data demonstration (Ref. 1) for Voyager interplanetary cruise navigation is expected to significantly alter the tracking data strategy for deep space missions. Since ΔDOR observations from two nearly orthogonal baselines effectively replace passes of two-way doppler as a source of geocentric angle and angle rate information, the role of coherent data for future navigation applications may be more limited. ΔDOR navigation typically requires a complementary data type, either two-way range or doppler, to resolve the geocentric radial and range rate components. In addition, navigation functions such as planetary flyby orbit reconstruction, planetary orbiter operations and maneuver reconstruction will still explicitly require some form of doppler. However, the success of the ΔDOR application for cruise navigation raises the question as to whether future missions can be navigated primarily with one-way or listen-only data types. This scenario would expand the use of the DSN's listen-only antennas for navigation applications and subsequently reduce the dependence on two-way tracking.

Several studies are currently being pursued to evaluate the performance of noncoherent data strategies for a variety of orbit determination situations including interplanetary cruise, planetary approach, maneuver support, and highly elliptic and low altitude circular planetary orbiters. This paper evaluates the navigation capabilities of noncoherent strategies for the interplanetary cruise and planetary flyby phases of a joint international mission which flies by Venus on its journey to an encounter with comet Halley.

The study was motivated by NASA's plans to provide an independent orbit determination capability to support a joint 1985 French Venus Balloon Experiment and a 1986 comet Halley "Pathfinder" concept. Both aspects entail independent DSN tracking of a Soviet Vega (Venus – Halley, but G≡H in Russian) spacecraft which encounters Venus, deploys a French balloon into the Venus atmosphere, and is subsequently targeted to encounter comet Halley. The comet encounter is scheduled to occur approximately one week before the ESA Giotto probe reaches the comet. The DSN's orbit determination role consists of reconstructing the Venus relative orbit of Vega during the balloon tracking period and determining the geocentric position of Vega at the Halley encounter.

The complete role of the DSN's participation in the Venus Balloon experiment entails using the DSN as part of a worldwide VLBI network for tracking the motion of the balloon in the Venus atmosphere. Wide and narrowband ΔVLBI data acquired between the balloon and the Vega spacecraft are used to determine the position and velocity of the balloon. Conceptually, the VLBI technique is similar to that used for Voyager—with the Vega signal serving as the known radio source for constructing relative angle differenced observations. The angular position and velocity of the balloon are referenced to the Vega flyby orbit—which must be estimated with accuracies of 10 km and 50 cm/sec during the balloon tracking phase.

The objective of the second phase of this task, the "Pathfinder" concept, is to improve the accuracy of the comet Halley ephemeris in time for the ESA Giotto targeting maneuver. Optical observations of the comet taken by Vega as it flies by the comet nucleus are combined with Vega trajectory information and ground-based comet observations to update the comet ephemeris knowledge. A critical element for the successful execution of this concept is an adequate determination (i.e., approximately 100-km geocentric position accuracy) of the Vega position at the time of comet encounter from earth-based tracking data.

One option being considered for determining the Vega trajectory entails independent DSN tracking of Vega using the 64-meter net. Unlike previous deep space missions which have relied on long spans of precise two-way doppler passes and occasional ranging for orbit determination, the Vega trajectory estimate will rely solely on data acquired by the DSN in a listen-only mode.

This paper presents results of a covariance analysis to evaluate one-way tracking strategies for both mission phases. Error model assumptions and data strategies are discussed and the navigation performance and its sensitivity to critical error sources are presented. Basically, results of the study are indicative of the capabilities of listen-only data strategies for typical cruise and planetary flyby orbit determination.

II. Observational Error Model Assumptions

A USO (ultra stable oscillator) on board the Vega spacecraft is programmed to transmit an L-band signal at 1.668 GHz consisting of either a carrier or two subcarrier tones separated by 6.5 MHz. Total signal power is 5 watts. DSN plans call for the implementation of an L-band reception capability at the 64-meter antennas. This configuration will be capable of receiving one-way doppler (using the Blk IV Receiver and the MDA) and ΔDOR (using either the current Blk 0 or Blk I VLBI subsystem). Since the DSN will be operated in a listen-only mode, data types available for navigation are one-way doppler and the Very Long Baseline Interferometric (VLBI) data, i.e., wide and narrowband VLBI. Of the latter, the most useful and the simplest to implement for navigation is the wideband ΔVLBI (ΔDOR), which is constructed by differencing VLBI from a spacecraft with VLBI from a nearly natural radio source. The measurement determines the angular position of the two sources relative to each other. Table 1 summarizes the complete observational error model assumptions for both mission phases. Details are described in the following sections.

A. One-Way Doppler Model Assumptions

Range rate measurements are made by estimating the doppler shift of a signal transmitted by the Vega USO. Based on experience with the signal from the Voyager USO, the received doppler signal will include errors due to an unknown frequency bias and linear frequency drift as well as errors due to USO instability and media effects. For the purpose of the covariance analysis the range rate error $\delta\dot{\rho}$ was assumed to be of the form

$$\delta\dot{\rho} = \delta f_b + \Delta t \delta f_d + \eta$$

where

δf_b is the frequency bias

δf_d is the frequency drift

η is the random measurement noise

Δt is a time difference between some arbitrary epoch and the current time

Although a possibility exists that precise estimates of the frequency bias and drift will be available during flight from two-way doppler measurements collected by Soviet stations, for the purpose of this analysis the bias and drift were both treated as essentially unknown constant parameters which are estimated by the filter. Doppler measurement noise was assumed to be zero mean Gaussian white noise with a random error of 1.5 cm/sec based on a 60-second count time.

B. ΔDOR Error Model Assumptions

The presence of a wideband 6.5-MHz spacecraft signal coupled with the availability of an adequate number of strong extragalactic radio sources (EGRS) near the Vega flight path provide the necessary conditions for acquisition of ΔDOR observations. ΔDOR is assumed to be acquired from the Goldstone-Madrid and Goldstone-Canberra baselines for maximum elevations angles during overlap greater than 8 degrees. This assumption limits the amount of data from the Goldstone-Madrid baseline for the Halley encounter phase.

The covariance analysis explicitly models the ΔDOR error sources to assess the effect of the individual errors on the navigation performance. ΔDOR error sources are characterized as either random or systematic. Random errors are combined into a single measurement noise quantity which is assumed to be Gaussian zero mean white noise. Systematic errors, which include troposphere, ionosphere, source position uncertainty, station location, UT1 and polar motion errors, are explicitly treated by the covariance analysis as unmodelled consider parameters. Such parameters are not modelled by the filter strategy but their a priori uncertainties are included in the computation of the statistics for the spacecraft state estimates. Details of the treatment of ΔDOR error assumptions are discussed below.

Random ΔDOR errors. The system noise for the spacecraft and for the natural radio source, dispersive instrumental phase and station oscillator instability errors are combined into a single random measurement noise. Estimates of the ΔDOR errors due to these sources are based on the analysis of J.B. Thomas. Table 1 summarizes the assumptions for the random errors for both mission phases, with the principal difference due to the strength of the natural radio sources used for each phase. For the Venus balloon phase, natural sources with source strengths greater than 0.5 Jy are available; the Pathfinder phase relies on sources with minimum strengths of 0.3 Jy.

Ionosphere and troposphere errors. At the time of this analysis our covariance analysis software did not have the capability to explicitly model troposphere and ionosphere calibration errors. A single ΔDOR bias was constructed for each baseline (Goldstone-Madrid and Goldstone-Canberra), which combined the total worst-case error expected for both error sources. Estimates of the errors are based on the analysis of S.Wu and assumed a worst-case minimum elevation angle for each phase.

Source position uncertainty. Natural source position errors included a frame tie error which characterizes the absolute uncertainty of the radio source reference catalog with respect to the planetary FK-4 frame and a relative error which describes the uncertainty of the source locations within the radio source reference frame. A correlated a priori error covariance was constructed based on this model. For the Venus flyby, a 500 nanoradian (nrad) frame tie was assumed. Postprocessing of the flyby data is expected to reduce the frame tie uncertainty to 100 nrad for the subsequent Pathfinder phase. Relative source errors were assumed to be 50 nrad.

Station location, baseline, UT1 and polar motion errors. Station location errors were also modelled in terms of absolute and relative errors. This model assumes station location estimates will be based on a combination of planetary encounter data and intercontinental baseline information derived from the VLBI radio source catalog determination. Errors due to UT1 and polar motion are combined into an "equivalent station location error." The absolute station location errors were assumed to be 2 m spin axis, 3 m longitude and 20 m z-height. An uncertainty of 0.8 m was assumed for the polar and equatorial components of the intercontinental baseline vector between the Goldstone-Madrid and Goldstone-Canberra sites.

III. Heliocentric Cruise Analysis

A. Cruise Model Assumptions

Noncoherent data strategies were evaluated for interplanetary cruise navigation based on tracking data for a 90-day heliocentric Vega trajectory terminating at Halley encounter. Dynamic parameters modeled in the covariance analysis included the probe position and velocity, solar radiation pressure acceleration and an arbitrary correction maneuver 30 days before encounter.

Tracking data was acquired during the 4 tracking periods shown in Fig. 1, which presents the trajectory profile during the 90-day arc. With the exception of the first tracking arc, the schedule is consistent with preliminary DSN plans for Giotto mission support. The earlier data was added to assess the effect of overall tracking geometry changes provided by the longer arc. Data included one-way doppler from Canberra and ΔDOR from the Goldstone-Canberra and Goldstone-Madrid baselines. The ΔDOR is sampled at one measurement per overlap period for elevation angles greater than 8°.

A batch least squares filter was used to determine the spacecraft state based on a simulated tracking schedule. The filter estimated the probe position and velocity, three components of the maneuver and the one-way doppler bias and drift. Source position uncertainty, station location errors, solar radiation pressure acceleration and ΔDOR biases were treated as unmodelled consider parameters. A priori error assumptions are given in Table 2.

B. Cruise Navigation Performance

Based on the preceding dynamic and observational error model assumptions, covariance studies were conducted with the objectives of (1) understanding the relative tradeoffs and information content of the noncoherent data types for cruise navigation, (2) identifying data strategies which achieve acceptable performance with a minimum of tracking time and (3) assessing the sensitivity of estimates to unmodelled error sources. The navigation performance achievable with conventional two-way doppler tracking was first established as a reference. A two-way doppler random measurement accuracy of 1 mm/sec based on a 60-second count time was assumed. Information inherent in a single pass of doppler determines the geocentric range rate, right ascension and declination of the spacecraft. Successive passes over a sufficiently long arc resolve the geocentric range and the angular rate of change. The geocentric information combined with knowledge of the earth's ephemeris determines the heliocentric state.

Figure 2 compares the performance of two-way doppler (F2) passes with the following noncoherent data strategies: one-way doppler (F1) only passes, ΔDOR-only observations and a combination of one-way doppler and ΔDOR (F1 + ΔDOR). Daily tracking data acquired for the 4 spans shown in Fig. 1 includes 33 passes (330 hours) of doppler and ΔDOR from both baselines (one observation for each overlap period.) The combination of the low spacecraft declination and 8° station elevation angle constraint limited the ΔDOR acquisition from the Goldstone-Madrid baseline to the first 60 days. Results in Fig. 2 are expressed in terms of the geocentric position error (radial, right ascension and declination) at the time of Halley encounter.

The result of replacing two-way doppler passes with one-way doppler (F1-only) is to increase the position error by a factor of 6 due to noisier data and the inability of the filter to adequately estimate the one-way bias and drift. The ΔDOR-only strategy determines the angular position and velocity but is unable to provide acceptable radial information. A solution based on the combination of one-way doppler and ΔDOR yields results that are comparable if not better than two-way doppler. This is due to the complementary information content of the data types. An accurate independent determination of the angular position and velocity is provided by the ΔDOR, while the one-way doppler yields information in which the angular estimates are highly correlated with the radial components and the bias and drift terms. In effect, the ΔDOR angular information constrains the one-way doppler error ellipsoid. The result of the correlations and the angular accuracy constraint is an order of magnitude improvement in range estimates and a factor of 4 improvement in the bias and drift estimates.

Having demonstrated that noncoherent data strategies can perform as well as two-way doppler for cruise navigation, the next phase was to study the sensitivity of the estimates to the quantity of tracking data. A navigation tracking cycle can be defined consisting of a doppler pass from Canberra and a ΔDOR observation from each baseline (with maximum elevation angles exceeding 8°). Figure 3 shows that reducing the number of tracking cycles from 33 to 9 (distributed over the 4 scheduled tracking spans) does not affect the navigation accuracy.

The rationale for using full 8-10 hour doppler passes is based on the angular information inherent in a full doppler pass. When used in conjunction with ΔDOR, doppler primarily is a source of geocentric range and range rate. The effect of reducing the pass duration to 3 hours for the 9-cycle strategy is also shown in this figure. The shorter doppler passes increase the radial uncertainty from 69 to 92 km; however, the solution still satisfies the navigation requirements. For the remainder of the study, this 9-cycle, 3-hour doppler pass strategy with 8° constraint is treated as the *nominal baseline strategy*.

The opportunity to acquire ΔDOR from the Goldstone-Madrid baseline is limited due to the negative declination of the probe during the final days. Figure 4 compares the navigation accuracies for the 9-cycle (3-hour pass) strategy assuming no ΔDOR from this baseline, and an 8° and 6° elevation angle limit. The latter permits ΔDOR acquisition from both baselines during the entire trajectory. It is apparent that data from both baselines is needed to meet the 100-km requirement.

Cruise phase orbit determination typically requires two-way doppler observations of the spacecraft motion over a sufficiently long arc to detect the changes in range rate and the trajectory bending caused by the sun's gravitational field. The long arc tracking coupled with a model for the spacecraft dynamics resolves the radial position component. For the noncoherent tracking strategy, a reduction of the length of tracking arc from 3 months to 2 months (by eliminating the first tracking segment) increases the radial position error from 92 km to 175 km.

The analysis treated an arbitrary and essentially unknown midcourse maneuver. Applying the same noncoherent (F1 + ΔDOR) tracking strategy to a maneuver free arc (or assuming the maneuver can be independently determined from telemetry) improves the accuracy of all components. The radial error is reduced from 92 km to 44 km with a reduction in angular position errors from 30 to 20 km.

The sensitivities of geocentric position estimates to unmodelled error sources are displayed in Fig. 5. The position error is decomposed into a component due to measurement noise and perturbations due to the considered error sources. Angular position errors are primarily influenced by the source position and intercontinental station baseline errors, which reflects the sensitivity of the ΔDOR to those error sources. The radial uncertainty is primarily corrupted by the station longitude error.

IV. Planetary Flyby Analysis

A. Flyby Model Assumptions

For the interplanetary cruise phase, we were primarily interested in determining the probe position and velocity with respect to either the earth or sun using ground-based observations. Planetary encounter navigation entails estimation of the probe's flight path relative to a target body. As the spacecraft approaches the target, the tracking data must be capable of detecting the accelerations induced by the planet's gravitational field and must be sufficiently sensitive to measure the trajectory bending.

The evaluation of noncoherent data strategies for planetary encounter orbit determination was based on an analysis of the Venus flyby for the Vega probe. The nominal trajectory is aimed for a Venus closest approach of approximately 40000 km. Two days before encounter the balloon is released and a bus deflection maneuver is executed, followed by a Halley targeting maneuver 7 days after encounter.

The covariance analysis models the following dynamic parameters: spacecraft state, Venus ephemeris (both position and velocity), Venus mass, solar radiation pressure accelerations and the two maneuvers. A priori error model assumptions are summarized in Table 3.

A nominal strategy was defined with a 10-day tracking arc—starting 5 days before encounter and ending 5 days after. Tracking data consisted of daily passes of one-way doppler from the three DSN complexes and ΔDOR observations from the Goldstone-Madrid and Goldstone-Canberra baselines. The 8° elevation angle constraint did not impact the ΔDOR availability for this phase. One ΔDOR observation was sampled from each baseline.

As in the cruise study, a batch least squares filter was used to assess the performance of noncoherent strategies. The performance criterion was the Venus relative position and velocity errors for the orbit segment starting one day before and ending two days after encounter. This corresponds to the balloon tracking phase which requires accurate knowledge of the flyby reference orbit for establishing the relative motion of the balloon. The filter estimated the spacecraft state, Venus ephemeris and mass, maneuver components and the one-way doppler bias and drift. Consider parameters were the same as in the cruise case—source position uncertainty, station location, solar radiation pressure and ΔDOR bias errors.

B. Venus Flyby Performance

Two-way doppler has traditionally proved to be most effective for planetary flyby orbit reconstruction. The ability of doppler to sense the range rate changes caused by the planetary gravitational field establishes the planet relative spacecraft state. Figure 6 compares the two-way doppler performance with one-way doppler only, ΔDOR-only and a combination of one-way and ΔDOR data strategies. Venus relative position and velocity errors for the three-day encounter arc are plotted—with errors expressed in terms of an error component along the probe-earth direction and a second component in a plane orthogonal to this vector. The latter represents the RSS of the two plane-of-sky (POS) errors.

Two-way doppler tracking easily satisfies the Venus flyby orbit determination requirements. Position error is a minimum at closest approach with the error ellipse defocused on either side of encounter. In general, errors are increased by an order of magnitude when one-way doppler replaces the two-way data. This is primarily due to the inability of the filter to adequately determine the one-way bias and drift. The uncertainties of the bias and drift estimates are 1.0×10^{-10} ($\Delta f/f$) and 1.6×10^{-12} ($\Delta f/f$/day). Approximately an order of magnitude improvement is required for the one-way doppler to yield results comparable to two-way. The ΔDOR-only option determines the POS position and velocity (with the exception of an anomaly at encounter) but fails to provide information along the earth-probe line. The solution based on one-way doppler combined with ΔDOR yields results comparable to the two-way data.

In some respects this behavior is similar to the interplanetary cruise performance. One-way doppler provides information in which the radial components, bias and drift are highly correlated with the POS position and velocity. The addition of ΔDOR constrains the POS errors and determines the remaining components via the doppler correlations. The accuracy of the bias and drift estimates, which are key for determining radial information, are improved by factors of 10 and 4 respectively. Figure 7 illustrates the manner in which the ΔDOR and one-way doppler error ellipses combine for the position components.

Figure 8 plots the perturbations due to the unmodelled error sources for the estimates based on the F1 + ΔDOR strategy. The sensitivity is presented in terms of the total RSS position and velocity errors at E + 2d. The accuracy of the estimates are primarily dominated by the measurement error and the a priori covariance assumptions for the Venus ephemeris and mass. The latter constrains the Venus relative position and velocity errors. Two-way doppler results are insensitive to considering or solving for the ephemeris and mass parameters. However, for the combined F1 + ΔDOR strategy, the ephemeris solution determines the planetary-radio source frame tie.

The sensitivities of the Venus relative estimates (based on the F1 + ΔDOR strategy) to the number of doppler tracking sites and to the duration of tracking are presented in Figs. 9 and 10. Results are expressed in terms of a single RSS position and velocity error. Reducing the number of doppler sites roughly increases the errors by the ratio of the square root of the number of measurements—which is characteristic of a situation in which the statistics are not dominated by unmodelled errors. The 10-km position requirement is only satisfied with tracking from three sites. Limiting the tracking span to 4 days at encounter also results in unacceptable performance. Only marginal improvement results from extending the arc to 20 days.

V. Conclusions

The objectives of this study were to assess the capabilities of noncoherent data strategies for interplanetary cruise and planetary flyby orbit reconstruction. Results of the cruise phase analysis demonstrate that modest quantities of one-way doppler combined with ΔDOR from two baselines can yield navigation accuracies comparable to two-way tracking. A 100-km position requirement can be met with a navigation cycle consisting of a 3-hour one-way doppler pass and ΔDOR observations from two baselines scheduled three times per month. Necessary conditions for adequate performance include tracking over a sufficiently long arc and ΔDOR data from both baselines.

A noncoherent strategy consisting of continuous one-way doppler and ΔDOR from two baselines was also shown to be as effective as two-way doppler for planetary flyby orbit determination. The Venus relative position and velocity requirements of 10 km and 50 cm/sec are satisfied with tracking interval starting 5 days before and ending 5 days after encounter.

The effectiveness of the combined strategy is primarily due to the independent geocentric angular determination provided by the ΔDOR data which aids in the separation of the doppler angular information from the earth-line and bias and drift components. This enables an adequate determination of the latter components.

Acknowledgement

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References

1. Border, J. S., Donivan, F. F., Finley, S. G., Hildebrand, C. E., Moultrie, B., and Skjerve, L. J., "Determining Spacecraft Angular Position with Delta VLBI: The Voyager Demonstration," paper 82-1471, presented at the AIAA/AAS Astrodynamics Conference, San Diego, Calif. August 1982.

Table 1. Observational error model assumptions

One-way doppler		
Random measurement noise (60 sec count time)	1.5 cm/sec	
A priori bias error ($\Delta f/f$)	1×10^{-6}	
A priori drift error ($\Delta f/f$/day)	3×10^{-6}	
ΔDOR system	**Cruise**	**Venus flyby**
Random errors		
System noise spacecraft	2 cm	2 cm
System noise radio source	30 cm	20 cm
Station oscillator	5 cm	5 cm
Dispersive instrument phase ($\epsilon = 2°$)	52 cm	52 cm
RSS random error	60 cm	56 cm
Ionosphere errors		
Goldstone-Madrid	26 cm	17 cm
Goldstone-Canberra	4 cm	17 cm
Troposphere errors		
Goldstone-Madrid	55 cm	30 cm
Goldstone-Canberra	28 cm	30 cm
Source position errors		
Frame tie	100 nrad	500 nrad
Relative	50 nrad	50 nrad
Station location errors		
Spin radius	2 m	
Longitude	3 m	
Z-height	20 m	
Intercontinental baseline	0.8 m	

Table 2. Cruise a priori error model assumptions

Parameters	A priori standard deviation
Estimated parameters	
VEGA position	10^7 km
VEGA velocity	10 km/s
Doppler bias	0.3 km/s
Doppler drift	10^{-7} km/s^2
Maneuver (E-30^d)	1.0 m/s
Considered parameters	
Station spin radius	2 m
Longitude	3 m
Z-height	20 m
Station baseline – (equatorial and polar components)	0.8 m
Quasar FK-4 frame tie (right ascension/declination)	0.1 μrad
Quasar relative position	0.05 μrad
Solar radiation pressure acceleration	10% of nominal
ΔDOR bias GLD-CAN	28 cm
ΔDOR bias GLD-MAD	60 cm
Random data noise	
One-way doppler	1.5 cm/sec
ΔDOR	60 cm

Table 3. Venus flyby a priori error model assumptions

Parameters	A priori standard deviation
Estimated parameters	
VEGA position	10^7 km
VEGA velocity	10 km/s
Doppler bias	0.3 km/s
Doppler drift	10^{-7} km/s^2
Maneuver (E-2^d)	1.0 m/s
Venus ephemeris	
Position (RA, DEC, RADIAL)	40, 40, 10 km
Velocity	1×10^{-5} km/sec
Venus mass	1 km^3/sec^2
Considered parameters	
Station spin radius	2 m
Longitude	3 m
Z-height	20 m
Station baseline – (equatorial and polar components)	0.8 m
Quasar FK-4 frame tie (right ascension/declination)	0.5 μrad
Quasar relative position	0.05 μrad
Solar radiation pressure acceleration	10% of nominal
ΔDOR bias GLD-CAN	34 cm
ΔDOR bias GLD-MAD	34 cm
Random data noise	
One-way doppler	1.5 cm/sec
ΔDOR	56 cm

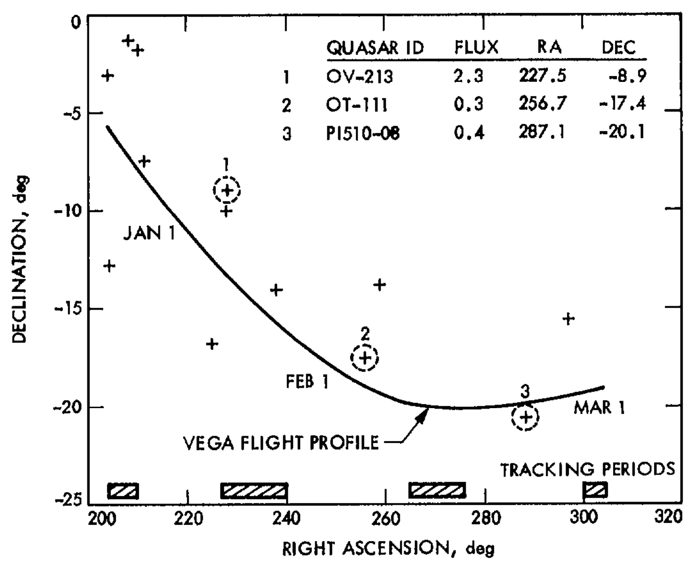

Fig. 1. Cruise profile

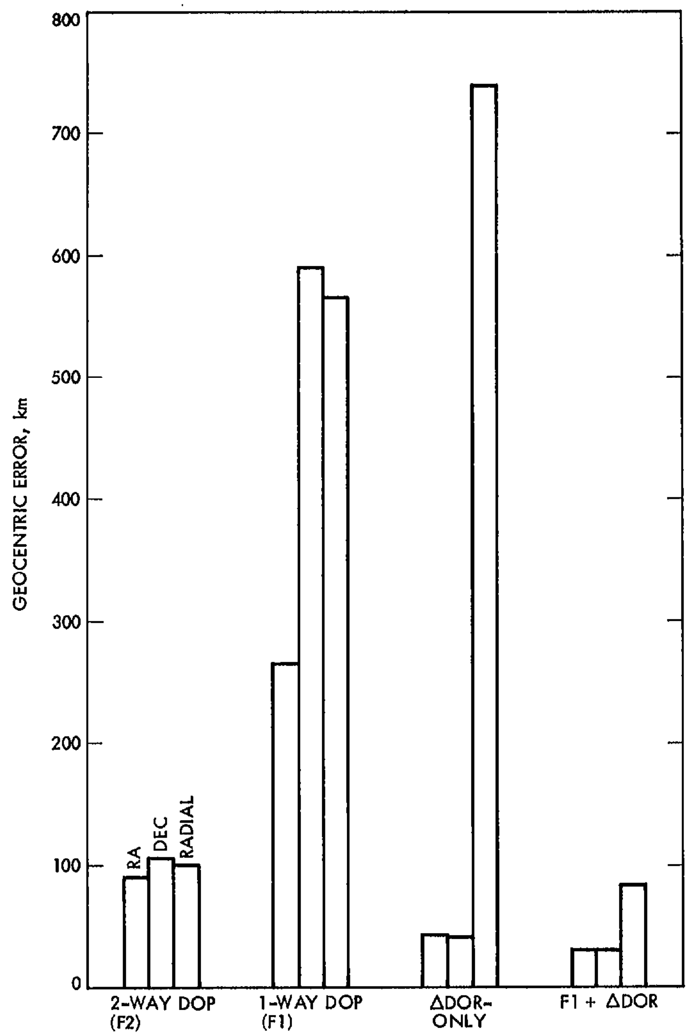

Fig. 2. Comparison of strategies for cruise navigation

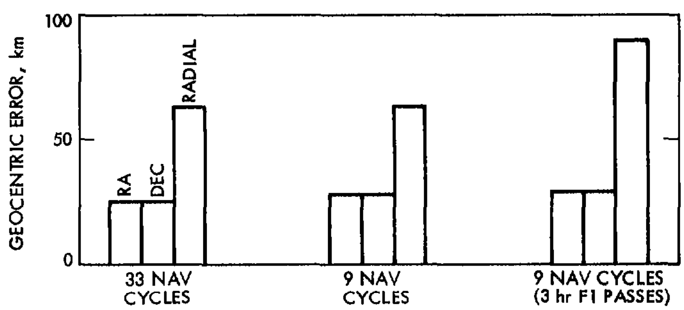

Fig. 3. Effect of quantity of data

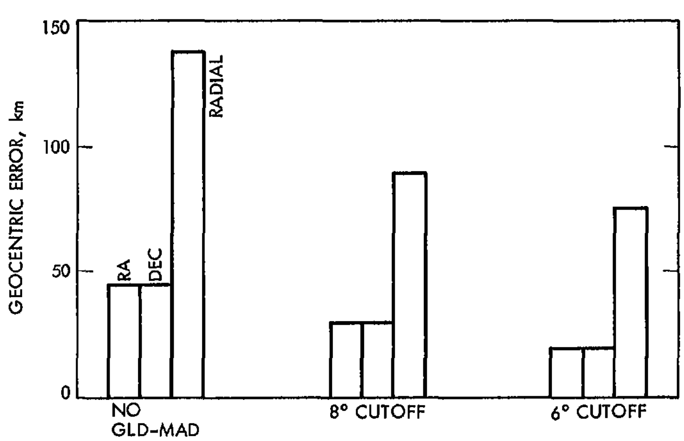

Fig. 4. Sensitivity to Goldstone-Madrid ΔDOR

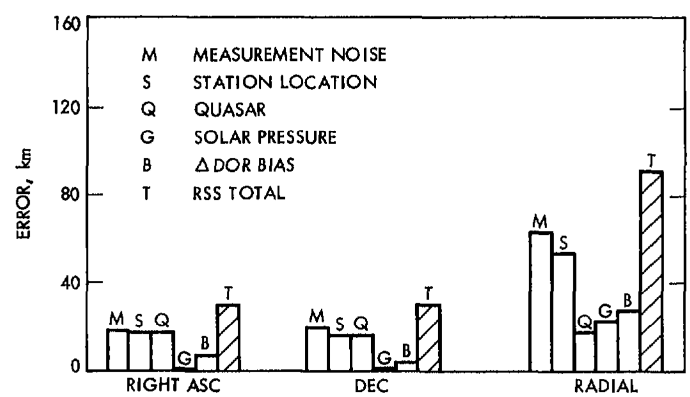

Fig. 5. Sensitivity to consider errors

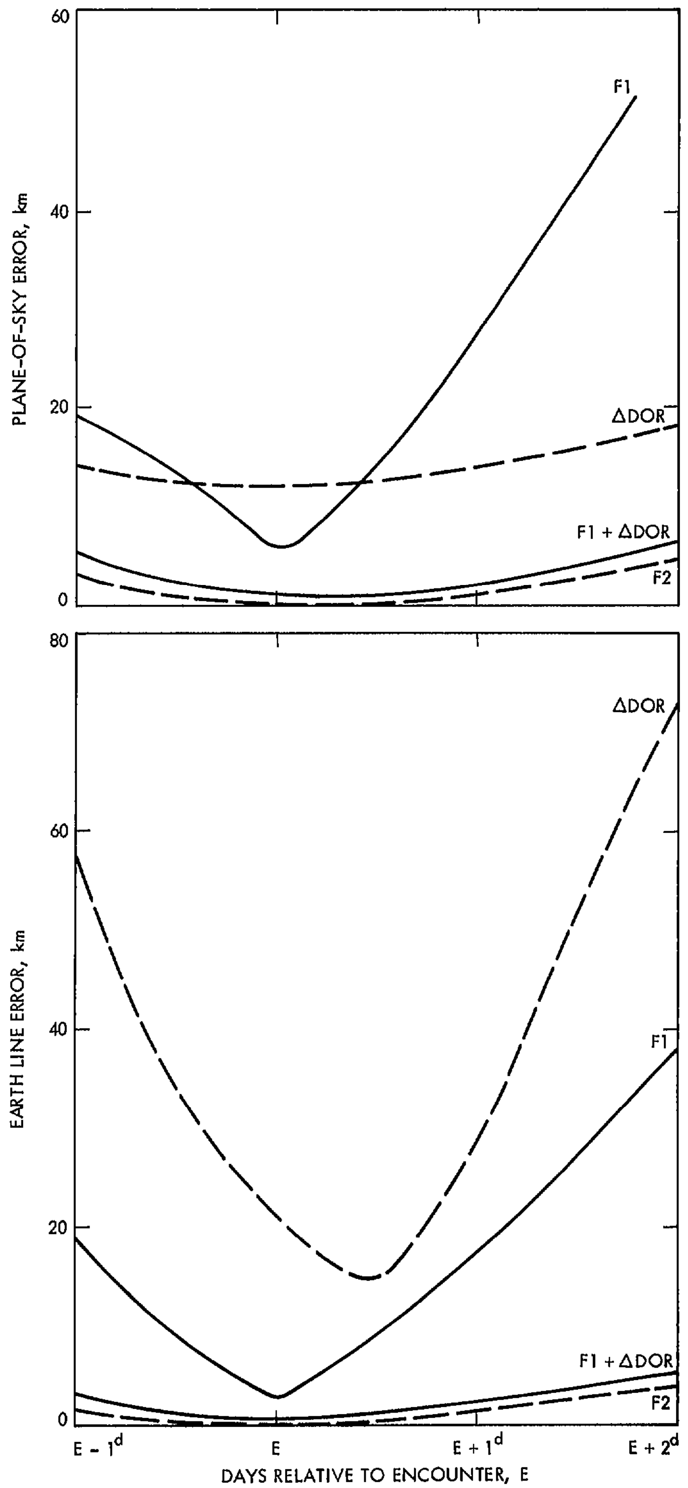

Fig. 6(a). Comparison of strategies for Venus flyby reconstruction – Venus relative position errors

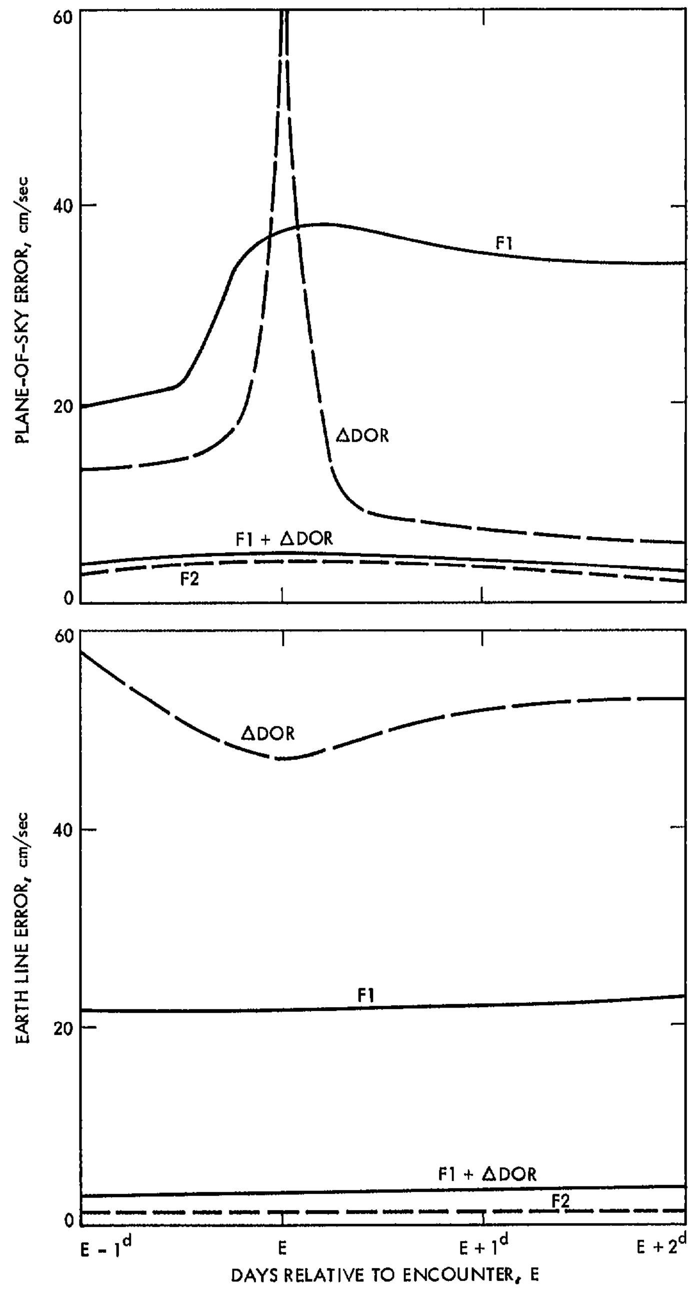

Fig. 6(b). Comparison of strategies for Venus flyby reconstruction – Venus relative velocity errors

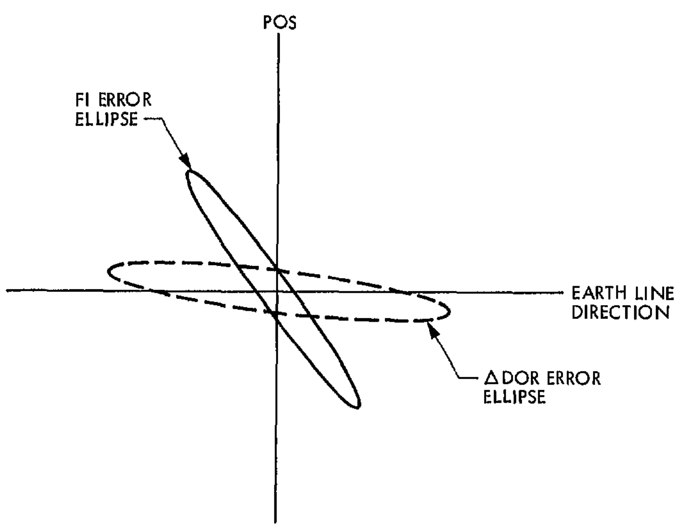

Fig. 7. F1-ΔDOR two-dimensional error ellipse representation

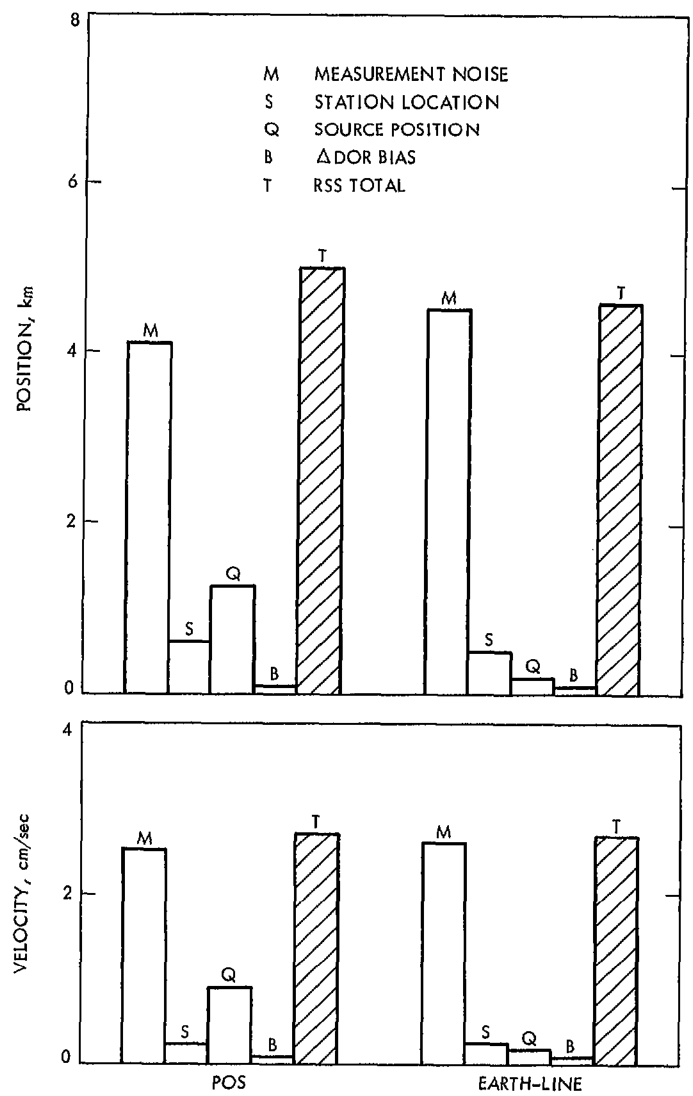

Fig. 8. Sensitivity of solution at E + 2d to consider errors

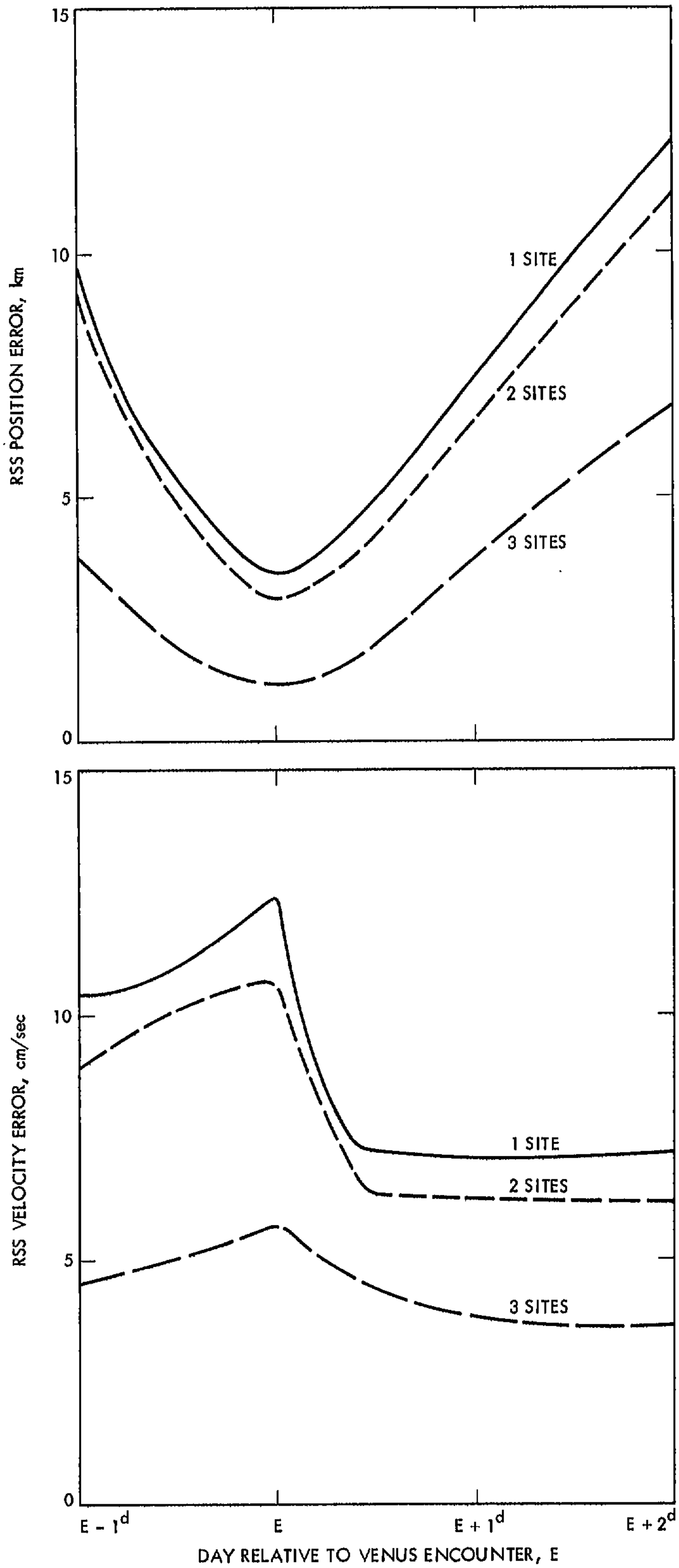

Fig. 9. Sensitivity to number of doppler tracking sites

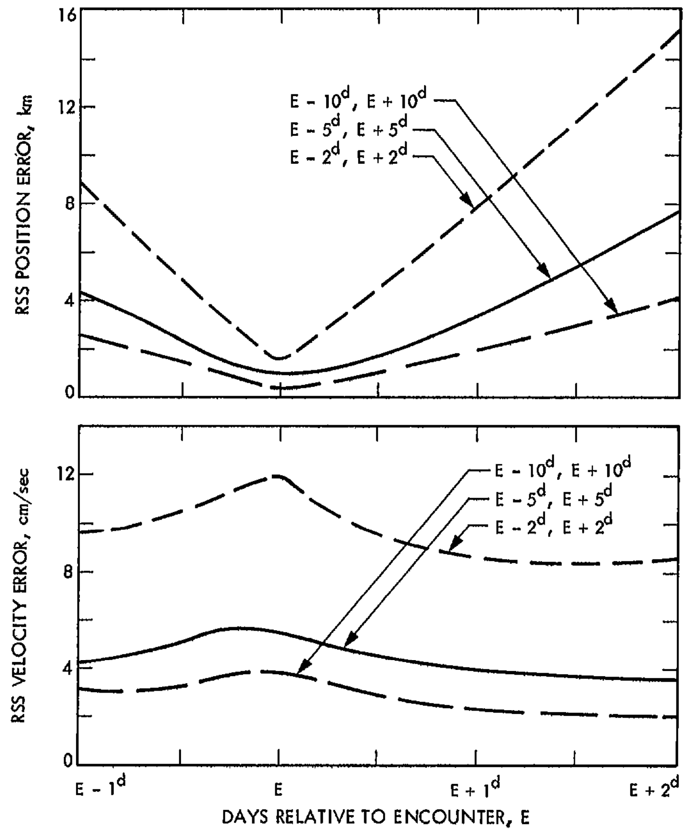

Fig. 10. Sensitivity to length of tracking arc