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The Giotto Project

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Abstract

ESA’s Giotto Mission to Halley’s Comet is a fast flyby at 00 UT on 14 March 1986, about four weeks after the comet’s perihelion passage, when it will have been at its most active. The scientific payload is made up of ten experiments with a total mass of approximately 60 kg: a camera for imaging the comet nucleus, three mass spectrometers for analyzing the elemental and isotopic composition of the cometary dust and gas environment, various dust impact detectors, a photopolarimeter for measuring the coma’s brightness, and a set of plasma instruments for studying the solar-wind/comet interaction. In view of the high flyby velocity of 68 km/s, the active experiment time will only be very short - of the order of 4 h - and all data are to be transmitted back to Earth in real time, at a rate of 40 kbit/s.

The Giotto spacecraft is spin-stabilized and has a despun, high-gain parabolic dish antenna inclined at 44.3deg which will point towards Earth during the cometary encounter. A specially designed ’bumper shield’ protects the front end of the spacecraft from being destroyed by hyper-velocity dust impacts.

The Giotto spacecraft will be targetted to pass the nucleus at a distance of 500 km on the sunward side.

1. Introduction

The Giotto project was approved in July 1980, allowing precisely five years between approval and launch. During the Giotto mission study phase, a Scientific Working Group formulated the scientific objectives and defined a mission concept and a model payload. The scientific objectives for the Giotto mission are:

- to ascertain the elemental and isotopic composition of the volatile components in the cometary coma, in particular to identify the parent molecules
- to characterize the physical processes and chemical reactions that occur in the cometary atmosphere and ionosphere
- to determine the elemental and isotopic composition of the cometary dust particles
- to measure the total gas production rate and the dust flux and size/mass distribution and to derive the dust-to-gas ratio
- to investigate the macroscopic system of plasma flows resulting from the interaction between the cometary and the solar-wind plasma
- to provide numerous images of the comet nucleus with a resolution down to 50 m, thereby allowing the nucleus’ size and rotation to be deduced and its mass to be estimated.

To accomplish these objectives, the Giotto spacecraft carries ten scientific experiments, selected in January 1981, some of which have more than one sensor. They are listed in Table 1 together with their mass, power and data-rate allocations.

An intense Earth-based observation programme forms a natural and necessary complement to the Giotto mission.

2. The scientific payload

2.1 The Halley Multicolour Camera (HMC)

The camera is designed to detect and image the nucleus of Comet Halley, to measure the nucleus’ size, shape and albedo, and to observe its active sublimation process. By following the moving comet nucleus, the camera’s microcomputers can determine the spacecraft’s trajectory parameters relative to the nucleus in real time.

The optical system of the camera is a modified Ritchey-Chretien design with correcting field lens (Fig. 1). The telescope is mounted behind the spacecraft bumper shield and therefore protected from direct dust-particle impacts. A 45deg deflecting mirror is used to look at the comet. A baffle ensures adequate reduction of diffuse sunlight and spacecraft-reflected light.

The telescope images onto a focal-plane arrangement of one reticon and two area CCDs (Charge-Coupled Devices). The reticon is used to detect the nucleus and later to clock the two area CCDs. The area CCDs are used in a mode in which only a few active lines scan the image of the comet during its apparent motion across the rotating (because of the spacecraft spin) field of view; the remaining lines are masked and used as a low-powerù highly efficient data buffer. The contents of the exposed lines are shifted into the masked CCD lines at precisely the same rate as the nucleus image moves. Using CCDs as the intermediate storage for a line scanner allows exposure times as short as 10 micro s to be used. Smear due to the spinning motion of the camera is then negligible, even for the detector’s high resolution of 22 microrad per pixel. In the nucleus-imaging mode, the camera works best if the nucleus is slightly (>~ 1deg) off spin axis. The two area CCDs each have two segments, three of the four segments being tinted to provide colour pictures.

Table 1. Giotto’s scientific payload

Experiment		Mass (kg)	Power (W)	Data Rate (bit/s) Format 1/2/3*			Principal Investigator	Mai (ha
Camera		13.51	11.5	20058		723	H.U. Keller, MPI fur Aeronomie, Lindau W. Germany	Lab & P Ins Ist DFV Bal
Neutral Mass Spectrometer	M-Analyser E-Analyser	12.70	11.3	4156		-	D. Krankowsky,. MPI fur Kernphysik, Heidelberg, W. Germany	Phy Uni Lab Ext The
Ion Mass Spectrometer	High Energy Range Spectrometer, High Intensity Range Spectrom.	9.00	6.3	3253		1084	H. Balsiger, Physikalisches Institut, University of Bern, Switzerland	MPI JPL Loo Lab
Dust Mass Spectrometer		9.89	9.1	2891	5782	-	J. Kissel, MPI fur Kernphysik, Heidelberg, W. Germany	
Dust impact Detector System	Meteoroid Shield Momentum Sensor, Impact Plasma & Momentum Sensor, Capacitor Impact Sensor	2.26	1.9	361	903	-	J.A.M. McDonnell, Space Science Laboratory, University of Kent, Canterbury, UK	Rut UK. MPI ONE Tou ESA Ist Ist
Plasma Analysis 1	Fast Ion and Implanted Ion Sensors	4.70	4.4	3975	1265	1355	A. Johnstone, Mullard Space Science Lab., Holmbury St. Mary, UK	MPI Ist

Plasma Analysis 2	Electron Elecrostatic Analyser, Positive Ion Cluster Comp. Analyser	3.21	3.4	2530	1807	904 ,	H. Reme Centre d’Etude Spatiale des Rayonnements, France Toulouse,	MPI Spa Ber
Energetic Particles		0.95	0.7		181		S.M.P. McKenna-Lawlor, St. Patrick’s College, Maynooth, Ireland	Dub Stu MPI
Magnetometer		1.36	0.8	1265		407	F.M. Neubauer, Institut fur Geophysik und Meteorologie, Koln, W. Germany	Ins Met Lab Phy Ist Rom
Optical Probe Experiment		1.32	1.2	723		-	A.C. Levasseur-Regourd, Service d’Aeronomie du CNRS, Verrieres-le-Buisson, France	La Ma Spa Uni
Radio Science Experiment		-	-	-		-	P. Edenhofer Institut fur Hoch- und Hochstfrequenztechnik, W. Germany	Rad Uni DFV
TOTAL		58.90	50.6	39393		4654		

* Format 1: From t(0)-4 h until t(0)-1 h   Format 2: from t(0)-1 h until mission end   Format 3:

The camera can be rotated through 180deg, allowing the nucleus to be followed and imaged during approach and even after the flyby. Even when 1400 km from the nucleus, the camera will be able to resolve its surface structure down to 30 m.

Table 2. Halley Multicolour Camera (HMC) characteristics

Telescope	Ritchey Chretien with corrector lens	Filters	
	focal length: 1000 mm, effective F/7.68	1st area CCD:	lines 5-10:red*
	aperture: 160 mm		lines 11-292:maske
	field of view: 1.5deg		lines 297-302:filte
			lines 303-584:maske
Detectors	1 multidiode array: Reticon, 2 lines with 936 diodes	2nd area CCD:	lines 5-8 :clear
	each diode size 30 x 375 micro m		lines 9-292 :maske
	2 area CCDs: TI, virtual phase		lines 297-304:blue*
	each 2 x292 lines with 390 pixels per line		lines 305-584:maske
	pixel size 22.3 x22.3 micro m		

Resolution 22 m/pixel at 1000 km slant range

Field of view linear CCD: 1.61 deg (1 .5deg unvignetted)

area CCD: 0.65deg

* More than one line because of TDI

Figure 1. The Halley Multicolour Camera (HMC). The baffle with its 10 elements is shown in the upper right, the deflecting mirror in the lower right, the primary and secondary mirrors in the lower left and centre, respectively, and the focal-plane layout (reticon, CCDs and filter wheel) to the left of the primary mirror

Figure 2a. The Neutral Mass Spectrometer (NMS) M-Analyser

Figure 2b. The Neutral Mass Spectrometer (NMS) E-Analyser

Figure 2c. The High-Energy Range Spectrometer (HERS) of the Ion Mass Spectrometer

2.2 The Neutral Mass Spectrometer (NMS)

As the spacecraft flies through the cometary coma, cometary neutrals will be encountered at the flyby velocity of 68 km/s. Since the gas outflow velocity is much smaller (<1 km/s), one might think that the mass of the cometary neutrals could be determined simply by measuring their energy (since E= 1/2 mv**2). However, the daughter molecules can derive significant kinetic energies from energetic interactions such as photo-dissociation and ion-molecular reactions, which appear either as a change in the incident direction, or as an increase or decrease in energy, e.g. an oxygen atom with a velocity of 5 km/s can appear anywhere between mass 14 and 18. Consequently, an energy spectrum will be smeared, predominantly in the lower mass ranges, and individual peaks corresponding to particular masses cannot be resolved. In the higher mass ranges, the cometary neutral velocity distribution will be ’cold’ and the energy spectrum will correspond to the mass spectrum.

In the lower mass range (1-36 amu), therefore, a double-focusing (angle and energy) mass spectrometer is used consisting of a parallel-plate electrostatic energy analyzer followed by a magnetic sector field momentum analyzer. The particle beam is imaged onto a microchannel plate with linear readout, where each position corresponds to a particular mass. The energy information that is lost in the ’M-analyzer’ is provided by the ’’E-analyzer’, which is simply a parallel-plate electrostatic analyzer with single focusing (angle) properties. Again, the particle beam is imaged onto a microchannel plate with linear readout, where each position corresponds to a particular energy. For analysis, the beam of cometary neutrals has first to be transformed into a beam of ions; this is achieved by bombardment with an electron beam, with the electrons being emitted from either of two redundant filaments.

Both sensors (Figs.2a,b) have separate and nearly identical gas inlet systems with an electron beam ion source of fly-through geometry. The ion source operates in two modes. In the neutral mode, cometary ions are reflected by deflecting plates in front of the entrance slit; in the ion mode, the deflecting plates are switched off and the electron emission is suppressed, allowing cometary ions to enter the analyzer. Further away from the comet nucleus, the instrument will measure predominantly ions, close to the nucleus predominantly neutrals.

Table 3. Neutral Mass Spectrometer (NMS) characteristics

	M-analyzer	E-analyzer	
Energy range		10-1410 eV	210-2180 eV
Mass range	1-36 amu	1- 57 amu	9- 89 amu
Resolution	0.15 amu 1 amu for particles 4.5deg off axis and 10 eV thermal energy	8- 142 eV	6- 11 eV
Field of view	+/-4deg	+/-4deg	
Integration time			
- neutrals	0.9 s	0.4 s	
- ions	1.0 s	0.4 s	
Sensitivity			
- neutrals	50 cm**-3	100 cm**-3	
- ions	8x10**-5cm**-3	1.6x10**-4cm**-3	
Dynamic range	10**12	10**2	

2.3 The Ion Mass Spectrometer (IMS)

The Ion Mass Spectrometer is made up of two sensors, a High-Energy Range Spectrometer (HERS) optimized for measurements in the outer coma where a turbulent transition between solar wind and cometary ions is expected, and a High-Intensity Spectrometer (HIS) optimized for measurements in the inner coma where high fluxes of relatively cold cometary ions are anticipated.

The HERS sensor (Fig. 3) consists basically of an electrostatic mirror to deflect the cometary ions into the instrument, a pair of grids with variable applied voltage, a sector magnet which serves as momentum-per-charge filter, and an electrostatic deflector which spreads the momentum-analyzed ions according to their energy per charge. The beam is then imaged onto a two-dimensional microchannel plate, with one dimension a measure of mass-per-charge, and the other a measure of the elevation angle of the ion’s velocity vector. Azimuth angle is scanned via the spacecraft’s spin and the energy distribution is determined by variation of the voltages applied to the pair of grids.

The HIS sensor (Fig. 4) employs two quadrispherical electrostatic analyzers with magnetic deflection and an array of 4 X4 channeltrons as detectors. The energy-per-charge of the particles to be analyzed is selected by the differential voltage applied to the first electrostatic analyzer, while the momentum-per-charge (and thus mass-per-charge) is determined by the acceleration potential applied between a pair of plane parallel grids located behind the exit of that analyzer. The ion species expected at the selected energy is imaged at the centre of the one-dimensional detector array of four channeltrons. Hence, the mass spectrum and the temperatures of all individual species can be measured by just scanning through the energy-per-charge range. The other direction of the channeltron array provides resolution in elevation, while azimuth angle is scanned by the spacecraft spin.

Table 4. Ion Mass Spectrometer (IMS) characteristics

	HERS	HIS
Energy range	20-8000 eV	300-1400 eV
Mass range	1-35 amu/q	12-57 amu/q
m/Delta m	>=20 at ~20 amu/q	>=20 at ~20 amu/q
Elevation range/resolution	(i) + 15deg to +75deg/7.5deg	- 3deg to +22.5deg/5deg
Azimuth range/resolution	Spin scanned/5.6deg	Spin scanned/22.5deg
Time resolution	16 s	4 s
Dynamic range	10**-3 - 10**2 cm**-3	10**-2 - 10**4 cm**-3

Figure 4. The High Intensity Spectrometer (HIS)
of the Ion Mass Spectrometer

2.4 The Dust Mass Spectrometer (PIA)

This instrument measures the chemical and isotopic composition of individual dust particles (Fig. 5). When a dust particle impacts on the instrument's target, a plasma is generated, from which ions are extracted and accelerated via a 1.5 kV acceleration grid. The accelerated ions pass through a time-of-flight tube approximately 1 m long, where they are separated in time according to their mass. The spectrum of elements of which the dust particle is composed is recorded by an electron multiplier at the end of the drift path. Since the elemental abundances of typical minerals found in meteorites vary significantly, it is possible to identify the predominant mineral in the impacting dust grain from the quantitative abundance in the spectrum.

Figure 5. The Dust Mass Spectrometer
(Particulate Impact Analyser or PIA)

Impact-ionization mass spectrometry is ideally suited for a fast cometary flyby such as Giotto will make, because the number of positive ions released upon impact increases significantly with the impact velocity. The time-of-flight tube actually consists of two tubes at an angle of 8 deg, with an ion reflector in between, used for energy focusing. This, together with the high ion yield, gives excellent mass resolution, so that isotopic ratios such as 7Li/6Li, 11B/10B, and 13C/12C can be resolved. Because of its small target area, which can be varied via a shutter mechanism, the instrument will predominantly analyze the most common dust particles, which are expected to be in the mass range 3 x 10**-16 - 5 x 10**-10g.

Table 5. Dust Mass Spectrometer (PIA) characteristics

Dust mass range	~3x10**-16 -5x10**-10g
Atomic mass range	1-110 amu
Mass resolution	Separation of peaks possible if I(m+1) : I(m) >= 1:50
Time resolution	~ 10**-4 s time of flight in the tube ~ 10**-2 s for impact counting 0.25 s for spectral analysis of individual dust particles
Target area/material	0.01-5 cm**2 (shutter-controlled)/Pt +5% Ag

2.5 The Dust Impact Detector System (DID)

Although larger dust particles are more infrequent, the bulk of the mass released from the nucleus in the form of solids is contained in them. Impacts of these large dust particles on the front sheet of the spacecraft bumper shield (Fig. 6) are detected by three piezo-electric elements (microphones) mounted 120deg apart at the outer edge of the front sheet (meteoroid shield momentum measurement, MSM). They register the shock wave that is generated by each dust-particle impact and propagates through the front sheet. In this way, the whole front-sheet area (2 m**2) can be used as a 'detector'. A similar element on the rear sheet (rear-shield momentum measurement, RSM) measures the mass of the even larger dust particles that are able to penetrate the front sheet (>10**-6 g) and impact on this rear sheet.

A Capacitor Impact Sensor (CIS) 1000 cm**2 in area measures the flux of dust particles > 10**-10 g penetrating a thin (70 micro m) mylar dielectric material. Aluminium deposits on both faces act as a capacitor. When impacted by a sufficiently large particle, the dielectric of the capacitor will be perforated and the device discharged through the impact-generated plasma. The counting rate is limited by the capacitor recharging process to ~ 1000 impacts/s.

Very small dust particles are to be detected by an Impact Plasma Detector (IPM), which has very high count-rate capability. This sensor is also located on the front sheet of the spacecraft bumper shield. The impact-generated plasma electrons and ions are separated by an electric field, the total charge being proportional to the particle mass. The impact plasma detector has two arrays, one without a foil, the other covered by a metalized penetration film 1 micron thick, which observes a somewhat reduced number of impacts depending on the penetrating power or bulk density of the dust particles. A piezo-electric microphone sensor (as in MSM) forms part of the IPM and simultaneously detects the impact momentum, independent of the ambient plasma. The impact momentum differs depending on whether the dust particle impacts on the covered (momentum of the debris cloud) or uncovered (momentum of dust particle only) part of the IPM. Furthermore, a thin metallic probe with a - 20 V potential, insulated from the spacecraft structure, forms part of the impact plasma detector and monitors the saturation current of the secondary electrons emitted by impacts of cometary gas and dust particles. The response of this sensor will be used to assess the density of the plasma cloud that forms around the spacecraft during its critical passage through the inner coma.

Figure 6. The Dust Impact Detector System (DID), mounted on the front sheet of the spacecraft’s bumper shield. Details of the Meteoroid Shield Momentum Sensor (MSM) and the Impact Plasma and Momentum Sensor (IPM) are shown on the right

The main objective of this system of dust-impact detectors is to provide the dust-particle mass spectrum between 10**-17 and 10**-3 g.

Table 6. Dust Impact Detector (DID) System characteristics

IPM	
(a) Sensor area	100 cm**2 (Au target), half of sensor covered by a metallized film (thick)
Impact charge range	10**-14 - 10**-8degC
Maximum count rate	1000/s
Density resolution	1 g/cm**-3 at 10**-13-10**-15 g
(b)Impact detector	One piezo-electric PZT-5H, longitudinally resonant element
Momentum range	10**-11 - 10**-8 Ns
Maximum count rates	100/s
MSM/RSM	
Impact detectors	Four piezo-electric PZT-5H, longitudinally resonant elements, 200 kH (three mounted on front sheet, 120deg apart, 1 mounted on rear side rear sheet)
Sensor area	2 m**2 (front sheet of bumper shield)
Momentum range	10**-11-10**-8 Ns
Maximum count range	10/s at 10**- 10 g 1/s at 10**-6 g
CIS	
Sensor area	1000 cm**2
Capacitor configuration	10 micro m electrode (Al foil) 70 micro m dielectric (Teflon) 0.1 micro m electrode (Al foil) 10 micro m insulation (Teflon)
Threshold sensitivity	10**-9 g
Maximum count rate	1000/s

2.6 The Fast Ion Sensor (FIS)

This sensor (Fig. 7) measures the three-dimensional velocity distributions of solar-wind ions, giving their flow speed and direction, temperature and density, and follows the development of the solar wind as it is thermalized, slowed-down and deflected. Ions streaming parallel to the relative-velocity vector will not be measured, as these are expected to have very high fluxes near the comet.

The sensor consists of a hemispherical plate electrostatic energy analyzer, with a subsequent quadrispherical sector (80deg) to disperse the trajectories according to the polar angle of incidence before they are registered by a microchannel plate with a series of eight metal anodes behind it. The energy band can be varied by changing the voltages on the plates of the energy analyzer.

The experiment can be operated in different modes, depending on the angular width and the energy spread of the ion distribution.

2.7 The Implanted Ion Sensor (IIS)

Some cometary neutrals may reach large distances from the nucleus before they are ionized and become ’implanted’ in the solar wind. The task of the Implanted Ion Sensor (Fig. 8) is to search for these cometary ions. It combines an elecrostatic analyzer with a time-of-flight measurement. The quadrispherical electrostatic analyzer selects positive ions of a given energy per charge (E/Q), which are then accelerated by a potential difference V before the time T to travel a path length D is determined. By measuring these quantities, the mass-to-charge ratio can be determined from

$$M/Q = 2(V + (E/Q)) T^{2}/D^{2}$$

Figure 7. The Fast Ion Sensor (FIS)

Since cometary neutrals are ionized by charge exchange or photons, the charge state is predominantly Q= 1, allowing the ion mass to be determined.

The instrument has a total of five electrostatic analyzers, each followed by a time-of-flight tube. The ions enter one of the electrostatic analyzers, depending on their incident elevation angle. As the ions leave the analyzer, they are accelerated before they enter the time-of-flight tube, which is only 4 cm long. The ’start’ signal is provided by secondary electrons generated by the ion’s passage through a thin carbon foil, the ’stop’ signal by secondary electrons generated in the surface layer of a spherically-shaped aluminium absorber. In both cases, the secondary electrons are accelerated by 0.7 kV and deflected towards a microchannel plate. In the ’4D’ mode, the ions are sorted into five different mass groups in the range 1-45 amu; in the ’TOF’ mode, they are sorted into 256 groups, depending on their time-of-flight.

Figure 8. The Implanted Ion Sensor (IIS) and electronics box. Three of the five electrostatic analyzers and one of the five time-of-flight tubes are shown in this illustration

2.8 The Electron Electrostatic Analyzer (EESA)

This sensor (Fig. 9) measures the pitch-angle distributions of suprathermal electrons in the energy range 10 eV - 30 keV. These measurements, together with those of the FIS, will define the solar-wind plasma and its interaction with the comet. EESA is an electrostatic analyzer which is hemispherical in shape, but has the characteristics of a quadrispherical analyzer. The particles enter through a circular opening in the centre of the hemisphere and are deflected through 90deg before they are detected by one of the 17 sections of a ring-shaped microchannel plate, depending on their incident polar angle. Azimuthal resolution is provided by the spacecraft’s spin. The potential between the analyzer plates is varied in 39 steps, providing a 10% energy resolution.

Table 7. Plasma Experiment characteristics

FIS (ions)	
Energy range	10 eV-20 keV
Field of view	5deg, azimuthally
Geometric factor	4.7×10^{-3} E (eV)
Max. count rate	10^{6}/s
Detector	Microchannel plate with 8 metal anodes

	Solar wind mode		HAR mode		FTR mode
Energy range	?				
Energy resolution	delta E/E = 9.6%		30%		60%
Time resolution	8 s		12 s		4s
Azimuthal range	-22.5 to +22.5 (wrt Sun)		0-360deg		0-360deg
Azimuthal sectors	8	1	8	16	8
Elevation range	46-98deg	46-150deg	20-180deg	72-124deg	20-180deg
Elevation sectors	1	5	4	2	3

IIS (ions)

Energy range	90 eV-90 keV
Energy resolution	E/E = 10%
Mass range	1-45 amu in five groups
Geometric factor	7.6 x 10**-2 E (keV) cm**2 ster keV
Max. count rate	3x10**4/s
Background count rate	<1/d
Azimuthal range	0-360deg
Elevation range	15-l65deg
Time resolution	128 s
Field of view	l2deg, azimuthally

	4D mode	TOF mode
Azimuthal sectors	16	1
Polar sectors	5	1
Mass groups	5	256 ('time' groups)

EESA (electrons)

Energy range	10 eV-30 keV
Energy resolution	Delta E/E = 10% (39 energy steps, one sweep takes 0.25 s)
Field of view	360deg x 14deg (from -5deg to +9deg from ram direction)
Elevation range/resolution	360deg/14 sectors with 22.5deg, two sectors with 19.5deg one sector with 6deg (centred around ram direction)
Azimuth range/resolution	360deg/22.5deg
Time resolution	2 s
Geometric factor	5.5 x 10**-3 E (kV) cm**2 ster keV
Detector	Circular ring microchannel plate with 17 sectors

PICCA (ions)

Mass range/resolution	10-50 amu/Delta E= 10 eV, Delta m=0.4 amu 50-203 amu/Delta E=25 eV, Delta m= 1 amu
Field of view	6deg x6deg
Time resolution	3.2 s
Dynamic range	10**-3-10**3 cm**-3
Acceptance area	0.1 cm**2
Detector	Two channeltrons (one fast, up to 10**7 counts/s, one normal, up to counts/s)

2.9 The Positive Ion Cluster Composition Analyser (PICCA)

This sensor (Fig. 10) is intended for operation in the innermost part of the coma, where the cometary ions are expected to be singly charged and to have negligible thermal velocities. In the spacecraft frame of reference, these particles will flow strictly radially towards the spacecraft with a velocity of 68.4 km/s, and their kinetic energy will range from 245 eV (10 amu) to 4.9 keV (200 amu). As the energy E and the charge Q of the ions are assumed to be known, an E/Q measurement translates directly into a mass measurement. Of particular interest are the clathrate hydrates (e.g. CO.6H2O), which are formed when some of the more volatile species such as CO, CO2, NH3, are trapped in a cage of H2O molecules. Once these clusters are ionized (I+.(H2O)m), PICCA has the ability to detect them because of its high mass range.

PICCA is a hemispherical electrostatic analyzer with two channeltrons as detecting devices. By varying the potential between the top and bottom parts of the aperture, the particles will be deflected from the general flow direction and will enter the analyzer according to their mass. To obtain a good and constant mass resolution, the ions are decelerated before entering the electrostatic analyzer. The hemispherical analyzer itself is operated at two different fixed voltages, corresponding to two mass ranges.

Figure 9. The Electron Electrostatic Analyser (EESA). Although the analyzer is hemispherical in shape, the electrons only traverse a quadrisphere after entering through the top cap.

Figure 10. The Positive Ion Cluster Composition Analyser (PICCA)

2.10 The Energetic Particles Experiment (EPA)

The prime purpose of the Energetic Particles Experiment (Fig. 11) is to extend the range of the Giotto plasma analyzers to higher energies. It will detect particles which are accelerated in the cometary environment from solar-wind energies (~ 1 keV), and it will allow determination of the dust-column density as the low-energy solar particles are absorbed by the dust. Monitoring of the energetic-solar-particle flux will also provide useful background information, in particular during a solar flare, to instruments using devices which are sensitive to these particles, such as channeltrons, channel plates and CCDs.

This experiment consists of three identical very small telescopes, each with two solid-state detectors. Two telescopes are mounted side-by-side at 45deg, and a third one at 135deg to the relative velocity vector. This allows observations of field-aligned particle streaming for all inclinations of the magnetic-field vector; in other words, together with the spacecraft spin, it allows three-dimensional viewing of particle pitch-angle distributions. One of the two adjacent telescopes is covered by a thin foil, the other is open. Low-energy protons cannot penetrate the foil and therefore the covered telescope measures only electrons, while the open telescope measures both protons and electrons. Neglecting statistical fluctuations, the count-rate difference then applies to protons only.

The energy of the incoming charged particle is determined by measuring its energy loss in the solid-state detectors in various channels and logic combinations (Table 8) Particles of different species and energy ranges are identified using the dE/dx versus E technique. The low energy threshold of 20 keV is essentially determined by the detector noise. It coincides with the upper energy threshold of the Fast Ion Sensor (20 keV).

During the encounter phase, spectral and angular information about particle fluxes will be provided with high time resolution (0.5 s). During the cruise phase, approximately 30 min average particle-flux measurements and angular information will generally be obtained in one energy channel. An experiment internal memory of 64 kbit of RAM will be used, which allows up to 13 days of data storage.

Table 8. Energetic Particles Experiment (EPA) characteristics

Detectors	Totally depleted surface barrier detectors, circular in shape		
		A	B
	Area	0.384 cm**2	1.35 cm**2
	Thickness	100 micro m	200 micro m

Geometric factor	8.2 x 10**-2 cm**2 ster per telescope
Field of view	30deg (full cone)
Azimuthal range/resolution	360deg/45deg (eight sectors)
Temporal resolution	0.5 s
Elevation range	30deg- 60deg (Telescopes 2 and 3)
	120deg-150deg (Telescope 1)

Channel specification	Energy range	Species	Detector threshold logic
- Telescope 1 (open)	29-46 keV	p e	A1 . A2 . B1
	44- 77 keV	p e	A2 . A3 . B1
	78-215 keV	p e	A3 . B1 . A4
	0.217-3.5 MeV	p	A4 . A5 . B1
	4.5-20 MeV	p	A4 . A5 . B2
	20-50 MeV	p	A4 . B1 . B2. A5
	3.5-12.5 MeV	alpha	A5 . B1
	> 180 keV	e	A1 . A4 . B1. B2
- Telescope 2 (with foil)	20- 30 keV	e	A1 . A2 . B1
	30-60 keV	e	A2 . A3 . B1
	60-150 keV	e	A3 . B1 . A4
	0.35-3.5 MeV	p	A4 . B1
- Telescope 3 (open)	26-44 keV	p e	A1 . A2 . B1
	45-76 keV	p e	A2 . A3 . B1
	78-213 keV	p e	A3 . B1 . A4
	0.22-3.5 MeV	p alpha	A4 . A5 . B1

Figure 11. The Energetic Particles Experiment (EPA)

2.11 The Magnetometer (MAG)

The magnetic field is to be measured by a wide-range (0.004-65536 nT) triaxial ring-core fluxgate magnetometer mounted on the antenna tripod, where it is furthest from the spacecraft and also protected from dust impacts (Fig. 15). The Giotto magnetometer is identical to the GSFC fluxgate magnetometers carried on Voyager and destined for flight on ESA’s Ulysses (formerly ISPM) spacecraft. Noise characteristics have been improved by use of different sensor core alloys.

The principle of the fluxgate magnetometer is as follows (Fig. 12). Suppose that in the simplest sensor arrangement a ferromagnetic core of soft magnetic material is periodically driven into saturation by a drive coil generating a periodic magnetic field strength of suitable wave shape at the drive frequence f(0). An additional sense coil around the core will then exhibit a distorted signal composed of frequency components at f(0) and odd harmonics. Addition of an ambient magnetic-field component along the core axis will lead to the appearance of even harmonics. Generally, in fluxgate magnetometers the second harmonic is detected because its amplitude turns out to be proportional to the ambient field component parallel to the core or the sense-coil axis. To obtain good linearity, a feedback coil is generally added to compensate the ambient magnetic field in response to the output from the sense coil. In this case, the sense coil is essentially used for zero detection only.

The measurement of the ambient magnetic field is disturbed by the spacecraft field, which generally has two sources: perm fields and induced fields due to magnetic materials, and stray fields due to varying electric currents. Because of their potential lack of stability, magnetically soft materials are particularly disturbing for magnetic measurements. The same is true for stray fields. Major sources of contamination are: the antenna despin motor, the NMS and IMS experiment magnets, the three HMC motors and the PIA motor, the HMC invar, the antenna feed, the TWTs and the latching relays. Present estimates indicate a combined experiment/spacecraft field strength of ~ 30 nT, with ~ 10% variability at the location of the outer sensor.

The magnetometer has two sensors, an outboard sensor located about 1.1 m above the upper face of the spacecraft body, and an inboard sensor located about 0.5 m above it. From the difference in the readings of the two sensors, the spacecraft field can be estimated and its contaminating effect on the ambient field can be eliminated to some extent. The outboard sensor is triaxial (three orthogonal sensors for the measurement of the three components of the ambient magnetic field vector), while the inboard sensor is biaxial (one ring core with two pick-up coils for the measurement of two magnetic field components only). The available data rate allows transmission of 25.4 vectors/s in Formats 1 and 2, 8.8 vectors/s in Format 3, and 1.2 vectors/min in memory mode (assuming that the experiment's 16 kbyte memory is read out after 24 h).

Figure 12. The principle of the fluxgate
magnetometer sensor (MAG)

2.12 The Optical Probe Experiment (OPE)

Observations of cosmic dust have traditionally been classified as either 'remote' (essentially optical) or 'in-situ' (mass spectrometers or impact detectors). Optical remote sensing results in a column brightness (integration over the line of sight), interpretation of which is impossible without assumptions about both the spatial distribution of the dust grains and their scattering properties. In a cometary flyby, a third type of observation, in-situ photopolarimeter observation - referred to as 'optical probing' - is possible. For a photopolarimeter aimed tangentially to the spacecraft orbit, inversion of the brightness integral is rigorous and provides (without any assumptions), in-situ observation of the local spatial density of dust and gas and of the scattering properties of dust grains.

The requirement to observe tangentially offers two possibilities: forward or rearward, corresponding to phase angles of 72.8deg and 107.2deg. Because of the less critical engineering demands (smaller baffle, no dust-particle impacts), a rearward-looking instrument was chosen (Fig. 13).

The photopolarimeter utilizes a small refracting photometer with an objective lens of 24 mm diameter (18 mm effective), eight interference filters, two spectrally matching polaroid foils, and a microchannel plate for spectral analysis. The rotation of the analyzers needed to determine the polarization is provided by the spin of the spacecraft. One complete polarization measurement is performed during half a spacecraft spin. The difference between successive line-of-sight measurements refers to the brightness and polarization of a small volume of space only (a 'cylinder' about 140 km in length and 7 km, corresponding to the instrument's 3deg field of view, in diameter).

The dust will be observed in four spectral bands which are free or almost free of gaseous emissions. Simultaneously, the discrete gaseous emissions of OH, CN, CO+ and C2 will be monitored.

Table 9. Optical Probe Experiment characteristics

Optics	Objective lens phi 24 mm (18 mm effective)	
	Field lens phi 8 mm	
Field of view	3deg (full cone)	
Viewing direction	-180deg (rearward, i.e. phase angle 107.2deg at encounter)	
Filters	Continuum (dust)	Discrete (gaseous emissions)
	361-375 nm	OH 307.5 +/-40 nm
	439-448	CN 387 +/-20
	565-585	CO+ 426 +/-20
	714-721	C2 514 +/-30
	Two polaroid foils (UV, visible)	
Time resolution	0.5 s (2 s for polarisation measurements)	
Sensitivity	S/N > 20 at <2 x 10**5 km from the nucleus	
Detector	Microchannel tube	

2.13 Radio Science (GRS)

It is possible to determine the total electron content in Halley’s ionosphere if two phase-locked (coherent) RF signals with different frequencies are transmitted and their phase difference

delta phi = phi(1) - (f(s)/f(x))*phi(x) = A * f(s)[(1/f(s)**2) - (1/f(x)**2)]

is measured at the receiver. f(s) = 2.3 GHz (S-band), f(x) = 8.4 GHz (X-band), A is a constant of proportionality and I= (integral) N(e)ds is the total electron content between the spacecraft and the receiving ground station.

Figure 13. The Optical Probe Experiment (OPE). On the left is the experiment housing, on the right details of the optical system

It is estimated that the cometary electron content is ~ 3 X 10**16 m**-2, while the interplanetary electron content is ~ 10**18 m**-2 , and the electron content in the Earth’s ionosphere is ~ 10**17 m**-2 . Evidently, the electron content of the comet is only a fraction of the total electron content. Therefore, the cometary electron content as measured during the encounter will appear as a small time variation of 10-15 min duration superimposed on the total background content, which is relatively constant over this time period, apart from variations in the Earth’s ionosphere (diurnal variations, wave-like fluctuations, solar-flare effects). It is therefore necessary to monitor the ionospheric electron content during the comet encounter.

3. The spacecraft

Figure 14 shows a cross-section of the Giotto spacecraft which is spin-stabilized, nominally at 15 rpm. During the comet encounter the spin axis will be aligned with the relative-velocity vector (’relative’ means in the comet frame of reference), i.e. cometary particle streaming is from below in Figure 14.

At launch, the spacecraft weighed 960 kg reducing to 550 kg when the solid-propellant kick motor had burnt out and part of the hydrazine has been used up for the various mid-course attitude and orbit-correction manoeuvres.

The particular comet environment, in combination with the high flyby velocity, leads to problems never before encountered on space flights. Dust particles with masses ~ 10**-6 g impacting at 68 km/s could easily penetrate the spacecraft structure. Each time, a cloud of debris would be formed inside the spacecraft and impact with high velocity on experiments and spacecraft components, leading to their destruction. To provide protection against dust particles of up to 0.1 g, a single sheet of aluminium would have to be more than 8 cm thick and would then weigh more than 600 kg, which is prohibitive. An ideal and in fact the only solution to the problem is a ’dual-sheet bumper shield’, consisting ofa thin front sheet and a thick rear sheet with a large space between. Upon impact on the thin front sheet, dust particle will be completely vaporized. The vapour cloud then expands into the empty space between the two sheets and impacts on the rear sheet, where its energy is dissipated by distributing it over large area.

The thin front sheet and thick rear sheet are in fact 23 cm apart (Table 10). Two quadrispherical shell sectors were closed over the kick-motor nozzle after firing to complete the bumper shield’s front sheet (Fig. 16).

Table 10. Dust shield

Front sheet	0.1 mm white aluminium oxide
	1 mm aluminium
	230 mm spacing
Rear sheet	7.5 mm epoxy kevlar
	5 mm polyurethane foam
	2 mm epoxy kevlar

15 mm MLI (mylar)
40 mm aluminium honeycomb
structure (exp. platform)

Figure 14. Cross-section through the Giotto spacecraft

Figure 15. Positioning of Giotto’s experiments on the spacecraft structure

The spacecraft has three equipment platforms, from top to bottom (Fig. 14): the ’upper’ and the ’lower’ platforms carrying Spacecraft equipment boxes, and the ’experiment’ platform mounted on top of the rear bumper shield (with a small separation) The sensors of the Dust-Impact Detector (DID) System are mounted on the front bumper shield, the Magnetometer Sensors (MAG) are mounted on the carbon-fibre tripod as far away from the Spacecaft’s magnetic-field sources as possible, and the Optical Probe Experiment (OPE) is mounted on the upper platform inside the spacecraft, looking rearward. All other experiment Sensors and electronics’ boxes are mounted on the experiment platform (camera shown as example). The experiment Sensors protrude up to 17 cm from the Spacecraft side wall to allow measurements in the undisturbed flow of cometary particles (Fig. 15).

The solar-cell array will provide 190 W of power during the encounter, which is not quite sufficient when one of the two redundant X-band travelling-wave-tube amplifiers (TWTs) (70 W), all other spacecraft subsystems (85 W), and all experiments (51 W) are switched on. Batteries are required in addition to the solar cells not only to bridge this gap, but also to provide full power during the last part of the encounter, in case the solar array’s power output deteriorates due to dust-particle impacts.

The main spacecraft antenna is a High-Gain Antenna (HGA) dish with an effective reflector diameter of 1.47 m. The HGA can be operated in either S-band (2.1 GHz uplink, 2.3 GHz downlink) or X-band (8.4 GHz downlink). The HGA beam is inclined 44.3deg with respect to the spacecraft’s spin axis and the antenna itself is despun so that it points permanently at the Earth during the encounter. The X-band link budget shows that 40 kbit/s of scientific data can be acquired during the encounter, including a 5 dB weather margin (rain at the receiving station). The pointing requirements in X-band are rather stringent: if the spacecraft spin axis is not well aligned with the spacecraft relative-velocity vector, or if the spacecraft attitude changes due to the impact of a large dust particle, the telemetry link to the ground receiving station may be lost (antenna gain decreases by 3 dB for 0.8deg misalignment in X-band and 3deg in S-band). For operations in the geostationary transfer orbit and near Earth, two low-gain antennas operating at S-band have been used. They are located at either end of the spacecraft: a cardioid antenna at the upper end of the hollow carbon-fibre tripod and a fill-in antenna (microstrip patch) flush-mounted on the front bumper shield.

A MAGE-1 SB solid-propellant motor is mounted centrally. It carried 374 kg of propellant, giving the velocity increment delta V = 1400 m/s needed to inject the spacecraft from Geostationary Transfer Orbit (GTO) into heliocentric orbit.

Figure 16. Giotto’s dust-impact protection system, with thin front sheet, thick rear sheet, and nozzle-closure shells

For attitude and orbit correction manoeuvres, a monopropellant hydrazine propulsion system with four tanks, using He as pressurant, and two identical and independent branches is used. Each branch is made up of four catalytic hydrazine thrusters. 69 kg of hydrazine is available, providing a total delta V capability of the order of 170 m/s, of which some 150 m/s still remained per 1 February 1986. Three types of sensors are used for attitude determination: an Earth Elevation Sensor consisting of two infrared pencil-beam telescopes, a Sun Sensor consisting of two detector units, and a Star Mapper with a 9deg x9deg field of view and a selectable threshold down to +2.4 silicon magnitude.

The Giotto thermal design makes use of both active and passive techniques. The passive means are radiators under the high-gain antenna and between the main and the experiment platform using Optical Surface Reflectors, and Multi-Layer Insulation blankets covering the space between the solar-cell array and the experiment platform. The active means are heaters which can be activated by ground command or by dedicated onboard software, three identical shutters (variable-area radiators), which can also be activated by ground command, 12 diode boards which use some of the solar array’s power to heat the enclosure during some cold phases, and commutation of the excess power generated by the solar-cell array in some External Power Dumper phases to the Internal Power Dumper, which is a circuit heating the TWTAs and a portion of the upper platform during critical phases. Finally, Giotto makes extensive use (several m**2) of a new thermal-control coating, the electrically conductive white paint PCB-Z (absorptivity alpha =0.25, emissivity epsilon =0.82).

4. The mission

The Giotto mission is a fast flyby of Comet Halley around midnight UT on 13 March 1986, near the comet’s post-perihelion crossing of the ecliptic plane, about 1 month after its perihelion passage. At this time, the comet will be at its most active. A pre-perihelion encounter was also considered at an early stage, but was not further pursued, primarily because the launch energy needed would have been much higher, which for a given launcher would have imposed a severe limitation on the mass of the scientific payload that could be launched.

After five years of development and testing, Giotto was launched on 2 July 1985 by an Ariane-1 rocket from Kourou, French Guyana. The spacecraft was initially injected into a Geostationary Transfer Orbit (perigee: 198.5 km, apogee: 36000 km, inclination 7deg). After three revolutions in this orbit, the onboard boost motor was fired near perigee to inject Giotto into a heliocentric orbit. The high-gain antenna was despun three days later.

The camera was switched on in Format 3 on 10 August 1985 to monitor the declamping of its barrel, followed by the Magnetometer Experiment and Energetic Particles Experiment switch-on on 22 August. These two experiments have remained on ever since, using their memories to bridge gaps in ground-station coverage. The complete switch-on/pyro firing sequence is shown in Table 11. All experiment functional tests have already been performed successfully.

During its cruise phase, the Giotto spacecraft is being controlled by a number of ground stations distributed around the globe. Depending on their size and equipment, these ground stations are used for different purposes and different mission phases (Table 12). ESA’s station at Carnarvon is the prime station for spacecraft commanding throughout the entire mission. Format-3 data can be received by Carnavon until mid-January, and by Weilheim until mid-February. The NASA 34 m Deep-Space Network (Goldstone, Madrid & Canberra) is being used in addition for spacecraft ranging during the cruise phase.

Throughout the mission, the spacecraft attitude defined by the Sun Aspect Angle (SAA) (0deg = Sun above the tripod) must be kept inside an allowed corridor (Fig. 17), which is defined by two constraints: the high-gain antenna must point permanently at the Earth to maintain the telecommunications link, and the spacecraft must generate enough power without being heated up too much (thermal/power constraint). The hotest phase of the mission occurred at the end of December 1985, when Giotto was only 0.72 AU away from the Sun.

Figure 17. Sun Aspect Angle from launch until encounter. The solid line shows the strategy that is actually being followed; the dashed lines represent various constraints (see text for details)

Figure 18. Reference trajectory for Giotto from launch on 2 July 1985 to post-perihellon encounter with Halley on 14 March 1986.

Halley’s orbit is retrograde and inclined at 18deg
with respect to the ecliptic

In the event that the telecommunications link to the Earth is lost, the spacecraft will drift slowly out of the allowed corridor. If, however, its attitude is kept within a certain narrow part of the allowed corridor, its boundaries given by the ’sheared constraint’, Giotto could be up to 12 days without contact and still remain in the allowed corridor. The nominal attitude strategy (solid line) is continuously in the narrow part of the corridor. It is based on minimum hydrazine consumption, with the further constraints that the SAA should not be > 130deg and that 107deg should be maintained from early February onwards. The large number of ripples on the line reflect daily attitude manoeuvres.

Figure 18 shows the interplanetary trajectory for Giotto from launch until the encounter on 13/14 March 1986. Giotto’s orbit lies in the ecliptic. Halley’s retrograde orbit is also shown, its plane being inclined by 18deg with respect to the ecliptic. After a cruise phase of eight months, Giotto will encounter Halley’s Comet at OO UT on 14 March 1986. The phase angle to the Sun will be 107.2deg (Fig. 19), i.e. the spacecraft will approach the comet nucleus from ’behind’, which is favourable for spacecraft survival, bearing in mind that most dust particles are injected into the sunward hemisphere. The flyby velocity will be 68.4 km/s. The main experiment switch-on will start, about two days before the encounter, and finish no later than 4 hours before t(0), the time of closest approach.

Table 11. Giotto switch-on/Pyro firing sequence

Date	Experiment	Format	Comments
10 August	HMC	F3	Pyro firing
22 August	MAG	F3	
	EPA	F3	
6 September	HMC	F1	
7 September	MAG	F1	
	EPA	F1	
	IMS	F1	
8 September	JPA	F1	
	RPA	F1	
12 September	NMS	F3	
13 September	NMS	F1	Memory check
	OPE	F1	
	NMS	F1	Pyro firing
7October	NMS	F1	
8 October	DID	F1	
9 October	OPE	F1	Pyro firing
13October	PIA	F1	

* Bold entries: Main functional performance check (implying priority over any other experimental operation).

Figure 19. Schematic of the encounter geometry. Giotto will be targetted to pass the nucleus a few hundred, nominally 500, kilometres on the sunward side. The spacecraft will enter the visual coma about an hour before the time of closest approach.

Table 12. Giotto ground stations and their roles

Phase	Station	Purpose	
GTO	Malindi	Housekeeping Telemetry	S-band

	Kourou Carnarvon	Telecommand Ranging	Low Gain Antenna (LGA)
Near-Earth Phase	Carnarvon Weilheim	Housekeeping Telemetry Telecommand Doppler and Range	S-band LGA
Initial Cruise	Carnarvon Weilheim	as Near-Earth Phase	S-band High Gain Antenna (HGA) up and downlink
Cruise	Carnarvon Weilheim	as Near-Earth Phase Option: Science Telemetry Format 3	S-band HGA uplink X-band HGA downlink
Encounter	Carnarvon Parkes	Telecommand Science Telemetry Format 1 and 2	S-band HGA uplink X-band HGA downlink

* The NASA 32 m Deep Space Network (Goldstone, Madrid, Canberra) is used in addition for spacecraft ranging, and the NASA 64 m station at Canberra is used as backup for Parkes during the encounter.

Table 13. Giotto Parkes passes (F1/F2) (60 in total)

	Days of the month																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	2
1985, September						x	x	x	x	x	x		x								
October	x						x	x	x	x	x	x	x	x	x	x		x			
November																					
December																					
1986, January		x	x			x	x		x			x			x						
February		x	x	x	x			x	x	x	x		x	x	x	x					
March	x	x	x	x	x	x x	x	x	x	x	x	x	x	x							

* Note: Parkes pass starts on the day shown. Bold x = rehearsals

During the cruise phase and certain days before the encounter, the 64 m station at Parkes in Australia will be used for transmission of science data at a high rate (schedule given in Table 13). In addition, Science data are transmitted at low rate [4.6 kbit/s (Format 3), about twice per week during the cruise phase. During the encounter, the NASA DSN 64 m Station at Canberra, Australia will be used as a hot back-up. Continuous data coverage will be provided in high-data-rate mode for about 50 h before and 30 h after closest approach, by Parkes and the NASA 64 m stations at Goldstone, Madrid and Canberra. However, only the MAG and EPA experiments will be able to make full use of this continuous coverage, as all other experiments will be switched off during periods of thruster firing, which can last several hours and are planned for 10, 11 and possibly also 12 March (Table 14).

Short manoeuvres (several minutes) are needed to correct the spacecraft's attitude and long-duration manoeuvres are needed to correct its trajectory and target it to the preselected point. Giotto's attitude will be such that the spacecraft spin axis will be precisely aligned with the relative velocity vector so that no dust particles can impact on the unprotected sides of the spacecraft. Giotto will be targeted to pass the nucleus on the sunward side in order to obtain images of the nucleus day side. The desired flyby distance of 500 km has been adopted as a compromise between the partially conflicting requirements of three groups of experiments. One experiment group (HMC) would like to fly by at 1000 km, but no closer than 500 km; a second group (OPE), MAG, NMS, IMS, GRE) would like to fly by the nucleus as close as possible, even if the spacecraft would not survive; while a third group (PIA, DID, EPA, JPA, RPA) would also like to fly by as close as possible whilst still maintaining a high survival probability.

Targeting the spacecraft to this preselected point is a difficult task as the nucleus is too small to be observed from the Earth even by the largest telescopes and moreover is disguised by the coma dust and gas. Also, due to the asymmetric outgassing - the dust and gas is mostly emitted into the sunward hemisphere - the nucleus is accelerated away from the Sun (nongravitational forces). Compared with the purely Keplerian orbit that it follows at large heliocentric distances, Halley 's orbit is extended by four days. This outgassing effect is irregular and therefore difficult to model. Between Halley's recovery on 16 October 1982 and mid-January 1986,4000 astrometric observations were made of Halley. They are being coordinated via the Astrometry Net of the International Halley Watch. From these observations, in combination with a model which includes the effects of nongravitational perturbations, the nucleus' position can be determined for the time of the Giotto encounter with an accuracy of 236 km in a radial direction from the Sun, 989 km in the direction of the comet's orbital motion and 15 km perpendicular to the comet's orbital plane (these are 1 sigma values). In calculating these values, an offset of 500 km between the centre of brightness (presumed to be the nucleus position) and the centre of mass (actual nucleus position) has been assumed, which is probably too pessimistic. For targeting purposes, the 1 sigma uncertainty ellipsoid reduces to an ellipse in the target plane, defined by the Giotto arrival direction. With the same assumption on the offset, its two components are 231 and 131 km. To these values has to be added the Giotto spacecraft position uncertainty of 80-100 km to give the overall targeting uncertainty. The resulting uncertainty of 200-300 km is still relatively large compared with the intended flyby distance of 500 km.

Table 14. Overview of encounter operations (Issue 5). The upper part shows the availability of the various ground stations, the lower part shows spacecraft and payload operations. 'A' denotes an attitude, 'O' an orbit correction maneouvre, the solid triangles indicate times of targeting decisions.

Fortunately, Giotto will be the last of the spacecraft to encounter the comet, and the earlier-arriving Vega-1 and -2 spacecraft, having located the nucleus, will pass this information on to Giotto. This is the so-called 'Pathfinder Concept', the principle of which is illustrated in Figure 21.

The uncertainty in spacecraft position (~ 100 km) is shown in Figure 21 as a small circle around the spacecraft path, at the time when the last orbit-correction manoeuvre will have to be made (1-2 days before the encounter). The large circle around the path of the comet reflects the relatively large 1 sigma uncertainty that can be achieved via the Astrometry Net. Vega will locate the comet nucleus during its flyby on 6 March 1986 with an uncertainty that is given by the angular uncertainties in spacecraft attitude and pointing direction of the platform on which the Vega camera is mounted.

Figure 20.The Giotto spacecraft approaching Halley's Comet. The comet is a painting after the Mt. Wilson Observatory photograph taken of Halley's Comet on 8 May 1910

After processing of the data, the position of the comet nucleus will be known with a much better accuracy (small circle around the Halley path). Giotto will be targeted to the centre of the small circle projected to the intersection of the comet and the spacecraft paths. Between the time of nucleus detection by Vega and the Giotto encounter, the uncertainty will grow slightly due to the nongravitational forces, which cannot be modelled precisely. It has been estimated that the Pathfinder Concept will reduce the targeting uncertainty to 130 km (1 sigma).

Although Giotto will be targeted very close to the comet nucleus, where the dust fluxes are high, the spacecraft is expected to survive. The perhaps most serious of all problems could be caused by spacecraft attitude changes following the impact of a large dust particle on the edge of the shield. Anything more than a 1 deg deviation from the nominal attitude would result in loss of the X-band downlink. Calculation’s show that this could occur following impact of a dust particle of >~ 0.1 g mass. However, according to current estimates of dust densities in the cometary coma, the probability of an impact of a dust particle with mass >= 0.1 g on the spacecraft is only a few per-cent. Giotto might well then survive the encounter, in which case it might be possible to retarget it towards the end of March 1986 (delta V = 110 m/s required) to return to Earth in 1990. With a series of Earth and/or lunar swingby manoeuvres, Giotto could then be sent off to another comet or to an asteroid.

Figure 21. The ’Pathfinder Concept’