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The Giotto Radio- Science Experiment

P. Edenhofer
Institut fur Hoch- und Hochstfrequenztechnik, University of Bochum, W. Germany

M.K. Bird
Radioastronomisches Institut, University of Bonn, W. Germany

H. Buschert
Institut fur Hoch- und Hochstfrequenztechnik, University of Bochum, W. Germany

P.B. Esposito
Jet Propulsion Laboratory, Pasadena, USA

H. Porsche
Institut fur Physik der Atmosphare, Deutsche Forschungs- und Versuchsanstalt fur Luft- und Raumfah
Oberpfaffenhofen, W. Germany

H. Volland
Radioastronomisches Institut, University of Bonn, W. Germany

Abstract

The scientific objectives of the Giotto Radio-Science Experiment (GRE) are to determine both the columnar electron content of Comet Halley’s ionosphere and the cometary mass fluence from atmospheric drag by using the radio signals from Giotto during the Halley encounter on 13 - 14 March 1986. The radio-science data (S- and X-band Doppler and range measurements) will be collected at NASA’s deep-space 64 m tracking antenna at Tidbinbilla near Canberra, in Australia. In order to separate the effects of the terrestrial ionosphere and the interplanetary plasma, S-band Doppler measurements will also be taken at Tidbinbilla along the line-of-sight of Japan’s cometary probe Sakigake during the Giotto - Halley encounter. The measurements of cometary electron content and mass fluence will be inverted to derive the spatial distribution of the electron and mass (dust and gas) density within Halley’s coma. The GRE is the only experiment on Giotto capable of measuring the low-energy (~ 10 eV) electron bulk population of Halley’s ionosphere and the total cometary mass flow impacting upon the spacecraft.

1. Scientific Objectives

The Giotto spacecraft is equipped with redundant radio transponders capable of downlink transmission at S-band (2.3 GHz) and X-band (8.4 GHz). It is expected to travel through the dayside atmosphere of Comet Halley (Reinhard, 1981), with a relative velocity of 69 km/s. The target distance for the cometary flyby will probably be 500 +/- 100 km. The goal of the GRE (Edenhofer, 1980) is to take measurements of the phase (Doppler) shifts of the downlink carrier signals both at S- and X-band as a function of time during the Halley encounter. The specific scientific objectives are determination of:
(a) the columnar electron content of the ionosphere of Comet Halley
(b) the cometary mass fluence and total mass flow due to atmospheric drag.

During encounter, the carriers of the telemetry signals from the Giotto spacecraft will be subject to: (a) dispersion by cometary plasma influencing the phase and group velocities of signal propagation (strongest at S-band); and (b) Doppler frequency shift induced by the deceleration of the spacecraft due to atmospheric drag (strongest at X-band). Since both effects will be intermingled in the data collected, joint S/X-band data analysis and evaluation will be required to determine both the columnar electron content and the mass fluence. By applying appropriate models of the cometary atmosphere and using integral inversion techniques, the spatial distributions of electrons as well as mass (dust and gas) density will be derived for the comet's coma.

The GRE investigations will complement the in-situ particle measurements to be made onboard Giotto. The GRE determination of the total cometary electron content (along the Giotto -Earth line-of-sight) and mass flow (along the spacecraft trajectory) will provide useful reference values for the on-board plasma analyzer (RPA experiment) and dust detectors (DID, PIA). In view of the sensitivity threshold of the RPA, only the GRE is capable of measuring the low-energy electrons (~ 10 eV) which constitute the bulk of the charged-particle population within Halley's coma.

2. Scientific Background

2.1 Electron content

The GRE is an occultation-type, remote-sensing experiment which relies on the propagation effects of electromagnetic waves. Radio-science experiments of this type have been performed in the past to probe the inner and outer coma of the Sun (Edenhofer et al., 1977; Esposito et al., 1980; Volland et al., 1977; Bird, 1982), or the planetary atmospheres (Fjelbo et al., 1975a: Fjelbo et al., 1975b; Levy et al., 1981; Vasilyev et al., 1980), using occulting space probes such as Helios, Pioneer, Mariner, Voyager, Venera, etc. A cometary dual-frequency radio-science experiment is also being undertaken in conjunction with the Vega- 1 and -2 missions (Armand et al., 1982).

As a function of time, the ground-received phase $\phi(t)$ (in cycles) of a stable, monochromatic radio signal of frequency f is proportional to the (downlink) columnar electron content $I(t)$, i.e. the integrated electron density N_e along the ray path from the spacecraft to the tracking antenna on Earth. The signal's phase will shift in time with respect to that of a local oscillator tuned to the undisturbed (i.e. vacuum wave propagation) Doppler frequency

$$f' = f(1 - (dR(0)/dt)/c)$$

by an amount

$$\Delta\phi(t) = -f(\rho(t))/c + 40.3/(cf)\, I(t),$$

where the quantity $dR(0)/dt$ (known from celestial mechanics and orbit determination) is the radial component of the relative velocity between Earth and probe at times close to encounter ($t = 0$), and the distance $\rho(t)$ is associated with the drag-induced deceleration $\Delta v(t)$ of the probe, via

$$\rho(t) = \int \Delta v(\tau)\, d\tau$$

(c = velocity of light; MKS units; phase constants omitted). This corresponds to a Doppler frequen

$$\Delta f(t) = [-f\, \Delta v(t)/c] + [40.3/(cf) \cdot I(t)]$$

(Bird et al., 1982; Porsche & Edenhofer, 1982: Bird et al., 1983; Bird et al., 1984). During the e
first term of this equation is expected to result in a 'blue shift' ($\Delta v<0$), caused by the dec
the spacecraft in the cometary atmosphere (frequency increase). The second term yields an increase in frequency for cometary plasma entering the line-of-sight (time derivative $I>0$; immersion), but reverses its sign for maximum electron content and then produces a 'red shift' or frequency decrease, respectively (emersion).

Since the Giotto radio subsystem features two downlink carrier signals at frequencies $f(s)$ and $f(x)$, two such phase shifts $\Delta\phi(s)$ and $\Delta\phi(x)$ can be measured simultaneo

The plasma and drag effects due to the cometary atmosphere (ionized and neutral part) can be separated unambiguously by a linear combination of these measured dual-frequency phase shifts:

delta psi(s) = delta phi(s) - (f(s)/f(x)) delta phi(x) = 40.3/(cf(s)) [1 -(f(s)/f(x))**2] I(t)
delta psi(x) = (f(s)/f(x)) delta phi(s) - delta phi(x) = f(x)/c [1 -(f(s)/f(x))**2] rho(t)

With just one downlink frequency, plasma and drag effects cannot be separated, even if an uplink is maintained. The only possibility is then a least-squares fit of the recorded data to model time profiles of the unknown quantities I(t) and rho(t).

To determine the deceleration delta v reliably, the ratio between the Doppler frequency shift delta f and the nominal downlink frequency f(0) must be less than about 10**- 10, which is the expected order of magnitude for delta v/c at the time of encounter, e.g. delta psi(x)= f(xo)(delta v/c - delta f/f(so)) [1 - (f(so)/f(xo))**2]. The quantity delta f(t) represents small tions due to systematic drifts, randomly distributed instabilities, etc.

The most important parameter controlling the electron density and therefore the columnar electron content in the cometary ionosphere is the total gas production rate Q. It depends, for example, on the size of the cometary nucleus and the distance from the Sun (Reinhard, 1981; Mendis & Ip, 1979). A postulated balance between photo-ionization and losses by recombination governs the physics of cometary plasma, yielding a model representation of the cometary electron density (Mendis & Houpis, 1982) of the form

N_c(r) = (A/r) m**-3   (r in meters; A ~ Q**1/2)

For Comet Halley, a reasonable value for the quantity Q is taken to be Q(0)= 1 X 10**29 s**-1 at 1 AU (Ip, 1980). Out to about 10**4 km, the electron density is found to be well represented by A = 3 X 10**15 m**-2. Further out, the radial dependence may be somewhat different because of the compressing solar-wind plasma. The outer boundary of the cometary ionosphere is estimated to be ab r(c) = 5 X 10**5 km. In a first approximation, the electron density distribution is considered to spherically symmetric.   Thus, in a nucleus-centred coordinate system, the cometary content is den

I(c) = Integral(from S(g) to (S(c)) N_c(r) ds = A ln [s(c) + r(c)/(s(g) + r(g))]

where s(g)**2 = r(g)**2 - p**2; s(c)**2 = r(c)**2 - p**2, and the quantities r(g), r(c), and p represent the distances to Giotto. to the outer boundary of Halley’s ionosphere, and to the Earth-Giotto (impact parameter) ray path, respectively (Edenhofer et al., 1980; Bird et al., 1982; Bird et al., 1983). For a flyby distance of 500 km, Figure 1 shows the temporal variation of I(c) (time profile) to be expected during encounter (S-band). The maximum columnar electron content I(comax) = 3 X 10**16 m**-2 will be obtained about 3.5 s after encounter, where this value may increase to some 7 X 10**16 m**-2, depending on whether or not there are locally enhanced regions from internal sources of additional ionization (e.g. jet-stream configurations) within the cometary coma intersected by the ray path.

Figure 1. (a) Columnar electron content of Comet Halley during Giotto encounter for a flyby distance of 500 km at S-band (1 hexem=10**16 m**-2). Models of cometary electron density distribution vary with r**-1 (photo-ionization only) and r**-2, respectively. (b) Electron content I(c) (---) and rate of change dI(c)/dt (---) versus time, corresponding to variations in phase and Doppler frequency shift. A noise level of +/-3x10**14 m**-2 s**-1 (+/-15 mHz) is indicated, as derived from Giotto Doppler residuals collected at the NASA DSS 42 ground station on 31 July 1985

The taking into account of such kinds of phenomena can result in significantly different profiles for I(c). For a gas production rate Q = 4 Q0, the maximum electron content will be raised by a factor of two. Computer simulations indicate, however, that I(comax) may vary only about +20% and -9%, if the distance changes to 100 and 1000 km, respectively. For the mission baseline (X-band downlink only during encounter), the electron content would be reduced by a factor of $(2.3/8.4)^2 = 1:13$, corresponding to a loss in signal strength for I(c) of about 11 dB. Obviously, neither optimistic variations of parameters for encounter geometry nor for cometary plasma physics can balance such large a loss in signal strength (see Sections 3 and 4 for intrinsic noise levels of GRE measurements).

Figure 2 shows some details of the geometry of encounter and the resulting cometary electron content. The temporal behaviour of the electron content during encounter is expected to be specifically different from the steady-state time signature of those portions of the total electron content measured that are due to the terrestrial ionosphere and interplanetary plasma.

Figure 2. Schematic of the geometry of Giotto's Halley encounter on 13/14 March 1986. The cometary electron content represents the integrated electron density of Halley's ionosphere along the ray path C - A, the cometary mass fluence being accumulated from atmospheric drag along the trajectory C - B

2.2 Cometary mass fluence: superposition of plasma and mass effects

As Giotto travels through the atmosphere of Comet Halley, dust and gas particles will hit its bumper shield. Cometary dust and gas particles typically consist of grain materials such as magnetite, graphite, quartz, water ice (grain radii roughly 10^{-7} - 10^{-2} m; mass spectrum 10^{-17} - 10^{-3} kg) and sublimation products of nuclear constituents in terms of molecules such as H_2O, CO_2, NH_3 (e.g. mean thermal speed 400 m/s, outflow speed at surface of nucleus 180 m/s) (Newburn, 1981; Divine, 19,81; Hubner & Keady, 1982; Hellmich & Keller, 1981; Schwehm & Kneissel, 1981). The impacts of these particles build up an atmospheric drag effect, causing a deceleration Δv of the spacecraft (Edenhofer et al., 1980; Porsche & Edenhofer, 1982; Bird et al., 1983). This deceleration can be estimated, from momentum and energy-transfer relationships, to be

$$\Delta v = m(0) v(0) (1 + q^{1/2} \cos(\phi)) / M$$

where $m(0)$ and $v(0)$ are the mass and the velocity of the impacting (recoiling) particles, M is the mass of the spacecraft (512 kg during encounter) and ϕ is the angle of intersection between the velocity vectors v and $-v(0)$. Here inelastic energy losses ΔQ (e.g. heat generation and ionization processes) are taken to be negligible, according to $\Delta Q \ll m(0)v(0)/2$. Since the quantity Δv can be measured from the observables of phase (and group) delay shift (e.g. $\Delta\psi(x)$) via $\rho(t)$, the cometary mass fluence is finally derivable as the mass flow integrated along the trajectory of the spacecraft. Multiplication by the corresponding spacecraft area (2.64 m^2) then yields the total impacting cometary mass.

The mass-fluence determination is complicated by the fact that the ratio q of the mass of the recoiling particles to that of the impacting particles is also a function of the energy of the impacting particles (Hirao, 1982). High-energy gas molecules in the cometary coma, for instance, may generate multiple secondary ions. At the encounter velocity of $v(0)=69$ km/s, energy levels higher than 1 keV apply for molecules of atomic weight as low as 42. As far as dust particles are concerned, the production rate for emission of secondary ions is expected to be even higher than in the case of gas particles. In laboratory experiments, q-values as high as 40 have been observed for velocities much lower than $v(0)$ (Porsche & Edenhofer, 1982).

Following refined calculations of the expected dust-particle fluence based on data from the last apparition of Comet Halley in 1910 (Newburn, 1981), and on the computations by Hubner & Keady (1982) for the cometary plasma mass which will also impact on the bumper shield of the spacecraft, the total integrated mass flow due to Halley's atmosphere hitting Giotto during the encounter is estimated to be of the order of $m(c)=9 \times 10^{-5}$ kg. Allowing for an uncertainty of $1<q<50$, the integrated spacecraft velocity decrement is expected to be in the range $0.02<\Delta v<0.1$ m/s (Porsche & Edenhofer, 1982). Complementary calculations anticipate an even higher dust-particle flow resulting in a factor of two for the total mass fluence (Divine, 1981; Hellmich & Keller, 1981; Schwehm & Kneissel, 1981).

For a flyby distance of 500 km, Figure 3 shows the drag-induced time variation in delta v to be expected during encounter. Taking into account the uncertainty limits for q, the deceleration of the spacecraft corresponds to a Doppler frequency shift

delta f/f=delta v/c)*cos alpha,

i.e. at X-band limits of 0.35 <delta f(x) <2 Hz are to be expected (alpha = 44deg being the angle between the relative velocity vector of the spacecraft with respect to Comet Halley and the position vector of the spacecraft with respect to Earth). A typical noise level of the order of 10 mHz can be achieved for two-way Doppler measurements, caused by the intrinsic frequency instability of the spacecraft transponder and the tracking station. The noncometary plasma-induced frequency shift is estimated to be as low as delta f(x)<0.11 Hz. Neglecting cometary drag effects, the Doppler frequency shift delta f(xo) due to the relative velocity between the spacecraft and the Earth will be 238.1 kHz.

It is important for the Giotto radio-science drag experiment to know the asymptotic behaviour of delta v(t) before and after encounter (approximately within t=0 +/- 5 min). The best way to accomplish this is to collect pre- (and in case of spacecraft survival post-) encounter range measurements (~ group time delay) using the S-band uplink and X-band downlink. While for Doppler frequency measurements the observables are proportional to the time derivative d rho(t)/dt ~ delta v(t) of the drag-induced range, range observables allow direct measurement of accumulated values rho ~ integral(v(tau) d tau), e.g. between limits l200 <rho <6200 m for a one-day interval around encounter. This is well above the noise level of about 10 m that is typical for deep-space ranging.

For Doppler measurements at either S- or X-band, the observables involve a superposition of the cometary effects of electron content and mass fluence. The best way to separate both effects is to collect dual-frequency downlink measurements according to delta psi(s) and delta psi(x) as outlined above. An alternative, but ambiguous and less efficie way of separating plasma and mass effects is to use the different time signatures of both phenomena: the electron content varies like a spike-function, and is mainly associated with measurements collected immediately before and after encounter (within about +/- 3 min or so), whereas the mass fluence changes like a step-function, with asymptotes essentially based on measurements (including range) taken sufficiently long before and after the encounter (within about +/- 2 h or so at minimum).

2.3 Experimental sensitivities and calibration requirements

During the Giotto-Halley encounter in March 1986, solar-minimum conditions will exist. Nevertheless, the electron content of Halley’s ionosphere is expected to be about one order of magnitude smaller than typical values of the electron content for the terrestrial ionosphere, and about two orders of magnitude smaller than the electron content of the interplanetary space for a total ray path length of 0.97 AU and a solar elongation angle of 54deg (Edenhofer et al., l980; Bird et al., 1982: Bird et al., 1983). Taking, for example, the results of the Helios Radio-Science Experiment, as performed during the solar-cycle minimum in 1976, a good estimate of the electron content of interplanetary plasma for the Halley encounter geometry turns out to be 2.4 X 10**18 m**-2 (Edenhofer et al., 1977; Esposito et al., 1980). To separate the contribution from the cometary plasma, an astute calibration scheme must be used. The radio-science measurements, for instance, for the Jovian dayside ionosphere (Fjelbo et al., 1975a), the dayside ionosphere of planet Venus (Fjelbo et al., I975b), and the plasma torus of Io (Levy et al., 1981) could only yield accurate altitude profiles of electron density after extensive corrections for the actual conditions of the Earth’s ionosphere, as recorded from geostationary radio beacons, had been applied. The interplanetary electron content was eliminated by simply subtracting the slowly varying component of phase shift from the total phase residuals measured during occultation.

Though the electron content of the terrestrial ionosphere will certainly be smaller for the GRE than that of the interplanetary plasma, the influence of the Earth’s ionosphere on the total electron content to be measured is something of a problem, since its scale of time variations might be comparable with the spike-like behaviour of cometary electron content during the encounter. This expectation is also based on the fact that the GRE radio measurements during the Giotto-Halley encounter are scheduled to take place from Australia at local morning time, i.e. within the perturbed

Figure 3. Cometary mass fluence in terms of drag-induced deceleration delta v of the Giotto spacecraft as a function of time during the Halley encounter (flyby distance 500 km)

transition interval of increasing electron content in between the steady-state values around midnight and noon. In a cooperative effort with NASA/JPL, two procedures have been initiated for the GRE to correct for the terrestrial ionosphere: VHF Faraday rotation measurements will be taken at NASA's deep-space station DSS 43 in Tidbindilla/Canberra, Australia. These measurements will use radio beacons of the geostationary satellites ATS 1 or ETS 2 at 136 MHz to derive the time variations in the electron content of the Earth's ionosphere (and magnetosphere) during the encounter (Royden et al., 1984). Residual errors in the order of 10**15- 10**16 m**-2 will remain when the line-of-sight of DSS 43 towards ATS 1/ETS 2 is transformed into that valid towards Giotto. At the same time dual-frequency time-delay measurements will be made at DSS 43 using L-band signals (1.2 and 1.6 GHz) transmitted by the Navstar satellites of the Global Positioning System (GPS). In 1986/87, 18 of these satellites will be operational, each of them with a 12 h siderial period to calibrate the ionospheric electron content for navigational applications also. Generally, at least four satellites will be visible from each tracking station, so that line-of-sight transformation errors are expected to decrease considerably compared with the procedure of Faraday rotation calibration.

In addition to the satellite-borne calibration, the University of Armidale, Australia, will support the GRE by means of ground-based ionosonde measurements to monitor the temporal evolution of a local electron density profile around Halley encounter with respect to the electron content of vertical incidence, at least up to the layer of maximum ionization.

If a calibration is to be performed for columnar densities of the order of 10**16 m**-2, or even smaller, by including also the interplanetary plasma, then corrections are best applied that make use of the ground-based radio observations of the International Halley Watch (IHW) (Irvine et al., 1982), in addition to a deep-space multispacecraft calibration as first proposed by Fjeldbo et al. (1975a). The concept of this calibration procedure is to exploit closely spaced radio sources that have nearly identical ray paths through the terrestrial ionosphere and interplanetary space. When one of these sources is being occulted by an additional plasma region (e.g. cometary coma or tail), a subtraction process using both radio links is applied to isolate the specific plasma contribution of interest. By means of this two-sources calibration technique, Vasilyev et al. (I980) were able to detect the nightside ionosphere of Venus with an electron content as low as about 4 X 10**15 m**-2.

During the Giotto flyby, five other spacecraft will be in the vicinity of Comet Halley: the Japanese spacecraft Sakigake and Suisei, the American ICE spacecraft (formerly ISEE-3) and the two Soviet spacecraft Vegas-1 and 2 (Bird et al., 1984). Figure 4 shows the orbital geometry for this satellite configuration and the various lines-of-sight involved. On the Vega mission, a dual-frequency radio-science experiment will be performed using a two-spacecraft configuration occulted by Halley's ionosphere during a flyby about one week earlier than that of Giotto (Armand et al., 1982). For the GRE, a mission-intercalibration concept has been set up in cooperation with NASA/JPL and Japan's Institute of Space and Astronautical Science (ISAS). A feasibility study has shown that the Sakigake spacecraft (Hirao, 1982) is the most suitable in terms of orbital position (full coverage of the ray path to Giotto by the ray path to Sakigake) and on-board radio subsystem (efficiency of S-band signal-to-noise ratio) to serve as a calibration radio source for Giotto in order to eliminate all the non-cometary plasma effects. At the same time as the Giotto downlink radio signals are received by DSS 43 for Doppler measurements during the encounter pass, the Sakigake downlink radio signal will also provide Doppler-measurements at the nearby 34 m DSS 42 antenna and, in addition, at the 64 m antenna at Japan's Udusa ground station. A cross-correlation of the Doppler data from DSS 42 and Udusa will allow potential plasma disturbances to be distinguished that may travel within the Earth's ionosphere in interference with the cometary plasma-spike of Halley's Doppler data. For the benefit of correlative data analyses, cooperative efforts are also being undertaken to collect simultaneous X-band Doppler (phase) measurements at CSIRO's Radio Astronomy Observatory in Parkes (64 m antenna dish about 400 km from Tidbinbilla, Australia).

Figure 4. Ecliptic-plane view of the interplanetary spacecraft around Comet Halley and their signal paths to Earth during the Giotto encounter. The integrated electron density along the line-of-sight to the Japanese Sakigake (Planet-A) spacecraft will be measured to calibrate noncometary plasma effects for the Giotto Radio-Science Experiment

3 Radio Subsystem of the Giotto Spacecraft

A block diagram of the characteristic features of the Giotto radio subsystem is shown in Figure 5 (a detailed description can be found in the Experiment Interface Document/EID, Part A). Those elements of the radio subsystem most important to the GRE are the transponder and the antennas. During the main phase of the mission, a high-gain antenna (HGA) capability wi11 be used for all telecommunication purposes such as telecommand, telemetry (housekeeping and scientific data), and radiometric operations. In association with the tracking station(s), ground-based radiometric operations will allow three different types of data to be received: Doppler measurements either in incoherent/openloop mode (one-way without uplink) or in coherent/closed-loop mode (two-way with an uplink); ranging measurements using a binary-coded phase modulation of the carrier; and DRVID (differenced range versus integrated Doppler) which combines the dispersive propagation properties of phase and group time delay. Radiometric data are essential for orbit determination and spacecraft navigation and, especially during the encounter, for the GRE.

The HGA (antenna gain 26/37 dB at S/X-band) radiates a transmitted power of 25 W (44 dBm) at X- and 6 W (38 dBm) at S-band downlink frequencies. In addition, there are two low-gain antennas (LGAs) for the near-Earth-phase operations. Two redundant transponders are used, each consisting of an S-band receiver and an S- and X-band transmitter. The radio-frequency distribution unit (RFDU), which connects either of the transponders with any of the three antennas (HGA or LGA), channels the S-band uplink and the downlink signals through a switching network with two redundant diplexers. The X-band exciters in either transponder can be coupled to either of the two travelling-wave-tube amplifiers (TWTAs) by means of a TWT interface unit (TWT-IF). The output signal is directed to the X-band feed of the HGA through the TWT-IF. During the closest-approach phase of the Halley encounter the two TWTAs will be operated in hot redundant mode (heaters turned on), one TWTA being operational and the other in standby mode. In the event of any operational anomaly, a changeover in the power subsystem will depower the failed TWTA, rotate the switch, and activate the standby TWTA.

As there is no X-band signal at the exciter output when the S-band high-power amplifier is turned on, simultaneous S- and X-band operation in one and the same transponder, whether in coherent or incoherent mode, is not possible. As the nominal configuration for the GRE encounter measurements requires coherent transmission of both S- and X-band downlink signals (maintained by an S-band uplink), the voltage-controlled crystal oscillator (VCO) of the chosen receiver must drive both transmitters from different transponders, one providing the S-band and the other the X-band output.

Figure 5. Block diagram of the radio subsystem of the Giotto spacecraft. Transponders 1 and 2 are connected to the S-band RFDU (from left/---) and to the X-channel TWT-IF (from right/---). The HGA operates in RHC polarization, serving the S-band up/downlinks via HGA/S (beamwidth ~ 5deg) and the X-band downlink via HGA/X (2deg). The HGA offset-reflector (diameter 1.46 m) is mechanically despun with respect to the spinning spacecraft (15 rpm) and inclined towards Earth (angle of 44deg between RF boresight and spin axis)

There are several modulation characteristics possible for the radio subsystem. The S-band uplink carrier may be either unmodulated, phase-modulated with ranging signals, or phase-modulated with telecommand signals. The S-band downlink carrier may be unmodulated (corresponding to Doppler measurements only), phase-modulated with ranging signals, or further phase-modulated with a coded housekeeping telemetry signal. The X-band carrier may be unmodulated (Doppler only), phase-modulated with ranging signals, further phase-modulated with a coded housekeeping telemetry signal, or with a coded science telemetry signal. For X-band telemetry, a maximum bit rate of up to 92.160 kbit/s is available.

Giotto is not expected to survive the encounter with Comet Halley because of particle impacts resulting in the malfunctioning of vital subsystems such as power supplies or causing loss of the radio link due to disturbance of the alignment of the HGA axis. In the latter case, spacecraft recovery for post-encounter science data may be possible, if the broader antenna beamwidth of the S-band downlink can be utilized. Nevertheless, a specific feature of the Giotto mission is real-time transmission to Earth of all science data using the highest possible bit rate during the 4 h data take.

Calibration tests on the intrinsic phase and ranging delay of the transponder have been carried out on the ground. These tests were performed for various RF input power levels, from -90 to - 130 dBm, and temperature conditions, from + l0 to +40degC. For the incoherent mode, the intrinsic phase delay turned out not to vary in standard deviation by more than 0.6 ns, corresponding to a columnar electron content of about 2.4 X 10**16 m**-2 at S-band (warm up time of 4 h). The reproducibility after stabilization within 0.5 K was found to be of the order of less than +/-0.5 ns. The temperature dependence was measured to be about +/-0.3 ns/K.

4. Giotto Radio-Science Ground Support

Station DSS 43 of NASA’s Deep-Space Network (DSN) at Tidbinbilla/Canberra will serve as the main telemetry backup antenna to the prime Giotto ground station at Parkes (Renzetti & Berman, 1983). Based on an interagency agreement, both Australian stations will receive Giotto telemetry data simultaneously during the Halley encounter. DSS 43, with its special radio-science capabilities, will be the prime station for reception and preprocessing of the GRE radiometric data. The ESA station at Carnarvon (15 m parabolic dish antenna) will also be engaged in Giotto communications. A radio uplink may be provided either by Carnarvon (transmitted power 1.2 kW or 61 dBm) or by DSS 43(20 kW up to as high as 100 kW, or 73 to 80 dBm). Table 1 (not included) summarizes some characteristic features of the various radio links involved. A block diagram of the DSN system components that are particularly important for the GRE is shown in Figure 6.

Figure 6. Block diagram of the interfaces for the radio-science subsystem at the GRE prime station (DSS 43). Four-channel reception with dual-frequency and dual-polarization capability is effected by three parallel receiver blocks (left). Generation and pre-processing of the radiometric data is controlled by the metric data assembly (top)

A Signal Processing Centre (SPC) in direct contact with the Network Operation Control Centre (NOCC) at JPL/Pasadena will control the Australian DSN complex. The NOCC can display real-time radio-science data at DSS 43 or 42. As many as three receiver blocks are ready to handle the Doppler ranging and DRVID measurements for the GRE, either in closed Planetary Ranging Assembly (PRA) or open-loop configuration. The phase residuals are delivered by two separate Doppler extractors for S- and X-band. DSS 43 is capable of receiving S- and X-band radiometric data simultaneously. The open-loop receiver is not servo-adjusted to the received downlink frequency, but rather preset to a computer-programmable frequency by radio-science predictions using an optimum bandwidth control as provided by a Spectral Signal Indicator (SSI). The SSI displays the received signal spectrum in real time.

The Precision Power Monitor (PPM) of the receiver exciter subsystem is used to measure the system noise temperature during cometary occultation by comparing the total power in a given channel with a known calibration noise source. The DSN radio-science subsystem, consisting of an Occultation Data Assembly (ODA) and two independent digital recording assemblies, processes the input signals and records them on tape for immediate delivery to the GRE via JPL/ESOC. Real-time displays of open- and closed-loop data, as well as the status and configuration of all data-receiving and recording systems (including station pre- and post-track calibration), will be provided to a radio-science monitoring station at JPL.

The phase residual is the actually recorded parameter of the downlink carrier signal and is given in cycles. The accuracy of the measurement is about 0.01 cycles at S-band, which is smaller than the specified phase noise of the downlink signals due to transponder instabilities (5deg rms at S-band, l4deg rms at X-band). Following a standard calibration procedure, pre- and post-track calibration data will be taken at DSS 43 at the beginning and end of the encounter pass of 13/14 March 1986 to correct for the intrinsic time delay effects of the radio system on ground (Renzetti & Berman. 1983). These measurements exclude all atmospheric and free-space propagation effects by using a station-bound radio-link transmitter - subreflector of the Cassegrainian antenna subsystem - receiver to calibrate a mean average of time delay, expected to be in the order of 3 ms, and a linear drift of about 2 ns/h (valid for a full-length pass of 8 h), which leaves a standard deviation of approx. 1 to 2 ns. The accuracy of the combined spacecraft-ground Doppler and ranging system is expected to correspond to a columnar electron content of some 10**16 m**-2, while the dual-frequency differential Doppler accuracy should be in the range of +2 X 10**14 m**-2. These accuracies will benefit from the GRE request to the Giotto project to provide the encounter uplink by utilizing the 100 kW transmitter capability of DSS 43 (power increase of about 19 dB compared with Carnarvon station). Such an uplink considerably enhances the phase stability of two-way Doppler data (coherent mode) and also increases the reliability and safety of the radio telemetry link during encounter, particularly if any spacecraft emergency should arise. The highest possible sampling rate capability, of 10 samples per second, will be used to record the phase measurements. The plasma contribution to the phase- and group-delay dispersion will be identified by dual-frequency differencing (see Section 2.1).

The encounter scenario for the GRE foresees operations starting about 24 h before the time t(0) of closest approach (EID, part B). They will start with radiometric measurements (ranging included) after final targeting selection and final spacecraft manoeuvring. At about t(0)-6 h, the measurements proper will start with an X-band downlink (telemetry/radiometric data). Simultaneous dual-frequency S/X-band radiometric data will be collected starting at t(0)- 15 min. If the spacecraft survives, post-encounter ranging and Doppler measurements will be taken, particularly to support the cometary mass-fluence analysis.

Figure 7 shows how the capabilities of the various ground stations affect the quality of Doppler measurements to be expected for the GRE. S-band measurements and preliminary analyses made so far indicate that the standard deviation of Doppler residuals from ESA’s Carnarvon station amounts to +/-0.7 Doppler counts, whereas from NASA’s DSS 42 station the corresponding standard deviation is as low as +/-0.06 Doppler counts (1 Doppler count or cycle at S-band is equivalent to 130.4 mm in free-space wavelength). The Doppler noise level at DSS 42 is thus approximately 11 dB lower than at Carnarvon, the difference in antenna diameter (34 m rather than 15 m) contributing about 7 dB in terms of antenna gain.
In addition, in coherent mode the transmitter uplink capability of DSS 42 can be increased to 20 kW, compared with a maximum of 1.2 kW for Carnarvon (corresponding to another 9 dB in noise reduction). Figure 7 shows also how significantly the rate of change in cometary electron content as simulated for the Halley encounter exceeds the noise level at DSS 42. Since the 64 m antenna of DSS 43 will be used for the encounter pass, we may expect the noise level to be reduced by at least another 5 dB (for S- or X-band). Such radio-science ground-support considerably improves the chances of unambiguously resolving the cometary plasma effects, including the bulk population of low-energy electrons, from Halley ’s ionosphere. A minimum noise level (and maximum radio-link safety) can be achieved by making use of the 100 kW uplink capability of DSS 43 to provide an additional 10 dB gain (19 dB) in link budget with respect to the nominal transmitter power of DSS 42 (Carnarvon). This means that

a total reduction in noise level of about 30 dB is achievable, if in coherent mode the uplink is provided by the DSS 43 rather than by Carnarvon. However, Giotto rehearsals using DSS 43 are scheduled to take place no earlier than February 1986.

Figure 7. Representative subset of residuals for high-order polynomial fits of raw Giotto S-band Doppler data (coherent) from the early cruise-phase after Earth acquisition, collected: (1) at Carnarvon on 8 July and (2) at DSS 42 on 31 July 1985. The rate of change of cometary electron content to be expected during the Halley encounter is shown

5. Summary

The Giotto Radio-Science Experiment will perform Doppler and ranging measurements during the Halley encounter on 13/l4 March 1986, in order to determine the cometary electron content and mass fluence. Using the spacecraft’s radio subsystem, these measurements will be collected at NASA’s Deep Space Station near Canberra. The experiment will involve scientific analyses to derive the spatial distribution of electron and mass (dust and gas) density within the ionized and neutral atmosphere of Comet Halley.

Noncometary plasma effects due to both the terrestrial ionosphere and interplanetary space will be calibrated via measurements using a ground-based ionosonde and geostationary satellites (VHF Faraday rotation/L-band dispersion) and via Doppler measurements from the Japanese cometary spacecraft Sakigake with a line-of-sight close to that of Giotto. Two-way Doppler measurements taken at a 34-m station during Giotto’s near-Earth phase show that, for S-band Doppler measurements (coherent mode), a noise level as low as 0.06 Doppler is achievable, corresponding to a sensitivity level of +/-4.5 X 10**14 m**-2 in terms of electron content, where a typical cometary electron content is 3 X 10**16 m**-2. The scientific objective of measuring Halley’s electron content can only be achieved if there are dual-frequency S/X-band downlinks during cometary encounter.

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