Giotto Navigation Support

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Cooperative efforts between NASA and the European Space Agency (ESA) in supporting the flight of Giotto to Halley's Comet included prelaunch checks of ESA navigation software and delivery of validated DSN radio metric tracking data during the mission. Effects of drag from passing through the coma are seen in data received pre and post encounter. The post encounter Giotto trajectory provides a solar occultation in January 1988, prior to returning to the earth in 1990 for possible retargeting to yet another comet.

The mission has not ended. Giotto survived the flyby, not unscathed, but intact enough for retargeting to the earth and perhaps eventually to another comet. In the interim, opportunities to probe the solar corona, including a solar occultation are present. Plans for using VLBI techniques to improve orbit determination and hence the occultation science return, may be tested using Giotto in early 1987.

II. Pre-Flight Navigation Activities

Beginning more than two years before the Giotto launch a series of navigation software workshops were held between JPL and ESOC to define and run test cases to verify that the ESOC orbit determination program could successfully process Giotto radio metric data. The tests concentrated on basic orbit determination functions:

(1) Integration of the spacecraft trajectory and variational equations.
(2) Light time solution, time transformations and polar motion.
(3) Computation of observables and partial derivatives.
(4) Differential correction, covariance matrix and mapping.
These functions were tested using the Voyager 1 trajectory and DSN radio metric data acquired from it when the geometry was similar to the forthcoming Giotto encounter. This tracking data was initially sent to ESOC by magnetic tape and later transmitted over communication lines as tests of the system to be used for sending DSN radio metric data during the mission.

An important part of the software tests involved the choice of a planetary ephemeris. It is not only the source of position and velocity of bodies in the solar system, but also of nutation and precession of the earth and a host of astrodynamical constants such as body masses, the length of the astronomical unit and the speed of light. It defines the coordinate system for the dynamics of the spacecraft flight and dictates the values of station locations required to properly process radio metric observables. The one chosen for Giotto operations and hence these tests was JPL Development Ephemeris (DE) 118, which uses the Earth Mean Equator and Equinox of 1950 reference system. It would be the source of data for all solar system bodies other than Comet Halley, which was of no immediate consequence in these tests.

Serving as a standard of comparison would be the JPL Orbit Determination Program (ODP) (Ref. 1) first used in support of Mariner VI and VII and all space missions tracked by JPL since. The test cases were run on the JPL ODP and compared with the same case run with the ESOC ODP. All the JPL cases were run on a UNIVAC 1100 computer with a double precision word length of 18 decimal digits. ESOC used a SIEMENS computer with 16 decimal digits double precision. For Giotto operations JPL switched to a VAX 780, which has the same word length as the SIEMENS. Tests between the two JPL computers showed no navigation degradation for a Giotto type trajectory due to the shorter word length.

The testing began by matching the integration of the spacecraft trajectory between the JPL and ESOC programs. The reference trajectory was based upon a 2.5 month long Voyager 1 trajectory modified to include large spacecraft maneuvers and non-gravitational accelerations to enhance the detection of any possible differences between the two programs. Good agreement between ESOC and JPL was noted at 1 meter in position and 1.6E-5 m/s in velocity at the end of the integration.

Two Voyager 1 Doppler points were selected for use in a detailed computation check. Quantities carefully compared were time transformations, polar motion, light time solution, EME50 station location, antenna corrections, and troposphere modeling. The final agreement obtained for the computed observables was 0.0001 Hz S-band or approximately 0.007 mm/s, which indicated that the ESOC ODP could process DSN radio metric data adequately to support Giotto navigation.

Checking the partial derivatives of the observable with respect to spacecraft state, station locations, and polar motion parameters could not easily be done due to differences in the formulation of the filters of the JPL and ESOC programs. The ESOC program uses a current state filter while JPL uses an epoch state filter. Although it would have been possible to map the JPL partials to coincide with the formulation of the ESOC program, this was not done when good agreement between the programs was obtained in the solution for the spacecraft state programs (noted below).

A more comprehensive test of the ESOC program involved the estimation of spacecraft position and velocity using an eight day span of Voyager data. Differences in the estimates obtained by the two programs were 22 km in position and 20 mm/s in velocity. In view of Giotto navigation accuracy requirements of approximately 100 km (1-sigma), exclusive of errors in the comet ephemeris, these differences were considered acceptable for successful navigation. A portion of the difference might be attributed to data processing techniques. For example, polynomial representation of the data smooths it in a preprocessing step before use in the ESOC ODP. Differences between the epoch state filter used in the JPL ODP and the current state estimator employed in the ESOC program might also be a contributing factor although attempts were made to match the filters as closely as possible.

Mapping tests conducted using the above estimation case, involved only a translation in time without changing coordinate systems. These showed the same type of agreement as noted above. Complete test results are reported in an ESOC document, “Giotto Quality Control Document, Single Tests, Results of Orbit Determination Test Runs on Voyager Data”, Document GIO-QCD-3, Issue no. 2, F. Hechler and H. Muller, European Space Agency Operations Center, 15 March 1985.

Another orbit determination test involved a 90-day arc of radio metric data. The data was based upon the geometry of the Giotto-like Voyager 1 trajectory, but for extended software checking purposes used precisely known solar pressure, instantaneous, and finite maneuvers. Also present during the last month was a constant acceleration (gas leak). The data observation model also included troposphere effects and random data noise representative of that expected when the DSN would track Giotto. Since the trajectory was known exactly, it was possible to determine when the correct state had been recovered by the ESOC ODP in runs using intentionally mis-modeled a priori spacecraft states and/or non-gravitational force models. The ability to recover the correct spacecraft
The results of these tests indicated that ESOC should be
able to process DSN radio metric data acquired from Giotto.
This was indeed confirmed during the mission when differ-
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Other material presented by ESOC at a navigation workshop
following the first campaign included residuals of the combined
DSN and DSTS tracking data. To successfully process data
from both tracking networks it was necessary to determine the
location of the DSTS stations in the coordinate system defined
by the planetary ephemeris. Planetary Ephemeris DE 118 had
previously been used to determine the locations of the DSN
stations thereby enabling ESOC to estimate the DSTS loca-
tions while holding the DSN locations fixed. These locations
were then used for the rest of the mission, which would be
especially significant during the encounter campaign when
radio metric data from the two networks would again be
combined for determining the orbit and designing the final
trajectory correction maneuver for a successful encounter.

The marked similarity in results served as another verifica-
tion of ESOC’s ability to process DSN radio metric data, as
expected after all the software testing, and established confi-
dence for successful data processing during the critical en-
counter campaign when DSN data would again be received.

The second navigation campaign, supporting the encounter,
occurred from 1 to 12 March 1986 in which DSTS radio metric
data were again augmented with daily DSN radio metric track-
ing obtained from the 34-meter stations, DSS 12 and 42, and
the 64-meter stations, DSS 14 and 63. At the end of a day’s
tracking, data were validated with the JPL ODP and transmit-
ted via NASCOM to ESOC. Minimal comparison of ESOC and
JPL data analysis occurred due to the high activity associated
with this phase of the mission. A change in the spacecraft trans-
ponder configuration implemented much earlier in the cruise
phase caused the received 2-GHz (S-band) signal to be retrans-
mitted at 8.5 GHz (X-band). Table 2 shows a summary of the
JPL processing of the DSN data taken during this campaign.
The noise of the Doppler appears higher than for the first cam-
paign due to two passes of 60-second count time data that
could not be compressed. Figures 3 and 4 show plots of the
two-way Doppler and range residuals obtained with the JPL
ODP.

There was not a requirement for the exchange of navigation
results between JPL and ESOC during either of the campaigns.
The exchange following the first campaign occurred several
months afterwards and served only as a final check of ESOC’s
ability to successfully process DSN and DSTS radio metric
data. The DSN data taken during the encounter campaign
aided ESOC in estimating the trajectory of the spacecraft, now
that daily attitude maneuvers were occurring, in preparation
for the design of the final trajectory correction maneuver. The
last DSN pass of this campaign followed that maneuver and
helped provide verification of the achieved trajectory change.

B. Navigation Campaign Data Processing

Several interfaces were required between JPL and ESOC in
order for the DSN to successfully track Giotto and transmit
validated tracking data to ESOC. One of the unique features of
the system devised was the capability to directly access data
stored in the operations computer at ESOC from JPL.
DSN antenna pointing predicts, required to acquire the spacecraft signal, were generated from a Giotto trajectory integrated by the JPL ODP using initial conditions and solar pressure model obtained from a file in the ESOC computer. Although the conditions in this file were updated weekly, it was not necessary to actually update the predicts very often. In spite of daily attitude maneuvers and the final pre-encounter trajectory correction maneuver, analysis with these current states indicated that predicts generated from a December 11, 1985 state and solar pressure model were adequate to support the project throughout the remainder of the mission, including the encounter phase.

Validation of the DSN radio metric tracking data was performed using a Giotto trajectory generated from a current state and maneuver information obtained from ESOC computer files. The tracking data were prepared by compressing the Doppler to an ESOC specified count time and verifying the use of the correct station and spacecraft hardware delays for the range data. The JPL ODP was then used to validate the data, noting any blunder points to remove before transmission to ESOC.

The NASA Communications Network, NASCOM, was used as part of a communications network to transmit the validated data from JPL to ESOC where it was routed to the operations computer for use in navigation.

C. Encounter Estimate

An estimate of the spacecraft arrival time and position at Halley was derived at JPL from DSN radio metric data collected during the second campaign. Although there was no requirement to deliver these estimates to ESOC, this was done for our own information and then compared with the value obtained by ESOC. Due to the many facets associated with the daily attitude maneuvers and possibly other information known only at ESOC about the attitude behaviour of the spacecraft, one might not expect close agreement between the two solutions. Cause for disagreement in the solutions could also easily come from differences in the comet ephemerides used.

The JPL solutions were obtained with a simple least-squares batch filter, while modeling the maneuvers using data from the ESOC maneuver file. After examining the effects of estimating various sets of the daily attitude maneuvers and the trajectory correction maneuver (TCM), which occurred on 12 March around 01:30 UT, in combination with different a priori uncertainties, the choice was made to estimate 10 of the 12 daily maneuvers with an a priori uncertainty of 10 cm/sec and the TCM with an a priori uncertainty of 50 cm/sec. Data statistics for the residuals obtained from this solution are those shown previously in Table 2. JPL Planetary ephemeris DE 118 and the International Halley Watch comet ephemeris HL47 were used. This Halley ephemeris is derived from earth-based observations ending 24 March 1986 and includes a center of light of mass offset. The gravitational effect of the comet on the trajectory of the spacecraft was ignored. The analysis used the consider option to augment the covariance of the estimated spacecraft position for the effects of possible errors in the tracking station locations of 2 meters in distance from the spin axis, 3.0 E-5 degrees (approximately 3 meters) in longitude, and 20 meters in distance from the equator plane.

A predicted comet miss distance of 610 km with an uncertainty of 104 km was obtained. Augmenting this uncertainty for the assumed station location errors resulted in an uncertainty of 138 km. The predicted time of closest approach is 14 March 1986, 0h 2m 58.5s UTC with an uncertainty of 0.8 s which grows to 1.1 s with the consider parameters.

Analysis by ESOC (Ref. 2) using both pre and post encounter DSN and DSTS radio metric data and their comet ephemeris derived from Earth-based observations augmented with the Vega-1 and Vega-2 Halley observations also indicates that the actual miss distance was 610 km with an uncertainty of 40 km with a time of closest approach of 0h 3m 0.4s UTC.

D. Passing Through the Halley Coma

A drag effect attributed to Giotto passing through the comet's coma can be observed in pre and post encounter two-way DSN radio metric data. Figures 5 and 6 show changes in Doppler and range residuals obtained when an ESOC provided post TCM Giotto state was integrated forward and used to form residuals. The first post encounter data was obtained about 12 hours after closest approach and shows an offset of 9.4 Hz, X-band or 171 mm/sec in the Doppler, Fig. 5. This is independently confirmed from the slope in the post encounter DSS 14 range data, Fig. 6, which yields similar velocity change of 168 mm/s. (There was no pre-encounter range taken following the TCM.) A value for the total reduction in the spacecraft velocity can then be computed knowing that the earth direction is 44.2 deg from the velocity vector. The value derived for the total velocity, 238.5 mm/sec, agrees to within 4 mm/s with estimates made by T. A. Morley at ESOC from DSTS two-way tracking ("Braking Effect of Dust Impacts on GIOTTO at Encounter," T. A. Morley, European Space Operations Centre, 18 March 1986). Simple assumptions of inelastic impacts along the velocity vector and the conservation of momentum infer the total mass of the impact dust to be 2.0 grams. This is obtained assuming the velocity of the impacting dust to be 68.377 km/s and using the ESOC value (Morley) for the spacecraft mass of 573.886 kg. More thorough analysis by Morley using longer spans of DSN and DSTS pre and post encounter two-way radio metric data gave an estimate of 1.9 g.
Analysis of this same data by the Giotto Radio Science Team reported in Ref. 3 indicates that large uncertainties in the momentum multiplication factor arising from enhanced momentum transfer due to inelastic high-energy particle impacts reduces the total mass of the impacting dust to the 0.1–1 g. range.

The two-way radio metric data analyzed above was collected several hours either side of encounter and therefore cannot be used to probe the nature of the coma itself. One-way Doppler received throughout the encounter period, could be used for studies of the coma, but requires substantial analysis to extract meaningful information. Figure 7 shows three minutes of this data recorded at DSS 43. Some signatures in this data correspond with known particle impacts, but cycle slips are most certainly present and lock was lost during this interval. These all probably invalidate the large offset of approximately 17 Hz observed pre and post encounter. This offset is about a factor of four greater than the effect observed in the two-way Doppler discussed above which indicates the need for careful interpretation of this data. It appears that if any information about the coma is to be gleaned from the one-way data, it will require analysis of the open loop recordings, a task which is currently underway. One-way observations at Carnarvon and Parkes, Australia reveal similar signatures. There do not appear to be any plans to continue the analysis of these data.

IV. Post Encounter Trajectory and Possible Future Activities

Following the encounter a series of spacecraft maneuvers were performed which placed Giotto in a trajectory which would fly by the earth at about 20,000 km in July 1990 for subsequent retargeting to another comet. Following these maneuvers, daily communication from the DSTS to Giotto ceased, DSN communication having previously ended following the DSS 14 pass on 14 March. Giotto is in a hibernation state with only occasional communications planned (Ref. 4). The resulting trajectory contains an extended period of some 150 days during which the angular separation of Giotto and the sun will be less than 10 solar radii climaxing with a 5 day solar occultation in January 1988. Figure 8 shows Giotto relative to the sun during this 150-day period in a coordinate frame in which the trace of the Giotto trajectory as seen from the earth is plotted in a plane located at the sun and perpendicular to the fixed earth-sun line. The axes of the plot show the angular separation in right ascension and declination of the spacecraft from the sun. A perspective of the trajectory throughout the entire hibernation period can be seen in Fig. 9 in the same type of a plot. The horizontal axis, which serves as an approximate sun-earth-Giotto angle, indicates that Giotto is always within 70 deg of the earth-sun direction.

Two additional plots of general interest are the geocentric declination, Fig. 10 and right ascension, Fig. 11, covering the time span November 1986 to June 1988. Note that the solar occultation occurs near -23 deg declination while the June solar graze occurs at about +23 declination.

In anticipation of the interest surrounding the solar occultation and the need for accurate orbit determination in the presence of fairly frequent maneuvers, a VLBI experiment using Giotto is being studied for early 1987. Preliminary analysis indicates that this data combined with conventional radio metric observables can be very effective in determining the orbit in this environment. Results of this proposed experiment should be of interest to the Ulysses project which uses the same radio transponder and will be probing the solar environment also.
References


Table 1. DSN data summary for Campaign #1

A. Amount of Tracking Data Processed

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<th>Number of Points</th>
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<td>Received</td>
<td>Used</td>
<td>% Used</td>
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<tr>
<td>Doppler (F2)</td>
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<td>532</td>
<td>100</td>
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<tr>
<td>Range (PLOP)</td>
<td>511</td>
<td>139</td>
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(Actual amount used reduced to facilitate processing.)

B. Total Amount of Tracking Data Received

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<td>DSS 61</td>
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<td>S</td>
<td>298</td>
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<td>DSS 61</td>
<td>PLOP</td>
<td>S</td>
<td>74</td>
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\(^a\text{S = 2 GHz}\)

C. Data Statistics and Weights

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<td>Range (Plop)</td>
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Table 2. DSN data summary for Campaign #2

### A. Tracking Data Received

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### B. Total Amount of Tracking Data Received

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<sup>a</sup><em>S = 2 GHz; X = 8.5 GHz</em>

### C. Data Statistics and Weights

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<td>Range (PLOP)</td>
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Fig. 1. JPL and ESOC DSN Doppler residuals from Campaign #1
Fig. 2. JPL and ESOC DSN range residuals from Campaign #1
Fig. 3. JPL DSN Doppler residuals from Campaign #2

Fig. 4. JPL DSN range residuals from Campaign #2
**Fig. 5.** Post encounter velocity change observed in Doppler residuals

**Fig. 6.** Post encounter velocity change inferred from range residuals

**Fig. 7.** DSN Giotto encounter one-way Doppler residuals, 1-second count time
Fig. 8. Giotto relative to Sun October 1987 to June 1988

Fig. 9. Giotto relative to Sun April 1986 to April 1990
Fig. 10. Giotto EME50 declination November 1986 to June 1988

Fig. 11. Giotto EME50 right ascension November 1986 to June 1988