

THE HELIOS SPACECRAFT/GROUND TELECOMMUNICATIONS SYSTEM CONCEPT

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Summary. The U. S.-German joint Helios Program is briefly presented with emphasis upon the Spacecraft Telecommunications System design and Ground Tracking and Data System. The design constraints for the radio system, and some tradeoff considerations germane to the Helios radio system are discussed. The block diagram, major performance parameters and some test results are given as bases for the understanding of more detailed telecommunications system discussions.

Introduction. In 1966, the United States and German governments agreed to bilaterally plan and execute a deep-space mission to explore solar phenomena in the close vicinity of the sun. NASA and the German Ministry of Research and Technology (BMFT) outlined the project's scope and objectives in a Helios Mission Definition Report in 1969. The salient objectives were:

- (1) Gather scientific data on properties and processes of the interplanetary medium and of solar physics.
- (2) Advance and disseminate knowledge in space science/technology and advance project management expertise.

Based on this understanding, the Helios spacecraft was developed and built in Germany on behalf of the BMFT, while launch vehicle and tracking and data system support was provided by NASA. Project management rested jointly with NASA and the Gesellschaft fuer Weltraumforschung (GfW), the German Agency for Space Research.

The Helios spacecraft is a spin-stabilized spool-shaped vehicle carrying 12 active scientific experiments (Table 1) and weighing 355 kg (Figs. 1 and 2). It will be launched into an elliptic orbit around the sun with the ellipse lying in the ecliptic plane. When farthest from the sun (aphelion), it will be 1.0 AU (1 astronomical unit $\approx 1.5 \times 10^8$ km) distant from the sun; at closest approach (perihelion) it will be 0.3 AU from the sun. As seen from earth, the Helios orbit plotted on a fixed earth-sun line reference is a characteristic helix curve

(Fig. 3). This orbit will come closer to the sun than any past or presently planned deep space venture. Launch will be from the U. S. Air Force Eastern Test Range by a Titan III-D/Centaur/TE-364-4 combination, with a parking-orbit ascent. The first of two launches will take place in October/November 1974, with the second in late 1975 or early 1976. Design lifetime will be 18 months for both spacecraft.

Tracking and Data Acquisition System Configuration. To attain primary mission objectives, continuous 24-hour monitoring of the spacecraft telemetry and command capability is essential, especially during the perihelion passages. The Helios telecommunications system has therefore been designed to be compatible with the NASA-JPL Deep Space Network (DSN), which can provide ground stations suitably placed at different longitudes. One transmitting station located at Weilheim (near Munich, West Germany) (GTS) and a receiving station using the 100-m radio telescope located at Effelsberg (near Bonn, West Germany) (GES), both fully compatible with the DSN, augment the U. S. Tracking and Data Network. Some parameters of the DSN and German ground stations are provided in Table 2.

Two mission control centers exist, the German Space Operations Center (GSOC) in Oberpfaffenhofen (also near Munich) and the U. S. Mission Control and Computing Center (MCCC) at JPL (Pasadena, California). GSOC will take over mission control from MCCC after four weeks into the mission. Both centers are equipped to generate and send commands via the tracking stations to the spacecraft and to collect telemetry data streams from the stations via high-speed data lines for documentation and further processing (see Fig. 4). Spacecraft and experiment housekeeping data serve mission control to monitor the state of the probe; science telemetry and radiometric data is forwarded to the respective experiments in near-real-time.

Telecommunications System Functional Constraints/Requirements. Commensurate with the constraints of the command and data acquisition network, the communications between earth and the Helios spacecraft is by S-band radio links, compatible with the command, telemetry and ranging system implementation of the DSN. Experimenter requests and mission-dependent constraints set other functional requirements for the telecommunications system including antennas. The spacecraft design set upper limits for the available transmitter power.

Accordingly, the design meets the requirements that telemetry transmission be possible up to 2 AU distance from earth. Bit rates from 8 to 2048 b/s are available with bit error probabilities below 10^{-5} . Command reception at 8 b/s is possible out to 2 AU with 10 kW and the 26-m DSN ground stations, with bit error rates less than 10^{-5} . Command acceptance and false command rejection probabilities are set at less than 10^{-3} and 10^{-10} , respectively. The downlink carrier can be commanded to be coherent with the uplink

carrier for accurate 2-way doppler measurements up to 2 AU. Also, the continuous and discrete ranging codes generated by the DSN planetary ranging assembly can be sent to and coherently transponded from the telecommunications system for direct distance measurements.

The antenna system design meets the requirement that omnidirectional command capability is provided for near-earth attitude maneuvers. In order to achieve the highest possible telemetry bit rates out to a maximum communication distance of 2 AU, the Helios spacecraft carries three S-band antennas: a low-gain (omni) antenna system consisting of an upper linear dipole/lower RCP horn combination for quasi-omnidirectional coverage; a medium-gain collinear array type antenna for a linearly polarized pancake pattern; and a high-gain antenna with a mechanically despun cylindrical paraboloid reflector for a linearly polarized spot beam antenna. The high-gain antenna is the principal transmitting antenna, with the medium-gain antenna serving as backup transmitting antenna.

Design Tradeoff Considerations. Aside from ground system constraints and the need to satisfy mission requirements, the Helios telecommunications design incorporates a number of design features which are based on tradeoff considerations. Some major tradeoff areas have been:

- (1) Engineering vs Science Data System.
- (2) Amount of data storage.
- (3) The number of telemetry channels.
- (4) Use of a telemetry error correcting code.
- (5) Single vs dual channel PSK command system.

The complex scientific payload for the experiment packages providing data to 12 experimenters imposed very distinct data transmission requirements - including changing bit rates. The on-board data formatting and structuring have thus been laid out to be very flexible. Six specific formats (one housekeeping and five scientific, with subcommutated housekeeping), are provided and employ bit rates from 8 to 2048 b/s. One scientific format specifically satisfies the needs of those experimenters which require high data resolution for fast transient shock events, storage and later recall. Table 3 summarizes the operating modes for the format-to-bit-rate correlation.

A considerable number of tradeoff considerations had to be undertaken to balance the desires for a programmable formatter ideally suited to these complex data processing tasks against the simplicity of using fixed format multiplexing techniques. For Helios, conventional multiplexing techniques and fixed formats were chosen because, to do otherwise, would increase the complexities for mission operation and ground data processing beyond planned resource allocations in this area.

In addition to real-time telemetry requirements, there is a mission requirement for the collection and storage of scientific data onboard the spacecraft during blackout periods caused by solar occultation (when the downlink is interrupted) and for higher time resolution of scientific information than probably would be possible by the telemetry bit rate in use. Approximately 500,000 bits of information storage was required for read-in at a 4- to 16-kb/s rate. Helios has chosen a core-storage system (compatible with power and weight requirements) which became available in Germany at the time design decisions had to be made. This meant that tape recorder mechanisms could be avoided, thus gaining an ensuing increase in overall system reliability.

The Helios spacecraft employs one telemetry channel to transmit both science and engineering data back to earth. Although other space projects have gathered good experience with two-channel telemetry systems for separate engineering and science data transmission, it was felt that a single-channel telemetry channel would provide higher science data rates - thus satisfying more Helios requirements. Spacecraft radio System engineering telemetry data, like receiver AGC and SPE values, is therefore not directly available to the ground receiving stations on a separate subcarrier - but must be transmitted back to stations over ground communications circuits after sublevel decommutation at the mission control center. The higher complexity of ground data system operation has been accepted by the Helios Project, in this case, as a tradeoff for achieving highest possible science data rate at perihelion (i. e., sun encounter).

Helios telemetry data is convolutionally encoded aboard the spacecraft, and after transmission to the ground is subsequently sequentially decoded at the stations. Block-coding techniques as employed by JPL's Mariner spacecraft had been considered as an alternate coding technique. Extensive discussions relative to this tradeoff were held with NASA's Pioneer Project at the Ames Research Center (ARC), Moffett Field, and at JPL. The decision was finally made on the basis of theoretical considerations showing the promise of a 2- to 3-dB improvement in STB/N_0 signal-to-noise ratio (at a 10^{-4} deletion rate) for convolutionally coding techniques (constraint length 32, rate 1/2) relative to block coding. We feel that the upcoming flight experience with Helios will confirm this decision.

At the Deutsche Forschungs-und Versuchsanstalt fuer Luft-und Raumfahr e. V (DFVLR) located near Munich and also at ARC, theoretical studies were undertaken to determine optimum frame length. These considerations had to take into account the large amount of experiment and engineering information which has to be transmitted. On this basis, the Helios frame length was set at 1152 bits/frame (constraint length 32, rate 1/2), which is 4 times Pioneer frame length. Even so, it takes 72 frames to complete one science main frame, while an engineering data main frame comprises only 4 frames. This long frame length (optimal from the coding point of view) has the drawback of a correspondingly longer time required, especially at lower bit rates, to achieve frame synchronization on the

ground and to recover data reception after a telemetry dropout. In addition, the Helios frame is transmitted nonsynchronously with the Ground Communication System's high-speed data block, hence requiring frame resynchronization at mission control.

The Helios radio system features two selectable modulation indices, one favoring the middle and upper bit rates, the other favoring the lower bit rates. The use of two modulation indices has proven to be a definite advantage over a single modulation index for this range of bit rates. A less marked improvement would be realized in going from two to three modulation indices. The final numerical values were established after substantial testing and analysis efforts by both ARC and JPL to understand and model the telecommunications total link performance.

On the command uplink, Helios Project had the option to utilize FSK, dual-channel PSK, or single-channel PCM/PSK/PM operating techniques. FSK and dual-channel PSK systems have been proven in previous flight projects, but here a single-channel PSK command system was chosen because of its higher efficiency in terms of signal-to-noise performance of 2- to 3-dB or 5-dB, respectively. Highest possible command efficiency was deemed essential for operating the spacecraft over 2 AU distance when using the 26-m/10-kW DSN network committed to the Helios mission. Manchester coding of commands with 68 symbols/command was chosen; two separate command subcarrier frequencies (448 and 512 Hz) access one of two redundant, continuously active receivers, one of which is fixed-wired to the omnidirectional low-gain antenna system and the other is fixed-wired to the medium-gain (pancake) antenna. The combination of these features provides ample insurance against double command entry and attains the desired command acceptance and false command rejection criteria.

Telecommunications System Development and Parameters. The telecommunications system hardware design was essentially defined and frozen in late 1971. Germany's Messerschmitt-Boelkow-Blohm Corporation (MBB), in Munich, acted as prime contractor for the entire spacecraft, while AGE-Telefunken, Inc., in Ulm, was responsible for the development of the S-band receiver system and the transponder integration. Thomson-CSF S.A. in Paris designed and built the transmitter equipment with Watkins-Johnson, Inc., in Palo Alto, California, as supplier of the traveling wave tube amplifiers. Standard-Elektrik-Lorenz A.G. (SEL) in Stuttgart, a subsidiary of ITT, was assigned the task of designing the Helios data handling equipment, which incorporates the 500,000-bit ferrite core memory developed by Siemens A. G. in Munich. The antennas were designed by MBB and manufactured by Entwicklungsring Nord (ERNO) in Bremen. The antenna reflector despun drive was delivered by Ball Brothers, Inc., Boulder, Colorado. The electronic components used throughout the Helios Project were supplied to all contractors by a centralized parts procurement office set up by the prime contractor for which Radiation, Inc., in Melbourne, Florida, acted as sole parts procurement agent responsible for quality

and high reliability of all electronic parts delivered and the attendant screening and testing documentation.

As shown by the geographic distribution of contracting firms for the telecommunications system, the Helios Project has been international in nature in the spirit of fostering cooperation between countries. This fact accounts for the many breakpoints and interfaces within the telecommunications system, which necessitated larger than usual efforts in managing timely information dissemination throughout the organization chain. These difficulties could only be overcome by such approaches as (a) early decisions to abandon promising developments in system subsections in favor of established technologies (for instance, a low-power space-qualified parametric amplifier was replaced by a transistorized amplifier), (b) very early breadboard and engineering model testing with the DSN to ascertain compatibility of the transponder with the ground installations, and (c) last but not least, an effective motivation-based team spirit of all persons engaged in the task, which transcended organizational and company lines.

The resultant telecommunications system is presented in Fig. 5 and a summary of some major performance parameters is summarized in Table 4.

Some Performance Results. The Helios telecommunications system has undergone extensive development, qualification and compatibility testing with the DSN. Design, performance and operating goals have been fully achieved, while only in-flight performance awaits confirmation after launch. However, a few outstanding test results deserve mentioning at this time.

Because of the limited availability of mission experience with convolutionally coded telemetry, some uncertainties existed about link performance, but tests at various bit rates have quite precisely agreed with theoretical link design predictions for nominal parameter values, including two-way effects. Provided the statistics of in-flight performance also bear out the model predictions, a telemetry bit rate vs distance profile for the nominal mission operating configuration can be expected, as depicted in Fig. 6.

Although the design goal for the uncertainty in the delay of ranging signals through the transponder was 80 microsec, measured ranging delay uncertainty is less than 25 nanosec over operating temperature and signal levels. The long-term instability drift over an 8-hour station view period for strong signal levels, as measured by the differential-ranging vs integrated-doppler techniques, was determined to be less than 3 nanosec, with and without uplink modulation.

A more detailed presentation of operating performance and experience relative to theoretical predictions and expectations of the Helios telecommunications and the ground tracking system will be presented in the near future.

Conclusions. This article briefly described the Helios Program, its international scope in management and tracking and data acquisition, its mission objectives, and in particular the spacecraft radio system design. This treatment has been intentionally general in nature in order to provide an overview as a basis for understanding the more detailed telecommunications and ground system discussions which appear in subsequent articles.

Table 1. Helios experiments

Number	Experiment	Scientific affiliation
1	Plasma Detectors (A) Proton and Alpha Detector High Angular Resolution	Max Planck Institut fur Extraterrestrische Physik, Garching
	(B) Proton and Alpha Detector Faraday Cup	Ames Research Center
	(C) Electron Detector	
2	Flux-Gate Magnetometer	Tu Braunschweig Institut fur Giophysik und Meteorologie
3	Flux-Gate Magnetometer	Goddard Space Flight Center University of Rome
4	Search Coil Magnetometer	Tu Braunschweig Institut fur Giophysik und Meteorologie Institut fur Nachrichtentechnik
5	(A) Solar Wind Plasma Wave Experiment	University of Iowa University of Minnesota
	(B) Radio Wave Experiment	Goddard Space Flight Center
6	Cosmic Ray Experiment 1 Mev to 1 Gev	University Kiel

7	Cosmic Ray Experiment (A) High Energy Telescope (B) Medium Energy Telescope (C) Low Energy Telescope (D) X-Ray Detector	Goddard Space Flight Center University of Adelaide
8	Electron Detector	Max Planck Institut fur Aeronomie, Lindau/Harz
9	Zodiacal Light Photometer	Landessternwarte Heidelberg
10	Micrometeoroid Detector and Analyzer	Max Planck Institut fur Kernphysik, Heidelberg
11	Celestial Mechanics	Jet Propulsion Laboratory University of Hamburg
12	Faraday Rotation	Jet Propulsion Laboratory

Table 2. Ground station parameters

Parameter	26-m station (DSN)	64-m station (DSN)	30-m Weilheim (GTS)	100-m Effelsberg (GES)
Receiving system noise temperature	33 k	28 k	-	43 k
Frequency range (down-link)	← 2290 to 2300 MHz →			
Antenna gain	53 dB	62 dB	54 dB	65 dB
Transient power	10/20 kW	20 kW	10 kW	-
Frequency range (uplink)	← 2110 to 2120 MHz →			

Table 3. Helios telemetry modes of operation

Distribution mode (DM)	Data conditioning for real-time transmission		Data conditioning for onboard storage	
	Format FM	Bit rate BM, bps	Format FM	Bit rate BM, bps
DM 0 Real time without memory read-in	FM 1 High rate FM 2 Normal rate FM 3 Reduced rate FM 4 Engineering FM 5 Very high rate	512-2048 64-512 8-64 8-4096 4096		
DM 1, 2, 3 Real time with memory read-in	FM 1 High rate FM 2 Normal rate FM 3 Reduced rate FM 4 Engineering	512-2048 64-512 8-64 8-4096	FM 6 Shock	4096 8192 16384
DM 4 Real time with memory read-in	FM 4 Engineering	128	FM 4 Engineering	128
DM 5 Black-out			FM 3 Reduced rate	8 (interrupted)
DM 7 Memory read-out	FM 3 Reduced rate FM 4 Engineering FM 6 Shock	8-4096 8-4096 8-4096		

Table 4. Helios radio system parameters

Parameter	Value
Uplink frequency	2115.699846 MHz (channel 2 lb)
Subcarrier frequencies	512/448 Hz
Dynamic range and threshold	-142.5 to - 70 dBm
Tracking range	$\pm 5 \times 10^{-6}$ centered on receiver rest frequency
Sweep rate	500 Hz/sec for 107.5 to - 0 dBm 80 Hz/sec for -142.5 to -107.5 dBm
Command symbol rate	8 b/s
Command modulation index	0.772 rad, command only 0.457/1.053 rad for command/ranging video
Command word	9 bits of information, Manchester encoded into a 68-symbol command word
Transmit/receive frequency ratio	240/221 in the coherent mode
Downlink frequency	2297.592593 MHz (channel 21a)
Output power	0.5/8/20 W
Carrier frequency stability	2.6×10^{-5}
Subcarrier frequency	32.768 kHz
Modulation index,	
Low carrier suppression	0.734 rad
High carrier suppression	0.953 rad
Ranging video	0.423 rad
Low-gain antenna	0 dB
Medium-gain antenna	9 dB
High-gain antenna	23 dB

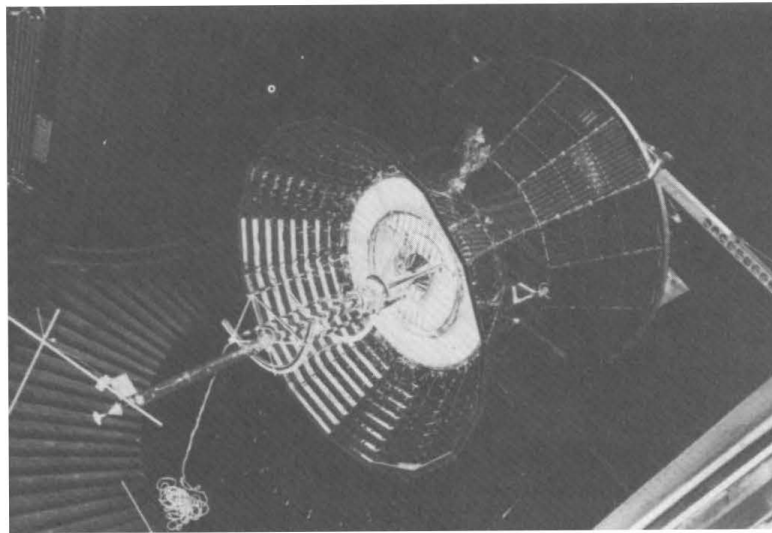


Fig. 1. The Helios spacecraft during solar simulation test preparation

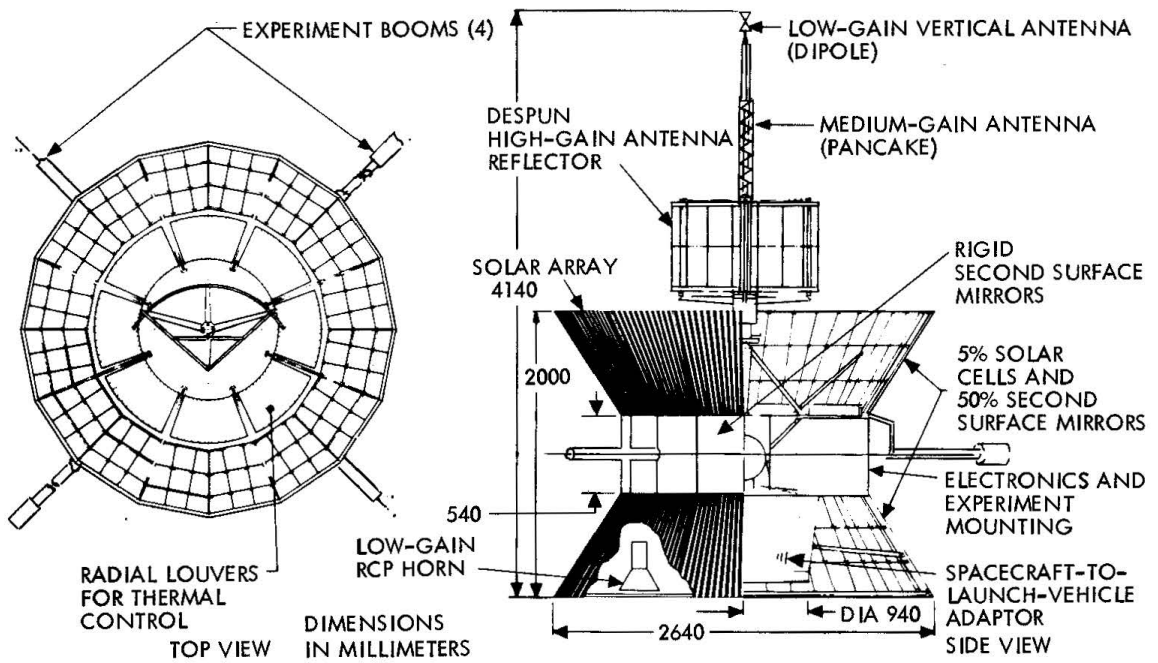


Fig. 2 . Helios spacecraft configuration

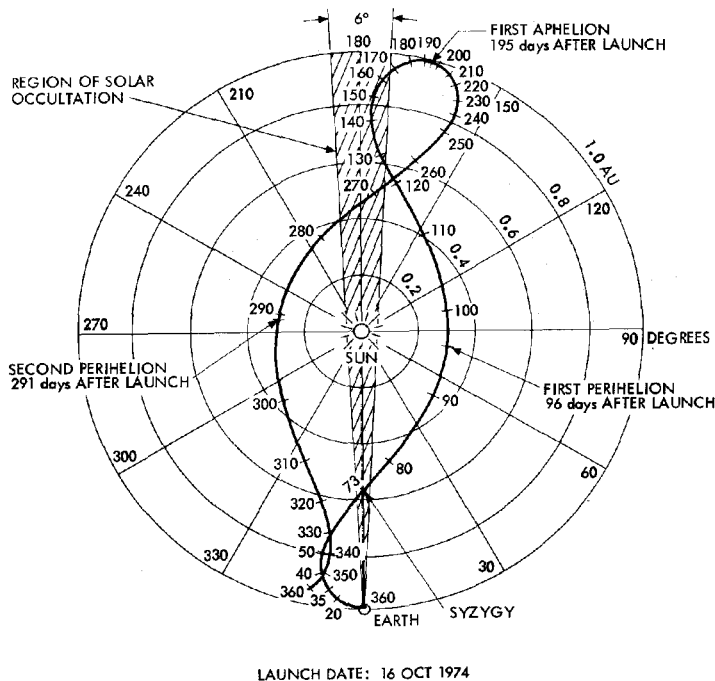


Fig. 3. Typical Helios-A trajectory at 0.3 AU, October 1974 launch (fixed earth-sun line plot)

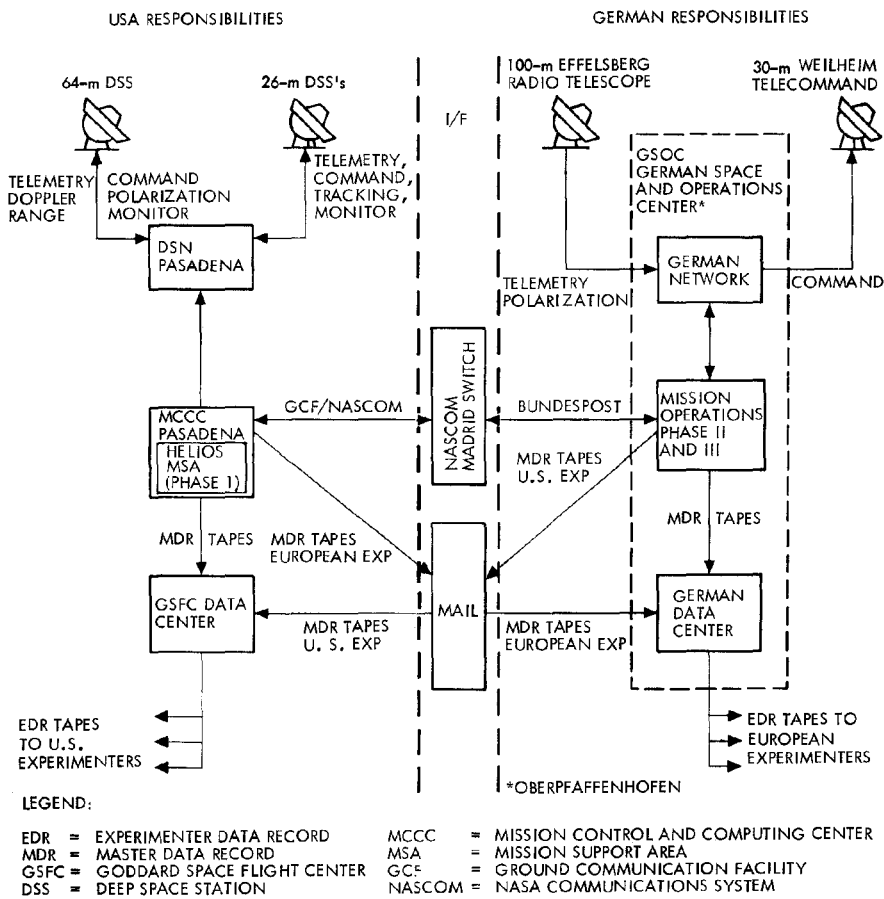


Fig. 4. Helios ground data system

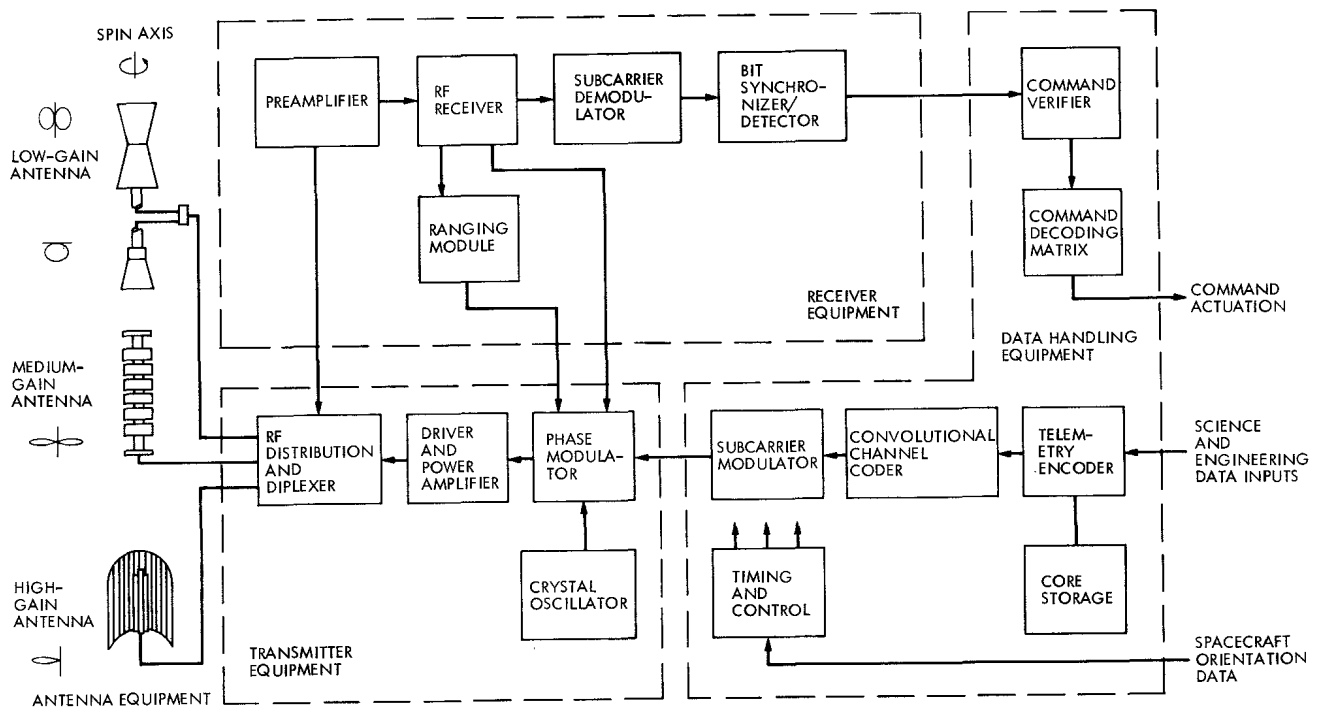


Fig. 5. Helios spacecraft telecommunications system, simplified block diagram

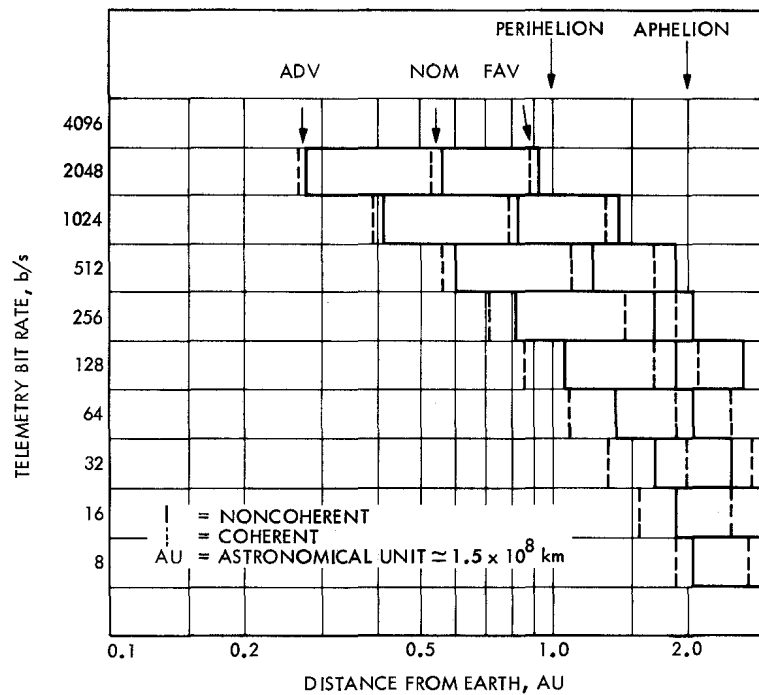


Fig. 6. Maximum data rate, high-gain antenna downlink to 26-m antennas