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1. Rème, H. *et al. Eur. Space Ag. spec. Publ.* **1077**, 33-52 (1986).
2. Carlson, C. W., Curtis, D. W., Paschmann, G. & Michael, W. *Adv. Space Res.* **2**, 67-70 (1982).
3. Mendis, D. A. *et al. Geophys. Res. Lett.* **13**, 239-242 (1986).
4. Bame, S. J. *et al. Geophys. Res. Lett.* **13**, 356-361 (1986).

First results from the Giotto magnetometer experiment at comet Halley

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The Giotto magnetometer experiment at comet Halley has for the first time provided magnetic field measurements in all the important spatial regions characterizing the front-side interaction between the solar-wind magnetoplasma and a cometary atmosphere. Upstream waves of cometary origin have been observed at distances of $>2\times10^6$ km from the comet, both inbound and outbound. A cometary bow shock has been identified at 1.15×10^6 km inbound on the dawn side and a thick quasi-parallel cometary bow shock outbound. A turbulent magnetosheath has been observed further inside. A magnetic pile-up region has been identified inside 1.35×10^5 km, inbound, and 2.63×10^5 km, outbound, with fields up to 57 and 65 nT, respectively. A cavity region with essentially zero magnetic field has been discovered, with a width of 8,500 km along the trajectory around closest approach.

The encounter of the Giotto spacecraft with comet Halley provided the first opportunity to study all the major spatial regions characterizing the interaction of the magnetoplasma of the solar wind with the cometary atmosphere. In particular, the innermost part of the interaction region was accessible for the first time due to the close fly-by distance of ~610 km (ref. 1) from the cometary nucleus.

The instrument uses two sensor systems, a triaxial fluxgate sensor system mounted outboard and a biaxial fluxgate system inboard (see ref. 2 for details). The prime outboard triaxial magnetometer provided magnetic field vectors at a constant rate of 28.24 vectors per s throughout the complete encounter period, from late 11 March 1986 to early 15 March, when the scientific payload was switched off. The data reported here were obtained in a measuring range of ±256 nT for each component with a digitization uncertainty of ±0.063 nT.

Because of the special design of the Giotto spacecraft, involving a dust shield for protection against cometary dust particles, no boom could be provided for the magnetometer experiment; this caused substantial magnetic cleanliness problems. The slowly varying part of the spacecraft magnetic field at the outboard magnetometer, of magnitude ~7.5 nT, was removed using the spin variation (spin period ≃ 4 s) for the spin-plane components and in-flight techniques together with the cavity field (see below) for the component parallel to the spin axis. In addition to the slowly varying spacecraft field, fast variations were caused by the motor despinning the antenna and by the Halley multicolour camera. These stray field problems were solved using the inboard magnetometer, which provided measurements at a rate of 2.824 vectors per s (that is, simultaneously with every tenth outboard full vector) for two components, one parallel to the spin axis and one in the spin plane. Using the inboard and outboard magnetometer and magnetic test results before launch, a model magnetic field could be determined for the despin-motor stray field. This model field was subtracted from the observed field, leading to a substantial reduction of the stray field problem.

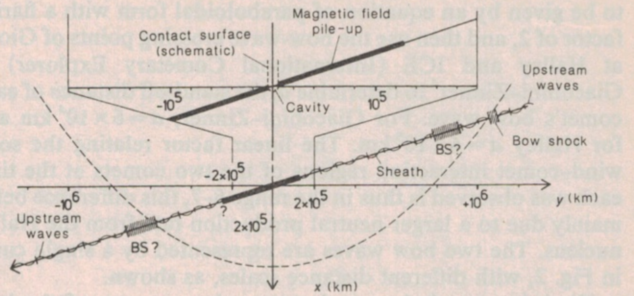

Fig. 1 The encounter geometry of Giotto at comet Halley, with the fly-by trajectory projected on the Halley-centred solar ecliptic x-y plane (see text). The most important interaction regions are marked on the trajectory; the large tick-marks are 1 h apart. A theoretical bow shock shape[17] (dashed line) has been fitted by eye to the bow shock observations. The null field cavity is shown at expanded scale.

Because of its complexity and the lack of test results before launch, the camera's magnetic field contamination could not be removed in the same way. During the period discussed here, the camera operated from 20:03 UT on 13 March until a few seconds before closest approach (00:03 UT); that is, during part of the inbound leg. (All times given here are spacecraft event times.) The camera disturbance field consists of very slow variations, variations on an intermediate timescale of several spin periods caused by the rotation of the invar barrel of the camera, and short impulsive field perturbations up to ~3 nT in magnitude at a rate of 2 per spin period. Because of the precise location of the interval of camera operations, the relatively large magnitude of the ambient cometary field, and our good understanding of the influence of camera perturbations on the measured and averaged magnetic field vectors, our results and conclusions are only affected in a minor way by the camera stray field problem.

The instrument worked flawlessly throughout the Giotto mission, although some data were lost due to dust-impact-related problems around and after closest approach.

Overview. After the observations of the International Cometary Explorer (ICE) spacecraft at comet Giacobini-Zinner[3], Giotto, Vega 1 and Vega 2, and the Japanese spacecraft Suisei provided the first measurements at a comet of intermediate gas production rate. Because of its very close fly-by, Giotto gave the first opportunity to study the innermost part of the interaction region.

The plasma interaction depends on the properties of the gas outflow from the comet and the characteristics of the incident magnetoplasma of the solar wind. The interplanetary medium was characterized by two magnetic sectors, and the current sheet was near the solar equatorial plane during the months before the encounter. During the 2-day interval centred on closest approach the magnetic polarity was predominantly outward, that is, positive, with some intervals of mixed polarity and a few hours of negative polarity. Thus the spacecraft was mostly located a little south of the current sheet separating the northern negative polarity from southern positive polarity. Because the

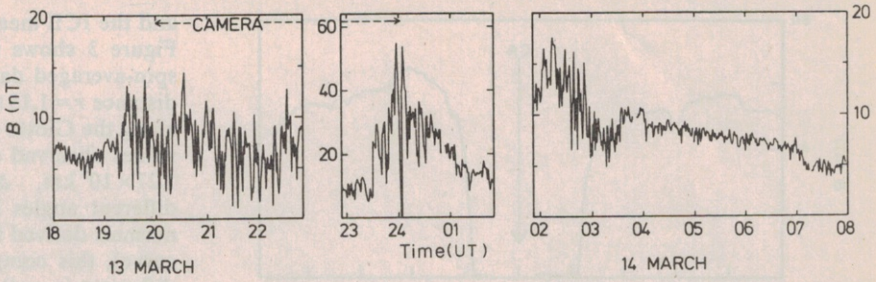

Fig. 2 Magnetic field magnitudes (B) based on 1-min average components from 18:00 UT on 13 March 1986 until 08:00 UT on 14 March. The interval of camera operations is indicated. Its influence on 1-min average vectors is estimated to be $\leqslant 0.6$ nT.

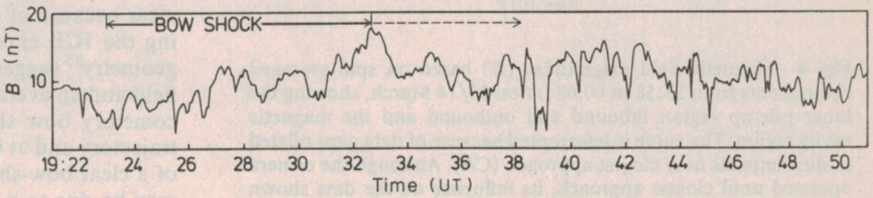

Fig. 3 Magnetic field magnitudes (B) based on spin-averaged components from 19:21 to 19:51 UT on 13 March, showing the inbound bow-shock crossing. The initial magnetic field increase is indicated by a solid line; the following variations (dashed line) may be part of the fine structure of the broad cometary shock, and/or due to non-uniform shock motion. The camera was not operating during this interval.

comet moved from north to south, it crossed the heliospheric current sheet from negative to positive polarity near the time of closest approach.

The first clear evidence for the continuous presence of magnetic field variations signalling the presence of the comet occurred at ~16:00 UT on 13 March, at a distance of 2×10^6 km from the comet. Other 'suspect' wave fields occurred long before this time. The wave fields of cometary origin displayed gradually increasing directional and magnitude variations as the comet was approached. The magnitude variations in particular are quite atypical for the solar wind. Typical periods of the dominant waves were 3-5 min; in addition, short, almost sinusoidal wave trains of much higher frequency were also observed. These waves can be attributed to instabilities generated by pick-up ions created by charge exchange and photoionization of cometary neutral particles.

Figure 1 shows the encounter geometry and the various interaction regions. The trajectory has been projected on the x-y plane of a Halley-centred solar ecliptic coordinate system, in which the x- and y-axes are parallel to the ecliptic plane, with x pointing towards the Sun and y antiparallel to the direction of planetary orbital motion. The spacecraft moves from south to north with respect to the x-y plane, crossing it shortly after the time of closest approach. The spacecraft relative speed of $68.4\ \mathrm{km\,s^{-1}}$ implies a spatial resolution of 2.4 km by the magnetometer experiment in the reference frame of the comet.

Figure 2 shows the variation of magnetic field magnitude (B) based on 1-min average vectors for the period from 18:00 UT on 13 March 1986 until 08:00 UT on 14 March. At ~18:00 UT the upstream waves reached amplitudes with maxima up to twice the magnitude of the minima. At ~19:23 UT, 1.15×10^6 km from the cometary nucleus, the magnitude began to increase, with superposed strong fluctuations, until at 19:33 a magnitude of 18 nT was reached. We consider this structure to be the first crossing of the cometary bow shock (see Figs 1 and 3).

The assumptions of average solar-wind conditions at 0.9 AU and a gas production rate of 4×10^{29} molecules $\mathrm{s^{-1}}$ according to Newburn and Reinhard[4] had led us to predict the bow shock at ~19:30 UT (ref. 2) by scaling the ICE observations at comet Giacobini-Zinner[3] with the help of some theoretical considerations[5]. A tentative estimate of the gas production rate Q from IUE observations now leads to an estimate of $Q = 5\text{-}6\times10^{29}$ molecules $\mathrm{s^{-1}}$ (C. Arpigny, personal communication) for the time of the Halley encounter.

After the bow-shock crossing, B decreased with strong superposed variations, until at ~20:11 UT a second structure began with characteristics similar to the first. It may be part of the fine structure of the bow shock, or represent a second bow-shock crossing. Subsequently B remained at a lower level of $\leqslant 10$ nT, with superposed variations which often reached minimum values of <2 nT; the periods of the dominant variations were typically one to several minutes. We call this region the 'magnetosheath' region. Towards its inner boundary the directional variations subsided somewhat.

Following the magnetosheath, at 23:30 UT the magnetic field suddenly increased to values near 30 nT at a distance from the nucleus of 1.35×10^5 km. We call the region inside the magnetosheath the pile-up region. The large magnetic fields on the flanks of the interaction region can be attributed to the lengthening of the frozen-in field lines due to the draping process and to a lesser extent to plasma compression, both effects being described by Walén's theorem. The pile-up region also contained several deep dips in B lasting several minutes, which may be diamagnetic cavities associated with pressure enhancements, possibly related to the formation of tail rays[6]. The magnetic field reached a maximum at 23:59 UT; spin-averaged data with better resolution yield a maximum value of 57 nT (Fig. 4). Afterwards the magnitude started to decrease rapidly, to essentially zero when the magnetic 'cavity' was entered at 00:01:51 UT on 14 March 1986. This cavity is bounded by an ionopause or contact surface. Its existence had been predicted by theory[7] and was expected by analogy with the case of Venus, where a null magnetic field region has been observed, and the ionopause has been extensively mapped[8]. A cavity has also been observed in association with the 'artificial comets' of the AMPTE mission[9].

After ~2 min in the cavity the spacecraft entered the outbound pile-up region on the dawn side of the comet. At 00:05 UT, only ~1 min after leaving the cavity, the outbound maximum magnitude occurred (Fig. 4). It was even sharper than the inbound maximum and had a value of 65 nT in spin-averaged components. Giotto probably left the pile-up region at 01:07 UT, and entered the dawn-side magnetosheath. The boundary of the pile-up region was much less clearly defined outbound than inbound.

In contrast to the inbound pass, the evidence for an outbound bow shock was not very clear. In the time interval from 02:30 to ~03:05 UT a region of increased fluctuation amplitude could be discerned which may represent the outbound bow shock. This transition region was quickly followed by a gradually decreasing level of B-variations. These were superposed on a gradually decreasing half-hourly-averaged field magnitude starting at ~04:00 UT. In the half-hour averages the magnetic field direction displayed small gradual changes consistent with magnetic field line draping. There was no evidence for disturbances due to major changes in the interplanetary magnetic field. We suggest that the cometary bow shock may be a thick quasi-

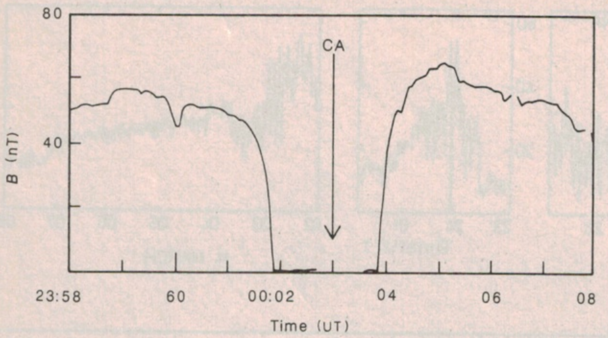

Fig. 4 Magnetic field magnitudes (B) based on spin-averaged components from 23:58 to 00:08 UT on 13/14 March, showing the inner pile-up region inbound and outbound and the magnetic cavity region. The curve is interrupted because of data gaps related to dust impacts near closest approach (CA). Although the camera operated until closest approach, its influence on the data shown is negligible.

parallel shock on the dawn side of the interaction region because the average magnetic field direction is close to the average normal to the discontinuity, as in the case of planetary bow shocks[10,11]. The gradual monotonous decrease of averaged field magnitude lasted until ~07:00 UT. Upstream waves of cometary type could be seen continuously until ~11:00 UT; that is, to a distance of $\sim 2.7\times10^6$ km from the nucleus. Thus, the outbound pass gives the impression of a much more gradual decrease of magnetic field magnitude and fluctuation level than does the inbound pass.

Cometary bow shock. One of the interesting questions of cometary plasma physics has been the problem of the existence of a cometary bow shock separating a super-fast flow region (in the magnetohydrodynamic sense) at large distances from a sub-fast region near the comet. Following the proposal of a well-defined cometary bow shock[12], the possibilities of no bow shock or only a weak shock were also discussed[13]. In their first paper on the results of the ICE encounter at comet Giacobini–Zinner, Smith *et al.*[3] joined other ICE investigators[14] in using the term 'bow wave' to avoid the premature anticipation of the term bow shock before some refined studies had been made.

A final identification of the structure and nature of the disturbance starting at 19:23 UT on 13 March awaits a careful study involving plasma and magnetic field observations. We suggest, however, for reasons given below, that the observed structure can already be called a cometary bow shock.

In the case of a bow wave as a hydrodynamic feature describing, for example, the flow around a ship, we would expect the dominant length scales of the bow wave structure to be given by the scale of the obstacle in the near flow field and by the distance from the obstacle in the far field. Hence the thickness of the structure at large distances r should increase with r at the same observer–comet–Sun angles. In the alternative case of a well-defined bow shock, the shock thickness should depend only on the magnetoplasma characteristics just upstream and on the shock strength. This situation is expected at least for the quasi-perpendicular shock observed on Giotto's inbound pass.

Because the upstream plasma is already loaded with cometary ions and is accompanied by instability-driven turbulence of intermediate strength, we expect the shock structure to differ from quasi-perpendicular shocks in the quiet, proton-dominated solar wind. The shock thickness should be related to the gyroradii of the pick-up ions. Assuming partially thermalized OH^+ ions with a velocity of 200 km s^{-1}, and the measured magnetic field of 8 nT, we obtain a gyroradius of 4,400 km. The thickness of the cometary bow shock should be approximately the same for the inbound Giotto measurements at comet Halley and the ICE measurements at comet Giacobini–Zinner (G–Z). Figure 3 shows the inbound shock transition as seen in the spin-averaged data. The Halley inbound shock is located at a distance $r = 1.15\times10^6$ km from the nucleus, and has a thickness along the Giotto trajectory, $\Delta r = 41{,}000$ km. The corresponding values observed during the ICE encounter with G–Z were $r = 1.27\times10^5$ km, $\Delta r = 31{,}000$ km. Neglecting the somewhat different angles between the relative velocity and the shock normals derived from the shock configuration in Fig. 1 (dashed curve), this comparison shows that in spite of a factor of 10 difference in radial distance the thicknesses are almost the same. The situation for the G–Z outbound bow-shock crossing is less clear because of interplanetary magnetoplasma variations during the ICE encounter; however, the peculiar ICE encounter geometry[15] suggests a relatively large angle between the magnetic field and an average shock normal. We tentatively conclude that cometary bow shocks were observed on the Giotto inbound trajectory and at G–Z both inbound and outbound. The absence of a clear bow-shock signature on Giotto's outbound trajectory may be due to a quasi-parallel shock configuration.

Innermost interaction region. A particularly interesting part of the Giotto encounter with comet Halley was the passage through the innermost magnetoplasma regions not visited before by any other spacecraft. The most interesting measurements were made during a few minutes around the time of closest approach; in Fig. 4, spin-averaged magnitudes for this period are plotted on an expanded time scale. The magnetic field magnitude decreased monotonically with increasing steepness as the cavity region (with approximately zero magnetic field) was approached. The reverse sequence of events is seen outbound, where even greater field strengths were measured, perhaps due to the closer proximity to the sunward portion of the pile-up region where the magnetic field should attain its maximum value. Giotto entered the cavity at 00:01:51 UT on 14 March and left it ~2 min later, at 00:03:56 UT. At the time of writing, the times provided by the Giotto project have an unknown offset, resulting in an uncertainty of ~3 s. The time difference between entry and exit is 124.5 ± 0.1 s, corresponding to $8{,}513\pm7$ km along the trajectory; the boundary is very sharp. A full discussion of its detailed structure requires use of the maximum time-resolution of the observations (not shown here), and is deferred to a future publication.

The distances relative to the point of closest approach are more uncertain, due to timing uncertainties which should soon be (at least partly) resolved. The distance from entry to closest approach is $4{,}700\pm500$ km and from closest approach to exit $3{,}800\pm200$ km. The corresponding distances to the nucleus are 4,760 km and 3,840 km, respectively.

A comment of the significance of the zero-field is appropriate. Due to the spacecraft magnetic field contributions discussed above, the uncertainty in the magnetic field component parallel to the spin axis is relatively large. However, the 10 spin-averaged components B_x and B_y in the spin plane following entry into the cavity showed absolute values less than 0.2 and 0.3 nT, respectively. During the same time interval the B_z component, with spacecraft fields determined from interplanetary data before and after the fly-by, yielded 1.6 nT. This was taken as evidence for a zero magnetic field in the cavity and the need to correct for a remaining spacecraft magnetic field in the z direction.

Some preliminary estimates of the ionospheric plasma pressure inside the ionopause (within the cavity) can be made by assuming pressure balance between the magnetic field and the internal pressure as in the case of Venus[16]. A magnetic field pressure of 1.7×10^{-8} dyn cm^{-2} is obtained for 65 nT. Assuming a temperature of 1,000 K for ions and electrons, this magnetic pressure is balanced by an ionospheric plasma of density 6×10^4 cm^{-3}. We note that the simple pressure balance used above is probably not a good assumption over a distance of 4,100 km between the outbound magnetic field maximum and the outbound ionopause. Frictional forces and the tensional part of the $\mathbf{j} \times \mathbf{B}$ force are probably important in the force integral over this distance.

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1. Reinhard, R. *Nature* **321**, 313-318 (1986).
2. Neubauer, F. M. *et al. Eur. Space Ag. spec. Publ.* **1077**, 1-14 (1986).
3. Smith, E. J. *et al. Science* **232**, 382-385 (1986).
4. Newburn, R. L. & Reinhard, R. *Eur. Space Ag. spec. Publ.* **174**, 19-24 (1981).
5. Schmidt, H. U. & Wegmann, R. in *Comets* (ed. Wilkening, L. L.) 538-560 (University of Arizona Press, Tucson, 1982).
6. Ness, N. F. & Donn, B. D. in *Extr. Mém. Soc. R. Sci. Liège* Ser. 5 **12**, 343-362 (1966).
7. Biermann, L., Brosowski, B. & Schmidt, H. U. *Sol. Phys.* **1**, 254-284 (1967).
8. Brace, L. H. *et al. J. geophys. Res.* **85**, 7663-7678 (1980).
9. Lühr, H. *et al. J. geophys. Res.* **91**, 1261-1270 (1986).
10. Scudder, J. D., Burlaga, L. F. & Greenstadt, E. W. *J. geophys. Res.* **89**, 7545-7550 (1984).
11. Greenstadt, E. W. *et al. Cosmic Electrodyn.* **1**, 279 (1970).
12. Marochnik, L. S. *Soviet Astr.* **6**, 828-832 (1963).
13. Wallis, M. *Planet. Space Sci.* **21**, 1647-1660 (1973).
14. Bame, S. J. *et al. Science* **232**, 356-361 (1986).
15. Slavin, J. A. *et al. Geophys. Res. Lett.* (in the press).
16. Elphic, R. C., Russell, C. T., Slavin, J. A., Brace, L. H. & Nagy, A. F. *Geophys. Res. Lett.* **7**, 561-564 (1980).
17. Brosowski, B. & Wegmann, R. *Meth. Verf. Math. Phys.* **8**, 125-145 (1973).

First results from the Giotto Radio-Science Experiment

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Doppler and ranging measurements, using the radio signals of the Giotto spacecraft and taken during the encounter with comet Halley, reveal a definite deceleration of the spacecraft due to drag in the cometary atmosphere. The total change in the radial velocity of the spacecraft was measured to be 16.7 cm s^{-1}, occuring over a time interval of ~100 s and corresponding to a shift in Doppler frequency of 4.7 Hz. Using this velocity change, estimates of the total cometary mass striking the spacecraft range from 0.1 to 1 g.

The scientific objectives of the Giotto Radio-Science Experiment (GRE) are to determine the columnar electron content of comet Halley's ionosphere and the mass fluence of the cometary atmosphere[1,2]. For this purpose the radio signals from the Giotto spacecraft were used during the Halley encounter on 13–14 March 1986. The radio-science data were collected mainly at NASA's Deep Space Network 64-m tracking station DSS 43 at Tidbinbilla near Canberra, Australia. 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.

Giotto was equipped with redundant radio transponders capable of downlink transmission in the S-band (2.3 GHz) as well as in the X-band (8.4 GHz)[1]; however, the Giotto project management decided for operational reasons to transmit only in the X-band during the Halley encounter. Due to this limitation the determination of the cometary electron content was badly degraded. The GRE was the only experiment on Giotto capable of measuring the low-energy ($\leq$10 eV) bulk electron population of Halley's ionosphere and the total cometary mass flow impacting the spacecraft.

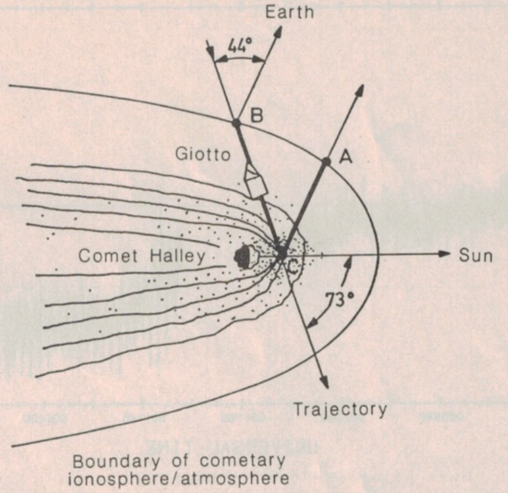

Fig. 1 The geometry of Giotto's Halley encounter on 13–14 March 1986. The cometary electron content represents the integrated electron density of Halley's ionosphere along the ray path C–A, the cometary mass fluence being accumulated from atmospheric drag along the trajectory C–B.

Table 1 Radio link budgets for GRE's prime station DSS 43 during Giotto–Halley encounter

	S-band uplink	S-band downlink	X-band downlink
Signal frequency (GHz)	2.117	2.299	8.429
TX power (dBm)	73	36.7	43.2
Ground antenna gain (dBi)	60.6	61.7	71.9
Propagation loss (dB)	−262.5	−263.2	−274.5
S/C antenna gain (dBi)	25.3	26.3	39
R.f. losses (dB)	−2.3	−1.9	−1.6
Signal level RX input (dBm)	−105.9	−140.4	−122
System noise temperature (dBK)	27.2	13.7	13.8
Boltzmann constant (dBm/HzK)	−198.6	−198.6	−198.6
Received S/N_0 (dBHz)	65.5	44.5	62.8
Modulation loss (dB)	0	−3.6	−8.2
PLL bandwidth (dBHz)	15.4	16.8	16.8
Required C/N (dB)	10	15	15
Margin (dB)	40.1	9.1	22.8

Coherent mode/ranging off: uplink unmodulated carrier, downlink telemetry plus Doppler. Noncoherent: column 3 only. Carrier recovery. Spacecraft elevation 30°. R.f. losses refer to circuitry, antenna pointing, atmosphere and polarization.

The geometry of the Halley encounter as relevant to GRE is shown in Fig. 1. Table 1 gives the radio link budgets representative for GRE data collection during pre-/post-encounter intervals (transponder in two-way, coherent mode) and during the Halley encounter (transponder in noncoherent mode).

Figure 2*a* shows the Doppler frequency shift measured around encounter with the highest possible rate of 10 samples per second. The post-encounter level of the Doppler shift has been normalized to the value of −4.7 Hz corresponding to a total change in radial velocity of −16.7 cm s^{-1}. This velocity change of the Giotto spacecraft, occurring over a time interval of ~100 s, is interpreted as a deceleration induced by drag effects due to the atmosphere of comet Halley (momentum transfer). Corrections of those contributions to the Doppler shift resulting from the relative motions of spacecraft and Earth and from the