COMET HALLEY ORBIT DETERMINATION BY MEANS OF THE PATHFINDER DATA: METHODS USED AND RESULTS OBTAINED

P de Broeck, F Hechler & P Kristiansen* **A Sukhanov**

European Space Operations Centre (ESOC) IKI Space Research Institute
Robert-Bosch-Str. 5, 6100 Darmstadt, FRG Profsojusnaja, Moscow, USSR
Computer Resources Int., Copenhagen, Danmark*

ABSTRACT

During the night of 13 to 14 March 1986, ESA's probe GIOTTO passed the nucleus of comet Halley at a distance of 600 km. The precise targeting was to a great extent due to the improvement of the comet orbit by means of Pathfinder Data. These consisted of the pointing angles from the two Soviet spacecraft VEGA-1 and VEGA-2 to the nucleus of the comet derived from attitude and camera data collected onboard the two spacecraft, and of NASA's VLBI data which enabled a precise orbit determination of the VEGAs. In this paper we concentrate on the methods which were used for improving the comet's orbit by means of the VEGA pointing angles. Also, the results of the Pathfinder activities are discussed.

Keywords: Pathfinder, Halley, Estimation Theory, GIOTTO; VEGA.

1. INTRODUCTION

The Soviet spacecraft VEGA-1 and VEGA-2 provided angular data for the position of comet Halley's nucleus during their fly-by on March 6 and 9 this year. A point just 550 km away from that nucleus on its sunward side was the target of the subsequent comet visitor, ESA's probe GIOTTO and the accurate determination of the ephemerides of the comet nucleus by means of the 'pathfinder data' was therefore essential for the well-known success of the GIOTTO mission. Before the VEGA observations became available the orbit of the comet nucleus had to be determined from ground based astrometric data collected by the astronomers of the International Halley Watch (IHW). It was impossible to measure the position of the nucleus to better than 1" - 2" as long as it was hidden in the dust of its coma and this coma reached its biggest extension shortly before the GIOTTO encounter. Futhermore the non-gravitational forces due to gas and dust emission on the nucleus also contributed to the uncertainties in the orbit determination results. For details we refer to Refs. 4,7,10,11. The uncertainty of the comet ephemerides determined from astrometric data alone led to a 1-sigma error ellipse for the target point perpendicular to the arrival velocity with semi-axis of 250 km and 75 km respectively. These accuracy figures were rather marginal for a safe navigation of GIOTTO to the desired fly-by distance of 500 km. And there were some doubts as to whether the figures quoted were possibly unrealistically small.
The VEGA spacecraft could see the nucleus from their fly-by distances of 8900 km and 8000 km respectively and previous mission analysis studies (Refs. 2,3,9) had shown that their angular observations could reduce the above uncertainties by almost a factor 10. But a prerequisit for such an essential and for the GIOTTO mission vital improvement was the careful preparation and operational realisation of the various pathfinder activities in the 3 navigation centres involved, Intercosmos in Moscow, the Jet Propulsion Laboratory (JPL) in Pasadena, and the European Space Operations Centre (ESOC) in Darmstadt. This paper will deal with the activities of the VEGA Team at Intercosmos and of ESOC. Both institutes received VEGA pointing angles (ESOC from Moscow via a computer to computer link), and obtained the astrometric data of the IHW and the VEGA ephemerides from JPL via an equivalent link with Pasadena; they processed these data and finally determined the position of the target for the GIOTTO spaceprobe with the desired accuracy.

2. PRINCIPLES OF THE PATHFINDER CONCEPT

The prime input to all pathfinder activities was the VLBI (Very Long Base Interferometric) data for the two VEGA spacecraft collected at 3 Deep Space Stations of NASA and correlated at JPL, and the inertial pointing angles for the nucleus derived from VEGA attitude and camera pointing data at Intercosmos.

JPL processed the VLBI data and thus guaranteed that the VEGA orbits could be determined with the required accuracy. Details of the VLBI technique are described in Ref. 8, and the results of the VLBI tracking campaign for the VEGAs are found in Ref. 12. We can summarize the results as follows. Using only conventional orbit determination techniques the 1-sigma uncertainty of the VEGA positions at encounter could be more than 300 kilometers. By means of the well known VLBI techniques the 1-sigma uncertainty was reduced to the order of 20 km.

Intercosmos processed the VEGA telemetry and extracted from it information on the spacecraft attitude, on the camera pointing angles, and on the optical images itself. From that information

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they derived the inertial directions from the VEGAs to the comet which, together with the improved VEGA Orbit, provided information to calculate a more accurate comet orbit.

In Figure 1, a schematic view of the Pathfinder Concept is depicted, were the relative flights of the VEGA spacecraft, GIOTTO, and the comet are indicated.

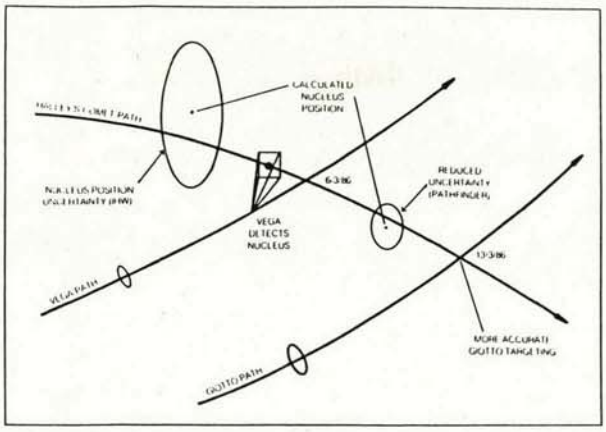


Figure 1. Schematic View of the Pathfinder Concept (by courtesy of J.F. Jordan)

3. COMET HALLEY OBSERVATIONS FROM THE VEGA SPACECRAFT

In order to clarify the major complications occuring during the process of Improved Comet Orbit Determination, it is necessary to gain some understanding of the way in which the inertial pointing angles (from VEGA to comet) are obtained.

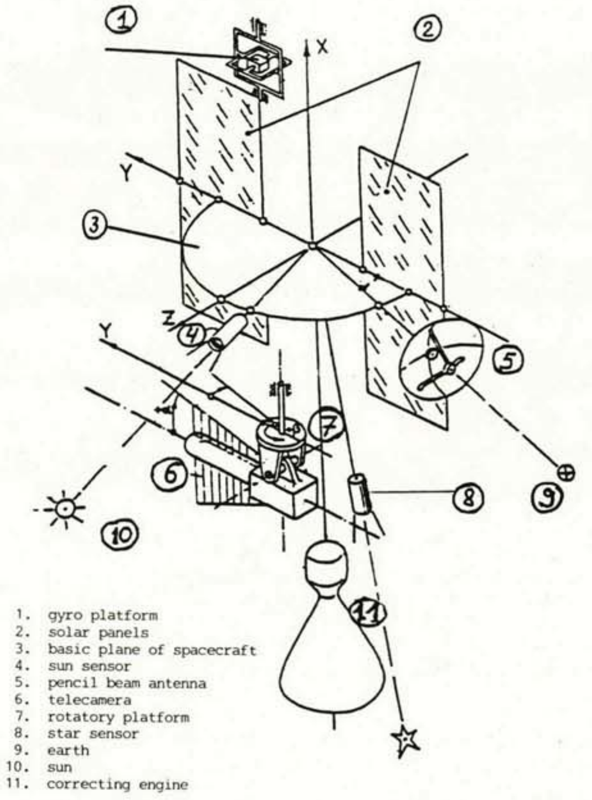
The VEGA spacecraft are three-axes stabilised, and a CCD camera is mounted on a tracking platform (ASP-G), which can rotate w.r.t. the spacecraft body about two perpendicular axes (Figure 2).

The camera is locked on the comet nucleus by means of an independent and automatic control system on the ASP-G. The camera pictures which were used for improving the comet orbit were taken during an interval of about three hours, going from 2 hours before the point of closest approach until 1 hour after the encounter point.

The inertial angles are constructed from information gathered in three steps:

i) Camera pictures taken of the comet; these are related to the ASP-G platform coordinate system .
ii) ASP-G orientation angles relatively the spacecraft; these are used to transform to the spacecraft body system.
iii) Attitude information of the VEGAs; this is needed to transform to the inertial system of coordinates

The VEGA attitude was determined and controlled on board in two different modes:



1. gyro platform
2. solar panels
3. basic plane of spacecraft
4. sun sensor
5. pencil beam antenna
6. telecamera
7. rotatory platform
8. star sensor
9. earth
10. sun
11. correcting engine

Figure 2. View of the VEGA Spacecraft with indication of the Attitude Sensors and the Camera

- mode 1
  is used until about 40 minutes before closest approach. The attitude is determined on ground and controlled on board from data collected by
  o a star tracker
  o a two-dimensional sun sensor
  o a high-gain antenna.

- mode 2
  is switched on for the rest of the fly-by. In this mode the spacecraft is stabilised by means of three perpendicular gyros. This makes sure that control is not lost during the flight through the coma where guide stars may be hidden in dust.

In Refs. 8 and 9 details are given about the characteristic errors which can be expected in each of the modes and in the different steps of the determination of the pointing angles.

A detailed modelling must take into account possible biases, and also the gyro drift effects. It was agreed with the VEGA team that the precise time of switch-over from attitude mode 1 to mode 2 was made available to the GIOTTO team in the course of the operations.

During the central part of the comet observations by the VEGAs, typical values for the accuracy are (1-sigma):

time	Attitude Error (3 angles)			ASPG error (2 angles)		Camera picture (2 angles) either	
	random	bias	drift	random	bias	narrow	wide
- 2 hr: start . .MODE 1 .	3'	3'	-	0.25'	1'	1'	4'
- 40 min: switch to gyros . .MODE 2 . + 1 hr: end	3'	jump 5'	0.3°/h	0.25'	1'	1'	4'

Table 1. Error sources in the process of obtaining inertial angles (nominal values, maximum errors, uniform distribution)

This table not only gives us the necessary information to construct the covariances of the observables, needed for the estimator, but also indicates the nature of parameters which should be included in the state vector of the estimation process.

4. IMPROVED COMET ORBIT DETERMINATION: METHODS USED

As agreed between the VEGA and GIOTTO teams, the calculation of the improved comet orbit were performed separately from each other, and the results compared. In the sequel, we present the basics of the methods used by the two teams.

4.1 GIOTTO Team

The VEGA pointing angles could in principle be merged with and processed together with the astrometric data of the IHW. ESOC however decided to develop a special purpose program to process the Pathfinder data independent of the astrometric data due to the following reasons:

- o VEGA data are taken only over a very short time span (a few hours compared to centuries of astrometric data). So it was possible to use simplified models for fly-by trajectories and geometry. This made the relevant software simpler, more flexible and much faster.
- o The errors of astrometric data and pointing angles are uncorrelated. Non-gravitational forces do not play any role on the short fly-by arcs. Hence, one can feed into the improved comet orbit determination algorithm, a least-squares fit of astrometric data in the form of the comet state and its error covariance matrix at some epoch close to the VEGA encounter.
- o It was convenient from an operational point of view.

The estimation method used in the Improved Comet Orbit Determination is a square root formulation of the weighted least squares estimation procedure, which delivers a differential update to an a-priori parameter vector and the corresponding covariance matrix.

The implementation of the procedure, used for this purpose, has the possibility to treat each of the model parameters as being either a solve-for or a consider parameter.

Consider parameters are characterised by the fact that one has got an initial estimate for them, but does not want to improve this during the estimation process. Rather, the uncertainty of the parameter, reflected in its a-priori covariance, will influence the covariance estimates of the solve-for parameters, and are therefore quite important to make realistic guesses of the accuracy of the obtained solution.

The theory behind square-root implementation of least-square filters can be found in Ref. 1.

The software version used here is very flexible in the sense that each model parameter has a flag associated which tells the estimator whether to treat the parameter as solve-for or consider. Furthermore, the software can treat the observations separately (sequential filter), or accumulate observations to be handled simultaneously (batch filter).

The weighted least squares estimation procedure requires the following items to be defined:

- system model: evolution of the state vector
- observation model
- partials of observables with respect to the state vector
- assumptions on a-priori error covariances of
  - o solve-for parameters
  - o consider parameters
  - o observations.

The estimation is performed within an iteration loop because the observables are non-linear functions of the model parameters.

4.1.1 System model. The system model, in our case, describes the evolution of the following state vector:

$$\underline{x}(t) = [\,\underline{rc}(t)\ \underline{vc}(t)\ \underline{rv}(t)\ \underline{vv}(t)\ \underline{e}(t)]^{T} \qquad (1)$$

where
- o $\underline{rc}$ is the position of comet Halley (the heliocentric EME50.0 coordinate system is used)
- o $\underline{vc}$ is the velocity of comet Halley
- o $\underline{rv}$ and $\underline{vv}$ are the position and velocity of the VEGA spacecraft
- o $\underline{e}$ is a compound vector describing the solve-for and consider parameters in the observation model. In fact the components of $\underline{e}$ are independent of time.

Because of the relatively short observation arc (a few hours maximum) during which useful camera pictures are taken, one can linearise the trajectory equations as follows:

$$\begin{aligned} \underline{rc}(t) &= \underline{rc}(T_O) + \underline{vc}(T_O)*(t-T_O) \\ \underline{rv}(t) &= \underline{rv}(T_O) + \underline{vv}(T_O)*(t-T_O) \end{aligned} \qquad (2)$$

the reference epoch T_O should be chosen as close as possible to the point of closest approach between comet an VEGA in order to obtain the smallest truncation errors possible.

The improved comet orbit determination will update the estimate of the comet position $\underline{rc}(T_o)$, and - if solved-for -, also the comet velocity $\underline{vc}(T_o)$ gained from astrometric data. In principle also the VEGA position and velocity can be solved for, and finally we solve for the error parameters of the observations. The state vector which is solved-for during the estimation process is thus, in its maximum form:

$$\underline{s} = [\,\underline{rc}(T_o)\ \ \underline{vc}(T_o)\ \ \underline{rv}(T_o)\ \ \underline{vv}(T_o)\ \ \underline{e}\,]^T \qquad (3)$$

The improved comet state at the epoch T_o can then be integrated to find the comet state at the GIOTTO encounter point, which in turn is used to perform a final GIOTTO targeting manoeuvre.

4.1.2 Observation model. A possible choice for the observables are the right ascension and declination (α, δ) of the comet nucleus as seen from the spacecraft and expressed in an inertial frame. If the relative position vector from VEGA to comet is noted in term of its components; and similarly for the velocity:

$$\underline{rc}(t) - \underline{rv}(t) = \begin{bmatrix} x(t) \\ y(t) \\ z(t) \end{bmatrix};\ \underline{vc}(t) - \underline{vv}(t) = \begin{bmatrix} \dot{x}(t) \\ \dot{y}(t) \\ \dot{z}(t) \end{bmatrix} \qquad (3)$$

$\alpha(t)$ and $\delta(t)$ are defined as follows:

$$\alpha(t) = \text{atan}\ \frac{y(t)}{x(t)}$$

$$\delta(t) = \text{atan}\ \frac{z(t)}{(x^2(t) + y^2(t))^{1/2}} \qquad (4)$$

As a matter of fact, not the inertial angles (α, δ) are used as measurement input to the filter, but rather derived angles Ψ, θ, which are defined as

$$\Psi = \text{ctg}\ (\alpha - \alpha(-\infty))$$

$$\theta = \text{tg}\ (\delta)/\sin(\alpha - \alpha(-\infty)) \qquad (5)$$

where $\alpha(-\infty)$ is the right ascension at $t = -\infty$.

The derived angles are used because they provide a more linear relationship between time and observations over the observation interval, than do (α, δ), as also noted in Ref. 5. One of the major advantages of using the derived angles, is that it becomes much more convenient to interpret the input data which are received, for example in order to identify obvious mistakes (blunder points), and jumps in the inertial pointing angles.

The transformation given in Eq. (5) is also taken into account when constructing the observation covariance matrix from the original noise figures of the Ψ and θ angles.

Using the notations x(t), y(t) and z(t) in Eq. (3), introducing the linear approximation given in Eq. (2), and noting $x(T_o) = x_o$; $\dot{x}(T_o) = \dot{x}_o$, etc., we find the following equations describing the functional relation between the observables and the elements of the state vector $\underline{s}$.

$$\Psi(t) = \frac{x_o\,\dot{x}_o + y_o\,\dot{y}_o + (\dot{x}_o^2 + \dot{y}_o^2)*(t - T_o)}{\dot{x}_o\,y_o - x_o\,\dot{y}_o}$$

$$\theta(t) = \frac{(\dot{x}_o^2 + \dot{y}_o^2)^{1/2} * (z_o + \dot{z}_o*(t - T_o))}{\dot{x}_o\,y_o - x_o\,\dot{y}_o} \qquad (6)$$

We will combine Ψ and θ into the observation vector

$$\underline{z}(t) = \begin{bmatrix} \Psi(t) \\ \theta(t) \end{bmatrix}. \qquad (7)$$

In fact observations may suffer from systematic errors. One can account for these errors to a certain extent by modelling them into the observations equations. We used a model with altogether 10 model parameters, the following 10 components of the bias model vector $\underline{e}$.

- o bias of the star tracker (2 parameters; attitude mode 1)
- o jump of the attitude at switch-over from mode 1 to mode 2 (2 parameters)
- o bias of the gyros (3 parameters; attitude mode 2)
- o drift of the gyros (3 parameters; attitude mode 2)

We can not give all the details on the model equations in this paper. They can be found in Ref. 9.

When running the estimation program, it can be decided which of these parameters to solve for, and which ones to consider.

From Eq. (3) and (6), and also including the observation error model, we obtain the observations equation $\underline{z}(t) = \underline{z}(\underline{s},t)$.

4.1.3 Partial derivatives of the observations w.r.t. state vector. From Eqs. (6) it is seen that the partial derivatives

$$\frac{\partial \underline{z}}{\partial \underline{rc}(T_o)},\ \frac{\partial \underline{z}}{\partial \underline{vc}(T_o)},\ \frac{\partial \underline{z}}{\partial \underline{rv}(T_o)},\ \text{and}\ \frac{\partial \underline{z}}{\partial \underline{vv}(T_o)} \qquad (8)$$

can easily be obtained analytically. Concerning the partial derivative of $\underline{z}$ w.r.t. the model errors $\underline{e}$ we refer again to Ref. 9.

4.1.4 Assumptions on the error covariances. In order to have the estimation filter working, one needs estimates of the error covariances of

- o solve-for parameters (a priori)
- o consider parameters (a priori)
- o observations.

The a priori covariance of the comet position and velocity at the reference epoch T_o, are found as a result of the process of ground-based comet orbit determination. Similarly, the a priori covariance characteristics of the VEGA position and velocity are an output of the process of VEGA orbit determination (by means of VLBI data). As concerns the a priori covariance of the observation error parameters which are solved for, or considered, as well as for the covariance of the observations, relevant information is given in Table 1, and for further details we refer to Ref. 9.

4.1.5 Remark: VEGA-1 and VEGA-2 data. In the presence of inertial angles taken both by the VEGA-1 and VEGA-2 spacecraft, the algorithm used by the GIOTTO Team consisted in solving for the Improved Comet state separately for both sets of data, and finally to combine the two results as a weighted mean, also improving the comet velocity on the basis of the difference between the two updates in position which were obtained.

4.2 VEGA Team

The VEGA Team used two different approaches for the determination of the comet orbit, a least-squares fit of all data like the GIOTTO Team and a special method based on the theory of the 'Optimal Observation Strategy' developed within the last 10 years at the IKI. There was, however, one essential difference between the two least-squares solutions. While ESOC only processed the VEGA observations proper, the VEGA Team had at their disposal and processed all the following observations in one step.

- astrometric IHW data of the comet
- on-board observations of the comet (inertial pointing angles)
- own Doppler and range data for the VEGA spacecraft, and the corresponding VLBI data of JPL.

Consequently, the parameters to be estimated from those data by means of the aforementioned least-squares method were as follows:

- state vector of the comet (6 parameters)
- state vector of the VEGA-1 and -2 spacecraft (12 parameters)
- observation error parameters; vector $\underline{e}$. (10 parameters, see also above).

The modelling of the observation errors is basically identical to the modelling used by ESOC (Ref. 9).

Those parameters formed the 28-dimensional parameter vector $\underline{Q}$. The functional to be minimised can therefore be represented schematically as in Ref. 8:

$$\varphi(\underline{Q}) = \sum_k \left[P_k \cdot (\Psi_k^{obs} - \Psi_k^{c}(\underline{Q}, t_k))\right]^2 \qquad (9)$$

In this function, Ψ_k^{obs} and Ψ_k^{c} stand for the measured and calculated values of the observations.

$\underline{Q}$ could be split into solve-for variables and consider variables. P_k is a weighting factor for the k-th measurement.

In fact, the estimation problem is solved for the fly-by of the two VEGAs simultaneously. This is another difference of the method used by ESOC.

The fact that the GIOTTO Team (ESOC), and the VEGA Team used quite different functionals for the determination of the Improved Comet Orbit, made the comparison of the final results extremely interesting.

For details about the second approach of comet orbit determination by means of the Optimal Observation Strategy, we refer to Ref. 6.

5. PRACTICAL CONSIDERATIONS ABOUT THE SOLVE-FOR PARAMETERS

In the most general case, the parameters which can be solved for are:

- the state vector (position and velocity) of the comet, at a reference epoch T_0
- (if data of VEGA-1 and VEGA-2 available:) the state vector (position and velocity) of the VEGAs, at a reference epoch T_0
- the vector containing the deterministic components of the observation errors: gyro biases and drifts; startracker bias; jump.

It was, however, doubtful whether all of these parameters could really be solved for. A thorough study of that problem and tests on the basis of simulated data revealed the following facts.

- In the absence of VEGA tracking data - as was the situation for the GIOTTO Team - the VEGA state cannot be solved for successfully using VEGA angular observations alone. The reason is quite simple: the angular data are a pure function of the difference of comet and VEGA state, and comet and VEGA state are therefore not observable independently of each other. One can only estimate the state difference from the data and then compute in turn updates of the linearly depending comet and spacecraft states from these state differences and from the a-priori information on the VEGA and comet state uncertainties. These updates will consequently become proportional to the given a-priori error covariance matrices for these states and a wrong a-priori information will then lead to a wrong 'distribution' of the updates on comet and VEGA state. Taking into account that the VEGA states were known with high accuracy (about 20 km 1-sigma in position), it was therefore the best policy for the GIOTTO Team not to solve for the VEGA state at all.

On the basis of the inertial pointing angles of only one VEGA spacecraft, it is not possible in practice to solve very accurately for the comet velocity. The reason for this is

- the short observation arc during which the VEGA inertial pointing angles are taken
- a correlation of the effect of a comet velocity error, with the effect of a drift of the VEGA gyros.

Nevertheless, some improvement to the comet velocity can be obtained.

If data from VEGA-1 and VEGA-2 are available, it is however very well possible to solve for the comet velocity. And this was also highly necessary due to the fact that the GIOTTO encounter with the comet took place more than 4 days after VEGA-2 encounter, so that a remaining error in the comet velocity would have 'destroyed' the good positional accuracy of the comet, by the time of GIOTTO encounter (for example, an error of 30 cm/sec in the comet velocity propagates to about 100 km in position error after 4 days; which is much bigger than the expected positional accuracy of the comet which could be obtained at the time of VEGA-2 fly-by.

- Concerning the e vector which contains the observation error parameters, the tests showed that especially the gyro drift components can be determined with sufficient accuracy.

6. RESULTS

6.1 After VEGA-1 Encounter

The VEGA-1 encounter took place successfully during the morning of March 6 1986, and good camera pictures were obtained over a period continuing during the time of closest approach. The data were processed, and led to an update to the comet position which was assumed from ground-based observations of the following order of magnitude:

x-component	960 km
y-component	-30 km
z-component	180 km

(the coordinate system is EME50.0).

This error made by the ground-based comet orbit determination was mainly along the track of the comet, which is equivalent to a shift in the perihelion time. The update which was obtained here, confirmed recent trends in the ground-based comet orbit, and the error can be explained to a great extent by an offset between the comet centre of light (as seen from the earth) and the centre of mass.

In terms of the GIOTTO encounter geometry, the update expressed in the target plane was approximately:

T-coordinate	-360 km
R-coordinate	-20 km,

and the out-of-plane component amounted to about 900 km.

The target plane is defined to be perpendicular to the relative velocity vector between comet and GIOTTO, and within the target plane the T-axis is lying in the ecliptic (pointing approximately away from the sun direction); the R-axis is pointing south. This is depicted in Figure 3.

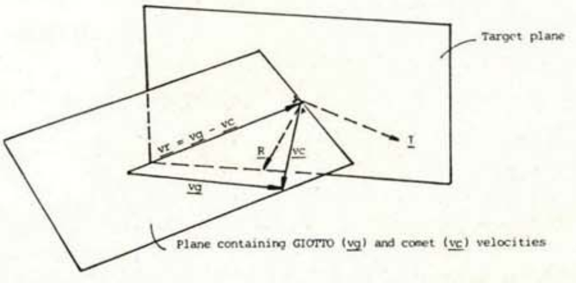


Figure 3. Geometry of the GIOTTO target plane

The updates to the comet position were in accordance with the formal accuracy estimates of the ground-based comet orbit. Expressed in the target plane, the 1-sigma uncertainty on the ground-based comet orbit was an ellipse with a semi-major axis of about 250 km, and a semi-minor axis of about 75 km, and with an orientation as depicted in Figure 5 (3-sigma ellipses are shown there). It should however be mentioned that some pessimistic estimates of the accuracy of the ground-based comet amounted to a 1-sigma uncertainty with semi-major axis of as much as 1500 km.

The error component lying in the target plane amounted to about 360 km. This error had to be compensated for by performing a correction to the GIOTTO orbit. However, due to the fact that the amount of the correction was relatively small (less than 1 m/sec if the manoeuvre would be executed on March 9 which was the scheduled day), it was decided to wait for the VEGA-2 encounter to take place, and to perform a manoeuvre on the basis of the Improved Comet Orbit, calculated by means of the inertial pointing angles over the two encounters. The maximum amount of the radial orbit correction for GIOTTO was, due to operational constraints, limited to about 10 m/sec.

The error component perpendicular to the target plane needed not to be compensated for, but simply constituted a shift in the time of GIOTTO's closest approach to the comet. The GIOTTO fly-by would take place approximately 13 seconds earlier than initially expected. Also this time difference was in accordance with the accuracy estimate from the ground-based observations, and which was about 20 seconds (1-sigma).

The calculation of the improved comet orbit were performed independently and simultaneously by the VEGA and the GIOTTO teams. The results, in terms of the state vector of the comet at the epoch March 14, 1986 at 0.0000 hours Ephemeris time were as presented in Table 2 (heliocentric EME50.0 coordinates; units are km for the position and km/sec for the velocity). Also the formal accuracy estimates for all components of the improved comet orbit state are given (these are the values obtained by the GIOTTO Team; the corresponding figures from the VEGA Team are however quite similar).

	GIOTTO Team	VEGA Team	1-sigma accuracy
X	-80526390.	-80526408.	37.
Y	-97904460.	-97904511.	42.
Z	-46387171.	-46387142.	92.
DX	-42.253771	-42.253772	2e-5
DY	4.3932568	4.3932411	2e-5
DZ	-10.590958	-10.590987	7e-5

Table 2. Comparison of results of GIOTTO team and VEGA team (VEGA-1 data only)

This means that the difference between the two results was quite small, and within the 1-sigma zones of the expected accuracies.

It can be seen in Table 2 that the uncertainty in the improved comet position is the biggest in the z-direction. This is a consequence of the fact that the VEGA orbits, the accuracy of which is directly related to the precision of the improved comet orbit, have got the worst precision in the z-direction.

It should also be mentioned that the difference between the VEGA team and the GIOTTO team solution is mainly due to the fact that the result for the comet velocity was slightly different between the two teams. During the period from VEGA-1 encounter to the reference time March 14, this effect led to a position difference. The solutions of the two teams, for the epoch equal the time of the VEGA-1 encounter, the results were only about 20 km different in position. As mentioned above, however, a precise determination of the comet velocity required data of the two VEGAs to be available.

It is furthermore of interest to have a look at the residuals of the observables. In Figure 4, the residuals are shown in the following cases:

Figure 4a: Residuals of the observable Ψ (derived angle), before the first iteration of the estimation filter.
Figure 4b: Residuals of the observable Ψ after convergence of the filter.
Figure 4c: Residuals of the observable Ψ after convergence, in case the bias and drift parameters of the observation model are not solved for.

From Figure 4a it is apparent that the switch-over between the two modes of attitude control can be identified in the observables. Furthermore, it is possible to see the effects of the limit cycling of the attitude control loop in mode 1. Comparing Figures 4b and 4c clearly shows the absolute necessity of using an accurate model for the observation errors, as explained in section 3. In the case of VEGA-1 for example, the determined gyro drift components resulted in an amount of about .2 degrees per hour, and bias values of .1 degrees were determined. These are significant figures if one knows that the rms values of the residuals after convergence were in the order of magnitude .02 degrees (1.2 arcmin).

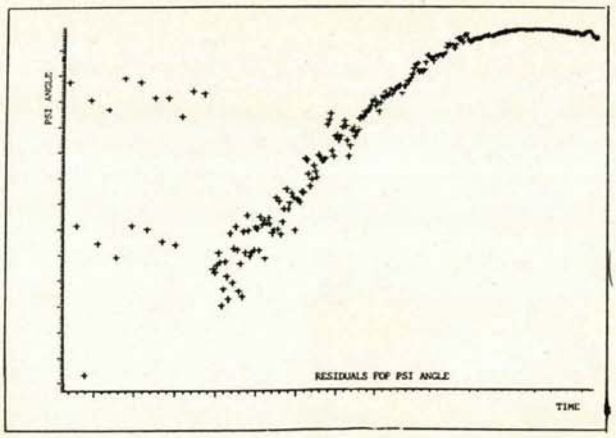


Figure 4a. Residuals of the observable Ψ (derived angle), before the first iteration of the estimation filter.

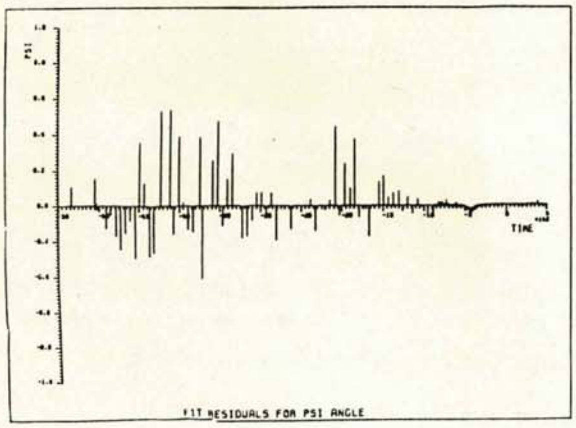


Figure 4b. Residuals of the observable Ψ after convergence of the filter.

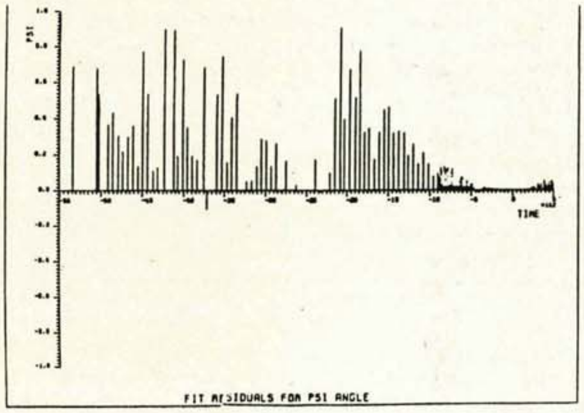


Figure 4c. Residuals of the observable Ψ after convergence, in case the bias and drift parameters of the observation model are not solved for.

6.2 After VEGA-2 Encounter

The VEGA-2 encounter, which took place in the morning of March 9, was also quite successful. Although the automatic digital tracking system of the VEGA camera temporarily lost track of the comet, inertial angles could be made available over the major part of the fly-by period. Again, the calculations for the improved comet orbit determination were performed and firstly, as a test, it was verified to what extent the updates to the ground-based comet orbit usng the VEGA-2 data alone would be in accordance with the updates found using the VEGA-1 data. This comparison was quite successful, as the difference between the two solutions was only of the order of 50 km.

Afterwards, both the GIOTTO and the VEGA team performed the calculations using both VEGA-1 and VEGA-2 data, leading also to a more accurate estimate of the comet velocity, and making possible a more precise propagation towards the epoch of the GIOTTO encounter.

The results of both teams, expressed at the reference epoch of March 14, at 0.0 hours Ephemeris Time, were as follows:

	GIOTTO Team	VEGA Team	1-sigma accuracy
X	-80526350.	-80526370.	37.
Y	-97904480.	-97904501.	35.
Z	-46387237.	-46387207.	55.
DX	-42.253739	-42.253772	2^{e-5}
DY	4.3932594	4.3932122	2^{e-5}
DZ	-10.591095	-10.5910651	6^{e-5}

Table 3. Comparison of results of GIOTTO Team and VEGA Team (VEGA-1 data and VEGA-2 data used)

As regards the bias and drift terms, similar effects and values were found as for VEGA-1.

It was therefore seen that the difference between the final GIOTTO Team and VEGA Team solutions was very small and, for the comet position near the GIOTTO encounter time, within the 1-sigma region of the formal accuracy estimate. The VEGA inertial pointing angles enabled a dramatic improve of accuracy in the comet orbit. Expressed in the GIOTTO target plane, the uncertainty ellipse was now reduced to dimensions of the principle axes (1-sigma) of 35 km x 25 km, which is for the semi-major axis about 7 times better than what would have been obtained without Pathfinder. Let us not forget that one of the limiting factors leading to this accuracy, was the orbit determination precision of the VEGAs. Without the support of NASA's DSN network, utilising the VLBI techniques VEGA orbit determination, the VEGAs would have only be known with an accuracy in position of more than 100 km (1-sigma). This means that, without the DSN support, the Pathfinder activities would have been far less helpful.

The remaining uncertainty in the comet velocity which was in the order of 8 cm/sec caused that the Pathfinder solution for the comet ephemeris was only a useful local solution; two months after the VEGA-2 encounter, this velocity uncertainty would have caused an error in position of abut 400 km (1-sigma), which would by then be 'outcompeted' by an updated ground-based solution using new astrometrical observations of the comet. This by the way implies that the GIOTTO Team was lucky to have the VEGAs passing the comet so closely in time before the GIOTTO spacecraft; while still leaving some time interval between VEGA-2 and GIOTTO fly-by, necessary to analyse the data and plan and perform the GIOTTO orbit correction manoeuvre. The coordination of the fly-by times was, in fact, reached as a part of the results of negociations within the IACG.

After the termination of the Pathfinder activities, the GIOTTO Science Working Team, also using cometary dust hazard information gathered by the VEGAs, decided to aim GIOTTO at a distance from the comet of 550 km, at an angle of 20 degrees south of the ecliptic, towards the sun-lit side of the comet (see centre of ellipse D in Figure 5).

The chosen distance of 550 km corresponded to 500 km + 1 sigma of the combined uncertainty of GIOTTO and comet, along the target direction. The corresponding orbit manoeuvre for GIOTTO was carried out on March 12, and the amount was 2.47 m/sec.

GIOTTO performed its successful encounter on March 14. On the basis of the camera pictures of the comet, which were obtained from GIOTTO, it was possible to calculate a reconstituted fly-by distance of about 605 km. The difference between this value, and the 550 km which were aimed for, is to be explained from four error sources:

- the remaining uncertainty in the improved comet orbit
- the dispersion in the GIOTTO orbit manoeuvre which was carried out
- the uncertainty in the GIOTTO orbit determination
- the accuracy of the reconstructed fly-by distance.

In fact, making use of additional GIOTTO tracking data which were obtained during and shortly after the encounter, it was possible to improve the accuracy of the GIOTTO position in the target plane. Utilising these data, one finds that the error which remained on the comet position at GIOTTO encounter time, was only 25 km in the target plane. This value is within the 1-sigma region of the expected accuracy (from Table 3).

In Figure 5, the GIOTTO targeting history is depicted, together with the uncertainty ellipses for comet Halley and GIOTTO in the GIOTTO target plane.
Ellipses 0-2 refer to the comet location:
0) the ground-based comet orbit, i.e. before Pathfinder
1) the solution after VEGA-1 encounter
2) the solution after VEGA-2 encounter.
Ellipses A-D refer to the GIOTTO targeting history; the transition from the centre of ellipse C to the centre of ellipse D corresponds to the manoeuvre which took place on March 12, after the Pathfinder operations.

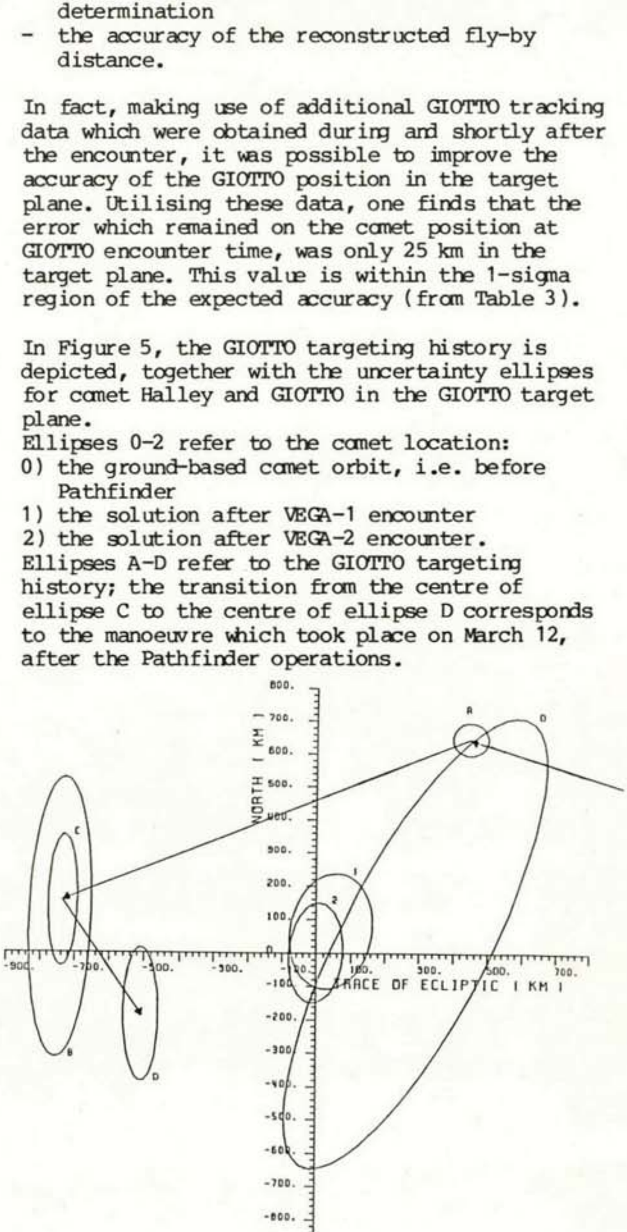


Figure 5. Uncertainty Ellipses (3-sigma) for comet Halley and GIOTTO in the GIOTTO target plane

7. CONCLUSION

It may be concluded that Pathfinder has been a very useful and successful cooperation between the three Agencies involved: NASA, INTERCOSMOS, and ESA.

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