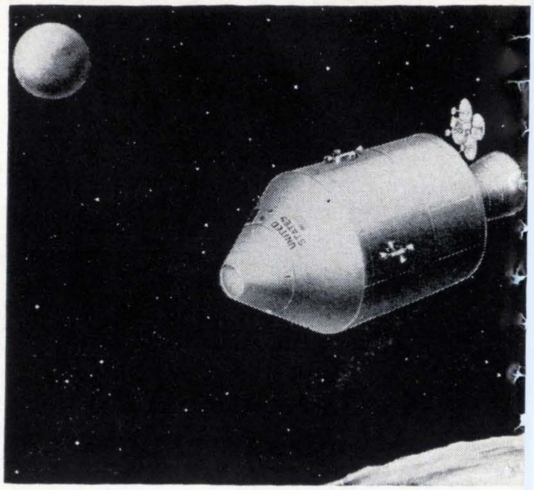

Apollo antenna fastens on the beam to the moon

Astronauts will receive and transmit signals over a variable-gain array that automatically tracks signals transmitted from earth stations

By Arthur P. Notthoff

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As the Apollo spacecraft streaks toward the moon it will be listening over its shoulder to signals transmitted from earth. Its ear, an array of antennas mounted on the spacecraft, operates at S-band and will carry all data and voice signals transmitted to and from the spacecraft.

The antennas will be the main communications link from the spaceship to earth and will operate until the craft is ready to reenter the earth's atmosphere. During the journey, the array will track on signals transmitted from earth, insuring good real-time communications. The array is mounted on the back of the vehicle as illustrated on this page.

The antenna array goes into operation about 2,500 miles above the earth. When it is deployed, the astronauts, operating controls in the spacecraft's cabin, will position the antenna so that the receiver can lock onto the signal transmitted from earth. Then the astronauts will switch into one of the two automatic tracking modes that will make the antenna follow the earth station's beam.

Why an array?

This is the first time a tracking array has been used in manned space vehicles. In earlier space programs, only ground stations performed tracking operations because the orbiting vehicles were close to earth and their antennas generally had wide beams that produced relatively uniform coverage.

In transmitting from the vicinity of the moon, however, radiation from a wide beam antenna would be wasted; most of it bypassing the earth. In addition, the transmitter power would have to be large to insure adequate signal levels for real-time communications.

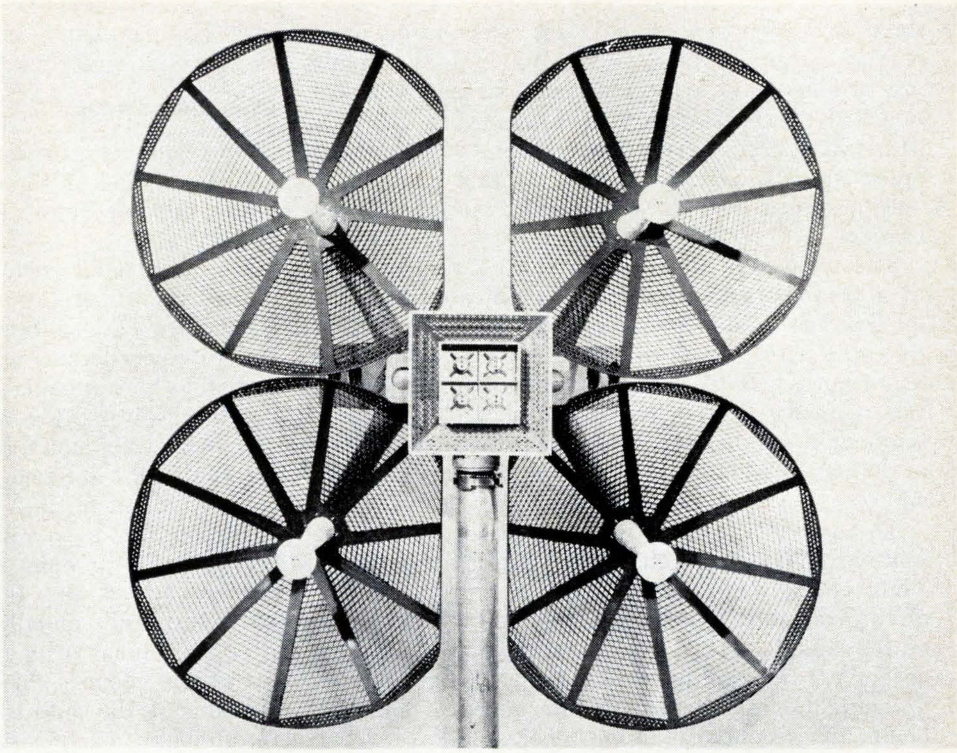
To increase efficiency, an antenna must produce a relatively narrow beam that confines the radiation within the diameter of the earth. But because the beam is narrow, the spacecraft's and ground station's antennas must point at one another. This requires a tracking capability.

An array was chosen rather than a single antenna so as to increase the system's efficiency and flexibility. The Apollo array consists of four 31-inch-diameter parabolas clustered around an 11-inch-square wide beam horn. [See picture on page 81]. If a single antenna, such as a large parabola, were used, it would have to have the maximum gain needed at lunar distances. Close to earth, the beam would illuminate such a small portion of the earth's surface that many ground stations would be needed to monitor the spacecraft's signals.

With the array, the transmitting beam can be changed by selecting various combinations of antenna elements. Near the earth the low gain (wide beam) horn is utilized for covering over half the earth's hemisphere. As the spacecraft moves away from the earth, the transmitting beamwidth—measured between half power points—is made narrower; coverage is maintained because of the increased range. Consequently, as the craft moves away from the earth, the transmitted signal is switched from the horn, which is wide beam, to a single parabola which produces a medium beam and finally to all four parabolas which, together, produce a narrow beam.

For receiving and tracking, logic circuitry in the spacecraft automatically switches between a wide receive beam or narrow receive beam. Beyond 26,000 miles, if the antenna is very close to the peak of the earth's signal, the spacecraft's receive

High-gain array at the right consists of four 31-inch-diameter parabolic reflectors clustered around a wide beam horn that is 11 inches square. Circularly polarized feeds on parabola are tilted and offset from center to increase array's beamwidth. The drawing at the left shows the array in its position at the rear of the Apollo spacecraft's command and service module.



beam is narrow; otherwise the beam is wide.

Ground stations

The Apollo spacecraft will communicate with the stations on the National Aeronautics and Space Administration's manned space flight network. For communications up to about 8,000 nautical miles, the majority of ground antennas are 30-foot dishes located at 13 sites around the world as well as on 5 tracking ships.

For gain needed in deep space communications there are three 85-foot dishes located approximately 120° apart around the earth, at Goldstone, Calif., Canberra, Australia and Madrid. Above 8,000 miles, one of the 85-foot dishes will always be in view as the earth rotates.

The S-band array will track the peak of the radio frequency signal transmitted by one of the ground stations. It will continue to track as long as it can or until another station comes into more favorable position.

Earth stations will transmit a 2,106.4 Mhz carrier that is phase modulated by voice, data, and pseudorandom noise (PRN) signals used for determining range. Only the PRN signal directly modulates the carrier; all other signals are first frequency modulated onto subcarriers. In the spacecraft the signals are detected by a phase-locked receiver, which is also in the antenna's servoloop.

The spacecraft's antenna will usually be within 0.45° of the peak of the received beam. However, the tracking error can be as great as 1.3° when gaseous exhausts from the rockets and attitude control system strike the antenna.

Transmitting to earth

For sending signals back to earth, the spacecraft has two transmitters which are at different frequencies and can operate simultaneously.

Narrow band information including pulse-code modulated data, voice, and the PRN signals are transmitted to earth on a phase-modulated carrier of 2,287.5 Mhz. The ranging signal or taped voice is directly modulated onto the carrier.

Wide band information including recorded voice information, recorded telemetry, various scientific

Beam mode as a function of altitude above earth

Distance from earth (nautical miles)	**Receive beam** (2,106.4 Mhz) Acquisition mode	Communication and tracking mode	**Transit beam** (2,272.5 Mhz) (2,287.5 Mhz)
2,500 to 26,000	Wide	Wide	Wide
26,000 to 107,000	Wide	Narrow	Medium
107,000 to lunar orbit	Wide	Narrow	Narrow

data, and television signals are transmitted on a carrier frequency of 2,272.5 Mhz. The tv signals are produced by a portable camera that will also be used on the surface of the moon [Electronics, March 6, p. 180]. Except for television and recorded voice signals, all information is first modulated onto a subcarrier before frequency modulating the carrier.

The array's predicted gain during transmission to a primary ground station is indicated in color in the left graph on the next page. Jumps in the gain correspond to operation with the wide beam horn, a single parabola, or all four parabolas. For comparison, the lines in black plot the minimum gain needed to communicate with a 30-foot or 85-foot parabolic dish at the primary ground station.

The antenna's beamwidth is varied so that it will cover at least an entire earth hemisphere. Thus two ground stations at the extreme edges of the transmitted beam could monitor the spacecraft's signals. The primary station that the craft's antenna is tracking receives a larger signal because it would be in the peak of the vehicle's antenna beam; the secondary station receives a lower level signal as indicated by the curves in the graph at the right on the next page.

For the secondary ground station, the spacecraft's predicted gain increases continuously because the angle between the station and the spacecraft approaches the peak of the antenna's beam as the spacecraft moves from earth. As with a primary station the jumps in gain, as shown by the predicted gain curves, are caused by operating with the horn, a single parabola, or all four parabolas.

Performance requirements for Apollo CSM high-gain antenna

Parameter	Required performance		
Frequency	Receive: 2,106.4 Mhz ± 2 Mhz Transmit: 2,272.5 Mhz ± 2.5 Mhz 2,287.5 Mhz ± 2.5 Mhz		
Polarization	Circular, left-hand		
Gain (absolute)	**Beamwidth**	**Receive**	**Transmit**
	Wide	3.8 db	9.2 db
	Medium	22.8 db	20.7 db
	Narrow	23.3 db	27.0 db
Beamwidth (half power)		**Receive**	**Transmit**
	Wide	40°	40°
	Medium	4.5°	11.3°
	Narrow	4.5°	3.9°
Power capability	15 watts continuous		
Angular coverage	Antenna axis A: 360° Antenna axis B: +30° Antenna axis C: −5° to +132°		
Electrical	28 volts d-c; 115/200 volts a-c, 3-phase, 400 hertz		

Operating modes

Three modes of operation are used to keep the antenna homed on the earth station: manual, automatic tracking (auto-track), and automatic reacquisition.

During manual operation, the astronauts change the antenna's direction with two electrical controls. The controls are calibrated in the spacecraft's pitch and yaw coordinates which are automatically converted to the antenna's coordinate system by 13 synchroresolvers. The astronauts can only control two axes of antenna motion at one time. The third axis moves the antenna through the zenith position.

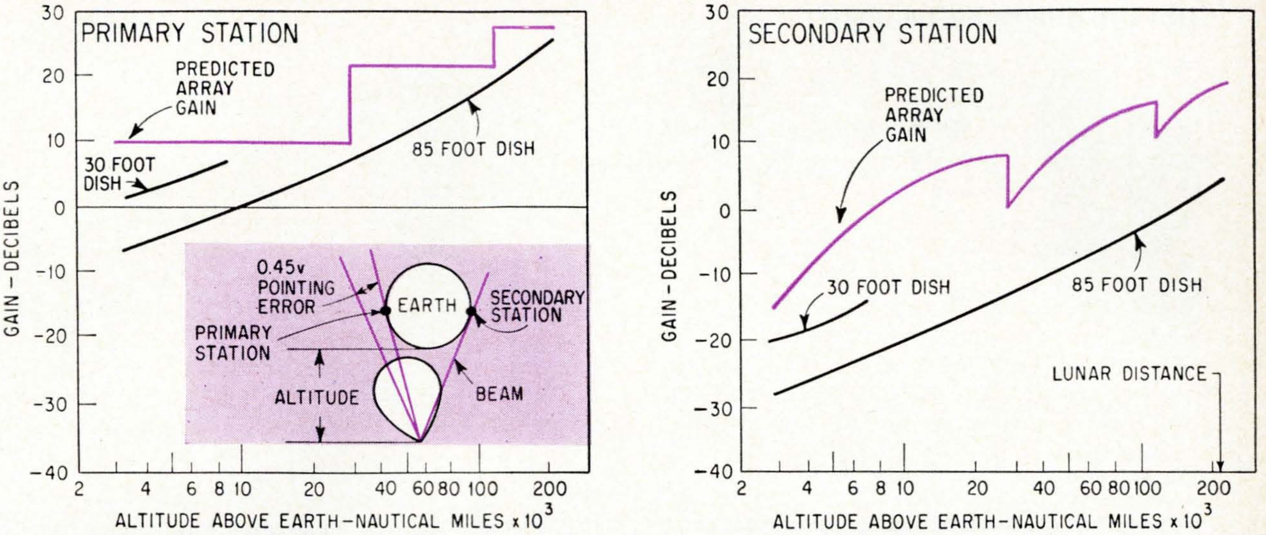
In addition to the initial acquisition, manual operation may be required after a rapid maneuver in which the antenna may not be able to follow the ground station. It is also planned that the astronauts will manually acquire the ground station after each lunar orbit when the spacecraft comes out of the moon's shadow. Manual mode is also available if the auto-track function fails.

Automatic reacquisition is required during passive thermal cycling, when the spacecraft slowly rotates about its roll axis to keep all the craft's surfaces at a constant temperature—the heat of the sun and cold of space are balanced. During each rotation the antenna automatically tracks the earth station until it reaches a gimbal limit. The gimbal limits keep the antenna from pointing at the spacecraft to prevent false signals caused by reflections. At the gimbal limit, integrated logic circuitry drives the antenna back to the opposite gimbal limit so the primary ground station may be quickly reacquired as the antenna emerges from the spacecraft's own shadow. The astronauts can set gimbal limits by operating controls within the command module.

Automatic tracking is employed during midcourse correction or braking into lunar orbit. At these times the craft is not in the thermal cycling mode. The antenna will track until a gimbal limit is reached, at which point gimbal brakes are set. The astronauts must then either position the spacecraft to maintain track or switch to manual mode.

Depending on the distance from the earth, the astronauts can select two beamwidths in either the automatic tracking or automatic reacquisition mode. In the narrow beam mode, four parabolas are used to produce a 4.5° beam. In the coarse (wide beam) mode only the horn antenna is employed and it produces a 40° beam.

Near the earth, the antenna tracks in the wide beam mode and transmits with the horn antenna. At intermediate ranges, the antenna tracks in the narrow beam mode; a diplexer in the microwave circuitry allows the antenna to transmit with a medium beamwidth (11.3°) produced by a single parabola. Near the moon, the four parabolas produce a 4.5° beam for tracking and a 3.9° beam for transmission. The beam mode as a function of distance is summarized in the table on page 81.



When antenna's beam is pointed at primary ground station, the signal can also be monitored by a secondary ground station within the spacecraft's beam, as shown in color inset. Curves in black indicate the Apollo array's minimum transmission gain needed to operate with 30-foot- and 85-foot-diameter dishes on the ground. The array's predicted gain, in color, increases in steps as a result of switching from the horn, to one parabola and then to four parabolas.

Other system parameters are listed in the table on page 82.

Initial acquisition, whether in the manual or automatic modes, is always done with the horn antenna. If the antenna is automatically tracking with a narrow beam and the antenna's boresight deviates more than 3° from the peak of the received beam, the servosystem will automatically switch into the wide beam acquisition mode. It will continue to track with the wide beam until the error decreases to below 1°. Then the system switches back to the narrow beam tracking mode.

Choosing an array

Two basic types of antenna arrays were initially considered for Apollo's S-band antenna:

- A two-dimensional array consisting of either low gain antenna elements such as crossed slots or dipoles or moderate gain elements such as helixes or disk radiators.
- An optical antenna array such as a parabolic or Cassegrain system that uses a focusing surface to collimate energy from a single feed source.

The two-dimensional array of low gain elements has the primary advantage of high aperture efficiency which can approach 100%. High efficiencies are possible because the array can be uniformly illuminated. However, there are disadvantages:

- There are many active elements, each requiring a separate feed line and resulting in a heavy package.
- An equal path corporate feed structure, needed to achieve the desired bandwidth, produces losses that negate the advantage of high aperture efficiency. A corporate structure is a standard arrangement in which a single input line branches out to the various feeds.
- It is difficult to protect the elements from the high temperature exhausts of the spacecraft's rockets and attitude control system.

A two-dimensional array of medium gain elements also has high aperture efficiency. Furthermore, since the antenna elements are broadband the antenna package is less complex. However, feed losses are still high and thermal protection is difficult.

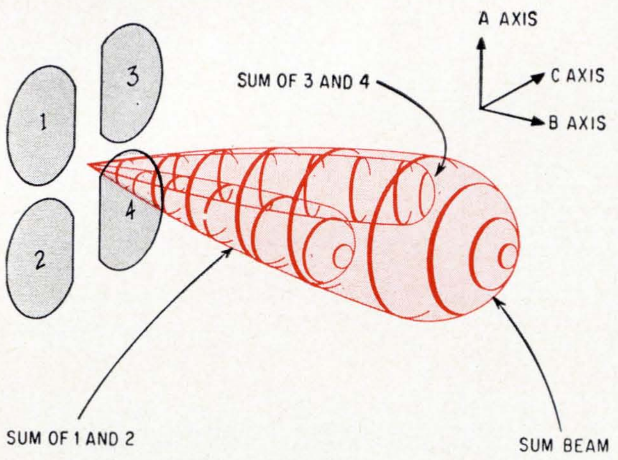
In an optical antenna array, the principle disadvantage is a poor aperture efficiency that may be as low as 50%. A multiple reflector optical antenna such as a Cassegrain can increase aperture efficiency up to 80%, because the dish can be illuminated more uniformly. However this approach merited only cursory examination because it is unduly complex, results in a heavier antenna, and is more susceptible to beam variations caused by thermal variations in the subreflector.

Although the simple parabolic reflector has an aperture efficiency of only 50% to 60%, its feed system is much simpler than that needed for a two-dimensional array. As a result, system losses are relatively small. Furthermore, the system is useful over broad bandwidths. Good mechanical properties lead to reduced weight and high mechanical stiffness. These considerations led to the choice of the parabolic array.

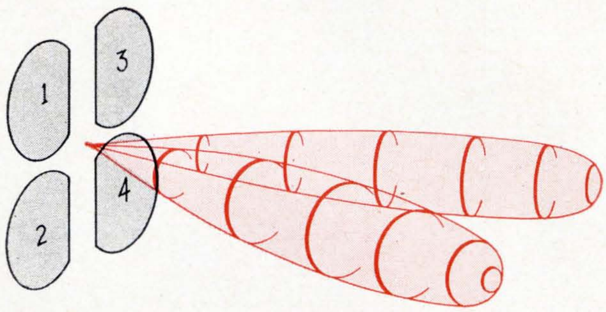
In choosing a feed for the antenna, spiral, helix, slot dipole, cavity helix radiators, and waveguide were considered, but a small, lightweight crossed V-sleeve dipole was selected. The other feeds were dropped because they suffered from poor efficiency, poor circularity over the band, or difficulty in withstanding the extreme thermal environment. The selected feed is left hand circularly polarized.

The photograph on page 81 shows that the bases of the feeds are offset from the center of the parabolas and the feeds are tilted—a design unique to this application. This arrangement increases the illumination near the center of the array and re-

Sum and difference beams



Sum beam is produced by adding beams from all parabolas. It is also sum produced by beams from parabolas 1 and 2 added to beam of parabolas 3 and 4.



Difference beam for A-axis error signal is produced by subtracting the sum of beams 3 and 4 from the sum of 1 and 2.

duces phase-center separation between parabolas. Electrically the parabolas are closer together resulting in a wider beamwidth at lunar distances and thus improving secondary station coverage.

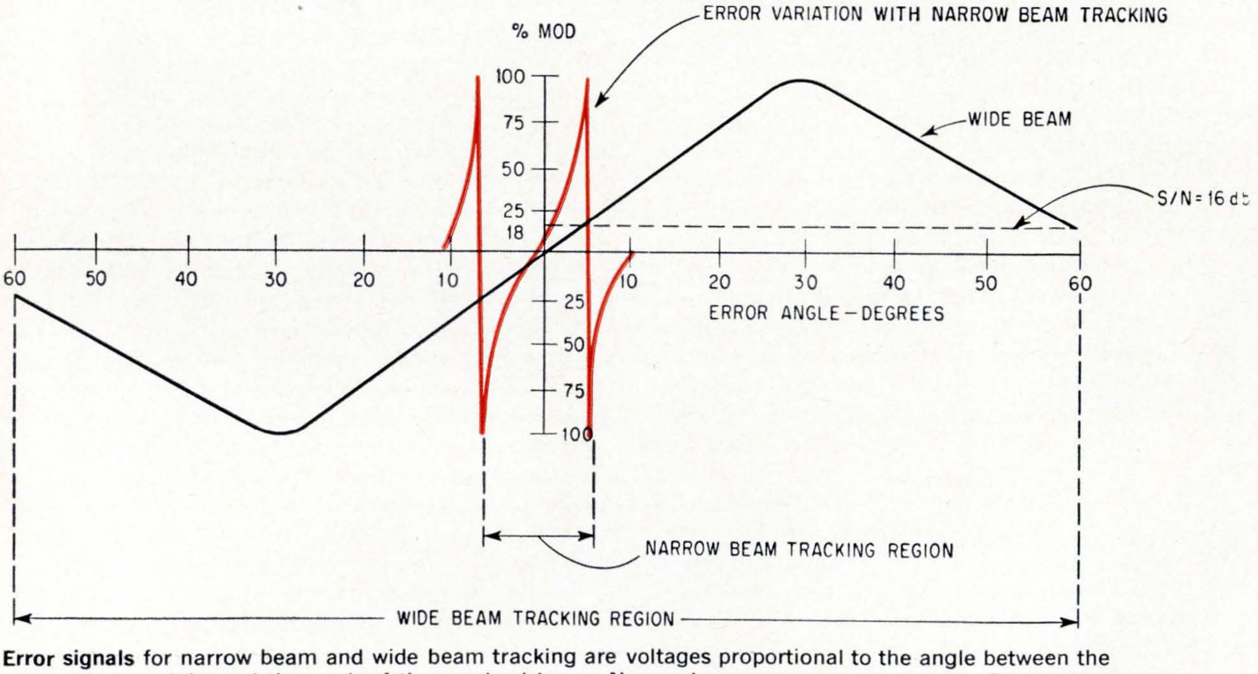
In the early design phases, the antenna was required to operate when it reached a distance of 8,000 nautical miles above the earth. The array consisted of five parabolas. A change in specifications for operation at 2,500 nautical miles made it necessary to replace the center parabola with the wide beam horn. The horn contains four crossed-dipole feeds for tracking in the wide beam mode.

The Apollo array must maintain high levels of gain and pointing accuracy even during the portions of the mission when the space vehicle is being maneuvered and undergoes high angular rotation rates and accelerations. In addition, the hot gasses from the spacecraft's rocket engines and attitude control jets may strike the antenna, producing temperatures as high as 1,200°F.

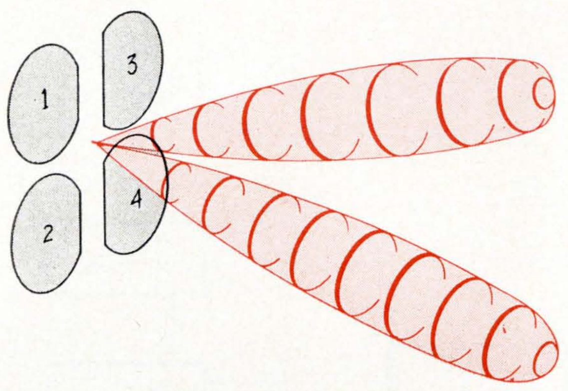
Because of these mechanical and temperature requirements, the parabolas are open-cell surface constructed from welded and brazed Rene-41 metal, a nickel alloy that withstands high temperatures. The open cell surface minimizes torques produced by the impinging gases and reduces stresses due to thermal gradients. This construction also provides high mechanical stiffness with reduced weight.

R-f tracking system

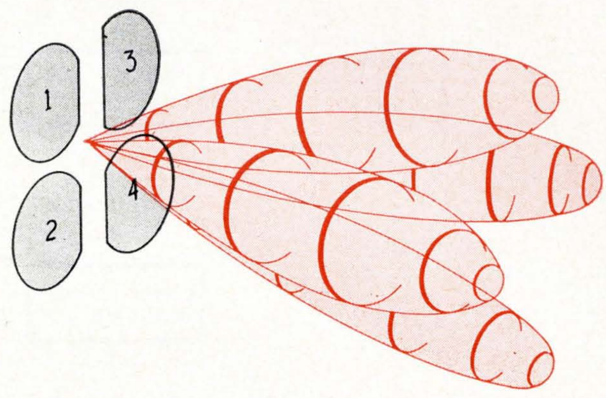
The feedback loop that maintains track on the



Error signals for narrow beam and wide beam tracking are voltages proportional to the angle between the antenna's boresight and the peak of the received beam. Narrow beam error curve is in color. Error voltage on vertical scale is 0.5 volt rms for every 1% of amplitude modulation at the spacecraft's receiver.



Difference beam for C-axis error signal is produced by subtracting the sum of beam 2 and 4 from the sum of 1 and 3.



Tracking beams sequentially move around the boresight axis. These beams are the result of combining the sum and difference beams.

signal develops an error voltage that is proportional to the angle between the peak of the received beam and the direction in which the spacecraft antenna is pointed. The error voltages drive servomotors that rotate the antenna towards the peak of the received beam.

Basically the error voltages are established by electrically pointing the spacecraft's beam on either side of the boresight axis. If the antenna is pointed at the peak of the received beam, the signals received on either side of the boresight axis will be the same and there is no error voltage. If the antenna is not pointed at the peak of the received beam, the signals on either side of boresight will differ, producing an error voltage. The beam is shifted sequentially in two perpendicular planes. as in the drawing at the top of the next column.

Error signals as a function of angle for both narrow beam and wide beam tracking modes are plotted in the graph at the left. The signals are in terms of percent modulation of the carrier signal but are equivalent to 0.5 volts rms for every 1% of modulation.

As mentioned, the servosystem switches to wide beam mode when the pointing error exceeds $\pm 3^\circ$. Switching eleminates the need for a conversion in scale factor between the narrow beam and wide beam tracking error curves. Within 3° the slope of the narrow beam tracking error is almost the same as the slope for the wide beam tracking signal.

The tracking system which controls the antenna is diagramed on page 86. It was chosen after an infrared system was found to be unsuitable.

To produce error voltages the system utilizes the sum Σ and difference signals Δ generated by combining the outputs from the various feeds in different ways.

As the name implies, the sum signal is the combined output of all the antennas used in a particular tracking mode. In the wide beam tracking mode, Σ is the sum of the signal received by the four crossed dipoles in the horn; in the narrow beam mode the sum signal is the combined output of the four parabolas, as shown in the drawing on the left at the top of the opposite page.

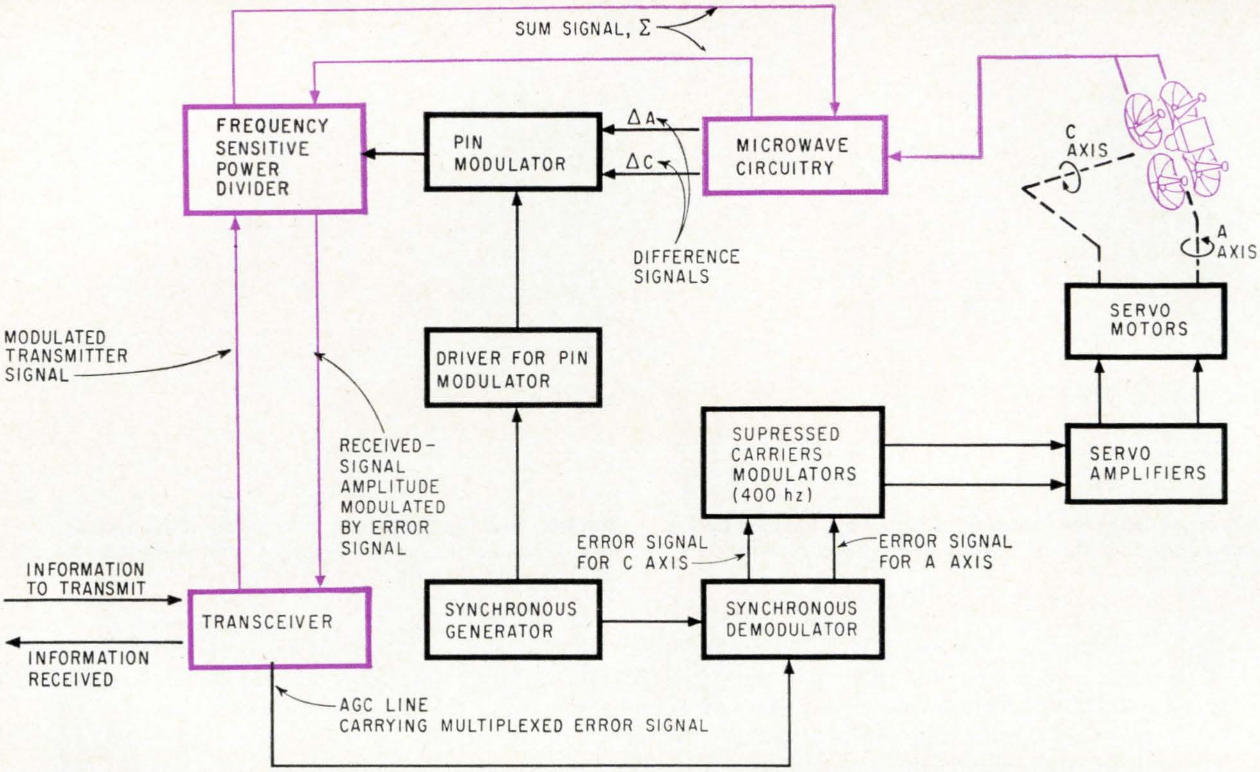
To generate the difference signal, ΔA, from the parabolas, the outputs of antennas 1 and 2 are combined and the outputs of antennas 3 and 4 are combined. The difference between these two signals, $1 + 2 - (3 + 4)$ is ΔA. Similarly, the difference signal, ΔC, on the other axis is obtained from $1 + 3 - (2 + 4)$. Each difference signal is equivalent to the signal from two beams pointing off boresight, with a null on the boresight axis, shown in the second and third drawings above.

The p-i-n diode modulator sequentially switches between the two difference signals ΔA and ΔC. The switching rate is 100 hertz and each difference signal is sequentially connected for five milliseconds. During the last 10 milliseconds of each 20 millisecond cycle, a half wavelength of line is inserted in the signal line to reverse the signal's phase. When the switched signals are added to the signal in the frequency sensitive power divider, the effect is to produce the sequentially lobed beams. This combined signal then amplitude-modulates the phase-modulated (information bearing) signal; the resultant signal is sent to the receiver.

Because of the switching in the p-i-n diode modulator, the error signals are actually time-division multiplexed which allows a single phased locked receiver to be used rather than three receivers—one for the A axis error signals, one for the C axis error or B axis error, plus one for the sum signal.

The receiver is the same one used for communications. In this servoloop, however, the receiver's output is the automatic gain control (AGC) line. The AGC voltage—the envelope of the amplitude modulated signal at the receiver's input—is the 100 hertz wave.

In the synchronous demodulator, the 100-hertz wave is synchronously demultiplexed to produce the error signals for each axis. The signals are filtered and go to a modulator which produces a



Receiving system is actually two systems in one. The portion in color is for information carrying signals. The full system is the servofeedback loop that aims antenna at peak of received signal's beam. Incoming signals are processed in microwave circuitry to produce a time division multiplexed error signal. After demultiplexing in synchronous demodulator, error signals actuate servomotors that drive antenna in direction that reduces error.

standard 400-hertz, suppressed-carrier modulated signal that drives the servomotors. In the suppressed-carrier modulated signal, the amplitude is proportional to the error voltage; the phase is 0° or 180° depending on the direction that the motor must move to correct the error.

Gimbal drive system

The three-axis gimbal system is designed for a maximum angular rotation of 5° per second and an acceleration of 15° per second per second. Under these conditions the average pointing error will be about 0.45°.

Geared a-c servomotors—rather than d-c motors—were selected because they are simple and reliable. They require no commutators or brushes, thus eliminating a source of r-f interference.

Warning circuitry indicates when a gimbal limit is being approached. When the limit is reached, spring-loaded, solenoid-actuated, friction brakes are set if the receiver loses track while in the autotrack mode. With the brakes set, the antenna's position is fixed to within 15 minutes of arc.

Because a redundant servodrive system is impractical, special care is taken to insure reliability. Air gaps in rotating components are twice normal size—the smallest is 0.004 inch. To minimize voltage breakdown, the highest voltage in servocomponents is 26 volts a-c. Servomotors have copper bar rotors that minimize resistance changes caused by temperature variations, but at the expense of weight and efficiency. To prevent the bearings from welding to their raceway in the vacuum environment, the gear boxes are pressurized. A unique multi-labyrinth rotor seal maintains pressure.

Thermal control

The parabolic reflectors are coated with high emissivity ceramics to limit the temperature to 1,200°F. The antenna is thermally isolated from the support structure and gimbal assembly allowing more conventional materials such as aluminum to be used in these sections rather than Rene 41 alloy. Thermal insulation is applied to the gimbals and support structure to further minimize temperature variations. For reliability, the gimbal's temperature is held within −60° to 160° F.

Acknowledgement

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