GIOTTO INTERPLANETARY ORBIT DETERMINATION

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ABSTRACT

GIOTTO was ESA's first interplanetary project and the European Space Operations Centre (ESOC) was responsible for the spacecraft's navigation. The development, testing and application of the orbit determination software are described. Emphasis is given to those characteristics specific to GIOTTO. The final targetting for a close fly-by of comet Halley is described in some detail.

Keywords: GIOTTO, Ranging, Doppler, Orbit Determination, Interplanetary.

1. INTRODUCTION

GIOTTO was launched on 2 July 1985 and after three revolutions in geocentric orbit, the firing of the MAGE 1S motor on 3 July at 19:25 placed the spacecraft into its earth escape trajectory. During the next three days in the Near Earth Phase (NEP), the tracking signals were received on board and re-transmitted initially via the fill-in antenna and later via the cardioid antenna. The fill-in antenna is off-set from the spin axis. By the afternoon of 6 July the High Gain Antenna (HGA) had been despun and pointed to earth one million km away. The Cruise Phase then began and for the rest of the mission the axis of the HGA, which is inclined 44°.3 from the spin-axis, was maintained earth pointing.

We describe here the determination of GIOTTO's orbit from the start of NEP through to encounter with comet Halley on 14 March 1986 (Figure 1) and up to hibernation of the spacecraft on 2 April 1986.

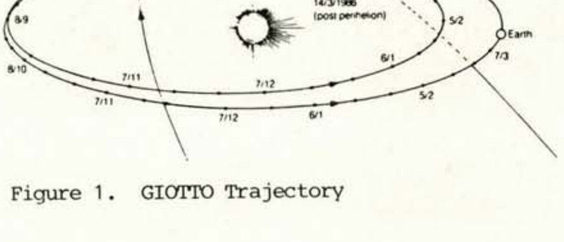

Figure 1. GIOTTO Trajectory

2. GROUND SYSTEM AND TRACKING DATA

Tracking support was primarily provided by the ESA-developed Deep Space Tracking System (DSTS), installed at Carnarvon in Western Australia and at Weilheim in the Federal Republic of Germany (Figure 2). During the mission there were three periods when the DSTS was augmented by radiometric data from the Deep Space Network (DSN) operated for NASA by the Jet Propulsion Laboratory (JPL).

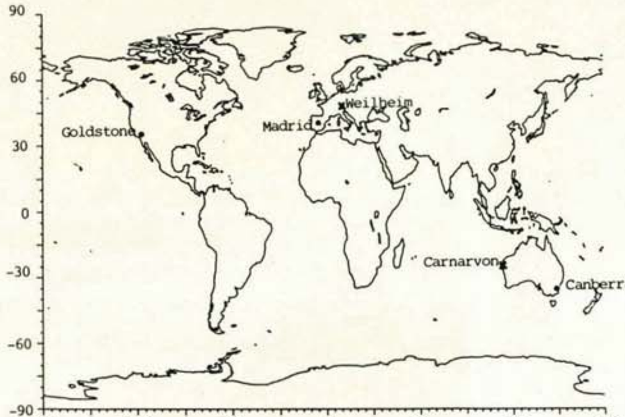

Figure 2. DSTS (x) and DSN (.) Station Locations

Range and Doppler (range-rate) data were obtained at all the stations. For orbit determination purposes, only coherent two-way data were used, i.e. transmission and reception of the signal by the same ground station and turn-around of the signal without change of phase.

The uplink carrier frequency was at S-band. A switchable transponder multiplication factor of either 240/221 or 880/221 allowed the downlink to be either S-band or X-band. From November 1985 onwards X-band was exclusively used. Earlier in the mission S-band was the usual downlink frequency though there were some exceptions due to operational reasons.

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2.1 DSTS

Carnarvon, with its 15 m. antenna (Ref. 1), was the prime station and tracked every day. Since GIOTTO's geocentric declination remained negative throughout the whole mission, daily passes of the order of ten hours were obtained. The passes using the 30 m. antenna at Weilheim were shorter and decreased during the mission as the spacecraft's declination became increasingly more negative (Figure 3). Weilheim tracked daily at the start and end of the cruise phase and twice weekly during the period from mid-July to December 1985.

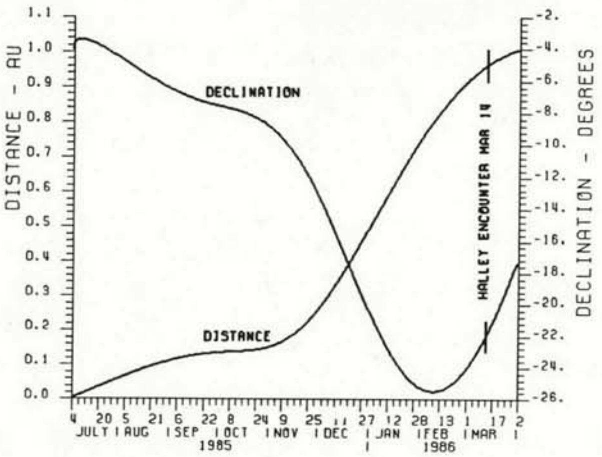

Figure 3. GIOTTO Geocentric Distance and Declination

2.2 DSN

The DSN was available under contract to ESA for telemetry reception, telecommand uplink and radiometric data measurement at pre-arranged times during the GIOTTO mission as well as for emergency telemetry or command support at any time. The tracking stations consist of subnets of 26, 34, and 64 m. diameter antennae in complexes located approximately every 120 degrees in longitude around the earth in both the northern and southern hemispheres. The complexes are located at Goldstone near Los Angeles, California; Canberra, Australia; and Madrid, Spain (Figure 2).

A 26 m. station established the first DSN-GIOTTO uplink and obtained radiometric data on 3 July 1985. DSN coverage continued until 6 August. DSN navigation data were also taken using the 34 m. subnet for two weeks in September 1985 and for the encounter phase beginning 1 March 1986.

Since simultaneous tracking from more than one station was not possible with GIOTTO, a full pass from either Carnarvon or Weilheim automatically meant a reduced pass from the neighbouring DSN station or vice versa.

2.3 Preprocessing

The DSTS provided ten Doppler measurements every second and one range measurement every ten seconds. Monitoring, smoothing and compression of the data were performed by means of a novel expanding memory polynomial filter (Ref. 2). Initially a Doppler count time of 1 minute was used, increased in August 1985 to 10 minutes. Range data were compressed to 2 or 3 observations per hour. Compression was usually performed at the station to limit the quantity of data which had to be transmitted to ESOC. There, the range data were corrected for the delays in the spacecraft and station hardware. Weather data were also collected at the stations and used at ESOC to correct for tropospheric effects.

The DSN performed their own compression and range data correction. JPL validated the data and removed any blunder points. Validation was made using their Orbit Determination Program (ODP) to generate a GIOTTO trajectory from state and manoeuvre information obtained from an ESOC computer file. One of the unique features of the JPL-ESOC interfaces was the capability for JPL to access directly data stored in the operations computer at ESOC. The NASA Communications network, NASCOM, was used to transmit the validated data from JPL to ESOC.

Before input to the ESOC orbit determination software, data derived from telemetry were used to correct all Doppler observations for the bias caused by the spin of the spacecraft (see subsection 6.1).

During the complete GIOTTO mission, a total of 16755 good quality tracking observations were filed and processed. On average, this represents just over 60 observations each day, with somewhat more than 75% being Doppler data.

3. ORBIT DETERMINATION METHODS AND SOFTWARE

Two orbit determination programs were developed at ESOC to run in double precision on the Siemens 7865 computer. Although they contain many common elements, they differed fundamentally in the estimation technique. Both programs estimate the spacecraft state (position and velocity components) plus, when desired, other uncertain parameters which include station locations, measurement biases, solar pressure and manoeuvre parameters.

The BATCH program differentially corrects apriori estimates to minimise the sum of weighted squares of residuals using a square root formulation. A consider option can be used to augment the covariance of the estimated parameters to account for known error sources which cannot be observed well enough to estimate.

The FILTER program processes observations sequentially using a Kalman-Schmidt formulation. System noise can be included and solve-for parameters can be treated as stochastic. In contrast to the BATCH program, consider parameters influence the state estimation as well as the covariance. The FILTER was foreseen to be used mainly during the 2nd half of the cruise phase when there were daily attitude manoeuvres. Its use avoids a large state vector (and hence high rank information matrix). After filtering, it is straightforward to derive impulsive manoeuvre estimates and their uncertainties by comparing the state velocity components and their covariance at the instant before and the instant after each manoeuvre.

The development of the programs' common elements made extensive use of the mathematical formulation of the JPL ODP (Ref. 3) and are described in the next subsection. Simplifications were made by tailoring to the needs of the GIOTTO mission. The BATCH program is the more similar to the ODP, the main difference being the method by which the orbit and partials are computed. Orbit generation is performed using Encke's method and a 4th order Runge-Kutta integrator. The partial derivatives are computed approximately using analytical techniques and the Peano-Baker method (Refs. 4,5). This method is fast and requires typically only two or three iterations.

3.1 JPL Software

The ODP was used in two ways in support of the GIOTTO project:

1) verification that ESOC navigation software could process DSN radiometric data and
2) processing GIOTTO radiometric data acquired by the DSN to verify data quality and for navigation comparison with ESOC.

The ODP was designed to compute earth-based Doppler and range observables to accuracies of 0.01 mm/s and 0.1 m. respectively, exclusive of errors in the troposphere, ionosphere and space plasma corrections. This program first supported the Mariner VI and VII spacecraft, which encountered Mars in 1969, and it has been used in the navigation of all space missions tracked by the DSN since then. In its current form Doppler observables are computed using a differenced range formulation in the solar system barycentric space-time frame of reference. Included are relativistic delays caused by the Sun, Jupiter, and Saturn. Transformations between coordinate time and proper time have been developed to the advanced degree required to compute the highly accurate range observables needed in this formulation (Ref. 6). This is in addition to accounting for offsets between station clocks, Broadcast Universal Time, and Observed Universal Time. Also included are polar motion corrections for computation of the station location in inertial space. Special techniques for accelerating the convergence of the light time equation eliminate some of the CPU expensive spacecraft and planetary ephemeris interpolations and station location computations. Corrections for the earth's troposphere are determined from a seasonal model and charged particle effects can be removed when calibration data are available.

The spacecraft trajectory is numerically integrated in the Earth Mean Equator and Equinox System of 1950.0 (EME50) using precomputed ephemerides for the positions of the planets. Models for oblateness and non-gravitational forces on the spacecraft due to solar pressure, manoeuvres, gas leaks, or atmospheric drag are available. The variational equations are integrated simultaneously with the spacecraft state.

An indication of the quality of the weighted least squares solution is gained from the display of linearly predicted residuals formed for each observable using the corrections to the estimated parameters and the partial derivatives. An apriori covariance matrix expressing the uncertainty associated with each estimated parameter may be supplied. The solution and covariance can be mapped and transformed to a wide variety of coordinate systems centred at designated bodies at specified or dynamically determined times of interest such as closest approach.

4. SOFTWARE TESTING

Beginning more than two years before GIOTTO launch, a series of navigation workshops were held between JPL and ESOC to define and run test cases to verify that the ESOC orbit determination software could successfully process DSN GIOTTO radiometric 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 radiometric data acquired from it when the geometry was similar to 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 GIOTTO DSN radiometric and telemetry data during the mission.

An important part of the software tests was 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 astrodynamic 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 compute properly radiometric observables. The one chosen for GIOTTO operations and hence these tests was JPL Development Ephemeris (DE) 118, which uses the EME50 reference system.

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 months Voyager 1 trajectory modified to include large spacecraft manoeuvres and accelerations to enhance the detection of any possible differences between the two programs. Good agreement between ESOC and JPL was noted at 1 m. in position and 0.01 mm/s in velocity at the end of the integration.

Two Voyager two-way Doppler points were selected for use in a detailed check of the computation of Doppler observables. Quantities carefully checked were time transformations, polar motion, light time solution, EME50 station location, antenna corrections, and troposphere modelling. The final agreement obtained for the computed observables was 0.1 mHz S-band or approximately 0.007 mm/s, which indicated that the ESOC software could process DSN radiometric data adequately to support GIOTTO navigation.

The most comprehensive test was a comparison of the solution for the spacecraft state obtained from an eight days data span of Voyager data. Differences in the estimates obtained by the ODP and ESOC FILTER program were 22 km in position and 20 mm/s in velocity, part of which may be attributed to differences in data processing techniques. Other differences might be attributed to the use of an epoch state filter in the JPL ODP and the current state estimator employed in the ESOC program, 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 can be found in Ref. 7.

Another orbit determination test involved a 90 days arc of DSN radiometric data containing non-gravitational forces. The data was based upon the geometry of the GIOTTO-like Voyager 1 trajectory, but used precisely known solar pressure, instantaneous and finite manoeuvres, and a constant acceleration (gas leak) during the last month. The data observation model included tropospheric effects and random data noise representative of measurements to be taken by the DSN during GIOTTO operations. Since the trajectory was known exactly, it was possible to determine when the correct state had been recovered by the ESOC software in runs using intentionally mismodelled apriori spacecraft states and/or non-gravitational force models. The agreement of the recovered spacecraft state with its known value was comparable to or better than the agreement obtained above.

The results of these tests gave confidence that ESOC should have no difficulty in processing the DSN data acquired from GIOTTO.

Additional tests were performed within ESOC using data simulated by the quality control team. These tests concentrated on tracking arcs when small attitude manoeuvres were expected to be executed daily.

5. ORBIT DETERMINATION - GENERAL REMARKS

As far as GIOTTO orbit determination is concerned, the cruise phase can be divided into two periods: from July to November 1985; and from November 1985 until the mission end. The first period is characterised by relatively few manoeuvres whereas the second period contains frequent small attitude precession manoeuvres, at more or less daily intervals (Figure 4). The attitude manoeuvres were performed in unbalanced mode and changed the orbital velocity slightly. The tracking data during the early cruise phase had to be exploited for improving a number of uncertain model parameters such as those of the solar radiation pressure model. Also, the DSN data from the July and September campaigns were used to improve the knowledge of the DSTS station locations. At launch, the uncertainty in each of the coordinates was thought to be of the order of 10 m.

Routine orbit determination was performed every week using tracking data arcs which varied in duration from ten days to one month. Each time the orbit was updated it was integrated up to and beyond the time of encounter with comet Halley. An important aspect within this task was the inclusion of all the planned attitude manoeuvres. Based on the latest ESOC-determined ephemeris for the comet, the time and distance at closest approach were computed. These results, together with the associated covariances provided the basis for deciding if an orbit correction manoeuvre should be executed . In this respect, GIOTTO differed from most interplanetary missions in that the uncertainty of the target's orbit was, until the VEGA fly-bys, much greater than the uncertainty of the spacecraft's orbit.

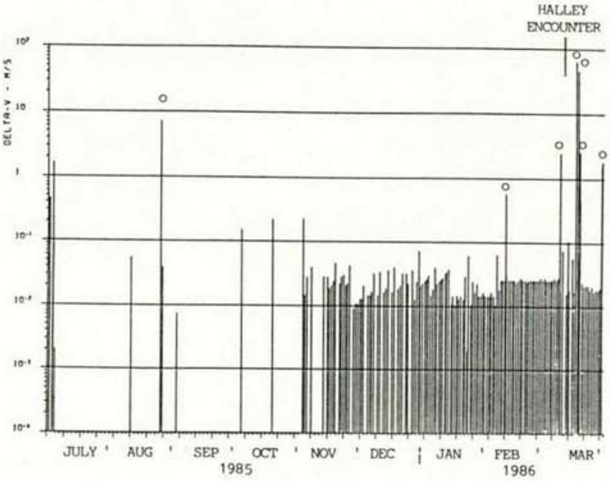

Figure 4. GIOTTO Manoeuvres - 'o' signifies Orbit Correction

Analysis of the DSTS observations' residuals shows that the two-way Doppler data noise during the mission was almost always in the range 0.4 - 0.6 mm/s (one-sigma, 10 minutes count time). The range noise was better than 20 m. Corresponding values for the DSN tracking data were 0.3 mm/s for Doppler with a one minute count time and 27 m. for range. For 10 minute count times, the Doppler noise was even smaller. The scatter in all the Doppler residuals has the appearance of random noise. This is not true for the range where the main feature is small jumps from one pass to the next, probably indicating shortcomings in the modelling of the atmospheric effects and equipment delays.

A good indication of the accuracy to which the GIOTTO orbit was determined is given by both the formal error statistics (consider covariance) and a comparison of the differences between the estimates of the orbit state at a particular epoch using different data arcs. By and large, the two results were consistent and show that in the early cruise phase the position error was usually less than 50 km and the velocity error less than 0.1 m/s. Even later on, when the range approached 1 AU (Figure 3) and daily attitude manoeuvres were being performed, the position uncertainty was of the order of 100 km or better. The position and velocity error ellipsoids were so orientated that the major uncertainty in the position was in the declination direction (perpendicular to the earth-spacecraft vector) and in the velocity was normal to the ecliptic plane. These results are typical for interplanetary orbit determination using range and Doppler data.

To first order, the accuracy to which the declination can be determined from Doppler data is proportional to the inverse of the absolute value of the sine of the declination. Since interplanetary flights are almost invariably constrained to very low inclinations with respect to the ecliptic, it can be seen from Figure 3 that during early 1986 the spacecraft's declination was the most favourable possible.

6. GIOTTO-SPECIFIC CHARACTERISTICS

6.1 Effects of Spin on Doppler

The Doppler measurements of GIOTTO are biased due to the spin of the spacecraft. This is true even for the despun HGA because of the rotation of the subreflector. According to Marini (Ref. 8), the bias on the two-way range-rate, $2\Delta\dot{\rho}$, is given by:

$$2\Delta\dot{\rho} = \pm f_s \lambda_u (1 \pm 1/K) \qquad (1)$$

where f_s is the spin frequency (Hz)
λ_u is the wavelength of the uplink carrier frequency
and k is the transponder multiplication factor.

The signs depend on the sense of polarisation of the received and transmitted signal in relation to the spin direction. For GIOTTO, the second sign was always positive. The first sign was also positive except during NEP when the fill-in antenna received the tracking signals.

During cruise the spin-rate was nominally 15 rpm. With λ_u = 13.6 cm., the bias was 65.3 mm/s when using S-band downlink and 42.5 mm/s when using X-band downlink. Since the uplink frequency was adjusted for each pass (to best suit the satellite receiver characteristics, taking into account the secular change in the range-rate), and the spin-rate was subject to variation, particularly during manoeuvres, it was important to monitor the two parameters carefully in order to correct the range-rate measurements to sufficient accuracy.

When the fill-in antenna was used, its rotational velocity caused an oscillation on the Doppler signal additional to the bias. The frequency was equal to the spin frequency and its amplitude proportional to the offset from the spin axis of 0.75 m. times the sine of the angle between the spin axis and the vector from the station to spacecraft. This oscillation was not filtered out in the preprocessing but the fill-in antenna was only used for less than two days at the start of NEP. At that time the spacecraft spin-rate was fractionally above 15 rpm and the Doppler count time was one minute. This led to a beat phenomenon in the range-rate residuals as is illustrated in Figure 5. The beat period of 25 minutes is consistent with the actual spin rate of 15.04 rpm. More details of this effect are given in Ref. 9.

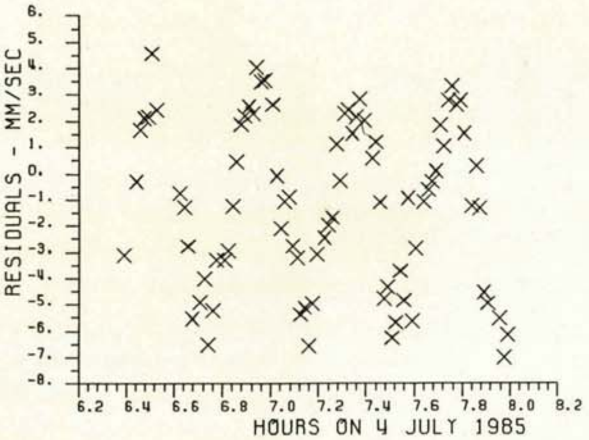

Figure 5. Oscillation on Canberra Range-rate Residuals due to Rotation of Fill-in Antenna

6.2 DSN Campaigns in July and September 1985

Independent reductions by ESOC and JPL of the DSN data acquired during these campaigns gave similar results. In one example, differences of 15 km and 17 mm/s in position and velocity, respectively, were noted in the estimates of the spacecraft state. The statistics and patterns of the residuals, particularly the range-rate, were almost indistinguishable. The campaigns established the confidence needed to ensure success during the approach and encounter phase when DSN data would again be collected to enhance the GIOTTO navigation.

ESOC also processed combined DSN and DSTS data to determine the locations of the DSTS stations in the DE118 coordinate system. At the same time the compatibility of the two sets of data was proved. Orbit determination runs using DSN data alone, DSTS data alone and combined data led to results whose differences were consistent with the formal error estimates.

6.3 DSTS Station Coordinates and Range Biases

The station locations are defined relative to the earth's mean pole and Greenwich meridian of 1903.0. The coordinate system has its origin at the earth's centre, the x-axis lying in the equator plane towards Greenwich, the z-axis along the pole and the y-axis completing the right-handed frame. The z-component of the DSTS stations' coordinates was not observable from the tracking data.

The range bias is modelled as a constant for each station and can be thought of as the sum of the errors in the nominal signal delay due to the spacecraft and station hardware. The estimates for these parameters from DSTS and DSN data are shown in Table 1.

		Before launch	After estim.	Diff.
	x	-2327.94104 km	-2327.94540 km	-4.36 m
Carnarvon	y	5301.59364 km	5301.59133 km	-2.31 m
	z	-2665.85483 km	not observ.	
one-way bias		0	-3.7 m	
	x	4206.11953 km	4206.11318 km	-6.35 m
Weilheim	y	823.54112 km	823.54555 km	+4.43 m
	z	4708.52185 km	not observ.	
one-way bias		0	11.8 m	

Table 1 Estimates of DSTS station locations and range biases

The uncertainties in the x- and y-coordinates are 1 to 2 m. and in the range biases are 7 to 8 m. It is of interest to note that the latest determined location for the Weilheim 30 m. antenna using conventional surveying techniques (Ref. 10) is very similar to that estimated from the tracking data. The x-coordinate differs by 42 cm and the y-coordinate by 72 cm. The measured z-component is 4.94 m. greater than the value assumed during the GIOTTO mission.

6.4 Solar Radiation Pressure Model and Calibration

The acceleration of GIOTTO due to solar radiation pressure was small - of the order of 2.10^{-11} km/s/s - but had to be taken into account in the orbit determination. As described in Ref. 11, the spacecraft was broken down into a number of manageably simple shapes. The orientations of these shapes and the reflectivity properties of the various surfaces were used to build up a model whose outcome was the three components of the force due to solar radiation pressure. The components were directed along the spin axis, normal to the spin axis and in the plane defined by the spin axis and sun-spacecraft vector, and the third axis was orthogonal to the other two. Knowing the spacecraft attitude allowed the transformation of the forces into the inertial system. The mass was monitored for conversion into accelerations. In fact, during the cruise, there was very little propellant depletion, so the mass decrease was very small.

The three force components in the quasi-body frame were each multiplied by a coefficient whose nominal value was unity. Corrections to these coefficients were the solve-for parameters in the orbit determination. The forces themselves were dependent upon two variables - the solar aspect angle and the phase angle of the HGA. If the model was perfect (and the orbit determination too), the estimates of the solve-for parameters would always be zero, irrespective of the values of the two variables. From the actual variations in the estimates, the basic model was re-examined and 'tuned' with respect to surface properties, shadows and reflection functions.

Between mid-July and early November 1985 the solar aspect angle increased from 65° to 125°. During the same period the antenna phase angle decreased from 300° to 200°. After each adjustment of the basic model, the old tracking data was reprocessed and new estimations of the calibration parameters were obtained.

Naturally, the solve-for parameters were not all observable to the same extent. In practice, the coefficient of the third force component could not be improved because the force acting along a direction always normal to the sun-line was very small. By the same token, the force acting along the spin axis was also small when the solar aspect angle was about 90°.

The retuning of the model did lead to more consistency in the estimates of the solve-for parameters. Most estimates of the corrections to the first two coefficients were finally in the range -0.1 to +0.1. From these results, it was considered that the error in the model was of the order of 10%, a value in line with that expected due to uncertainties in the surface properties (Ref. 11).

The most precise orbit determination would be needed at the end of the mission in early March 1986. At that time, the solar aspect angle would be 106° and the antenna phase angle about 25°. Since the range of phase angles early in the mission was quite different, reliance would have to be placed on the basic correctness of the model. On the other hand, the 106° solar aspect angle had been experienced in mid-October 1985. Therefore, for the final iteration in tuning the model, most weight was given to the calibration results obtained using tracking data from the period mid-September to early November 1985.

6.5 S- and X-Band Downlink

During the early cruise phase there were eleven passes from Carnarvon which were split into two parts, one part of the pass using the X-band downlink and the other the S-band downlink. These split passes provide some information on the consistency of the two radiometric frequencies, not just in the data but in the modelling of the observables. Note, though, that there was no true dual-frequency tracking but rather tracking data at two distinct frequencies separated by hours in time.

In the residuals, there were no discernible differences in the Doppler but the S-band range residuals were consistently 10 - 15 m. greater than the X-band residuals. Off-line analysis showed that these differences could be reduced by about 5 m. using a better model for the ionosphere, that of Klobuchar (Ref. 12). This model has the merit of being globally applicable but does not rely on large tables of data or on measurements of ionospheric parameters in the neighbourhood of the station. It is thought to account for the signal delay due to the ionosphere to an accuracy of 70 - 80 %.

Since the split passes were made only with Carnarvon, it is not known if the 5 - 10 m. error is station-specific or general, for instance, due to mismodelling of the spacecraft transponder delay at the two frequencies.

6.6 Manoeuvre Calibration

Between 7 July and 3 November 1985, GIOTTO performed six manoeuvres, all of which were executed by ground command. Most of these manoeuvres were well spaced out in time which allowed the components to be estimated from the tracking data. By this means it was shown, for example, that the first and largest orbit correction manoeuvre on 26 August underperformed by just 3%.

In contrast, in the last 130 days before encounter, 118 manoeuvres were executed, all but five being attitude precession manoeuvres. These manoeuvres varied somewhat in magnitude (Figure 4) and direction and were usually quite small, the average change in the orbital velocity being just 26 mm/s. Because of the frequency of the manoeuvres, it was not possible to calibrate them individually and accurately.

A prima facie indication of manoeuvre performance was determined by comparing the actual change in the Doppler signal with that expected. How representative this was of the manoeuvre as a whole depended upon the component of each manoeuvre in the radial direction, earth to spacecraft. The continuous pointing of the HGA to earth and the orientation of the axial thrusters meant that the proportion of attitude manoeuvres in the radial direction was anything between 27% and 97% depending upon the phase angle of the pulsing.

Using the BATCH program, it was also possible to estimate parameters common to a group of manoeuvres. Usually, this took the form of a scale factor for the magnitudes of the components of the manoeuvres. Often, successive manoeuvres were similar in size and direction, in which case one could expect a high degree of repeatability, i.e. consistency in the differences between expected and actual manoeuvre performance. At other times the grouping together of rather dissimilar manoeuvres led to reasonable estimates of their combined effect but jumps of a few metres in the range residuals indicated some mismodelling of the individual manoeuvres.

Overall, the estimates of the corrections to the manoeuvre components only occasionally exceeded 5% in magnitude. As was expected, the components of the manoeuvres in the direction perpendicular to the ecliptic could not be well estimated. More details on manoeuvre calibration are given in Ref. 13.

7. TERMINAL NAVIGATION

The final phase of the GIOTTO navigation began on 1 March 1986 coincident with the first pass of the third DSN tracking campaign which was to last until 14 March. After processing the initial data from Goldstone and Canberra, the correctness was immediately confirmed of the orbit whose determination over the previous five months had relied exclusively on DSTS data. Two-way data were acquired every day until the end of the Carnarvon pass, 17 hours before encounter. Continuous DSN encounter support of telemetry began on 11 March with the 64 m. subnet. Both Carnarvon and Canberra obtained one-way radiometric data up until two seconds before closest approach when telemetry was temporarily lost for 34 minutes due to attitude disturbance caused by collisions of dust particles.

The spacecraft's orbit was re-determined every day but because of the intensive activity, including the daily attitude manoeuvres, there was minimal comparison of ESOC and JPL data analysis. Of especial interest was the variation in the successive estimates of GIOTTO's predicted position in the target plane at closest approach. This plane is perpendicular to the relative velocity vector (GIOTTO - comet). The projection of the ecliptic onto the plane forms the BT target axis (Figure 6). In early March it was known that GIOTTO should arrive close to the negative side of this axis but exactly how far from the comet had not been decided.

The uncertainties in GIOTTO's orbit state were also mapped onto this plane and formed the target error ellipse. In Figure 6, the numbered ellipses and their centres refer to predicted positions of the comet based successively on ground based data alone up to 5 March (Ref. 14), VEGA-1 pathfinder data, and VEGA-1 plus VEGA-2 data. The origin of the coordinate system lies at the centre of the third of these ellipses and was determined on 10 March. It was the final estimate of the comet's position (Ref. 15).

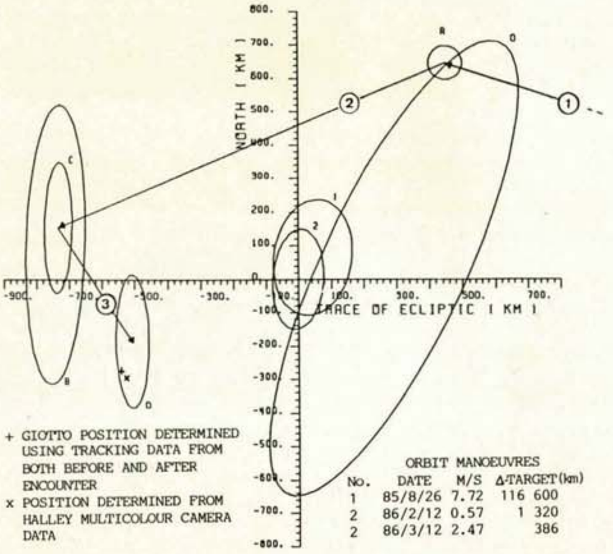

Figure 6. GIOTTO Targetting History and 3σ Error Ellipses

Ellipse B and its centre were the estimates of GIOTTO's uncertainty and predicted position after the 2nd orbit correction manoeuvre on 12 February 1986, based on tracking data until 5 March. Ellipse C shows the same but after almost another week's tracking data. This ellipse is considerably smaller because of the decreasing effect of velocity uncertainties as the encounter date drew nearer.

A few days before encounter, the desired target point was decided upon - 540 km miss-distance and 20° below the projection of the sun-line on the target plane. The 3rd radial pulsed orbit correction manoeuvre of 2.47 m/s was performed in the early hours of 12 March. It took 32 minutes and moved the target about 400 km.

The planned manoeuvre would have changed the Doppler data by 2371 mm/s. The measured change was 2359 mm/s. Thus, at first sight, the manoeuvre underperformance was just 0.5 %. The expected target and its uncertainty was now ellipse D.

8. HALLEY ENCOUNTER

The best position estimates at a specified epoch are determined when the epoch lies towardsthe centre of the tracking data arc. For the best estimates of GIOTTO's parameters at encounter then, the two-way radiometric data after the encounter was also used.

The first two-way data were received at Weilheim at 08:00 on 14 March. An initial analysis revealed that the Doppler observations were 0.335 m/s lower than expected. The single two-way range measurement obtained at 08:51 was almost 10 km lower than expected. Data from subsequent passes at Madrid and Goldstone corroborated these results and showed the difference between expected and actual range measurements was growing with time. There was only one reasonable explanation: the spacecraft had been decelerated by impacts of dust and gas. A subsequent orbit determination using data up to and including 17 March showed the relative velocity to have been decreased by 0.2306 m/s due to the impacts (Ref. 16).

From the tracking data, the best estimates of the encounter parameters were computed to be:

miss-distance 610 km; time of closest approach 1986/3/14 00:03:00.4 UT. The position in the target plane is marked by '+' in Figure 6.

The Halley Multicolour Camera Experiment team were also able to calculate the encounter parameters by an extrapolation of the camera movement and the timing of the images with respect to the sun reference pulse. According to Ref. 17, their results were:

miss-distance 605 km; time of closest approach 1986/3/14 00:03:02.0 UT. The position in the target plane is marked by 'x' in Figure 6.

Just because the differences between the expected target conditions and the later estimates are marked within ellipse D, it should not be supposed that these differences are solely due to GIOTTO orbit determination errors. In reality, the rather small targetting error was due to a combination of the separate errors in the state estimates of both the spacecraft and comet. The roughly similar sizes of ellipses 2 & D show that, finally, the uncertainties in the position estimates of the two bodies were about the same.

9. POST-ENCOUNTER

Because of the nominal ARIANE launch and, above all, the extremely accurate insertion into interplanetary orbit, only 10 m/s in total had been needed for orbit correction manoeuvres. Thanks to the remaining fuel on board and the good performance of the spacecraft, a GIOTTO follow-on mission could be contemplated.

The strategy which keeps many options open was identified as a transfer back to earth. Depending upon the fly-by conditions on 2 July 1990, there are a number of possible targets, comet Grigg-Skjellerup being an attractive candidate.

The optimum timing for the necessary orbit manoeuvres was soon after encounter. Two large and one small axial burns were executed on consecutive nights between 19 and 21 March (Figure 4). Monitoring of the Doppler showed that the manoeuvres underperformed by about 2 %. This calibration information was used to replan each manoeuvre in succession. There followed eleven days of DSTS tracking (still with daily attitude manoeuvres) and an accurate orbit was determined.

In the evening of 1 April a final touch-up manoeuvre was executed and early the following morning GIOTTO was commanded into its hibernation attitude and telemetry abruptly ceased.

The accuracy of the final orbit determination is such that there will be no problem, for at least three years, to point an antenna with adequate accuracy in the direction of the spacecraft as the first stage of re-establishing contact.

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