Antennas for sounding of a cometary nucleus in the ROSETTA mission

E. Nielsen(1), W. Engelhardt(1), B.Chares(1), L. Bemmann(1), M. Richards(1), F. Backwinkel(2), D. Plettemeier(2), P. Edenhofer(2), Y. Barbin(3), J.-P. Goutail(3), W. Kofman(3), L.H. Svedhem(4)

(1) Max Planck Institute for Aeronomie, D-37191 Katlenburg-Lindau, Germany
(2) Institute for High Frequency Technique, Ruhr-University, D-44780 Bochum, Germany
(3) Service d'Aeronomie, BP 3, Route des Gatines, F-91371 Verrieres-le-Buisson Cedex, France
(4) ESTEC, NL-2200 AG Noordwijk, The Netherlands.

CONSERT (= COmet Nucleus Sounding Experiment by Radiowave Transmission) is a 90 MHz radio wave experiment in the ROSETTA mission to be launched by ESA in 2003. It is designed to sound the interior of a comet to determine spatial structures and the electrical properties of the cometary material [1].

It has been suggested that collisional accretion of material in a solar nebula leads to formation of 10 to 100 m size planetesimals. At that size the planetesimals effectively decouple from the gas and their dynamics is governed by gravitational forces. This produces a more uniform velocity distribution, and the gravitational instability can as a result form larger primary nuclei or comets out of the planetesimals [2]. The break-up of the comet Shoemaker-Levy-9 into many fragments have been interpreted as a break-up of the comet into the smaller planetesimals of which the comet originally was composed. Thus, the size of the planetesimals are controlled by the processes and conditions in the solar nebula and are therefore an important parameter for understanding of the conditions and processes leading to condensation of matter out of the solar nebula. CONSERT will probe the interior of a comet with radio waves to reveal its structures and electrical properties: permittivity, absorption, correlation length of signal (planetesimal size), and volume scattering coefficient.

In the ROSETTA mission a spacecraft will orbit the cometary nucleus, and another spacecraft, a Lander, will settle on its surface. 90 MHz radio waves will be transmitted through the comet between the two spacecrafts [3]. The main objective of the experiment is to determine the mean permitivity from measurements of the travel time of radio waves through the comet. As the relative position of the Lander and orbiter will vary with time owing to the motions of the orbiter and the (possibly rotating) comet, the cometary interior will be swept by radio waves. Thus, the variation of mean permitivity along a ray-path can be determined as a function of aspect angle, and that vartiation is a measure of the spatial inhomogeneity of the internal structures of the comet [4, 5]. The transmission experiment operates as follows: a coded signal with a sub-pulse width 100 ns, is transmitted from the orbiter. The signal propagates through the comet and is detected on the Lander. The Lander acts as an 'active reflector', i.e. the received signal is effectively reflected back into the comet. The signal again propagates through the comet and is detected on the orbiter. This is a time transponder technique. This lowers the requirements on the accuracy of the clocks to make compliance with mass and power limitations on a space experiment possible. In this report the antenna systems on the orbiter and on the Lander spacecraft are described.

The low mass allocated to the experiment means that no mechanically or electronically steerable narrow antenna main lobe can be contemplated. The antennas must be fixed on the spacecraft, and have a wide antenna lobe centered on the comet, such that the whole comet is illuminated; this will ensure the best possible signal intensity on the direct ray between orbiter and Lander.

ORBITER ANTENNA

The CONSERT orbiter antenna consists of two crossed half wave dipoles placed above parallel reflectors. The normal to the plane of the dipole elements is directed towards the comet. The distance between the active elements and the reflectors is 0.3 wavelength. The reflectorts serve to slightly increase the gain, and the distance between the reflectors and active elements is chosen to again broaden the antenna lobe of the antenna to ensure the whole of the comet is well inside the main lobe. The dipole- and reflector elements are kept in place by a mast. Another mast displace the array away from the side of the spacecraft with experiment apertures. The displacement serves partly to avoid interference from the antenna with other experiments (especially

11th International Conference on Antennas and Propagation, 17-20 April 2001, Conference Publication N. 480 © IEE 2001, p. 436-441, UMIST, Manchester, 2001

optical experiments), and partly to place the antenna in a position where signals reflected from the spacecraft body and the solar panels are nearly in phase with the direct antenna signals propagating towards the comet. This to avoid nulls in the radiation pattern in directions towards the comet.

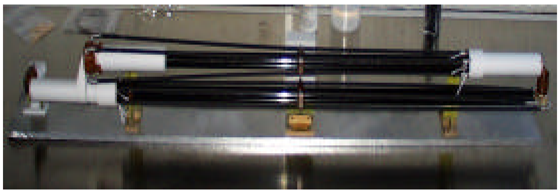


Figure 1: Orbiter antenna in launch position. Length of folded antenna is 1150 mm.

The 90 MHz half-wave crossed dipole antenna has dimensions of the order 1.5x1.5x1 m in deployed position. The antenna is constructed of 10 rods (4 dipole elements (aluminum), 4 reflector elements (aluminum), 2 masts (carbon fibre)), which are appropriately connected to each other by springs. The rods are placed parallel to each other in launch position, and near their center they are lashed with a steel wire to a support mounted on the spacecraft body. Two further supports placed near the ends of the rods, serve to place the bundle under tension, and thereby increase the mechanical resonance frequency above the limit (> 140 Hz) required to survive rocket vibrations during launch. A further support serves to anchor the deployed array to the spacecraft. Once in interplanetary space the wire will be cut by a pyro device; this releases the antenna which then deploys automatically under the action of the spring forces, and locks into place. The antenna mass is ~1.5 kg. The Antenna sweeps a volumn of ~ 8 m³ during deployment.

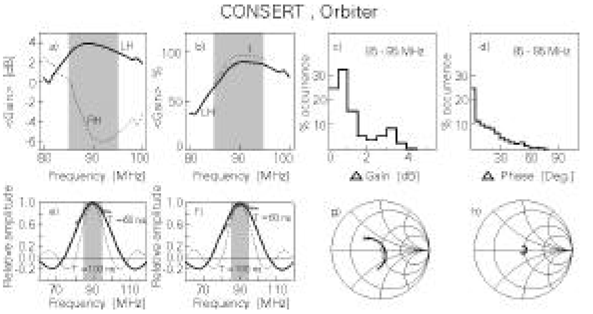
The springs connecting the dipole- and reflector elements to the 'masts' are coils. The deployment of the antenna takes place in a weightless environment, so the spring forces only have to overcome weak friction forces. Inside each coil is a small spring-loaded pin, which serves to lock each element into place once it has reached its forseen position. The deployed antenna is mechanically connected to the spacecraft with Carpenter-Springs. A Carpenter-Spring is also used to connected the two masts together. Compared to a coil a Carpenter-Spring is fairly stable in its straight position. To further stabilizing these connections a spring-loaded manchet is pushed across the Carpenter-Spring as it straightens out during deployment, thereby preventing future bendings of the Carpenter-Springs. The manchet is kept under tension after deployment to reduce toroidal oscillations of the masts. The carbon fibres in the light weight masts are place both parallel to the mast (for increased bending stiffness (2.7 * 108 Nmm^2)), and at angles of +45 degrees to the direction of the mast (for increased toroidal stiffness (11.2 * 107 Nmm2)). The lowest mechanical eigenfrequency (toroidal oscillation) of the antenna in deployed position is > 2 Hz, excluding mechanical resonances between antenna and spacecraft during spacecraft manoeuvres.

To prevent that the antenna serves as a heat source or heat sink for the spacecraft, the antenna system must be well thermally isolated from the spacecraft. The resulting maximum heat flow between antenna and spacecraft is required to be < |2W| during the mission. The solar radiation will vary a factor 28 for solar distances between 1 and 5.25 AU. Near the Earth orbit the antenna will be warmer than the spacecraft, while at larger distances it will act as a heat sink. The thermal isolation is achieved primarily by using a material, Polyomid, of low heat conductivity (0.25 W/mK) for the supports. Owing to the high bending strength (560 N/mm2) of Polymide each support could be made of thin and narrow sheets of Polymide, such that the total area of intersection between the four supports for the antenna and the spacecraft is only 6.4 cm^2 , while maintaining the required high mechanical stability. The resulting heat conductivity across the supports is 0.01 W/K. Furthermore, the antenna masts are made of carbon fibres, which also has low heat conductivity (30 W/mK for the mast cross section of 1.1 cm^2). For one meter long mast the heat conductivity is 0.0032 W/K. The antenna surface is covered with Plasmocer (emissivity= 0.76; absorption= 0.34); this is primarily to prevent overheating of the folded antenna near 1 AU.

The mechanical antenna system (including the electrical components) has been successfully qualified in a strength load test up to 50 g, in a vibration stand with dynamic accelerations up to rms = 29 g in the frequency interval 200 to 220 Hz, and in temperature cyclings in a thermal vacuum chamber between -150^o and +100^o C. It was also demonstrated that the antenna could deploy successsfully 30 consecutive times, which is the required number of deployments that is considered necessary to ensure successful deployment in space.

The antenna network matches the dipoles to the 50 Ohm impedance of the signal cable connecting the antenna to the electronics box with receiver and transmitter. The impedance of each dipole is ~73 Ohms. Each of these unbalance impedances is transformed to near 50 Ohm using a half wave balun followed by a cable transformer (cable length 0.096 - and stub length 0.120 wavelength). The two dipole outputs are connected in a 90 degrees space qualified hybrid, which ensures a Left Hand circular polarization in directions towards the comet. The dipole elements are DC connected to ground by an inductance (2 mH) to avoid charge build up on the elements. This electrically simple and mechanical and thermal robust solution is placed on a single board located inside the antenna mast near the dipole cross.

The impedance of the two dipoles are very closely equal to each other. The transformation of one dipole impedance in a 90 degrees hybrid has the effect of mirroring that impedance in the center of the Smith diagram. The combination of the two impedances in parallel in the hybrid results in a combined impedance that is real and close to 50 Ohm. This complementarity remains when the frequency change across the bandwidth and also (approximately) if the surroundings change. Thus, the combined impedance is relatively insensitive to variations in frequency and in surroundings.



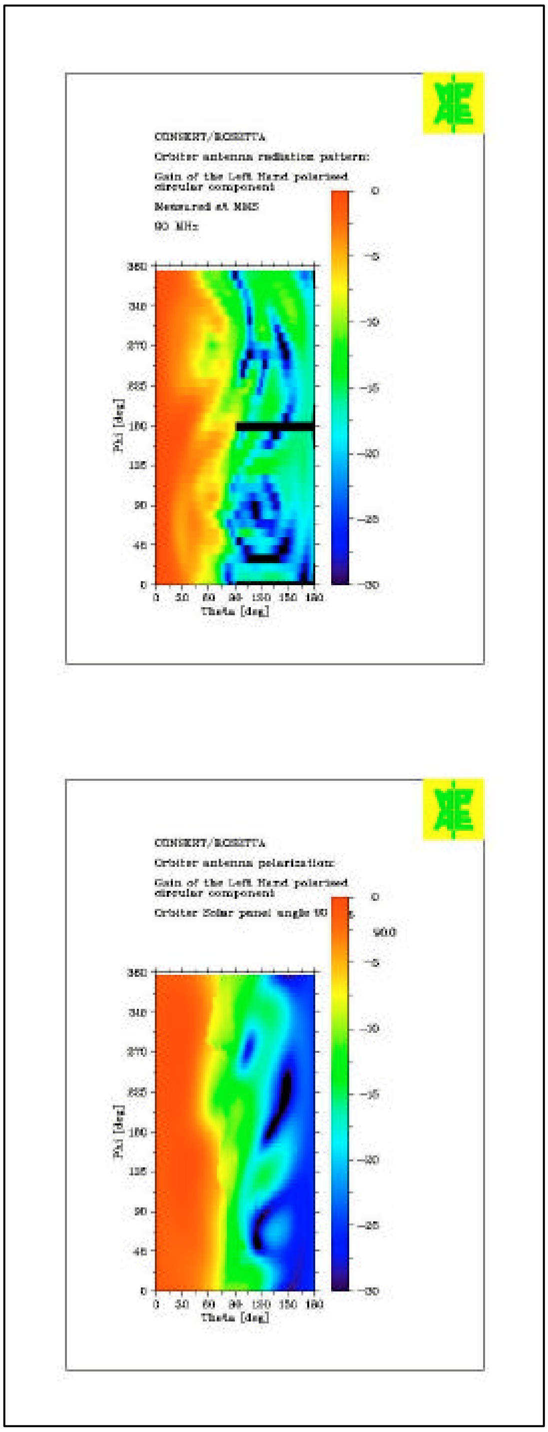
"Figure 2": Compilation of the electrical properties of the orbiter antenna (se text).

Actually the dipoles are not tuned to exactly 50 Ohm at 90 Mhz, but to a relatively flat response across the bandwidth (Figure 2, panels 'g'). Model calculations have predicted, and 'free space' impedance measurements have confirmed, that the SWR across the 10 Mhz bandwidth is < 2.3 for both dipoles. The impedance of the combined signals at the antenna output is very close to 50 Ohm across the whole bandwidth (panel 'h') owing to the complementarity of the dipole impedances. The measurements were made with the antenna mounted on an electrical model of the spacecraft so that the antenna is placed ~6 m over ground. The measured return loss is -31.5 dB (measured at ASTRIUM, see below).

The calculated electrical antenna peformance is illustrated and summed up in Figure 2. The Calculations were made using NEC (=Numerical Electromagnetic Code). The directional gain, averaged over 0/+45 degrees polar angle, of the Left Hand and Right Hand component of the antenna signal, are shown as functions of frequency (from 80 to 100 Mhz) in panel 'a'. The frequency dependence of the ratio of the spatially (0/+45 deg.) averaged power in the Left Hand component to the total power, is in panel 'b'. In the same panel is also shown the power transmission coefficient for the dipole antenna impedance ($t=1-r^2$, where 'r' is the amplitude reflection coefficient) as it varies with frequency. The stability of the signal across space and as a function of frequency, is illustrated in panels 'c' and 'd'. Here the occurrence in percent of the total solid angle (0/+45 deg.) of gain- and phase fluctuations owing to frequency variations across the bandwidth, are shown as a function of the amplitude of the fluctuations. The fluctuations in directional gain and phase over the field of view do not deteriorate the transmitted and received signals. In panel 'e' the voltage amplitudes in the direction of the antenna normal are superimposed on the ideal amplitude spectrum for a 100 ns and 60 ns pulse; in panel 'f' the spatially averaged amplitudes are displayed. The antenna impulse response allows the 100 ns pulses to be transmitted and received.

Figure 2 demonstrates that the antenna is an effectively Left Hand polarised in all directions towards the comet over a 10 Mhz bandwidth centered at 90 Mhz., with an impulse response appropriate for a 100 ns pulse.

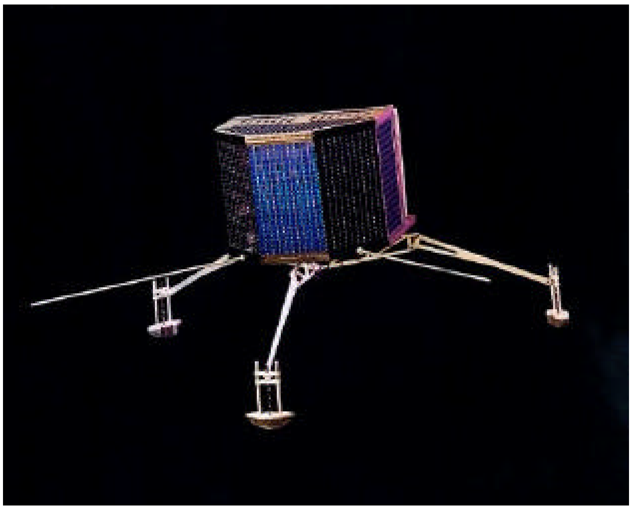
The spatial variations of the directional antenna gain of the antenna mounted on a spacecraft was calculated (using NEC), and compared to experimental measurements of the radiation diagram made in an anechoic chamber at ASTRIUM in Porthmouth, UK. The chamber was however only qualified for frequencies >200 Mhz. Nevertheless, the measurements confirmed the designed performance of the antenna system, Figure 3. Importantly, measurements confirmed the designed relatively uniform gain within a cone with a 90 degrees opening angle centered on the direction to the comet.



"Figure 3": Radiation pattern of the orbiter antenna. Panel 'a' is the relative pattern measured at ASTRIUM, and panel 'b' is the theoretical pattern predicted using NEC. The calculated maximum gain over an isotropic radiator is 5.2 dB (the measured gain of the orbiter antenna alone in 'free space' is 2.5 dB; it was measured at RUB, see below).

LANDER ANTENNA

A fundamental requirement to the Lander antenna is that its main lobe must be directed into the comet, and furthermore, that the antenna must be placed as close as mechanically possible to the cometary surface in order to obtain the best possible coupling of the radiated energy into the comet [6].



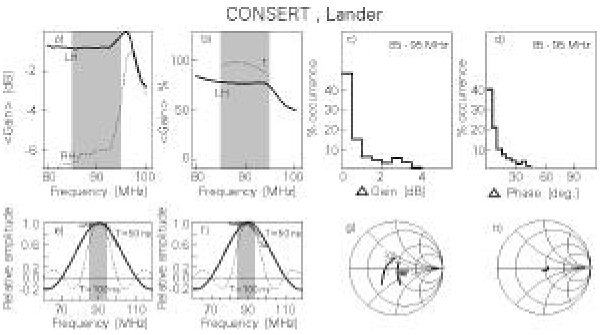
"Figure 4": A schematic with Lander and deployed monopoles

The smaller mass resources available for the experiment on the Lander spacecraft leads to a simplified antenna system. The Lander has roughly the form of a 'drum' standing on three legs. The CONSERT Lander antenna consists of two monopoles placed on the lower part of the drum (in a height of ~0.1 wavelength), and they extend 'horizontally' away from the body in the deployed position (Figure 4). During launch the monopoles are folded back along the body. In the launch position the legs are also folded back along the body, and the folded monopoles are placed such that the folded legs fixes the monopoles in the launch position. When the Lander is ejected from the orbiter spacecraft, the legs deploy, and thereby release the monopoles.

The mechanical boundary conditions on the Lander limit the length of the aluminum monopoles to 70 cm. The two 90 MHz crossed 0.21 wavelength long monopoles are mounted on the Lander body with an interface, an antenna-foot, which is in electrical contact with the Lander body . The monopole is mounted in an electrically isolated area on the interface with a spring (a coil). The spring allows the monopole to be folded back during launch. To allow that the whole of the monopole can fold back against the Lander body a further spring (coil) is inserted about half way along the monopole. When the landing gear release the monopoles, they will deploy under the spring forces. Inside each coil is a small spring-loaded pin, which serves to lock the monopole into place once it has reached its forseen position.

Each monopole is connected via an inductance (~100nH; placed in the antenna-foot to compensate for the short length of the monopole) to a coaxial cable, which takes the monopole signal to an antenna network located in a box on the underside of the "drum". The network consists mainly of a 90 degrees hybrid, which ensures the correct Left Hand circular polarization in the downward direction, i.e. into the comet. Furthermore, the monopoles are DC connected to ground by an inductance (2 mH) to avoid charge build up on the elements.

The antenna system is very light (~200 g) and robust. The mechanical strength, eigenfrequencies, and the heat flow between antenna and Lander were qualified together with the Lander itself. Since the Lander antenna network uses components also used in the orbiter network, since it is otherwise similar to the orbiter antenna network, and since the qualification requirements are compatible, the mechanical, thermal, and electrical qualification of the Lander network is considered satisfied by the qualification of the orbiter network.



"Figure 5": Compilation of the electrical properties of the Lander antenna (see text).

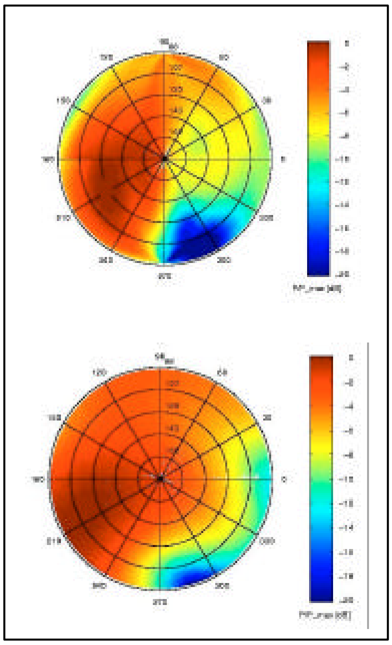
Figure 5, panel 'g', shows the measured and calculated impedances of the two monopoles, and panel 'h' the combined impedances at the output of the Quadratur hybrid. The measurements were made with monopoles mounted on an electric equivalent Lander model placed in approximately free space envionment (~6 m over the ground). The standing wave ratio for each monopole is < 2.5 across the bandwidth of 10 MHz. The coupling between the monopoles is < -15 dB.

Figure 5 demonstrates the performance of the antenna, and is the equivalent to Figure 3 for the orbiter antenna. - Figure 5 shows that the antenna is an effectively Left Hand polarised in all directions into the comet over a 10 Mhz bandwidth centered at 90 Mhz. The fluctuations in directional gain and phase over the nadir hemisphere do not deteriorate the transmitted and received signals. The antenna impulse response allows the 100 ns pulses to be transmitted and received.

The spatial variations of the directional antenna gain of the antenna mounted on the Lander in free space were calculated (using CONCEPT), and compared to experimental measurements of the radiation diagram made between the roofs of two high buildings at Ruhr University Bochum (RUB), Germany. The measurements confirmed the designed performance of the antenna system, Figure 6.

"Figure 6": Radiation pattern of the Lander antenna in the nadir hemisphere. Panel 'a' is the relative pattern measured at RUB, and panel 'b' is the theoretical pattern predicted using CONCEPT.

Here we have considered the antenna radiation diagram in free space. Of course, when the Lander is located on the comet, the nadir half space will be in effect filled with the comet, with its structural inhomogeneities and varying permittivities. As a result both the antenna impedance and the antenna diagram into the comet may be modified from the free space values. At RUB impedance measurements at 900 Mhz on a 10:1 Lander model placed on sand (ε=2.8) demonstrated that the antenna impedance is weakly influenced by the ground as long as the antenna is above the surface. Since cometary material has been suggested to have a permittivity near 2, and to have low conductivity, this result indicates that the comet may have little effect on the antenna impedance. On the other hand, it has been found that the radiation diagram of an antenna, placed over a half-space with permittivity larger than one could be strongly modified [6]. The modification is governed by the height of the antenna over the comet surface and by the cometary material and internal structure, which are both the object of our observations. This means that the interpretation of the observed amplitudes of the



"Figure 6": Radiation pattern of the Lander antenna in the nadir hemisphere. Panel 'a' is the relative pattern measured at RUB, and panel 'b' is the theoretical pattern predicted using CONCEPT.

received signals must be treated with care, and to resolve the cometary structures from antenna radiation diagram variations will require an iterative analysis of the cometary influences on the antenna diagrams.

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