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VEGA Pathfinder Navigation for Giotto Halley Encounter

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Results of the VEGA Pathfinder concept which was used to successfully target the European Space Agency's Giotto spacecraft to a 600 km encounter with the comet Halley are presented. Pathfinder was an international cooperative navigation activity involving USSR, European and U.S. space agencies. The final Giotto targeting maneuver was based on a comet location determined from optical data acquired by the earlier arriving Soviet VEGA spacecraft. Inertial pointing angles extracted from optical images of the comet nucleus were combined with a precise estimate of the VEGA encounter orbits determined using VLBI data acquired by NASA's Deep Space Network to predict the location of Halley at Giotto encounter. This article describes the VLBI techniques used to determine the VEGA orbits and shows that the insensitivity of the VLBI data strategy to unmodeled dynamic error sources resulted in estimates of the VEGA orbits with an accuracy of 50 km.

I. Introduction

In March 1986, five spacecraft encountered the comet Halley—gathering scientific data and transmitting the first optical images of a comet nucleus. This armada consisted of 2 identical Soviet Spacecraft VEGA-1 and VEGA-2, the Giotto mission launched by the European Space Agency (ESA) and the MS-T5 (Sakigake) and Planet-A (Suisei) missions launched by Japan's Institute of Space Science (ISAS). Encounter conditions for the five probes are summarized below.

Space Missions to the Comet Halley

Mission (Agency)	Flyby Date, 1986	Distance, km
VEGA-1 (USSR)	6 March	8,900
VEGA-2 (USSR)	9 March	8,000
SUISEI (ISAS)	8 March	151,000
SAKIGAKE (ISAS)	11 March	7,000,000
GIOTTO (ESA)	14 March	600

During the early mission planning phase, an Inter-Agency Consultative Group (IACG) was formed to seek ways of mutual cooperation among the Halley missions. Membership in the Group included delegations from ESA, Intercosmos of the USSR Academy of Science, ISAS and NASA. An outgrowth of this effort was the formulation of the Pathfinder concept in which onboard optical data acquired by the earlier arriving VEGA probes as they flew by the comet nucleus were used to improve the comet Halley ephemeris and aid the Giotto terminal navigation (Ref. 1). A schematic diagram of the concept is illustrated in Fig. 1 which depicts the relative flight paths and error ellipses of the VEGA spacecraft, Giotto and the comet at encounter.

The most stringent navigation requirement for the Halley mission set was the 500 km sun-side Giotto encounter. Because the accuracy of the comet location determined from earth-based astrometric data was considerably less than the spacecraft location accuracy determined from conventional radiometric tracking data, the comet ephemeris uncertainty was the dominant error in estimating the accuracy of targeting a spacecraft to encounter Halley. Estimates of the comet uncertainty ranged from 200 to 1500 km (one sigma). This situation was particularly significant to the Giotto mission which was designed to make direct in situ measurements of the comet's dust and gas composition and transmit television images of the nucleus, therefore requiring both a close flyby and a target accuracy which would ensure a flight path on the sun side.

The Pathfinder concept was a joint NASA, Intercosmos and ESA cooperative effort. The roles of the three agencies were as follows:

(1) The USSR Space Research Institute (IKI) provided ESA with the inertial camera pointing angle data from the VEGA comet flybys. The 3-axis stabilized VEGA spacecraft were equipped with a TV system which automatically detected and tracked the comet during the encounter phase. Inertial comet pointing angles (right ascension and declination) were extracted from the TV system for a two hour period at each encounter. To use this information, it was necessary to determine the location of the VEGA probes at the time of comet encounter (Refs. 2–4).

(2) NASA's role was to track the VEGA probes using Very Long Baseline Interferometry (VLBI) techniques and precisely estimate the VEGA encounter orbit. It was recognized that estimates using conventional two-way range and doppler, as employed by IKI, could not achieve the level of accuracy required for Pathfinder. However, this level of accuracy could be met using VLBI data acquired by NASA's Deep Space Network (DSN) (Refs. 5, 6). NASA's Jet Propulsion Laboratory (JPL) had pioneered the use of VLBI for deep space navigation of the Voyager probes and had applied the technique to determine the Venus relative orbits of the VEGA probes for the Venus Balloon Experiment in June 1985.

(3) The final Giotto target maneuver, executed two days before the Halley encounter, was based on an updated comet ephemeris determined by ESA using the IKI Pathfinder camera information and the NASA VLBI orbit estimate combined with earth-based astrometric observations.

Pathfinder required a stringent timeline for the exchange of information—especially to ensure that the results from the March 9th VEGA-2 encounter were available in sufficient time for the March 12th Giotto maneuver. A technical team was formed to implement this concept consisting of members from ESA, IKI and JPL. The team prepared a series of documents (Refs. 7–9) describing the project requirements, data interfaces and operations schedule. Test activities were defined and executed during the Venus-Halley cruise phase to verify the compatibility of models, test the data interfaces and simulate operations during the encounter phase.

The critical technical activities of the Pathfinder project occurred during the 48 hour period following each VEGA Halley encounter. The DSN concluded its tracking of the VEGA spacecraft on March 4th, and VEGA orbit solutions using the DSN VLBI data were determined independently by JPL and IKI, compared and transmitted to ESA. After each VEGA flyby, camera images were transmitted to IKI and direction angles from the VEGA probe to the comet nucleus were computed and relayed to ESA within 24 hours. The position of the comet nucleus as computed by both IKI and ESA using the comet angle data and VEGA VLBI orbits agreed to within 30 km. Pathfinder reached a successful conclusion on March 11 when ESA and IKI agreed on a final comet nucleus position and estimated the Giotto-Halley target line accuracy to be 40 km. Based on this information, the Giotto Science Working Team recommended targeting Giotto to an encounter at 500 km + one sigma (40 km) from the nucleus and 20 degrees below the comet-sun line. The one sigma error was added to increase the probability of a flyby distance greater than 500 km. A velocity change of 2.5 meters/sec was executed by ESA on March 12th to achieve the desired target point.

Results from the VEGA Pathfinder were not only critical for targeting the Giotto encounter but provided the basis for improving the observational model used to process the ground-based International Halley Watch (IHW) data. The discrepancy between the IHW and VEGA-1 Pathfinder comet Halley ephemeris was 248 km in the Giotto target plane. Based on this difference, Giotto maneuver planning was delayed until the VEGA-2 Pathfinder results were available. The VEGA-2 results essentially confirmed the VEGA-1 Pathfinder estimate. The final Giotto target maneuver was based on a comet Halley ephemeris update using the combined Pathfinder data. Upon subsequent analysis, the IHW post-perihelion astrometric data was revised to account for a significant offset between the comet center of light and center of mass. Once this effect was modeled in the IHW data, the Pathfinder and IHW ephemerides agreed to within 50 km in the Giotto target plane.

This article describes the results of the VEGA Pathfinder effort. The principal focus is on the VLBI techniques and the results of the VLBI orbit determination.

II. DSN VLBI Tracking

A. The VLBI Observable

The VLBI technique uses two widely separated tracking sites to simultaneously receive the wideband signal broadcast by the VEGA probes. As shown in Fig. 2, cross correlation of the signal furnishes a precise measure of the difference in arrival time of the signal at the two stations–which determines the angle between the interstation baseline and the source. By alternately tracking the VEGA probes and an angulary nearby extragalactic radio source (EGRS) or quasar, whose location is known, a doubly differenced measurement is formed in which common errors are canceled. This data type is called delta Differential One Way Range or ΔDOR. Differencing the EGRS and VEGA signals cancels errors due to clock synchronization, transmission media and platform parameter uncertainty, with the degree of cancellation dependent on the probe-source separation. Two nearly orthogonal baselines are required to resolve the geocentric right ascension and declination of the source. For DSN VLBI, this situation is satisfied by the Goldstone-Canberra and Goldstone-Madrid baselines.

B. DSN Implementation and Operations Support

The VEGA mission consisted of a Venus flyby phase and a Halley encounter phase. In mid June 1985, each spacecraft encountered Venus and successfully released an entry probe and a wind-measuring balloon into the Venus atmosphere. Post Venus encounter maneuvers were executed following the flyby to target the probes to a March comet encounter. The VEGA spacecraft and the ballons 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 specifically for the Venus Balloon Experiment to be compatible with the reception capabilities of an international network of 20 radio observatories. Conventional (two-way) tracking and commanding of the VEGA spacecraft used a C-band frequency at approximately 6 GHz.

The balloon experiment was a cooperative venture of the Soviet Union and France. The international network, which included the DSN 64 meter subnet, was organized by the French space agency Centre National D'Etudes Spatiales (CNES) to receive the one way L-band signal broadcast by both the VEGA probes and the balloons during the 48 hour balloon lifetime. The DSN modified the 64 meter antenna subnet to receive this L-band signal. An L-band microwave feed horn subsystem was mounted on the 64 meter antennas and a low noise amplifier and frequency upconverter were configured to convert the L-band spectrum to a DSN compatible S-band signal for input to the S-band microwave subsystem. The DSN L-band capability was used for the Venus Balloon Experiment and for the Pathfinder operations.

The VEGA L-band signal consisted of either a pure carrier or two subcarriers separated by 6.5 MHz. The two subcarrier tones were transmitted for half hour periods every two hours. This signal was commanded on and off by a Soviet tracking station. Consequently, for Pathfinder operations transmission times were explicitly coordinated between IKI and JPL to ensure that the tones were transmitted during the interval that the two DSN stations simultaneously viewed the spacecraft.

A program to construct an L-band catalog of natural radio sources to be used for the VEGA VLBI observations was organized by the DSN. This consisted of selecting known sources from the S/X-band VLBI catalog that were in the vicinity of the VEGA flight path and validating that the source structure and correlated flux density were suitable at L-band. The locations of the sources relative to the VEGA orbits are plotted in Fig. 3.

III. VEGA VLBI Orbit Determination

A. Data Processing Strategy

Both JPL and IKI independently determined the VEGA flyby orbits using the DSN ΔDOR data acquired during the encounter phase. VLBI observations from Goldstone-Canberra and Goldstone-Madrid baselines for both spacecraft were acquired weekly in December 1985 and approximately twice per week starting in February 1986. This consisted of 3 observing sessions in December, 7 in February and 3 in March. The final VLBI observations for VEGA-1 were acquired on March 3 (Encounter–3 days) and for VEGA-2 on March 4 (E–5 days). A typical VLBI observation session from a single baseline consisted of a EGRS, VEGA-1, VEGA-2, and EGRS scan sequence with 7 minute scans for each spacecraft and 7 minute scans for the natural radio sources.

IKI orbit estimates were determined by fitting the IKI two-way range and doppler data and DSN ΔDOR observations. Because the IKI tracking philosophy consisted of acquiring short (20 minute) passes of two way data twice per week from two tracking sites, the estimate using only two-way data required long arcs to achieve a reasonable degree of accuracy and did not result in a consistent estimate. For this reason, IKI chose to use the ΔDOR solutions for their own encounter planning. The JPL orbit estimates were based on a combination of ΔDOR measurements and geocentric range and range-rate measurements. The latter were constructed from IKI state vector information and two-way range and doppler residuals with respect to this state. Typically, one pair of geocentric observations were included biweekly.

The criterion for formulating a data processing strategy to fit the data was to select a strategy which would be insensitive to unmodeled dynamic error sources. In particular, JPL was not always informed about spacecraft events which could have had an effect on the orbit estimates. Soviet experts indicated that velocity variations could be expected due to attitude control maneuvers of 1 cm/sec over 1 day and that the solar pressure constant could be in error by 15 to 20%. Also, IKI was having difficulty converging to a consistent solution with long arcs of two-way data and the values of the solar pressure constant estimated from such arcs differed considerably from the theoretical value. IKI attributed the solution inconsistency to unmodeled nongravitational effects such as frequent attitude maneuvers. In addition, for VEGA-1 a final Halley target maneuver of approximately 18 meters/sec was executed February 10 (Encounter–24 days) with an execution error estimate of 1 meter/sec. An a priori maneuver estimate of the delta-V's was provided by IKI. No additional encounter maneuver was required for VEGA-2.

Because of the concern with unmodeled dynamic error sources, JPL preferred to rely on short arc solutions which tend to be less sensitive to such errors. For short arc solutions the accuracy is dominated by the measurement error while for long arc solutions dynamic errors can be expected to dominate. The JPL solution strategy was based on selecting the arc length and estimated parameter set which simultaneously yielded the best fit to the observations and minimized the consider covariance. Parameters which influenced the uncertainty of the estimate but could not be adequately determined by the filter were included or considered in computing the statistics of the estimated parameters.

For the maneuver-free VEGA-2 arc, the baseline strategy was to fit the February–March data arc (E-35 to E-5 days) and estimate state only. Solar pressure acceleration errors were considered in computing the statistics of this solution. Because of the VEGA-1 maneuver at E-24 days, the VEGA-1 solution was based on fitting data starting in December (E-91 to E-3 days) and estimating state, solar pressure and maneuver components.

All solutions assumed a ΔDOR data weight of 1 meter, geocentric range of 10 km and range-rate of 0.1 meters/sec. The ΔDOR error model was comprised of systematic and random error sources. The random errors included station oscillator errors, dispersive instrumental phases errors and SNR for the spacecraft and quasar signals. Tropospheric and ionospheric errors were combined into individual bias errors for each baseline. The natural radio source position error consisted of a frame tie error which characterized the uncertainty of the quasar catalog reference frame with respect to the planetary FK-4 frame and a relative error which described the uncertainty of quasar locations within the radio source reference frame. The 250 nanoradian frame-tie uncertainty was based on an estimate of the error derived from the VEGA Venus flyby solutions for the Venus Balloon Experiment. Quasar position errors and ΔDOR bias errors were treated as consider parameters in computing the statistics of the solutions. Table 1 summarizes the filter model assumptions.

B. Solution Convergence

Solution convergence was evaluated by plotting the B-plane estimates as a function of the data termination time. Figure 4 displays the sequence of VEGA-1 and VEGA-2 B-plane solutions with respect to the final converged solution. The one sigma error ellipses are also plotted for each solution. Only the postmaneuver solutions are plotted for VEGA-1 with tracking data arcs terminating at E-3 days, E-8 days and E-15 days. The comparatively large uncertainty at E-15 days reflects the uncertainty in the estimates of the maneuver at E-24 days. VEGA-2 solutions based on data from E-35 days to E-5 days, E-12 days and E-19 days are plotted in Fig. 4(b). Rapid convergence to the final solution is attained in each case. The final solution uncertainty, as will be shown later, is dominated by the frame-tie error.

C. JPL-IKI Final Orbit Determination Results

Solutions computed using the baseline strategy were evaluated by comparing them with estimates derived using alternative procedures. Figure 5 displays the JPL and IKI comet-relative B-Plane solutions and corresponding one sigma consider error ellipses with the origin of each plot at the JPL baseline solution. The B-Plane values are computed with respect to JPL Halley comet ephemeris (DE118) HL39. The effect of comet ephemeris uncertainty is not included in the statistics. The nominal long-arc VEGA-1 solution is compared with the IKI solution and a shorter post-maneuver arc (E-19 to E-3 days) case. Solar pressure acceleration errors were considered for all short arc cases. Because of the maneuver, the VEGA-1 estimates were relatively insensitive to the choice of strategy with the JPL and IKI solutions agreeing to within 15 km in B.R and 5 km in B.T. The VEGA-1 encounter maneuver was determined with an accuracy of

0.03 meters/sec and the solar pressure with an accuracy of 10% of the nominal value. For VEGA-2, the nominal short arc solution is compared with the IKI solution and a long arc case (E-95 to E-5 days). Although the uncertainty of the estimate decreased for the long arc VEGA-2 case, the ability to fit the ΔDOR data degraded. The baseline JPL and IKI VEGA-2 solutions differed by less than 5 km. However, the long arc solution, which was more sensitive to unmodeled dynamic errors, differed from the short arc case by 37 km in B.R and 6 km in B.T.

The effects of the individual error sources on the encounter statistics are plotted in Fig. 6. The errors are expressed in a geocentric reference frame with one axis along the earth-spacecraft direction and the other two orthogonal axes in the right ascension and declination directions. The two angular components are directly determined by the ΔDOR data and the geocentric range by the quasi-geocentric range data. The limiting error is due to the 250 nanoradian radio-optical frame tie uncertainty.

The ΔDOR residuals for the JPL solutions are displayed in Fig. 7. Residuals for both solutions have a one-sigma standard deviation of 0.6 m. The residuals were corrected for tropospheric but not ionospheric calibration errors. Tropospheric corrections were based on a standard wet and dry component model for the DSN stations. Attempts to correct the data for ionospheric using Faraday rotation data yielded inconsistent results—which may reflect on the quality of the corrections derived from the Faraday data. Including the ionospheric corrections decreased the VEGA-1 residual errors by 30%, but increased VEGA-2 residuals by 20%. The change to the baseline solutions was insignificant.

The standard deviation of the geocentric range and range-rate residuals were 3.1 km and 0.55 cm/sec for VEGA-1 and 1.6 km and 0.3 cm/sec for VEGA-2.

D. Attitude Control Maneuver Sensitivity

Throughout the approach phase frequent attitude maneuvers were executed to maintain the spacecraft orientation. The sensitivity of the baseline orbit estimates to such effects was investigated by assuming that the dynamics were corrupted by gaussian white noise accelerations of 1.0×10^{-10} km/sec^2 acting along each axis of the spacecraft. A batch sequential filter and smoother procedure was used to estimate the stochastic accelerations assuming a 7 day batch size. The results are summarized in Table 2.

The net effect of including the stochastic accelerations was to improve the fit of the ΔDOR data without significantly affecting the solution. The VEGA-1 solution is less sensitive to stochastic acceleration effects due to the maneuver. The relative insensitivity of the solutions to stochastic accelerations demonstrates the strength of the information content of the ΔDOR data. With conventional two way doppler and range a long arc would have been required to determine the orbit. The use of ΔDOR enabled the solution to be determined by a short arc which is less sensitive to unmodeled acceleration effects.

IV. Pathfinder Results

The VEGA VLBI orbit determination was just one element of the Pathfinder concept. This information was combined with inertial camera pointing angle data to determine the comet ephemeris at the time of Giotto encounter. Figure 8 reconstructs the situation prior to the final Giotto trajectory correction maneuver (TCM) on March 12th. The comet relative B-Plane locations of Giotto (prior to this TCM) are plotted based on the following assumptions:

(1) JPL Halley Comet Ephemeris (DE118)HL39 which included IHW postperihelion astrometric data to February 17. This essentially was the ephemeris used at JPL prior to any Pathfinder results and was similar to the ephemeris used at ESA.

(2) The comet ephemeris as determined from the VEGA-1 Pathfinder results (PF01).

(3) The comet ephemeris resulting from the combined VEGA-1 and VEGA-2 pathfinder results (PF03). This was designated as the official combined VEGA-1 and VEGA-2 solution. The combined solution (PF05) which was used for the encounter TCM is also plotted.

(4) The JPL Halley Comet Ephemeris (DE118)HL45 which was constructed after the VEGA-1 Pathfinder results were available and accounted for a comet center-of-light center-of-mass offset of 1100 km at 1 AU.

As can be seen from this figure, the VEGA-1 Pathfinder result differs from the pre-Pathfinder JPL ephemeris by 229 km. ESA reported a difference of 248 km from their 'pre-Pathfinder' ephemeris. Based on this difference, Giotto maneuver planning was delayed until the VEGA-2 results were available. The combined VEGA-1 and VEGA-2 solution (PF03) was within 50 km of the VEGA-1 results with the largest difference observed in the B.R component. When the JPL ephemeris was subsequently updated (HL45) to include a center-of-light center-of-mass offset for postperihelion observations, the difference between the JPL and PF03 target plane state was reduced to 27 km.

Two days prior to the Giotto Halley encounter, the final decision was made to target Giotto to a sunward side encounter at 500 km + one sigma (40 km) from the nucleus and 20 degrees below the sun line. The 40 km uncertainty is a formal predicted uncertainty, as determined by ESA (Ref. 10), which includes the Pathfinder determination of the comet location and spacecraft errors. The predicted B-Plane aim point was B.T = -507.4 km and B.R = -184.7 km. Based on pre- and postencounter tracking data and the best estimate of the encounter parameters was B.T = -545 ±30 km (1-sigma) and B.R = -275 ±80 km.

The Pathfinder results not only played a critical role in the final Giotto navigation but also influenced the development of the comet observation model. The ability to fit earth-based observations of the comet Halley collected after the comet's perihelion passage on February 9th, 1986 degraded significantly. A systematic bias of 2 arcseconds was observed in the astrometric measurements collected following perihelion which translated into a position error of 1500 km. This was believed to be largely due to the center of light, center of mass difference caused by the increased activity of the comet and the short term fluctuations in this activity. Since this bias lies along the sun-comet vector, its effect is not separable from the comet nongravitational accelerations and consequently is nonobservable. The consistency of the Pathfinder solutions confirmed the need to model a bias to account for the light shift and aided in the development of an empirical bias model for processing the ground-based observations.

V. Conclusions

Based on the results of the error analysis and our observations of the solution consistency, the maximum error in the Earth relative determination of the VEGA encounter states was 50 km. In terms of comet relative B-plane components the critical B.T direction was determined to better than 30 km. Without the DSN VLBI data, it is unlikely that short arc solutions could have been employed to achieve this level of accuracy.

The Pathfinder encounter essentially provided the comet information required for targeting Giotto to a close sun-side comet encounter. The estimate of the comet location at the time of Giotto encounter was improved and the uncertainty of this estimate was significantly reduced. A premaneuver decision was reached by the Giotto Science Working Team to target Giotto to a 500 km plus one sigma encounter distance. The ESA determination of this one sigma uncertainty using the Pathfinder data was approximately 40 km. A preliminary assessment of the Giotto camera data showed that Giotto achieved a comet encounter at a distance of between 580 and 605 km.

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Table 1. Nominal filter error model assumptions

Parameter	A Priori Standard Deviation	
Estimated Parameters	VEGA-1	VEGA-2
Position	1×10^5 km	1×10^5 km
Velocity	10 km/s	10 km/s
Maneuver	1 m/s	–
Solar Pressure Acceleration	2×10^{-10} km/s^2	–
Consider Parameters		
Solar Pressure Acceleration	–	15% (0.6×10^{-11} km/s^2)
EGRS-Radio Frame Tie	250 nrad	250 nrad
EGRS Relative Location Error	50 nrad	50 nrad
ΔDOR Bias Goldstone-Canberra	0.28 m	0.28 m
ΔDOR Bias Goldstone-Madrid	0.60 m	0.60 m

Table 2. Effect of stochastic accelerations

	ΔDOR 1-Sigma Error, m	Change to Baseline Solution		
		B.R, km	B.T, km	S, km
VEGA-1	0.3	–8.4	5.6	7.0
VEGA-2	0.4	–24.5	2.0	5.3

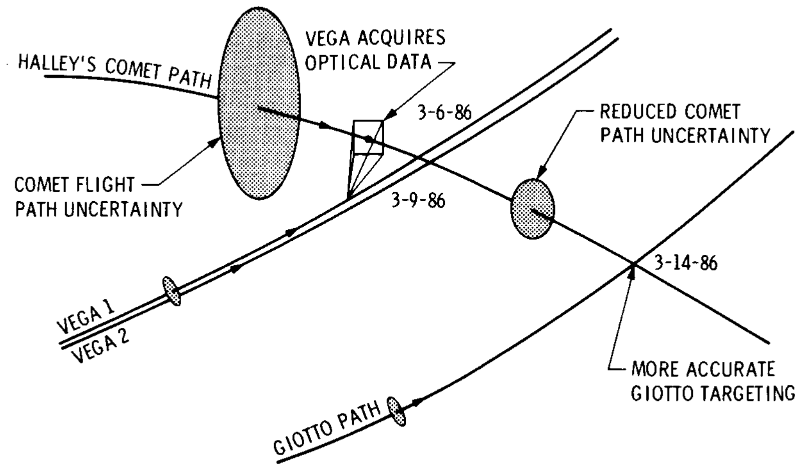

Fig. 1. Schematic diagram of Pathfinder concept

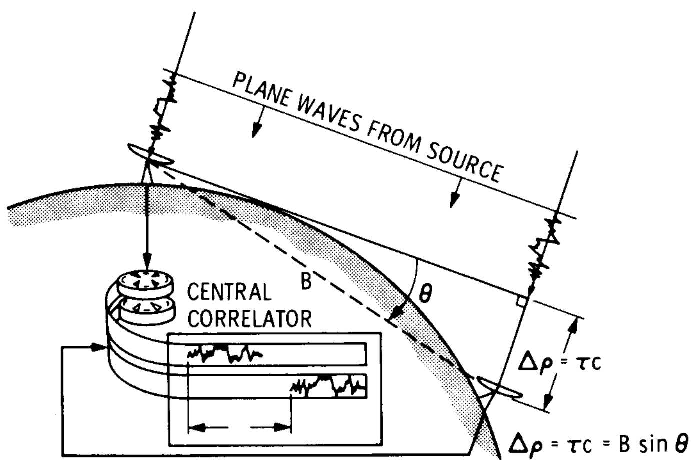

Fig. 2. VLBI observable

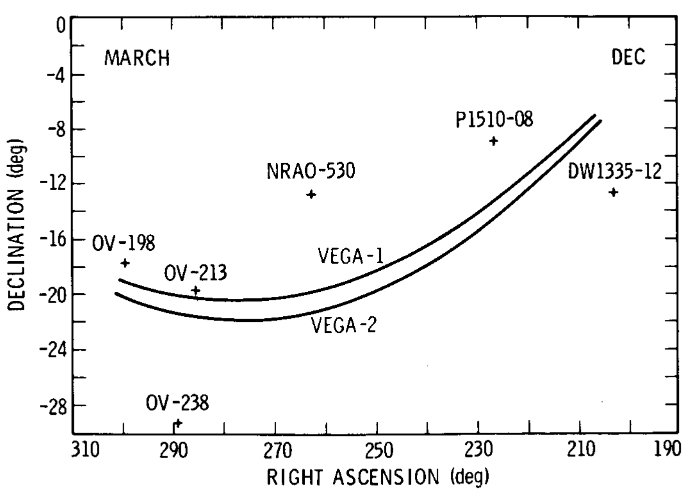

Fig. 3. VEGA L-band radio sources

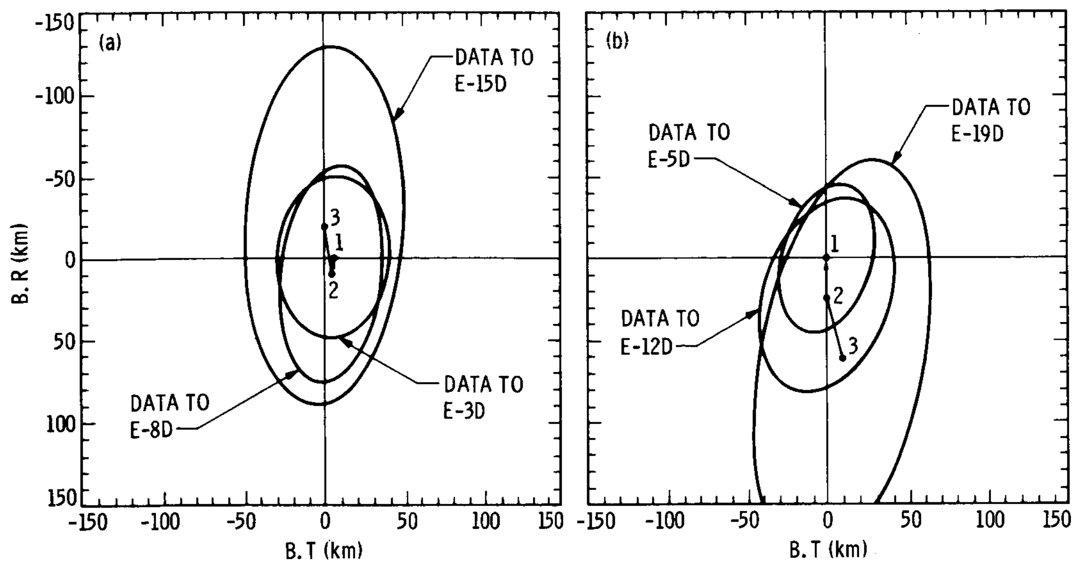

Fig. 4. B-Plane covergence: (a) VEGA-1, (b) VEGA-2

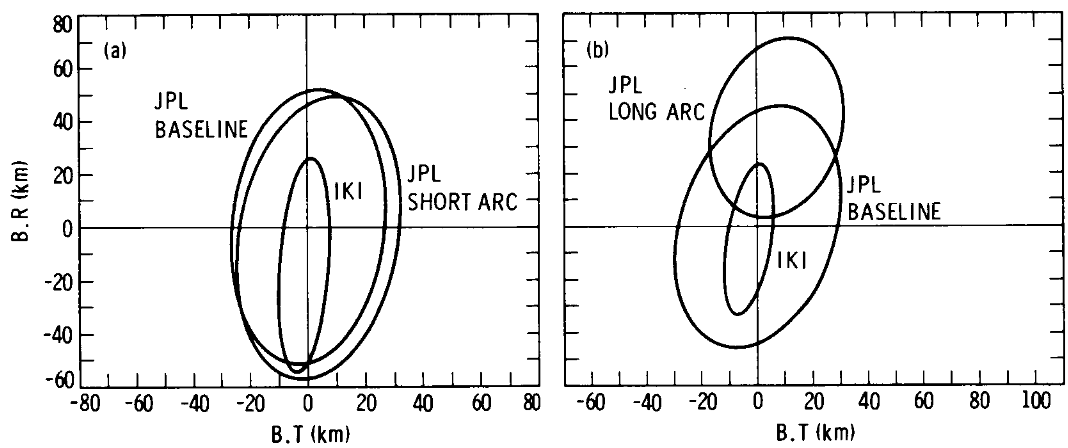

Fig. 5. Final B-Plane results: (a) VEGA-1, (b) VEGA-2

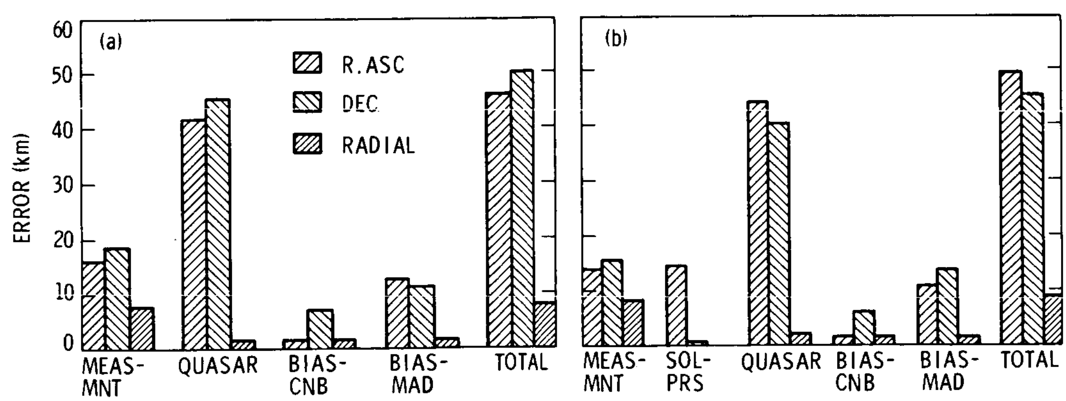

Fig. 6. Error sources: (a) VEGA-1, (b) VEGA-2

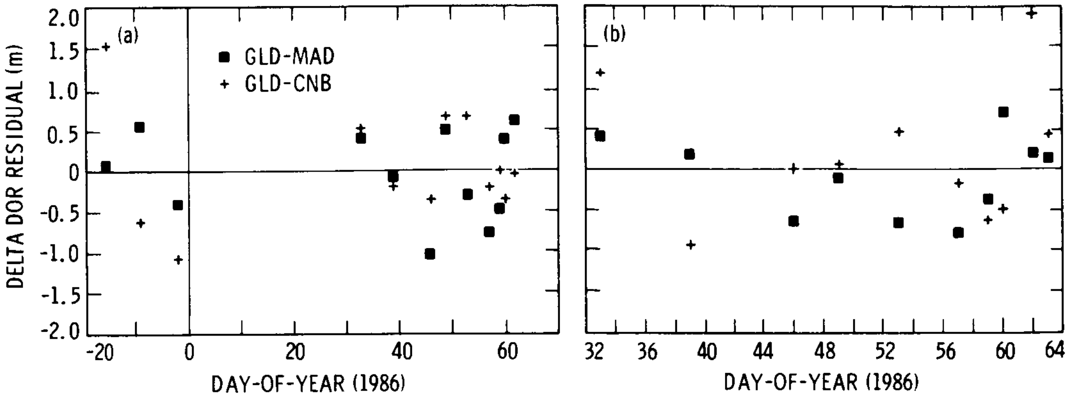

Fig. 7. The ΔDOR residuals: (a) VEGA-1, (b) VEGA-1

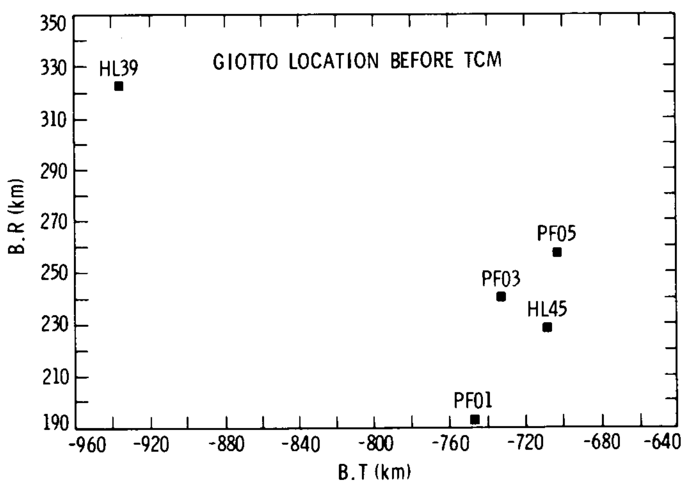

Fig. 8. Giotto B-Plane