Determination of the Venus Flyby Orbits of the Soviet Vega Probes Using VLBI Techniques

J. Ellis
Navigation Systems Section

T. P. McElrath
Federal Electric Corporation

In December 1984, the Soviet Union launched two identical Vega spacecraft with the dual objectives of exploring Venus and continuing to rendezvous with the comet Halley. The two Vega spacecraft encountered Venus in mid-June 1985 and successfully deployed entry probes and wind-measuring balloons into the Venus atmosphere. An objective of the Venus Balloon experiment was to measure the Venus winds using differential VLBI from the balloon and the flyby bus. NASA's Deep Space 64-meter subnet was part of a 20-station worldwide network organized to collect data from the Vega probes and balloons.

A critical element of this experiment was an accurate determination of the Venus relative flyby orbits of the Vega spacecraft during the 46-hour balloon lifetime. Venus flyby solutions were independently determined by the Soviets using two-way range and doppler from Soviet stations and by JPL using one-way doppler and VLBI data collected from the DSN. This article compares the Vega flyby solutions determined by the Soviets using a sparse two-way tracking strategy with JPL solutions using the DSN VLBI data to complement the Soviet data and with solutions using only the one-way data collected by the DSN.

I. Introduction

In December 1984, the Soviet Union launched two identical Vega spacecraft with the dual objectives of exploring Venus and continuing to rendezvous with the comet Halley [1]. The two Vega spacecraft encountered Venus in mid-June 1985 and successfully deployed entry probes and wind-measuring balloons into the Venus atmosphere. Two weeks after the Venus encounter, maneuvers were executed to target the probes to a March 1986 comet encounter.

Each spacecraft released an instrument-laden balloon which floated at an altitude of 54 km and traveled approximately one-third of the way around Venus during the 46-hour balloon lifetime. An objective of this Venus Balloon experiment was to measure the Venus winds using differential VLBI (Very Long Baseline Interferometry) techniques. The position and velocity of each balloon relative to the corresponding Vega bus were determined from simultaneous VLBI measurements from the balloon and the flyby bus. A differenced spacecraft and balloon VLBI measurement was formed in which common errors due to clock offsets, baseline errors, and media effects were canceled. An independent estimate of the flyby trajectory relative to Venus was used to infer balloon position and velocity relative to a Venus-centered reference frame.

The balloon experiment was a cooperative effort of the Soviet Union and France. A worldwide radio interferometry network was organized by the French space agency, Centre National d'Études Spatiales (CNES), to continuously receive the signals broadcast by the Vega probes and the balloons. This network included the 64-meter antennas in California, Spain, and Australia that are part of NASA's Deep Space Network.

Since the accuracy of wind determination was directly related to the flyby accuracy, a critical element of the Venus Balloon experiment was an accurate determination of the Vega spacecraft orbits during the 46-hour balloon lifetime. The goal was to determine the flyby position and velocity to a one-sigma accuracy of 15 km and 1 meter/sec.

Both JPL and IKI (the USSR Space Research Institute) independently determined the Vega flyby orbits and exchanged radio metric data and trajectory information to arrive at a solution using combined Soviet and NASA data. Soviet solutions were based on daily 10- to 20-minute passes of two-way doppler and range acquired during the Venus flyby phase. JPL independently determined a solution using continuous passes of one-way doppler and delta VLBI data. A combined solution was determined by JPL using the JPL delta VLBI and pseudo-geocentric range together with range rate information constructed from the Soviet radio metric data. The Soviets independently determined a similar solution by combining the JPL VLBI data with the Soviet two-way data.

This article compares the Vega Venus flyby solutions determined by IKI and JPL. The sensitivity of the solutions to filter strategy, tracking data, and unmodeled error sources is discussed along with the merits of using VLBI data for planetary flyby navigation. The application of VLBI data to the Halley encounter phase is described in [2].

II. Mission Characteristics

A. Encounter Conditions

Vega-1 was targeted to fly by Venus on June 11, at a closest approach distance of 45,200 km, and Vega-2 on June 15 at a distance of 30,500 km. Two days prior to encounter, each spacecraft released the balloon/lander package and executed a Venus deflection maneuver. The maneuver to target the spacecraft to the Halley encounter was executed 14 days after closest approach. Although both encounters occurred within a 4-day period and closest approach was at the same time of day, the flyby geometries were sufficiently different to significantly influence the orbit determination accuracies. The effect of approach geometry on orbit determination accuracy is discussed in Section V.

B. Spacecraft Signal Characteristics

The Vega probes and balloons each carried a stable crystal oscillator which was used as a reference for transmitting an L-band signal at 1.668 GHz. The L-band frequency was selected to be compatible with the reception capabilities of the international network of 20 radio observatories that were supporting the Venus Balloon experiment. The Vega L-band signal consisted of either a pure carrier or two subcarrier tones separated by 6.5 MHz. The two tones were transmitted for half-hour periods every two hours. The DSN 64-meter stations were configured to receive the L-band signal broadcast by the Vega probes and balloons. Continuous passes of one-way doppler were obtained from acquisition of the carrier signal. VLBI data were formed by correlating the wideband tones received simultaneously at two widely separated DSN sites.

In addition to the L-band capability, the probes also transmitted at a C-band frequency of approximately 6 GHz. This frequency was used by the Soviets for two-way doppler and ranging.

III. Radio Metric Tracking Data

During the Venus flyby phase, the Vega probes and balloons were tracked by the DSN 64-meter stations at Goldstone, Madrid, and Canberra and by two tracking sites in the Soviet Union. Tracking activity was nearly continuous during the balloon lifetime phase. Venus relative flyby orbits of the Vega probes were determined based on data collected during the 16-day maneuver-free phase. This data span commenced two days before closest approach following the execution of the Venus deflection maneuver and terminated 14 days after encounter prior to the Halley target maneuver. Table 1 summarizes the Soviet and DSN tracking data.

The Soviet tracking strategy consisted of acquiring daily 10- to 20-minute passes of C-band two-way doppler and range with a 60-second sampling rate. Data were acquired from two sites in the Soviet Union which were widely separated in longitude.

During the same period, the DSN acquired L-band one-way data from the DSN 64-meter subnet. Nearly continuous passes of one-way doppler were acquired by the DSN during the balloon lifetime from the 3 DSN sites. DSN VLBI observations were collected from the Goldstone–Madrid and Goldstone–Canberra baselines throughout the 14-day flyby phase. The DSN data were calibrated for troposphere effects using a seasonal model. Faraday rotation data were used to generate ionospheric calibrations for the VLBI observables. At encounter, the Sun–Earth–probe angle was approximately 45 degrees.

By alternately tracking the Vega spacecraft and an angularly nearby quasar whose location was known, a doubly differenced VLBI measurement was constructed called Delta Differential One Way Range (ΔDOR). Differencing the spacecraft and quasar VLBI measurements to form the ΔDOR observable cancels common errors due to clock synchronization, transmission media, and platform parameter uncertainty. A typical VLBI observation sequence from each baseline consisted of quasar–spacecraft–quasar scans with a 7-minute scan for each source. For the Venus flyby phase, all delta VLBI observations were formed with respect to the quasar P0202+14 which has a source strength greater than 1 Jansky. The maximum spacecraft–quasar separation during the VLBI tracking phase was 16 degrees.

IV. Flyby Orbit Determination Strategies

Planetary flyby navigation entails estimation of the probe's flight path relative to the target body. When only ground-based radio metric data are available, the data must be a measure of the accelerations induced by the planet's gravitational field and must be of a sensitivity sufficient to measure changes in the flight path. By fitting the observations to a model of the spacecraft dynamics, a planet relative orbit is determined.

The Soviet approach to deep space navigation is fundamentally different from the approach used at JPL. The Soviets depend on short 10- to 20-minute daily passes of range and doppler. The orbit is determined by fitting the data over relatively long tracking arcs in which there has been sufficient change in the spacecraft geometry relative to the earth. This procedure, because of its reliance on lengthy tracking arcs, requires an accurate model of the spacecraft dynamics and tends to be sensitive to any unmodeled non-gravitational effects. In addition, the use of range data, especially for planetary encounter navigation, increases the sensitivity of the solutions to planetary ephemeris errors, station location errors, and ranging bias errors.

JPL's approach to planetary encounter navigation typically relies on continuous 8- to 10-hour horizon-to-horizon passes of two-way doppler. The diurnal signature inherent in a long continuous pass of doppler is a source of geocentric angle and angle rate information [3]. Consequently, solutions can be determined using comparatively shorter tracking spans. For planetary encounters, the ability of the nearly continuous doppler to sense the range rate changes induced by the planet's gravitational field establishes the planet relative spacecraft state. The time of closest approach can be directly observed in the doppler residuals during the flyby.

For flyby orbits, range data, because of their sensitivity to planetary ephemeris errors and station location errors, either are not used by JPL or are severely deweighted. Consequently, one concern was that the Soviet Vega flyby solutions, with their dependence on range data, would be unduly sensitive to these error sources. A Soviet solution using only two-way doppler was not feasible due to the short duration of the tracking passes.

For the Vega missions, the only radio metric data available at JPL for independent orbit determination were data collected in a passive, listen-only mode. This consisted of L-band one-way doppler and ΔDOR. Nearly continuous passes of one-way doppler from 3 sites were acquired from the L-band carrier signal broadcast by the Vega probes. For these data to be useful for orbit determination (i.e., to determine the range rate from the doppler shift), the frequency characteristics of the on-board oscillator must be modeled. Typically, it is assumed that the one-way doppler signal includes errors due to an unknown oscillator frequency bias and drift and is corrupted by oscillator instability and media effects.

The ΔDOR observations, from the two nearly orthogonal baselines, directly determine the two angular components of position and velocity in a plane-of-sky (POS) frame, which is a plane perpendicular to the Earth–probe direction. Information about the third component along the Earth–spacecraft direction can be determined from doppler tracking. A continuous 8-hour pass of doppler will yield an estimate in which the geocentric radial component and the doppler bias and drift are highly correlated with the plane-of-sky position and velocity estimates. The independent estimate of the POS components provided by the ΔDOR enables a determination of the remaining components via the doppler correlations [4]. Consequently, use of the doppler data depended on the ability to model the frequency behavior of the Vega oscillator.

Although both Vega oscillators were similar in design, the frequency characteristics of the one-way L-band signal were different. The Vega-1 oscillator drifted at a rate of –0.5 Hz/day, and the Vega-2 drift rate ranged from 6 to 7 Hz/day. Throughout the course of the continuous 46-hour tracking period, random jumps in the oscillator bias were observed which ranged from 0.1 Hz to 0.4 Hz. A possible cause of the discontinuities in frequency was on and off cycling of on-board instruments.

V. Comparison of Solutions

Both JPL and IKI independently determined the Vega flyby orbits using a consistent and common set of assumptions to describe the spacecraft dynamics. The solar radiation pressure constant was determined by the Soviets from two-way tracking data collected during the Earth–Venus phase. Both agencies used the JPL DE118 planetary ephemeris. JPL station locations and the location of the quasar (used to construct the ΔDOR observations) were expressed in a frame consistent with the DE118 planetary ephemeris. The following three solutions were computed from the encounter data:

(1) A Soviet solution based on the C-band two-way doppler and range. The Soviet solution strategy consisted of estimating the position and velocity of the Vega probes using a Gaussian least squares estimator. Data weights of 1 cm/sec and 500 meters were assumed for the two-way doppler and range. Range bias errors were not treated in the estimation process.

(2) A JPL solution using the L-band one-way doppler and ΔDOR data. A batch sequential filter was used to estimate the spacecraft state, the one-way doppler bias and drift, and the quasar right ascension and declination. Because of the random jumps in the transmitted L-band carrier frequency, the bias and drift for the on-board oscillator were modeled as a random walk process over the two-day balloon lifetime. This assumed a batch size of two hours with an additive process noise of 1 Hz and 0.01 Hz/day for the doppler bias and drift. The location of the quasar was estimated to account for an offset between the quasar catalog frame and the planetary FK-4 reference frame. Data weights of 10 cm/sec (for a 60-second count time) and 1 meter were assumed for the one-way doppler and the ΔDOR.

(3) A "combined" JPL–Soviet solution using the Soviet two-way data in combination with the JPL ΔDOR. Since JPL did not have direct access to the Soviet two-way data, pseudo-geocentric range and range-rate observations were constructed from the IKI two-way solutions. The Soviet tracking schedule (given in Table 1), along with information about the two-way range and doppler residuals with respect to these solutions, was used to construct the geocentric measurements. Because of the problems inherent in modeling the one-way doppler, the combined solution did not include these data. However, it was shown that inclusion of the one-way doppler had only a small effect on the combined solution and on its statistics. The combined solution was based on using a simple least squares estimator to determine the spacecraft state, the quasar location, and a ranging bias. The latter was included to model ranging bias errors inherent in the Soviet two-way range data. The range and range rate were weighted at 500 meters and 1 cm/sec, respectively, and the ΔDOR at 1 meter.

The three independent flyby solutions were evaluated by comparing the consistency of the estimates, their relative statistics, and the sensitivity of the solutions to unmodeled error sources and to filter strategy. The quality of the fit to the observables, as given by the data residuals, was also used as a criterion. A consider covariance was computed for each solution by JPL based on considering the effect of a correlated 12-by-12 Earth–Venus ephemeris covariance and the uncertainty of the JPL station locations. No a priori information was available on the uncertainty of the Soviet station locations or on the ranging bias errors. Table 2 summarizes the filter model and data weight assumptions.

The consistency of the Vega solutions was compared using the combined solution as a reference. The criteria for this comparison were the RSS differences in position and velocity during the 46-hour balloon lifetime. Figures 1 and 3 display the RSS differences between the solutions. Corresponding consider statistics for the three solutions are plotted in Figs. 2 and 4.

A. Vega-1 Solutions

A comparison of the Soviet solution and the combined solution for Vega-1 (Fig. 1) shows that the addition of VLBI data to the Soviet two-way range and doppler solution changes this solution by less than 5 km and 3 cm/sec. Expressing the components of this difference in solutions in a plane-of-sky frame shows that the difference is largely due to the components in the plane perpendicular to the Earth–Venus direction (i.e., plane-of-sky components). The complementary information content of the two-way and ΔDOR data is illustrated by these solution differences. For the combined solution, the radial component (i.e., along the Earth–Venus line) is determined by the two-way data and the angular (plane-of-sky) components by the ΔDOR.

The agreement between the two solutions is consistent with the consider statistics for the solutions given in Fig. 2. During the 46-hour span, the maximum one-sigma position and velocity errors for the Soviet solutions were 12 km and 10 cm/sec. For the combined solution, the maximum uncertainties were 4 km and 5 cm/sec. Delta DOR residuals with respect to the combined solution had a one-sigma error of 0.27 meter, which translates into a 3.4-km error at Venus distance.

The behavior of the position and velocity errors (Figs. 2 and 4) as a function of time is characteristic of the error focusing effect due to the Venus flyby. Position errors are at a minimum and velocity errors are at a maximum at closest approach. Beyond periapsis, the position errors increase linearly to the end of the data arc due to a constant velocity error. Unmodeled errors in the Earth–Venus ephemeris, which constituted the dominant consider error source, contributed an error of less than 8 km and 7 cm/sec to the Soviet solution. The sensitivity to unmodeled ephemeris errors is reduced to less than 1 km and 1 cm/sec by combining the ΔDOR data with the two-way data. Station location perturbations were found to be negligible.

The JPL solution based on using one-way data differs from the combined solution by at most 14 km and 26 cm/sec, with the dominant component of this difference in the radial direction. For the JPL solution, this component is determined by the one-way doppler. By treating the bias and drift as a random walk process, the information content of the doppler data is degraded. Maximum uncertainties for the JPL solution are 26 km at the end of the arc and 46 cm/sec at periapsis. The increased uncertainty is due to the random characteristics of the one-way doppler bias and drift models. The effect of ephemeris and station location errors is less than 1 km and 1 cm/sec.

B. Vega-2 Solutions

Because of the difference in approach geometry, the behavior of solutions and the statistics for Vega-2 are considerably different from those for Vega-1. The key to understanding the effect of approach geometry is based on expressing the Venus relative orbital parameters in a plane-of-sky frame. Table 3 lists the orbital parameters for the Vega-1 and -2 combined solutions. In the POS frame, the inclination of the orbit plane for Vega-1 is 107.22 degrees and for Vega-2, 90.98 degrees. Consequently, the Vega-2 orbit will appear as a disk viewed edge-on to an Earth-based observer. The orientation of this orbit plane about the Earth–Venus line cannot be well determined from Earth-based range and doppler. Essentially, the orbit can be rotated about this line and still yield the same range and doppler observations. The orientation of this plane is explicitly determined from the angle and angle-rate information derived from the ΔDOR data. Consequently, we can expect a significant improvement in the ill-conditioned doppler and range solution with the addition of VLBI data.

The Soviet solution (Fig. 3) differs from the combined solution by a maximum of 53 km and 61 cm/sec. Components in the plane-of-sky direction account for a position difference of 53 km and a velocity difference of 59 cm/sec. In the radial direction the maximum differences are 1.5 km and 18 cm/sec at periapsis. The latter difference decreases to less than 1 cm/sec 4 hours after periapsis.

The effect of the near singular approach geometry is manifested in the large position and velocity uncertainties (Fig. 4) for the Soviet solution. Maximum uncertainties are 48 km and 77 cm/sec, with the plane-of-sky components accounting for errors of 48 km and 75 cm/sec. Of this total, Venus ephemeris uncertainty contributes an error of 40 km and 50 cm/sec, and measurement errors result in a 24 km and 48 cm/sec error. When the ΔDOR data are included to form the combined solution, position and velocity uncertainties are reduced to 6 km and 32 cm/sec. For this combined solution, the perturbation due to ephemeris errors is less than 1 km and 2 cm/sec. The ΔDOR residuals with respect to the combined solution had a one sigma error of 0.24 meter which maps into a 2.4-km error at Venus at the time of encounter.

A comparison of the JPL one-way solution and the combined solution shows a maximum difference of 16 km and 32 cm/sec, with the largest difference, 14 km and 28 cm/sec, in the radial direction. The closer agreement between the JPL and the combined solutions reflects the significant contribution of the information content of the ΔDOR data. Maximum position and velocity uncertainties for the JPL solution are 24 km and 54 cm/sec.

C. Solution Sensitivity

1. **Ephemeris errors**. The sensitivity of the range and doppler solutions to ephemeris is a function of the flyby geometry. As the POS inclination approaches 90 degrees, the sensitivity to ephemeris errors increases. However, the addition of ΔDOR significantly reduces the sensitivity of the solutions to ephemeris errors, independent of the approach geometry.

2. **Range bias errors**. Range bias estimates for the Soviet ranging data were obtained for both combined solutions. The estimates for Vega-1 and Vega-2 were −0.33 km and 1.76 km, respectively. In both cases, the uncertainties of the bias estimates were 1.8 km. Estimating the range bias changed the combined Vega-1 solution by less than 1 km and 1 cm/sec. The Vega-2 solution changed by 1 km and 20 cm/sec at periapsis and 4 km and 0.8 cm/sec at the end of 46 hours. In both cases, the sensitivity to unmodeled ephemeris errors was reduced by estimation of the range bias. An unmodeled 500-meter range bias error would have resulted in perturbations to the statistics of the Soviet Vega-1 and Vega-2 solutions of 4 km and 12 km.

3. **Quasar locations**. The location of the quasar was estimated to reduce the sensitivity of the solutions to the dominant ephemeris errors and to remove any bias in the ΔDOR

residuals due to frame tie errors. Quasar location estimates derived from the two Vega solutions agreed to within 20 nanoradians in declination and 140 nanoradians in right ascension. Uncertainties were 110 and 320 nanoradians, respectively.

4. **Delta DOR data span**. The sensitivity of the combined estimate to the VLBI data arc was evaluated by a comparison of solutions based on a subset of the ΔDOR data. A Vega-1 solution was determined using only the ΔDOR data acquired from June 10–17, representing six of the ten available observations. Delta DOR data from June 14–17, comprising ten of the fifteen observations, were used for a Vega-2 estimate. A comparison of these solutions with the combined solutions using all the data showed a maximum difference of less than 1.5 km and 1.0 cm/sec. The consistency of the solutions was further demonstrated by the residuals of the VLBI data not used for the solution. No significant increase or trend was apparent in these pass-through residuals.

VI. Conclusions

Results of this analysis demonstrate the value of VLBI data for planetary flyby navigation. Solutions using the "sparse" Soviet two-way data combined with ΔDOR satisfied the accuracy goals of the Venus Balloon experiment. By complementing the two-way data, the use of ΔDOR data improved the accuracy of the Vega solutions and reduced their sensitivity to errors in the ephemeris, which was the dominant error source. The radial component of the solutions was determined by the two-way data and the plane-of-sky components by the ΔDOR. Based on the consider statistics, accuracies of 4 km and 5 cm/sec were obtained for Vega-1 and 6 km and 32 cm/sec for Vega-2. In the case of the ill-conditioned two-way solution for Vega-2, the ΔDOR data were explicitly required to satisfy the accuracy goals.

The results also demonstrate the feasibility of deep space navigation using listen-only or one-way data. The accuracy of the Vega solutions using one-way data was limited by the need to model the behavior of the oscillator instabilities as a random walk process. Even with these limitations, the one-way solutions differed from the "baseline" combined solutions by less than 14 km and 32 cm/sec and had a maximum uncertainty of 26 km and 55 cm/sec. A Voyager quality ultrastable oscillator would have yielded solutions using only one-way data with accuracies comparable to the combined solutions.

Acknowledgment

The authors wish to acknowledge the support provided by Dr. C. T. Stelzried for guiding the successful implementation, planning, and operation of the Venus Balloon effort.

References

[1] R. Z. Sagdeev, *et al.*, "The Vega Venus Balloon Experiment," *Science*, vol. 231, March 21, 1986.

[2] J. Ellis and T. P. McElrath, "Vega Pathfinder Navigation for Giotto Halley Encounter," *TDA Progress Report 42-87*, vol. July–September 1986, Jet Propulsion Laboratory, Pasadena, California, November 15, 1986.

[3] T. W. Hamilton and W. G. Melbourne, *Information Content of a Single Pass of Data From a Distant Spacecraft*, JPL Space Program Summary No. 37-39, vol. III, May 1966.

[4] J. Ellis, "Deep Space Navigation With Noncoherent Tracking Data," *TDA Progress Report 42-74*, vol. April–June 1983, Jet Propulsion Laboratory, Pasadena, California, August 15, 1983.

Table 1. Summary of Soviet and JPL tracking data

Data type	Vega 1	Vega 2
IKI 2-way data (daily 10-min passes)	June 9–14, 16–25	June 13–18, 20–29
JPL 1-way doppler (nearly continuous)	June 10, 08:40, to June 13, 07:30	June 14, 08:40, to June 17, 03:38
JPL ΔDOR		
Goldstone-Canberra baseline	June 10, 11, 17, 18, 24 (5 observations)	June 14, 15, 16 (2), 17, 20, 21, 28 (8 observations)
Goldstone-Madrid baseline	June 11, 12, 17, 18, 23 (5 observations)	June 14, 15, 16 (2), 17, 21, 27 (7 observations)

Table 2. Filter model assumptions

Variable	A priori standard deviation
Estimated parameters	
Spacecraft position	1×10^6 km
Spacecraft velocity	1 km/sec
Quasar right ascension	1×10^3 nanoradians
Quasar declination	1×10^3 nanoradians
Range bias	1×10^3 km
L-band one-way doppler bias	2×10^3 hertz
L-band one-way doppler drift	25 hertz/day
Process noise for stochastic parameters	
L-band one-way doppler bias	1 hertz
L-band one-way doppler drift	10^{-2} hertz/day
Consider parameters	
DSN station locations	
Spin radius	2 meters
Longitude	3 meters
Z-height	15 meters
Intercontinental baseline length	0.3 meter
Venus ephemeris	
Heliocentric position components	
Radial	1 km
Downtrack	30 km
Out-of-plane	8 km
Heliocentric velocity components	
Radial	1 mm/sec
Downtrack	0.1 mm/sec
Out-of-plane	4 mm/sec
Data weights	
C-band two-way doppler	1 cm/sec
C-band two-way range	500 meters
L-band one-way doppler	10 cm/sec
L-band ΔDOR	1 meter

Table 3. Venus relative orbital elements in plane-of-sky frame

Variable	Vega 1	Vega 2
Time (GMT)	June 11, 1985, 02:00	June 15, 1985, 02:00
Semi-major axis, km	−29521.75	−27461.66
Eccentricity	2.530010	2.111951
Inclination, degrees	107.2224	90.98203
Longitude of ascension node, degrees	84.24727	49.66605
Argument of periapsis, degrees	166.9286	166.4388
Mean anomaly, degrees	−10.69728	−16.22563

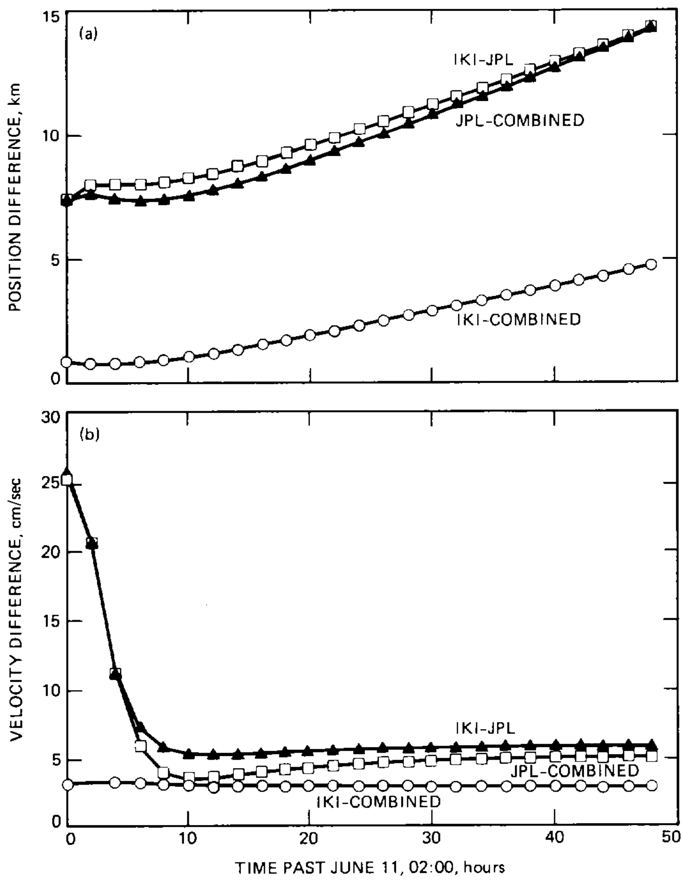

Fig. 1. Vega 1 (a) position and (b) velocity differences

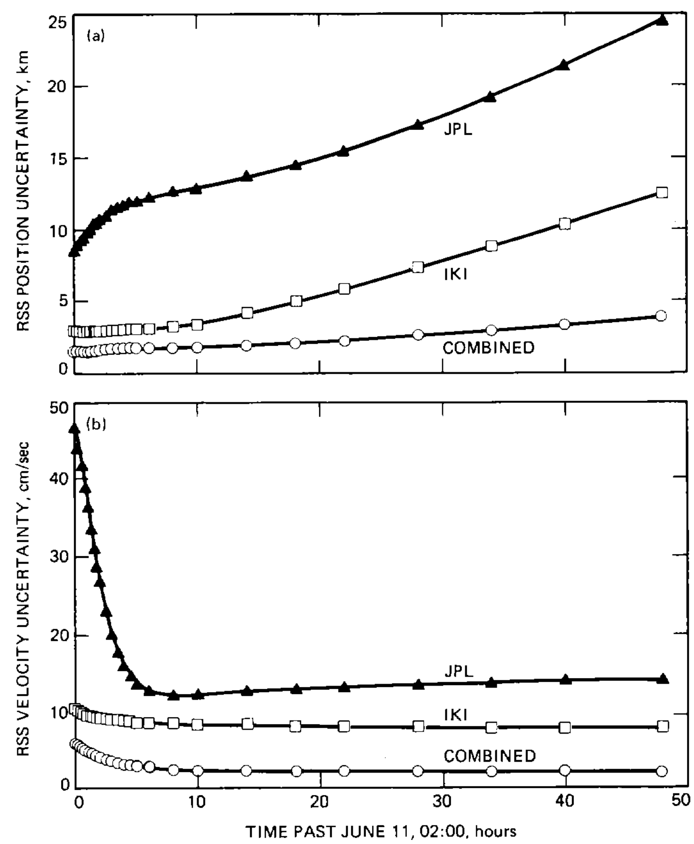

Fig. 2. Vega 1 RSS (a) position and (b) velocity uncertainties

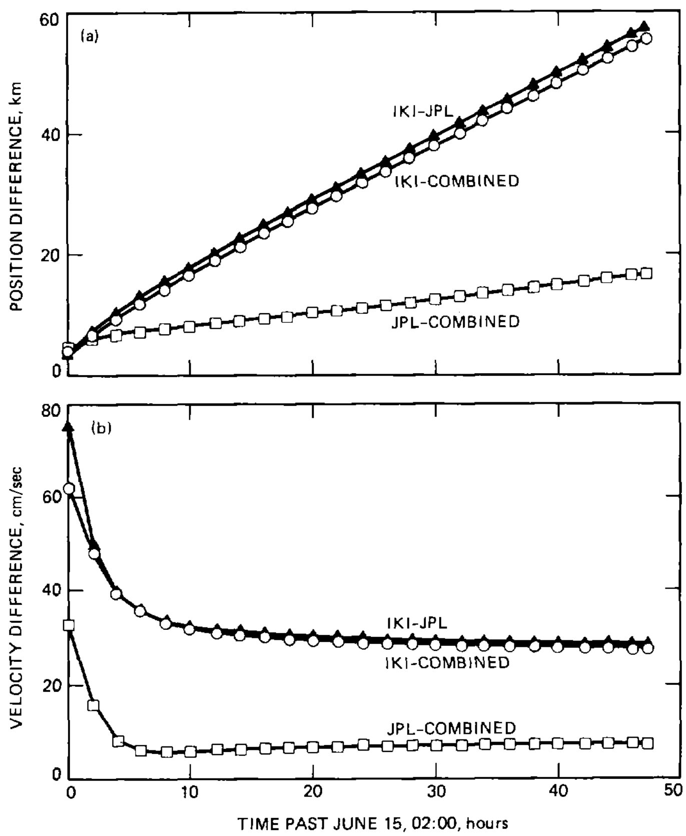

Fig. 3. Vega 2 (a) position and (b) velocity differences

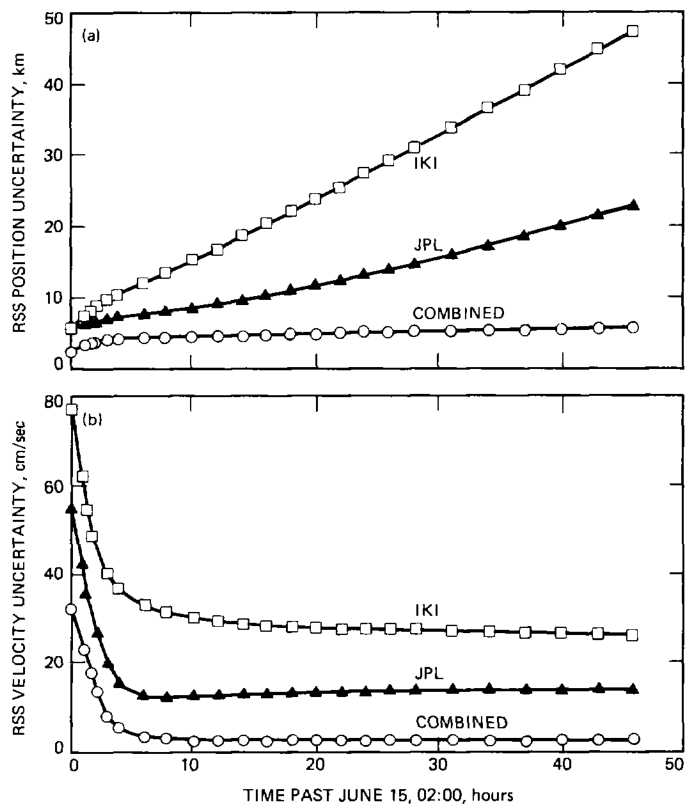

Fig. 4. Vega 2 RSS (a) position and (b) velocity uncertainties