

THE ANTENNA SYSTEM OF THE HELIOS SOLAR PROBE¹

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Summary. For the Helios solar probe a complete antenna system was developed and manufactured which is suitable for the various mission requirements, as near earth phase varying aspect angles, close sun flyby and maximum distance of $3,0 \cdot 10^8$ km with spin axis orientation perpendicular to the ecliptic.

The near earth phase requirements were covered by a low gain antenna system with an isotropic radiation pattern. After the rough orientation of the spin axis a medium gain antenna with an omnidirectional radiation pattern will be used. After final orientation of the spin axis perpendicular to the ecliptic plane a high gain antenna with a despun wire grid reflector will be used for the telemetry link. By switching devices and/or hardwire connections the antenna systems are partly redundant in order to get the required high reliability. The maximum operating temperature range of the antenna system is + 200° to - 200°C.

Introduction. The Helios mission profile requires an exceptional antenna system performance which makes it necessary last not least also for redundancy reasons to use three antennas. The wide operating temperature range of -200° to + 200° C, the avoidance of too high solar pressure and the requirement that all antennas have to be mechanically self-supporting have influenced the antenna design to a high extent. [1]

The coverage of the antenna surface by second surface mirrors, the design of the antenna reflector as grid wire reflector, the choice of slot radiators and the avoidance of synthetic material were the consequence of the above requirements.

Because of the requirements of the antenna system during the various mission phases and out of reliability reasons three antenna systems were chosen, which can be switched by telecommand according to the mission requirements.

For the near earth phase, where the aspect angles to the earth stations vary in a wide range, an antenna with a nearly isotropic pattern was designed. Beginning with the reorientation phase II an antenna, radiating in the s/c equator plane omnidirectionally was chosen. For the far distance a high gain reflector antenna with a linear feeder and despun mechanism for

¹ This work was carried out under contract of the Gesellschaft für Weltraumforschung (GfW)

the reflector was necessary, to allow 2048 bps datastream at 2 AU distance. The isotropic and the omnidirectional antenna are each hardwire connected to a command receiver, the high gain antenna is only used for telemetry connection. High gain antenna and omnidirectional antenna are redundant for the telemetry link, however a reduction of bit rate must be suffered if the despun mechanism of the high gain antenna fails and the omnidirectional one is used.

Design of the antenna system. A special antenna system, shown in fig.1, was necessary for the different requirements during the mission of the Helios solar probe. The frequencies of the Helios are 2.297 GHz for the transmitter and 2.115 GHz for the receiver.

The orbit of the Helios solar probe is shown in fig.2 for a fixed earth sun line versus the time after launch. The orbit is in the ecliptic and the spin axis of the space craft is orthogonal to the ecliptic. During the mission the solar probe approaches the sun to a distance of 0.3 AU (1 AU = 1,495.10⁵ km) and goes away to a maximum distance to the earth of 2 AU. In the study phase it was planned a minimum distance to the sun of 0,25 AU so that the antennas are designed for this value. From the launch to the distance of approximately 2.10⁵ km the alignment of the spin axis is not perpendicular to the ecliptic plane.

The solarintensity at 0.25 AU is 16 solarconstants. This means a temperature of + 500° C for polished aluminium and + 200° C for aluminium coated with-second surface mirrors. The temperature at the maximum distance is -200° C. By these mission parameters the requirements for the development are determined. After the first rough estimates it was shown that the telemetry link from the space craft to the earth is very critical, because the power of the transmitter is only 20 W and/or 10 W for low sun intensity. The required maximum bitrate is 4096 bit per second. This requires a telemetry antenna with a gain of 23 dBi taking into account the available ground stations. Such a high gain antenna (HGA) can be realized only by a reflector antenna, because of the spin stabilized spacecraft, the reflector has to be despun from the spacecraft. The despun drive assembly is a critical point for the reliability of the high gain antenna.

An additional requirement for the reorientation phase of the spacecraft was a medium gain antenna (MGA) with a minimum gain variation in the equatorial plane. The shape of the main lobe of this antenna shall be used as a backup information about the spin axis orientation during the reorientation manouvres. Further this antenna will be used as a spare antenna for the data link with reduced bitrate if the high gain antenna fails, and for the command reception during the normal mission of the solar probe.

In the first time when the spacecraft is not aligned, a third antenna with nearly isotropic radiation pattern is required. This low gain antenna (LGA) also can be used as spare

antenna for command reception, so that the high gain antenna could be designed only for the transmit frequency.

The Low Gain Antenna. A low gain antenna with quasi-isotropic radiation pattern is difficult to realize on a spacecraft with large dimensions (about 20 wavelengths in diameter, height about 30 wavelengths including antenna system). The design of the LGA met the specified quasi-isotropic radiation without any switching of antennas in the spacecraft.

The antenna consists of a dipole antenna positioned in the spin axis at the top of the antenna boom and of a horn antenna fixed at the underside of the spacecraft and radiating in the-Z-direction of the spin axis (fig.1). The interferences resulting from the spacing between both radiators can be considerably minimized by a special selection of the dipole and, in particular, of the horn radiator.

A horn antenna with a circular aperture of 1.3 to 1.4 wavelengths in diameter fed by a linearly polarized wave (TE₁₁) exhibits in the plane parallel to the E-vector a 3 dB-beamwidth of approximately 40 deg. and in the perpendicular plane 46 deg. Differences in the order of magnitude of 10 dB occur between the two radiation patterns at an angle of 50° from the main radiation direction.

When this horn antenna is fed with a circular polarized TE₁₁ wave, it shows circular polarization in its main radiation direction, whilst in the directions with increasing angles from the main direction the polarization becomes more elliptical. The degree of ellipticity will be at about 50° to 60° from the main radiation direction 10 dB.

The dipole radiation will intersect the horn radiation in the angle region $\theta = 130-140^\circ$ eg. 40 to 50 deg. from the horn boresight ($\theta=0^\circ$ at dipole; coordinate system according to IRIG-Standard). The polarization of the dipole radiation is orthogonal to the major component of the elliptically polarized horn radiation; for this reason the dipole radiation can only interfere with the smaller part of the horn radiation. In order to compensate the difference in gain between dipole and horn, the two radiators are connected with an adequate powersplitter.

For a more detailed information about the principle of the low gain antenna and first experimental studies see [2].

By reason of an easy lightweight construction on the one hand and the moderate input impedance response at length variations of the dipole (pattern shaping) on the other, a biconical dipole was chosen. It is supported by its coaxial feed line, which is mounted on the top of the antenna boom (fig.3). In the coaxial feed line between mounting flange and

feed point there is a matching zone for the radiator. The total weight of the dipole, including flange and thermal coating, is 130 g.

To realize a lightweight and compact horn radiator with the proposed radiation characteristic a circular waveguide section with about 90 mm in diameter and 200 mm in length is excited by a helix. This helix is a photo-etched copper strip on a thin glassfiber tube, which is mounted on a stripline-sandwich-plate at the one end of the waveguide. The stripline-triplate contains a matching section between the helix feed point and the horn antenna connector, and in addition a 10 dB-directional coupler with a separate output connector. The triplate serves additionally as a short circuit for the horn antenna. In the circular waveguide there are two capacitive loading section on opposite sides, which on the one hand improves the axial ratio of the horn and on the other hand the impedance matching. The following conical part was designed to shape the radiation pattern in the perpendicular planes as mentioned above.

With the conical part the horn antenna has a length of 400 mm and an aperture diameter of 200 mm. Around the aperture there is a choke to obtain a sufficient back lobe level.

The horn was machined out of one piece of aluminium and then grown thin at several areas by etching. So the total weight of this horn antenna only amounts to 530 g, see fig.4.

The powersplitter is a stripline triplate device with a power split ratio of about 1 : 4 between dipole and horn. This ratio considers not only the difference in the gains but also the different cable attenuations to the horn and the dipole antenna.

The low gain antenna system requires a large distance for radiation pattern measurements because of the great dimensions of the spacecraft and the separation of the two low gain radiators. The pattern shows a good compliance with the specified values (see fig.5). In the pattern the influence of the polygonal spacecraft structure is visible. It can be seen that, with a proper switch over of the linear polarization on the telemetry ground-station antenna, good quasi-isotropic radiation patterns are feasible even with spacecraft structures of very great dimensions. (see also [3])

The Medium Gain Antenna. The Medium Gain Antenna is integrated into the HELIOS antenna boom between the HGA and the LGA dipole. The requirements for this vertical polarized omnidirectional antenna are very tight due to thermal and mechanical stress, circularity of radiation and bandwidth. To meet the specified requirements the best solution was the application of a collinear dipole array, as was shown by a thorough investigation. [4]

With 10 dipole elements the antenna has a gain of about 9 dB in the equatorial plane over a 10 % frequency band. In this plane the radiation pattern has a circular symmetry with a deviation from circularity of no more than ± 0.3 dB. Because of high temperatures it is very critical to use dielectric materials. So the antenna was constructed completely out of aluminium without any dielectric materials.

The dipole cylinders are arranged around a tube, which is the supporting structure of the array and the outer, conductor of the coaxial feed system (fig.6). The inner conductor of this coaxial system has to allow feedthrough of the LGA and the MGA coaxial feeding cables, the latter because the feed point of the MGA is placed in the center of the array.

One dipole element consists of two cylinders 0.2 wavelength long and about 0.6 wavelength in diameter at medium frequency. To get a better electrical performance and a rugged construction, the two cylinders of each dipole element are connected at four points. So the circumferential slot is subdivided into four single slots each of them less than a half wavelength long. The slots are excited by three-wire lines, so that a sufficient broadband impedance matching can be achieved. This balanced feed is simple in mechanical design, meets the severe thermal requirements, as no dielectrical material is needed.

The rugged outer lines of these three-wire baluns which are fixed on the supporting tube of the array, are a good mechanical support for the dipole elements. The center lines are the exciting probes. They are fastened directly to the inner conductor of the array providing an additional support.

In axial direction the coupling probes of the collinear dipoles are excited at a distance of half a wavelength by the TEM-mode which only is existent in the coaxial feed system of the antenna array, e.g. that succeeding dipoles would radiate in phase opposition. To get an equal phase excitation, succeeding dipoles and the appropriate three-wire lines have to be turned 180 degrees to each other.

If the system is fed at one end of the array, the radiation will be a maximum in the equatorial plane only at the medium frequency, for which the distance between two coupling planes is exactly half a wavelength. At lower frequencies there is a deviation of maximum radiation in direction to the feed point, at higher frequencies a deviation of radiation in opposite direction. Beside this effect, the input impedance is very low and herewith a broadband matching very difficult. In order to get the required 10 % bandwidth the antenna has to be fed at the center of the array.

A broadband feed system is attainable if the two halves of the array are connected over an inverse T-connection to the coaxial feed line inside the inner conductor of the feed system. In this case the feed point is located in the center of array and the resulting maximum of

radiation lies in the equatorial plane not only at medium frequency but at lower and higher frequencies also, because the frequency dependent beam tilting is compensated.

Moreover this kind of feeding has an important mechanical advantage. The coaxial feed system has to be terminated by a short circuit about a quarter wavelength behind the last coupling plane. So with the feed point in the center of the array there has to be a metallic connection between inner and outer conductor at both ends. This allows a very rugged mechanical arrangement.

The connection of the two halves of array has to be performed at a point which has a high input resistance. Seen from the feed section this point lies about 0.25 or 0.75 wavelength before the first coupling planes, which exhibits low resistance. The distance between the first coupling planes is than 0.5 respectively 1.5 wavelength. By reason of an easy installing procedure of feed cable and the suppression of higher order modes excited by the asymmetric feed within the center section of the array a distance of 1.5 wavelength was chosen.

A distance of one wavelength between the coupling planes next the feed point would be advantageous in relation to the radiation pattern, but impedance matching would be difficult, because the low resistance of their coupling planes would be transformed to the feed point. Meanwhile a solution is found to reduce the distance of the coupling planes at the array center to about half a wavelength.

A fast and reliable mounting of the feeding cable was possible by the development of a center feed device, which is accessible from the outside of the array (fig.7). By this device the inner and outer conductor of the array and of the feeding cable are connected by screws. This feed allows an adjustment for impedance matching.

An optimum broadband impedance matching has been attained by employment of dumbbell slots for excitement of the dipole elements and by application of a constant characteristic impedance of 28Ω for the coaxial feed system. With this value the inner conductor has a diameter of about 0.2 wavelength, big enough to insert two coaxial lines.

For the flight unit the specified frequency bands from 2.11 to 2.12 GHz and from 2.29 to 2.30 GHz have been optimized so that within the specified temperature range the SWR was smaller than 1.5. Fig.8 shows the radiation pattern measured at 2.115 GHz. The relative high sidelobes don't affect the proper performance of the antenna. They are caused by the large spacing of the radiators at the array center.

The antenna is covered by a second surface mirror to protect it against solar heat impact. (fig.9) The length of the antenna is 1 meter and the weight is 1150 g. With this antenna all

specified requirements have been fulfilled and partly exceeded. The principle of the antenna is applicable not only for this special mission but in a wide field of commercial application.

The High Gain Antenna. The requirements for the High Gain Antenna [5] (HGA) are very tight due to mechanical and thermal stress and antenna gain. For the required antenna gain of 23 dBi a spot beam antenna was necessary. The antenna was designed as parabolic reflector antenna with a line feed. Because of the spinstabilized spacecraft the reflector has to be despun against the spacecraft rotation, so that the antenna boresight points always to the ground station. In fig.1 it is shown that above the HGA, the MGA and the LGA-dipole are mounted, which results in extraordinary mechanical requirements.

The line feed of the parabola was therefore chosen as a tube with the greatest possible diameter and slot radiators of minimum size, in order not to weaken the mechanical stiffness. For a better stability of the solar probe the height of the antenna was limited.

So the dimensions of the reflector were limited to a height of 600 mm and a width of 1100 mm. The focal length for the reflector was chosen to be 220 mm. In connection with a subreflector the necessary fieldstrength distribution could be achieved. The polarization of the high gain antenna is linear parallel to the spin axis, so wire grid reflectors could be used to minimize the solar pressure and the heat radiation into the spacecraft.

Because the feeder of the HGA must support the whole antenna boom, the supporting tube of the feeder was limited to a minimum diameter of 70 mm. This requirement made it necessary to find an antenna design, where the antenna structure is part and/or included in the supporting tube. A coaxial slot array [6] was found to be the best solution. This means the supporting tube is used as the outer conductor of a coaxial line interrupted by four horizontal slots at defined planes. The slot array will be fed from one side and the coaxial feed system has to be terminated by a short circuit about a quarter wavelength behind the last slot plane.

Realization The diameter and the wall thickness of the outer conductor of the coaxial slot array are determined by mechanical requirements. The diameter of the inner conductor of the coaxial feed line is limited in its diameter so that only the TEM mode is existent and the two RF-cables (type UT 250) for the LGA and MGA can be led through the inner conductor.

As radiating elements horizontal slots are cut into the vertical outer coaxial conductor thus exciting a vertical polarized electric field by interrupting the vertical currents flowing in the coaxial line. The phase of the currents in the wall is opposite after every half wavelength. To get an equal phase excitation of the slots in the vertical line the distance

between two slot planes must be one wavelength. This required distance is not the optimum for the radiation pattern of a collinear array, the optimal distance is about 0.8 wavelength. For an equal phase excitation at a slot plane distance of 0.8 wavelength a coaxial line with a greater phase delay was necessary. Because of the high temperature stress the use of dielectric synthetic material was not applicable. In this case a corrugated innerconductor [7] was used with a delay as to get for 0.8 wavelength slot distances equal phase distribution.

The slot dimensions are also limited by mechanical requirements. The permitted maximum length was 30 mm which is about 0.23 wavelength, so that the use of dumbbell slots is necessary. During the measurements on a single slot plane consisting of four symmetrical slots, it was shown, that if the hole at the ends of the dumbbell slot is given with a maximum diameter of 10 mm because of mechanical requirements, the slot width itself must be 0.5 mm. The required accuracy was figured out to be 0.01 mm. This accuracy could only be achieved by special spark eroding methods.

With a special developed nearfield measurement equipment the manufacturing accuracy was controlled by measuring the equality of amplitude and phase of every slot. By this detailed analyses with the nearfield measuring method the above mentioned minimum tolerance of 0.01mm the slot width was demonstrated.

The feeding system positioned at the lower array side, was fully separately developed from the slot array. At the beginning inductance couplings with loops similar to the coupling of cavity resonators were examined. But these coupling devices excited partly higher order modes which were capable of existence on the whole coaxial line. It was developed a feeding system with a smaller outer conductor diameter excited by a probe galvanically connected to the inner conductor. At a distance of about a half wavelength from the probe the outer conductor expands to the normal diameter. By this method the suppression of higher order modes was achieved.

A overall drawing of the HGA-feeder is shown in fig.10. Fig.11 shows a photograph of the prototype model, which exhibits the dismantled inner conductor with feeding section in the foreground.

The outer dimensions and the focal length of the reflector were determined in the first study phase for the best achievable fieldstrength distribution on the reflector. The subreflector was optimized in course of the hardware development work.

A very critical point of the reflector were the wires, because there are calculated maximum temperatures of about 500°C in some reflector areas. In order to keep the wires straight the temperature expansion was compensated by spring load of the wires. Platinum rhodium

wires were found to withstand the environmental temperatures. A wire diameter of 0.2 mm was found to be a good compromise between mechanical strength and effective reflecting area for heat radiation and solar pressure. The spacing of the wires was chosen to be 5mm in order to get the penetrating energy 20 dB below the one reflected at the grid surface.

With this antenna all specified requirements of the Helios solar probe were fulfilled. In fig. 12 and fig. 13 the radiation pattern of the HGA are shown. These diagrams were measured when the high gain antenna were mounted on Helios metal mock up. The reached frequency range was 2.295GHz 10MHz for the required VSWR 1.5 by 20°C.

Spezial tests For the extreme requirements on the Helios antenna system made necessary some special tests for qualification. The VSWR must be measured over the required temperature range. For these measurements only a metal thermal chamber was available which exhibits naturally considerable reflections. Nevertheless the results of these tests give a good idea of the antenna performance during temperature impact. The high gain antenna feeder was additionally tested versus the temperature in a free space test. In this test the feeder was heated by infra red radiators, which were removed after heating up. The radiated power was measured during temperature decrease.

The antenna patterns were measured in the MBB antenna test range. For these measurements a Helios metal mock up was manufactured with all details. Fig.15 shows a photograph of the MGA and HGA prototype during the functional performance tests in the anechoic chamber. During these tests the radiation pattern and the gain of both antennas were measured. For the omnidirectional medium gain antenna, the boresight error of the main beam in reference to the S/C spin axis was measured for all angles of θ . The mean value was calculated to be 0.1deg. This accuracy is tolerable for the use of this antenna as backup information about the alignment of the S/C axis during reorientation manoeuvre II. The radiation pattern of the nearly isotropic low gain antenna was measured when the space craft was mounted in the anechoic chamber in a horizontal position on a special turning device enabling rotation in both axes so the field strength and phase distribution over the whole solid angle could be measured.

Environmental tests on subsystem level were performed in the MBB test facilities. Fig.14 shows a photograph of the whole antenna boom mounted on the shaker at the MBB test facility during the vibration tests of the prototype antennas.

Conclusion It could be shown by the above described antenna system, that by a sensible combination of various antenna types even almost contradictory requirements e. g. isotropic radiation pattern and high gain could be met for the Helios solar probe.

The combination of three antennas forming a self supporting antenna boom meets all requirements of the mission due to radiation patterns and redundancy, how ever in case the redundant antenna is used reduction of the bit rate must be suffered. All antennas can be switched to the onboard transmitter, whilst the two command receivers are hardwire connected to the low and medium gain antenna.

The application of the antennas are not limited to the used frequency band and to space craft application. Mainly the medium gain antenna seems to be applicable for commercial purposes because to its rugged self supporting construction. The possibility of beam tilting of this antenna is researched at the moment at MBB.

Acknowledgement The authors thank Mr. Zerwes for his important contribution to the whole development and Mr. Haas for his work on the low gain antenna.

References:

- [1] G. Schroer, "Das Antennensystem der Sonnensonde Helios," Seminar über Antennentechnik, November 1973, Internationales Elektronikzentrum München
- [2] B. Liesenkoetter, "The Quasi-Isotropic Antenna of the Helios Solar Probe", Conf. on Aerospace Antennas, June 1971 IEE Conf. Publication N.77, pp. 106-111
- [3] B. Liesenkoetter, "Ein Antennenprinzip mit allseitiger Rundstrahlung für große spinstabilisierte Fluggeräte" NTG-Fachtagung, Februar 1972, Nachrichtentechnische Fachberichte Band45, pp. 171-175
- [4] G. Tymann, "Die Helios Mittelgewinnantenne", Seminar über Antennentechnik, November 1973, Internationales Elektronikzentrum München
- [5] L. Horwath, "Die Helios Reflector Antenne", Seminar Über Antennentechnik, November 1973, Internationales Elektronikzentrum München
- [6] H. Jasik, "Antenna Engineering Handbook", McGraw-Hill Book Company 1961 pp. 26-2 and 26-3
- [7] S. Silver, "Microwave Theory and Design", McGraw-Hill Book Company 1949, pp. 318-321

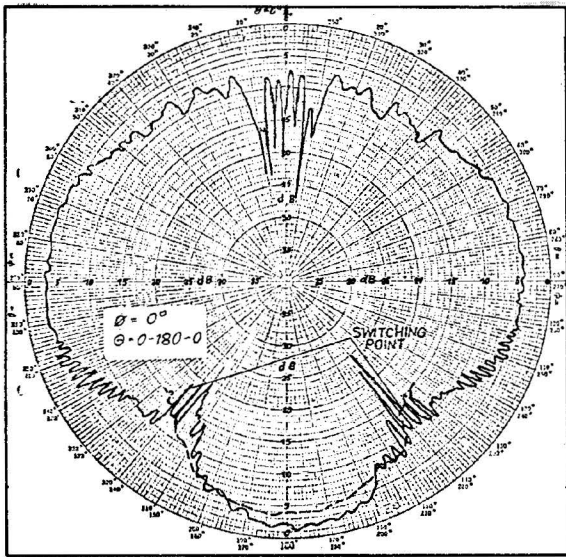


Fig.5-Radiation pattern of the LGA

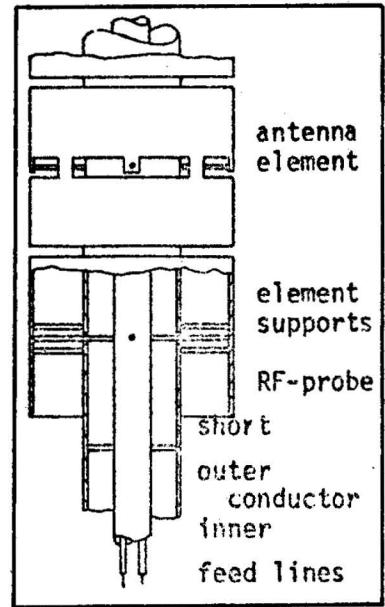


Fig.6-Pinciple of the MGA collinear array

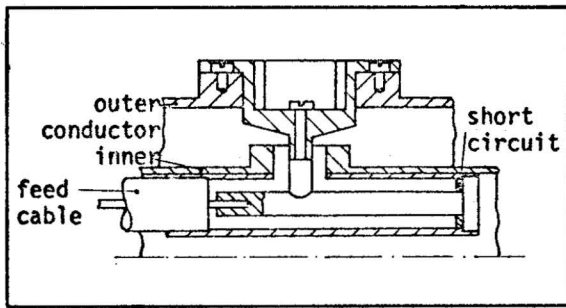


Fig.7-Center feed device of the MGA

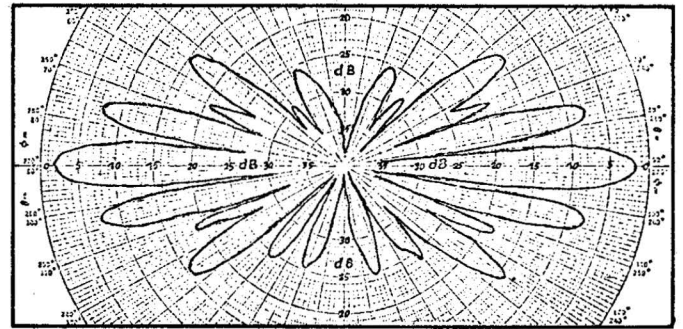


Fig.8-Radiation pattern of the MGA
 $\theta = 0^\circ$ $\theta = 0-180^\circ$

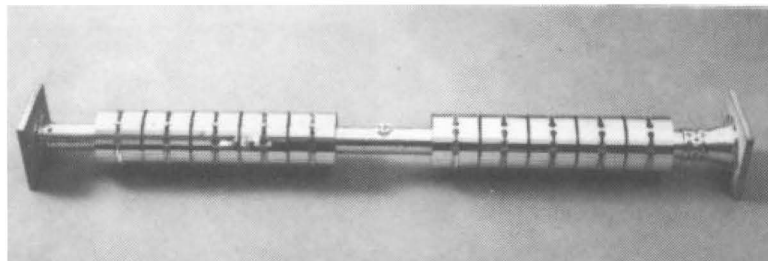


Fig.9-Prototype model of the MGA

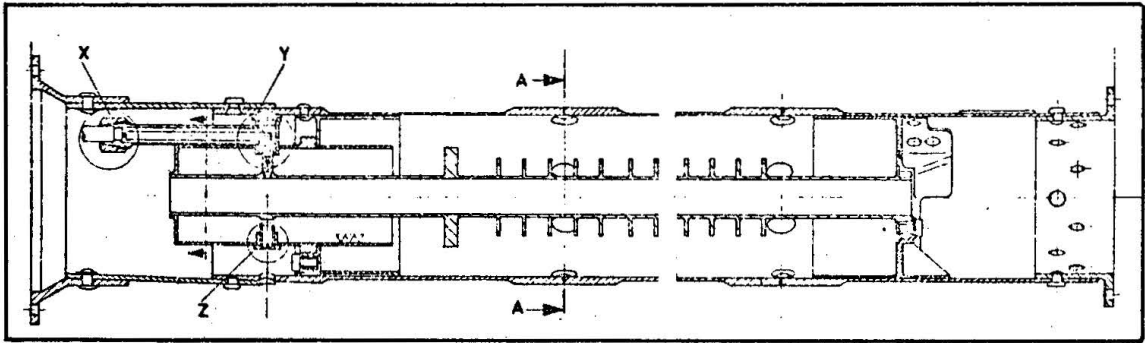


Fig.10-Overall drawing of the high gain antenna feeder

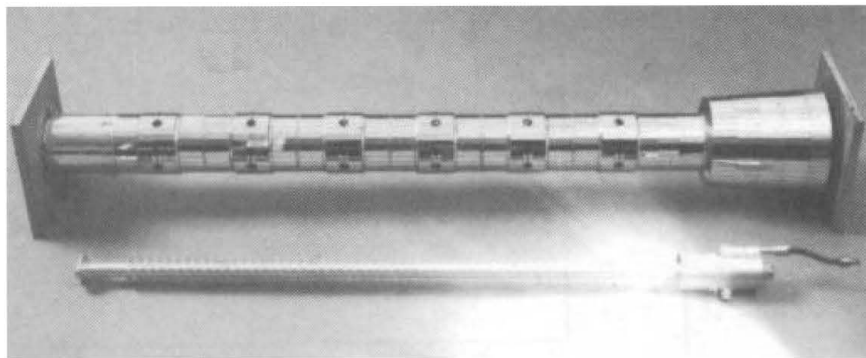


Fig.11-Prototype model of the high gain antenna with dismantled inner conductor

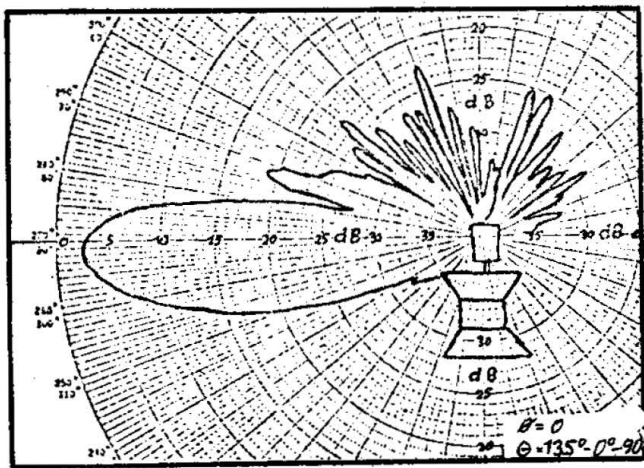


Fig.12 -Elevation pattern of the HGA

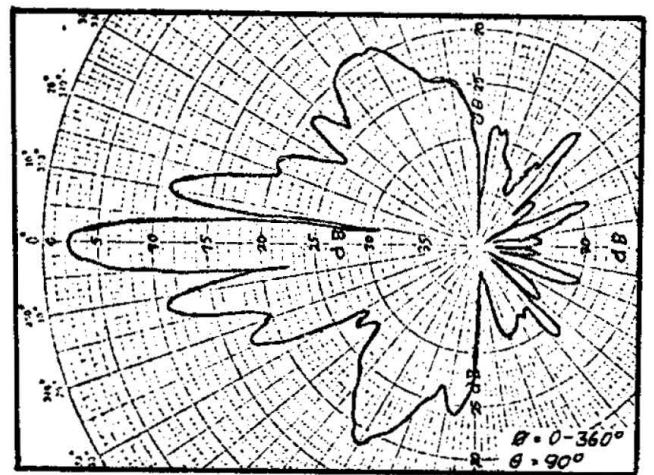


Fig.13-Azimuth pattern of the HGA

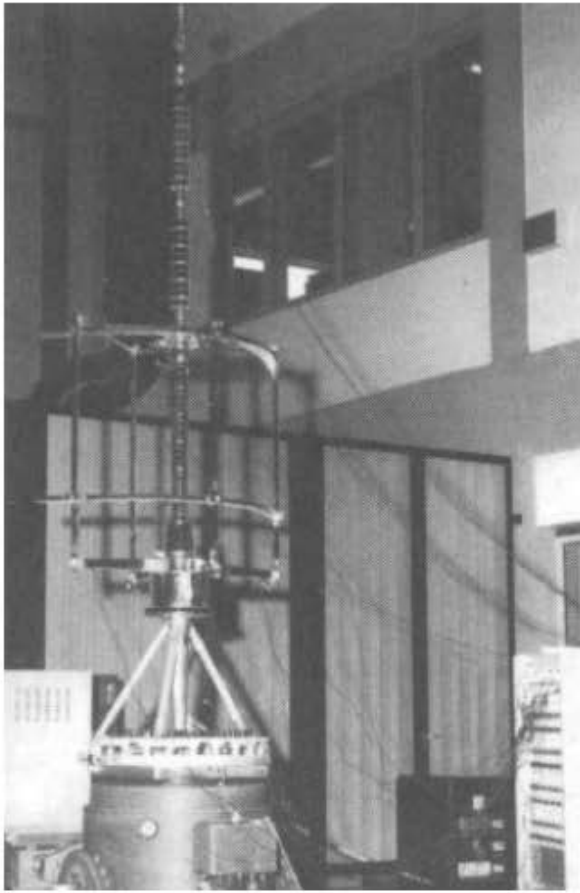


Fig.14-Antenna boom during vibration tests

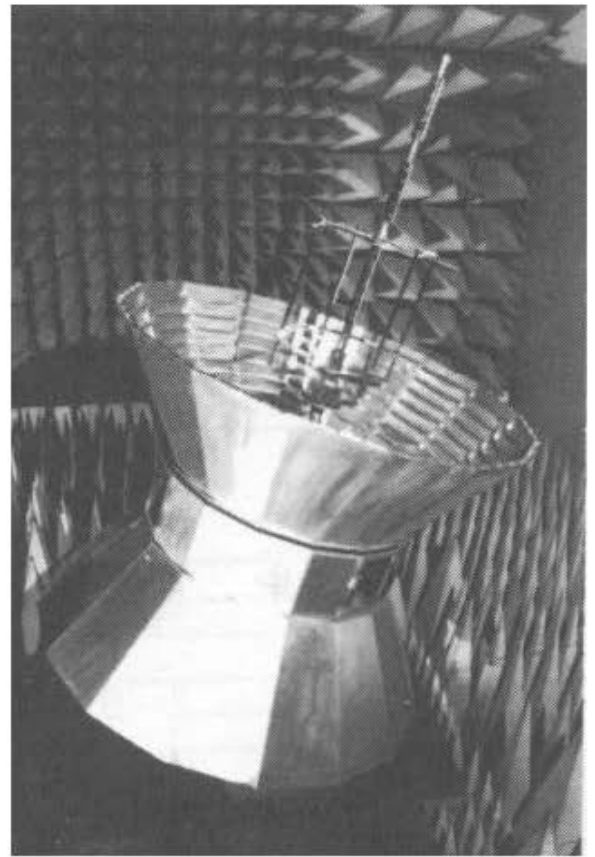


Fig.15-Helios antenna model with HGA and MGA in the anechoic chamber