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NODDING FEED ANTENNA FOR COMMUNICATIONS WITH SATELLITES IN SYNCHRONOUS ORBIT

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SUMMARY

This paper describes an antenna system fabricated and tested by NASA to demonstrate the advantage of small angular displacements of a feed horn to achieve small angular deviation of the main beam of a parabolic antenna. In applications where limited motion of one to three beamwidths is required, moving only the feed does not significantly degrade the antenna characteristics but does substantially reduce the required structural support. In addition nodding the feed in one axis simplifies tracking and eliminates the need for expensive tracking equipment. The nodding feed antenna described in this paper was designed to be operated by unskilled operators and to be used with the Communications Technology Satellite (CTS). Also described are the orbit characteristics that affect the design and cost estimates for one and 100 units.

INTRODUCTION

Offset feeds have been used for deviating the beam of a parabolic antenna from boresight in scanning antennas (ref. 1, pp. 15-23 to 15-27) and conical scan radar (ref. 1, pp. 25-26 to 25-27). This principle also has been proposed for satellite antennas to achieve beam steering or using multiple beams to achieve beam contouring. The nodding feed antenna makes use of continuously adjustable offset feed to achieve beam pointing at low cost for ground stations in a satellite communications system.

When a satellite is used in a communications system where there is one ground station receiving signals from the spacecraft, it is economical to invest in an expensive ground terminal to save on the cost of the space segment. The total system cost approaches an optimum when the ground segment cost equals that of the space segment. The cost of launching a communications satellite into orbit represents a significant portion of the total system cost and the launching cost increases rapidly with spacecraft weight and, therefore, spacecraft primary power. It pays, therefore, to design a very sensitive ground receiving terminal and a high powered ground transmit terminal to lower the primary power of the satellite. However, as the number of ground terminals receiving signals from the satellite increases, the total system cost is optimized by increasing the power in space and lowering the cost of ground terminals.

NASA is presently demonstrating the feasibility of transmitting to 100 or more ground terminals with the Communications Technology Satellite (CTS). The CTS spacecraft has a 12-gigahertz, 200-watt output stage traveling wave tube (TWT). The satellite is in a circular equatorial orbit at synchronous altitude (35 800 km). It is located in a nearly geostationary position over the equator at 116° west longitude.

The design of the nodding feed antenna is part of a program to develop the technology of low cost earth terminals to be used with high power satellites in geostationary orbit. The objective of the nodding feed antenna design was to lower its cost by eliminating the bulky pedestal, using a small drive motor, and providing a simple control unit that can be operated by unskilled operators. This paper discusses the design approach and describes the prototype antenna. Included in the discussion is the cost of the prototype and estimates of the per unit cost for 100 units. Some of the orbit characteristics of satellites in near geostationary orbit will also be discussed to explain the relevance of some of the design approaches.

CHARACTERISTICS OF NEAR GEOSTATIONARY ORBIT

If a satellite were to be placed in a perfectly circular orbit and alined perfectly with the equatorial plane, the gravitational forces from the sun and the moon will disturb its orbit. Its orbital plane will rotate and become inclined to the equatorial plane as shown in figure 1. CTS was placed in an orbit which was biased with an initial inclination of 0.67°. The forces from the sun and the moon produced a decreasing inclination which went through zero and then increased on the opposite side. It took 22 months for the transition from 0.67° to -0.67°.

An observer at the sub-satellite point looking at the satellite, will look slightly south at noon (local time) and slightly north at midnight, if the orbit conditions are as shown in figure 1. Similarly an observer due north of the sub-satellite point at 116° west longitude will look (or point his antenna) at a lower elevation at noon than at midnight. Simultaneously there are east-west disturbances from the solar wind and the sun's gravity. It turns out that an observer on earth sees the satellite motion as an ellipse which occurs during a 24-hour period. If the observer now moves east or west from 116° west longitude the phase of the east-west motion shifts and the ellipse appears to rotate. Figure 2 shows a plot of relative spacecraft position in terms of antenna pointing azimuth and elevation at intervals of 1 hour. This motion can be viewed from Austin, Texas, when the orbital inclination is 0.65°. The slope of the major axis of the elliptical motion is typical for that location. However, the slope does not remain constant, but deviates about ±5° from the nominal. Figure 3 is a diagram representing a window in space which is the locus of all possible spacecraft locations as seen from Austin, Texas during the life of CTS. The diagram is a translation of spacecraft position in latitude and longitude to the viewing angle in azimuth and elevation. The east-west motion is limited by station keeping but the north-south motion is not bounded. However, CTS was designed as a 2-year experiment and its orbit was biased to keep the inclination within 1.0° during the 2-year life.

The 24-hour east-west motion is generally less than 0.5° which makes the ellipse narrower than the window. Under certain conditions the ellipse may degenerate to a straight line or a figure eight. These narrow figures drift across the window from 116.25° to 115.75° west longitude during a period of a few weeks and a station keeping maneuver returns it to 116.25°.

As the earth orbits around the sun the phase of the elliptical cycle changes. Visualize for example, in figure 1, 6 months later the sun will be to the left side of the earth and the phase will have changed 180°.

DESIGN APPROACH

The overall approach in designing the nodding feed antennas was:

(1) To modify a commercially available parabolic antenna so that the feed could be deviated continuously through a small angle in one axis using a small motor driven actuator.

(2) To design the antenna to be used at any location on earth by including the provision for rotating the polarization and rotating the nodding axis.

(3) To make antenna pointing control simple, inexpensive, and operable by unskilled operators.

(4) To assume that the initial installation, the initial pointing and the maintenance would be performed by the supplier.

(5) To design the antenna to be erectable by two men in a few hours without the use of heavy equipment and without additional construction.

The plan included fabricating an adapter for the feed mount with a ball bearing pivot and an actuator driven by a small reversing motor. The feed mount nods in one axis at the vertex of the parabolic reflector (see figs. 4 to 6).

To achieve the single design suitable for all users regardless of their location, it was necessary to include 2° of adjustment, one for rotation of the feed for polarization and the other for rotation of the nodding axis. The spacecraft transmits and receives with each of the two antennas using polarization isolation. It transmits with the electric field in the north-south direction as viewed from the sub-satellite point. However, when viewed from other locations on earth, the north-south direction at that location and the direction of polarization do not coincide. There is an apparent rotation of polarization and the feed horn must be rotated to compensate for it. It is called an apparent rotation here to distinguish it from phenomena like atmospheric rotation where the direction of polarization actually rotates during certain propagating conditions. The antenna purchased for this project had polarization adjustment included. Similarly the nodding axis needs to be rotated as a function of location on earth because of the apparent change in the motion of the satellite from various points of view on earth described in the previous section. A 36 hole adapter ring was fabricated and mounted on the reflector to rotate the nodding axis in increments of 10° (see fig. 5).

The general purpose stations will be operated by classroom instructors, paramedics, nurses, or other similarly unskilled (in radio communications) operators. Therefore, single axis nodding and a simple to operate, easily fabricated and inexpensive control unit is required. The approach used was to drive the feed back-and-forth with a reversing motor controlled with a reversing switch. Limit switches at each end prevent the feed mount from rotating more than 1.23° from boresight (2.46° total). Indicator lights show which way the feed is moving, if it is moving and if it has reached a limit. The beam pointing is optimized by observing signal strength (when available) on a receiver or picture quality on a TV monitor.

The antenna will have been initially installed and pointed by skilled technicians. It is planned that these technicians will travel to the user's site after the antenna has been shipped there and install it essentially with no heavy equipment except possibly a winch on their truck. The antenna is small enough that no additional construction needs to be performed. A mast was designed that can be mounted on bare ground and held in position with cables and ground stakes (not shown in figs. 4 to 6). Figure 7 is a sketch of the antenna with the portable mast.

ANTENNA CHARACTERISTICS

Figure 2 indicates that several options are available to the receiving station designer to cover spacecraft motion. A 0.9 meter (3 ft) diameter antenna which has a gain of 38.6 dB at 12 gigahertz can provide coverage with no steering necessary after initial pointing. A 2.4 meter (8 ft) diameter antenna will require some steering which can be substantially reduced if the beam steering has only one degree of motion along the major axis, of the ellipse. Any antenna having narrower beamwidth (higher gain) will require two-dimensional steering and a complicated tracking system.

The 2.4 meter diameter antenna was selected for the nodding feed prototype to be used to receive television pictures from CTS. It can be seen in figure 3 that, when the boresight of the antenna is initially pointed at the center of the CTS window and the beam is moved along the centerline, a 0.73° beamwidth can adequately cover all possible positions of the spacecraft. Adequate coverage is shown by the link calculation in Table I to be available whenever the spacecraft is within the 3 dB contour of the beam. A tunnel diode amplifier (TDA) with 6 dB noise figure is required.

If a 0.9 meter diameter antenna were to be used, a cooled parametric amplifier with 1.4 dB noise figure will have been needed to provide marginal coverage. The higher gain antenna might have eliminated the TDA but it would have led to expensive two-dimensional tracking. Both options were more expensive using state-of-the-art technology available at the time of this report.

A control for moving the feed (or pointing the beam) is described in the following section. This control moves the beam along the centerline of the CTS window with no feedback or locking mechanism. After initial installation the operator merely moves the beam back and forth until the best reception is obtained. It was anticipated that customers would be provided current information on the motion of the spacecraft with the purchase of the antenna. If not, they could easily make gross (but sufficiently accurate) estimates with a little experience operating the antenna. Then, this information can be used to predict which way to move the beam either to obtain maximum signal pointing or to bias the antenna pointing for extended periods of unattended operation. The extended operating periods can be from 2 to 10 hours. Visualize in figure 2 with the beam pointed as shown about 2.5 hours of coverage is feasible as the spacecraft moves through the beam. If the beam is properly placed at the end of the ellipse 10 hours of unattended operation is possible.

When a feed is moved from boresight the beam moves in the opposite direction. The beam deviation divided by the feed deviation is defined (ref. 1) as the beam factor. Figure 8 is a reproduction from reference 1 showing the beam factor as a function of F/D and edge illumination (where F/D is the ratio of reflector focal length to diameter). F/D is 0.4 for the nodding feed antenna thus the beam factor is about 0.85. Since the feed motion was not calibrated the beam factor could not be measured accurately but it was in the range of 0.8 to 0.9. Since ±1.0° of beam deviation was required, the feed deviation was specified to be 2.5°.

As the feed deviates from boresight the gain of the antenna drops. However, Silver (ref. 2) showed that the gain loss is insignificant for small deviations from one to three beamwidths. Figure 9 is a reproduction of Silver's data. Figures 8 and 9 are included to provide design limitations for nodding feed antennas.

MECHANICAL DESIGN

The assembly of the nodding feed antenna is shown in figures 4 to 6. The nodding feed mechanism was adapted to the purchased antenna and antenna feed parts. A single axis rotation is supplied by a yoke and bearing shown in figure 6. The nodding angle requirement for the beam was 2°, and the system was designed for $2\frac{1}{2}$° feed deviation. The motor has a 30 rpm output. This allows the feed to nod at 0.0385 dec/sec.

Structure

The structural moving element consists of the triangle shown in figure 10. It is made up of the purchased feed horn with waveguide which is mounted in the feed housing, a small channel type beam that is driven by the actuator, and the support rod. The triangular structure provides the stiffness in the plane of the triangle, and two guy wires that are 90° apart provide the stiffness in the orthogonal direction, and little or no resistance to the movement of the feed.

Bearing/Feed Pivot

The bearing/feed pivot which allows the one degree of freedom is shown in figure 6. Normally the existing housing would pilot into the existing plate on the reflector and be clamped by the collar-housing.

The antenna adapter plate and the feed collar adapter plate were added to the system with a pivot between them in order to give the feed horn and housing assembly the required one degree of freedom. A yoke and bearing system was used in order to minimize long term friction.

Actuator

The actuator is a simple lead screw or jack screw type of linear actuator. It is hard mounted by a bracket to the reflector. The actuator is shown in figure 11. A bi-directional motor-gearhead drives the male part of the lead screw. The female part of the lead screw is allowed to extend and retract. The pin in the channel prevents torsional rotation. A linear bearing and all lubrication of the lead screw is eliminated by making the female part of the lead screw from "Delrin." The male thread and the sleeve on the box are made of 304 stainless steel. A switch trip was added to the top of the female part of the lead screw, to limit the travel to $2\frac{1}{2}^{\circ}$. The limit switches were mounted directly to the actuator wall. The box was sealed with gasket material in an attempt to protect the actuator from moisture. No attempt was made to seal the female part of the lead screw shaft.

An adjusting and alining mechanism is provided in the triangular structure. In order to allow an equal amount of angular travel from the boresight of the reflector, the triangular mechanism must be alined. Two adjustments in the linkage which work together allow this flexibility. One is a double nut which allows the length of the support rod to be adjusted. This would allow a small change in the angle between the feed horn and the channel. The second adjustment is shown in figure 10. A plate is firmly fastened to the collar housing. A pivot point is provided by a yoke about the channel. Angular adjustment is made by screwing the adjusting screw in or out. When it is alined, the jam nut is locked to provide the joint with stiffness.

Mounting Ring

The mounting ring for the antenna (shown in fig. 5) is necessary to rotate the nodding axis with respect to the mast of the antenna depending on the location on earth of the ground station. In order to cover all possibilities 36 mounting holes were drilled every 10°. The total dish could then be rotated in 10° steps and a position could be found for the horn movement that would closely aline with the movement of the spacecraft.

The high cost item in the adaptation of the commercial antenna to the nodding feed design was the 36 hole ring for rotating the nodding axis. An alternate (paper) design was considered, in which a tubular ring was fastened to the antenna. Then a clamping mechanism on the antenna mount permitted continuous adjustment rather than incremented as in the original approach. However, cost quotes from potential sources showed significant savings for one unit but not for quantities of 100 or more.

Control Unit

One of the important goals of the antenna design was to make the pointing control as simple to operate as the rabbit ears on your television set. Thus the control unit was designed to merely move the feed up and down (basically) by driving the reversing motor one way or the other. A schematic diagram of the electrical circuit is shown in figure 12. The motor and limit switches are located on the antenna in the actuator housing. The other components are mounted on a 3½-inch instrument rack panel and connected to the actuator with a 15-meter cable. Thus the control unit can be located with the receiver and television monitor.

Generally the pointing is accomplished with the antenna out of view of the operator and indicators are needed to show that the feed is moving, which way it is moving, when it reaches the limit, and when it is pointed properly. Four indicator lamps on the control unit provide the first three functions and the optimum pointing is indicated by the signal strength meter on the receiver or the best picture on the monitor.

Portable Mast

The antenna purchased was a mast mount type, the lowest priced parabolic antenna at the time of the purchase. To make the antenna portable and complete, a portable mast was required. Figure 7 is a sketch of the mast designed and fabricated for this prototype antenna. It is designed to be set up on the ground with no additional construction required. Eight cables and a square plate are used to eliminate torque on the 4½-inch mast section.

PERFORMANCE

The nodding feed antenna performance was evaluated in terms of:

(1) Ease of erection and mechanical stability

(2) Reliability of achieving initial pointing

(3) The ability of unskilled operators to point the antenna properly.

Antenna characteristics such as gain variation, sidelobe variation, and beam deviation as a function of feed deviation were not evaluated.

The antenna was erected at two sites, one on a roof and the other on the ground. The roof installation showed the antenna was too heavy to be considered portable. It was evident that the antenna could be made lighter by eliminating the mast and mast adapter and using a simpler angle iron frame support. The nodding axis and the feed polarization were set using computer generated data for the correct angle for various locations on earth. Table II shows the angle the feed horn should be rotated from the vertical polarization position determined from the latitude and longitude of the ground station. Tests showed, as can be expected, that the feed can be set according to the predicts reliably, because the sensitivity to an error in polarization angle is low in the vicinity of the correct polarization. The gain changes as the cosine of the error angle.

It was not verified that the nodding axis was set to the correct angle because the inclination of the CTS orbit was too low at the time of the tests.

Initial pointing of the antenna was accomplished within a few hours using the following procedure:

(1) Determine azimuth (AZ_0) and elevation (EL_0) of center of CTS window for the ground station location from computer predicts.

(2) Determine the time (T_1) that the spacecraft is located at AZ_0.

(3) Determine the time (T_2) that the spacecraft is located at EL_0 (not generally the same time as T_1).

(4) Set feed at boresight of parabolic reflector.

(5) Set reflector boresight to AZ_0 and EL_0 using compass and clinometer.

(6) At time T_1 fine tune reflector pointing in azimuth only using CTS signal and receiver with signal level detector.

(7) At time T_2 fine tune reflector pointing in elevation only (steps 6 and 7 may be interchanged).

After the antenna was initially pointed, CTS signals were received at any time of the day by moving the feed.

An evaluation was made to determine if unskilled operators could indeed operate the antenna. A set of operating instructions were written (see appendix). Three secretaries and three technicians, who were not experienced in operating communications equipment, were selected to operate the antenna. Each one read the instructions and they received separately about 5 minutes of tutorial explanation of the theory and operation of the antenna. The tutorial session was the type a factory representative or installation technician might give a customer. After a few minutes of practice, all were able to not only point the antenna for best reception, but they also biased the pointing for extended operating time.

COST

Whenever the cost of an item is discussed, one must be careful to distinguish between fabrication and development cost, selling price, and turn key operation. Table III lists the selling price of the components that were paid or would have been paid where the components were made in-house. These do not include development cost or the cost of assembling the antenna system from these components. They also do not include installation, maintenance and capitalization costs which must be considered by the final user for turn key operating cost. It is estimated that the selling price of the nodding feed antenna system will be about twice the total shown in Table III and triple those values for turn key operation.

CONCLUDING REMARKS

The nodding feed antenna system described in this paper has demonstrated that, for communications with satellites in near geostationary orbit, antenna systems can be simple, portable, inexpensive, and easy to operate. When an antenna is required to cover a small window (1 to 3 beam widths) moving the feed does not markedly deteriorate the performance. Moving just the feed instead of the whole parabolic antenna substantially reduces the structure size and the size of the drive motors. Moving the feed in one axis instead of two eliminates the need for complex tracking equipment, which not only reduces the cost substantially, but also simplifies the operation.

APPENDIX

OPERATING PROCEDURE FOR NODDING FEED ANTENNA

Theory of Operation

The nodding feed antenna is a low cost system for communications using satellites in synchronous orbit. A satellite in synchronous orbit has an orbit period of 24 hours which gives it the appearance of being stationary over one spot on the earth. However, due to disturbances from other bodies in space (the sun, moon, etc.) satellites like CTS have a small motion, primarily up and down.

Many ground stations using the CTS spacecraft have expensive automatic tracking antennas to follow the motion of the satellite. In order to reduce the cost of ground stations the nodding feed antenna was developed. In this antenna system only the feed is moved instead of the whole antenna and it is done manually rather than automatically.

To adjust the pointing of this antenna, imagine that the antenna beam is a search light beam illuminating a spot in space in the vicinity of the satellite. Refer to figure 14 which shows the motion of the satellite around an oval path and the spot that the antenna beam makes. It can be seen that the spot is large enough that motion in one direction only is required. The antenna has been installed and adjusted so that the beam will move in the direction which will cover all possible locations of the satellite.

When the satellite is within the circle, good TV reception can be expected. However, the reception is best at the center and degrades only slightly between the center and the edge of the circle. When the satellite passes beyond the edge of the circle, the reception degrades rapidly.

The receiver used with this antenna has a signal level meter. This meter will have a maximum reading when the satellite is near the center of the beam and the reading will drop lower as the satellite moves toward the edge. This signal level reading is a more sensitive indication than watching the TV monitor. Therefore, to acquire the best TV reception for a short period of time, the beam should be moved up and down until the maximum reading on the signal level meter is attained. When long (2 to 5 hr or more) unattended operation is desired the beam can be adjusted so that the satellite is at one edge of the beam and moves through the beam.

Operating Instructions

1. Refer to figure 13 front panel of antenna control box for location of controls and indicators.
2. Turn power switch 3 to ON. Indicator 1 should turn on.
3. Move control lever 6 to UP and/or DOWN positions. Note that indicators 4 turn on when the control is in either position indicating that the beam is moving. A limit switch stops the beam motion automatically at the upper and lower extremes. Indicators 5 turn on when this occurs.
4. Move the beam up or down until there is a good picture on the TV monitor.
5. Adjust the beam for best reception by observing the signal level meter on the receiver. As the beam moves through the satellites position the meter indication will increase slowly, reach a maximum reading and then decrease. Adjust the beam position until you find the maximum reading and then set it to that point.

<u>Note</u>: Now the beam is positioned so that the satellite is as close as possible to the center of the beam. In this position good TV reception will be available for about 1 to 2 hours without further adjustment. If unattended operation for longer periods, 2 to 5 hours, is required, do optional steps 6 and 7.

6. Optional: Study figure 14 and determine which way the satellite will be moving (up or down).
7. Move the beam in the same direction the satellite is moving while watching the TV monitor. Stop the beam when the picture begins to be noisy. Readjust slightly if necessary to restore good quality.

<u>Note</u>: The beam is now positioned with the satellite at one edge. The satellite will move through the beam during the next 2 to 5 hours. The actual time depends on the present position of the satellite. By studying figure 14, a good estimate of the time can be made.

REFERENCES

1. Antenna Engineering Handbook; Jasik, Henry, ed.; First Edition, McGraw-Hill, 1961.
2. Microwave Antenna Theory and Design; Silver, Samuel, ed.; Boston Technical Publishers, Inc., 1964.

TABLE I. - DOWNLINK CALCULATIONS FOR NODDING FEED ANTENNA

Downlink - frequency, 12.1 GHz	06:20:78
Spacecraft output tube power, dBW (200.0 W)	23.01
Spacecraft feed loss, dB	-0.85
Spacecraft antenna gain, dB (2.5 × 2.5 ft diam, 2.35 × 2.35 HPBW)	36.90
Spacecraft EIRP, dBW	59.06
Spacecraft antenna beam edge loss, dB	0.00
Spacecraft antenna pointing error, dB (0.35°)	-0.22
Margin, dB	-3.00
Propagation loss, dB (23 973 st. mi., lat. = 41.4, rel. long. = 35.1)	-205.81
Rain loss, dB (0.100% outage, CCIR rainfall region 2)	-1.52
Atmospheric loss, dB	-0.17
Polarization loss, dB	-0.25
Terminal feed loss, dB	-1.00
Terminal antenna gain, dB (8.0 ft diam, 0.73° HPBW)	47.10
Terminal antenna stationkeeping loss, dB (0.00°)	0.00
Terminal antenna pointing error, dB (0.36°)	-3.00
Terminal received carrier power, dBW	-108.81
Terminal noise power density, dBW/Hz (T = 973 K)	-198.72
Bandwidth, dB (Hz) (27.0 MHz)	74.31
Terminal receiver noise power, dBW	-124.41
Uplink noise contribution, dB (uplink C/N = 21.1 dB)	1.08
Terminal net noise power, dBW	-123.33
Terminal carrier power to receiver noise ration, dB	14.52
FM improvement, dB (M = 2.00)	21.58
CCIR noise weighting factor, dB	10.30
Signal to noise ratio, dB	46.40

TABLE II. - ROTATION OF POLARIZATION FROM VARIOUS LOCATIONS ON EARTH

[A positive angle of feed rotation indicates a clockwise rotation when looking toward satellite.]

Latitude	Longitude														
	130.0	125.0	120.0	115.0	110.0	105.0	100.0	95.0	90.0	85.0	80.0	75.0	70.0	65.0	60.0
70.0	-5.0	-3.2	-1.4	0.4	2.2	3.9	5.7	7.3	9.0	10.5	11.9	13.3	14.5	15.6	16.6
65.0	-6.4	-4.1	-1.8	.5	2.8	5.0	7.2	9.4	11.4	13.4	15.2	16.8	18.4	19.7	20.9
60.0	-7.9	-5.1	-2.3	.6	3.4	6.2	9.8	11.6	14.1	16.4	18.6	20.5	22.3	23.9	25.3
55.0	-9.5	-6.2	-2.8	.7	4.1	7.5	10.8	14.0	16.9	19.6	22.2	24.4	26.5	28.3	29.9
50.0	-11.4	-7.4	-3.3	.8	5.0	9.0	12.9	16.6	20.0	23.2	26.0	28.6	30.9	32.8	34.5
45.0	-13.5	-8.8	-4.0	1.0	5.9	10.7	15.3	19.6	23.5	27.0	30.2	33.0	35.5	37.6	39.4
40.0	-16.0	-10.5	-4.7	1.2	7.1	12.7	18.1	23.0	27.4	31.3	34.8	37.8	40.3	42.5	44.4
35.0	-19.0	-12.5	-5.7	1.4	8.4	15.2	21.4	27.8	31.9	36.1	39.8	42.9	45.5	47.7	49.5
30.0	-22.8	-15.1	-6.9	1.7	10.2	18.2	25.4	31.7	37.1	41.6	45.3	48.4	51.0	53.1	54.9
25.0	-27.3	-18.5	-8.5	2.1	12.6	22.2	30.5	37.4	43.1	47.7	51.4	54.4	56.8	58.8	60.4
20.0	-33.5	-23.2	-10.8	2.7	16.0	27.6	37.1	44.5	50.2	54.6	58.1	60.8	63.0	64.7	66.1
15.0	-42.0	-30.2	-14.6	3.7	21.3	35.4	45.7	53.1	58.5	62.4	65.4	67.6	69.4	70.8	71.9
10.0	-53.9	-41.6	-21.6	5.6	30.6	47.2	57.4	68.0	71.0	71.0	73.2	74.9	76.1	77.1	77.9

TABLE III. - COST ESTIMATE NODDING FEED ANTENNA

	Quantity	
	1	100
8-foot dish with feed	680	600
Antenna mount to 4½-inch mast	220	200
Pressurizing system	175	150
Parts for nodding feed	[a]2300	560
4½-inch mast	1250	1000
Total	$4625	$2610

[a] Second, improved design would cost $1500 for one unit, $560 for 100 unit quantity.

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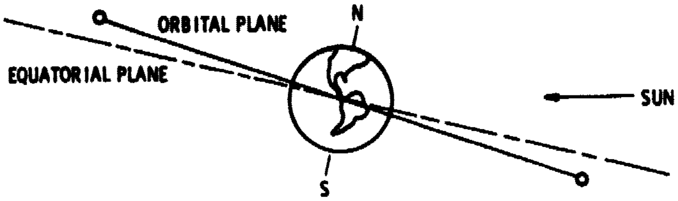

Figure 1. - View of Earth and Spacecraft in orbit from deep space.

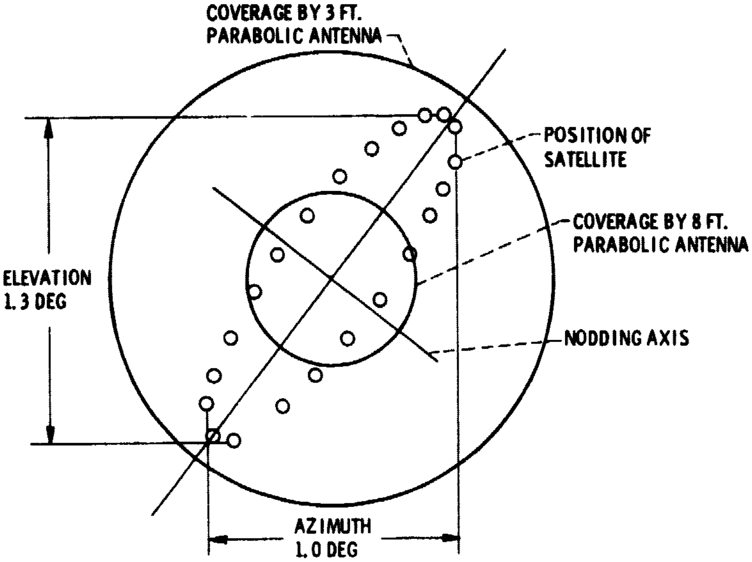

Figure 2. - View from a ground terminal located at 30.0° north latitude and 97.7° west longitude.

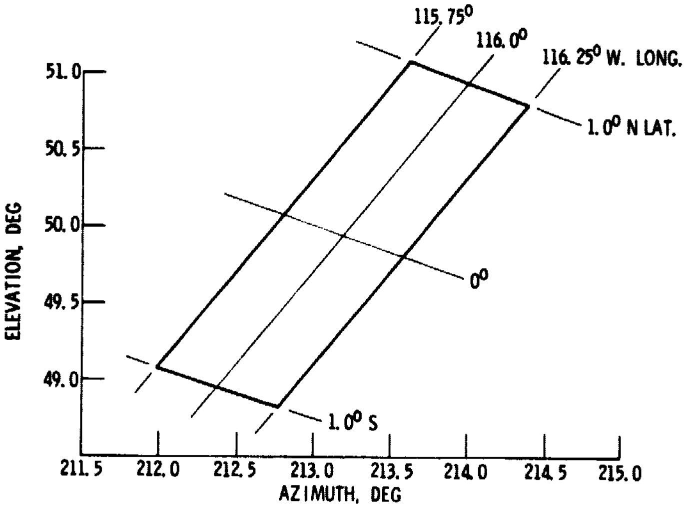

Figure 3. - View of CTS window from ground station in Austin, Texas at 30° north latitude and 97.7° west longitude.

Figure 4. - Front view of nodding feed antenae.

Figure 5. - Rear view of nodding feed antenae.

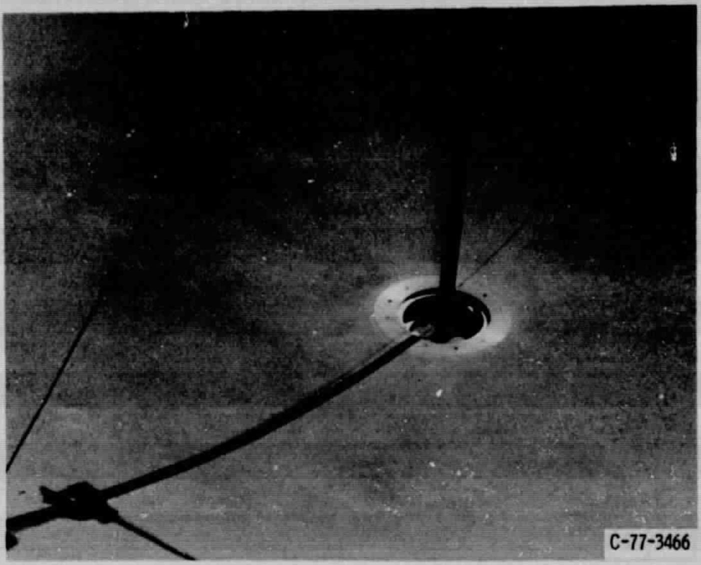

Figure 6. - Close up view showing detail of bearing plate.

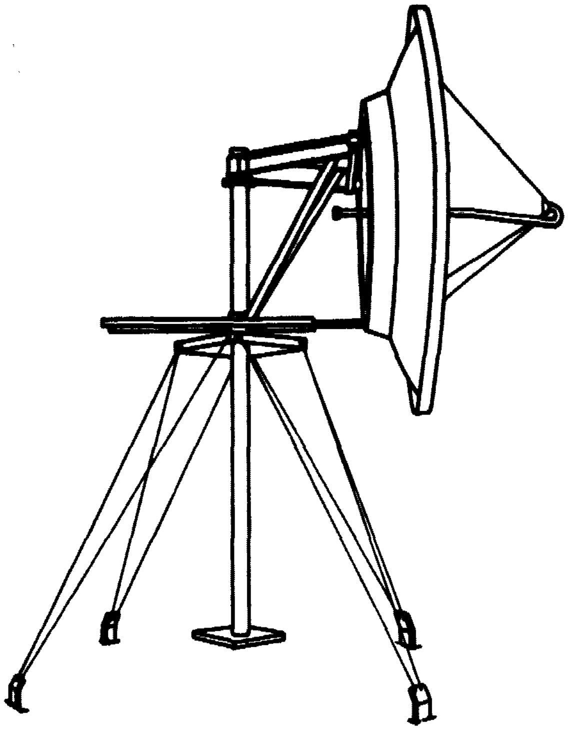

Figure 7. - Sketch of parabolic antenna on portable mast.

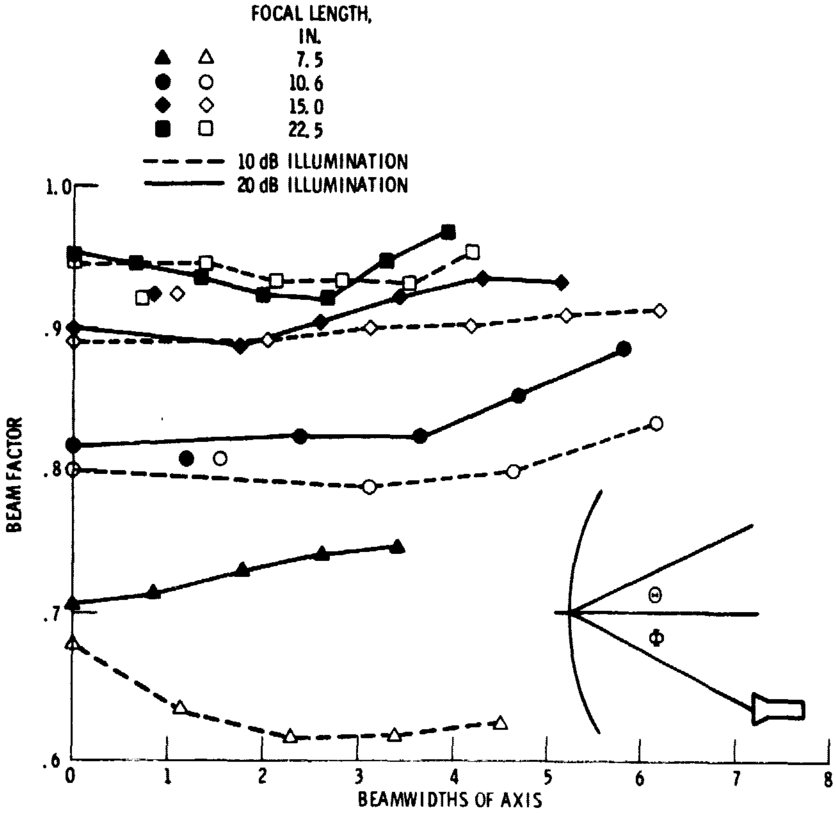

Figure 8. - Beam factor as a function of focal length and edge illumination in a 30 inch diameter paraboloid.

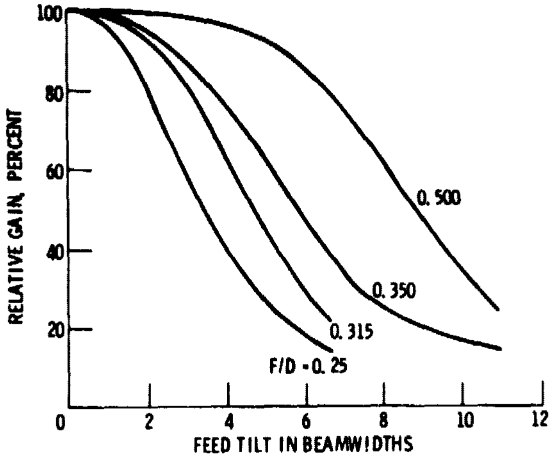

Figure 9. - Dependence of antenna gain on feed tilt and paraboloid shape. F/D is the focal length to diameter ratio.

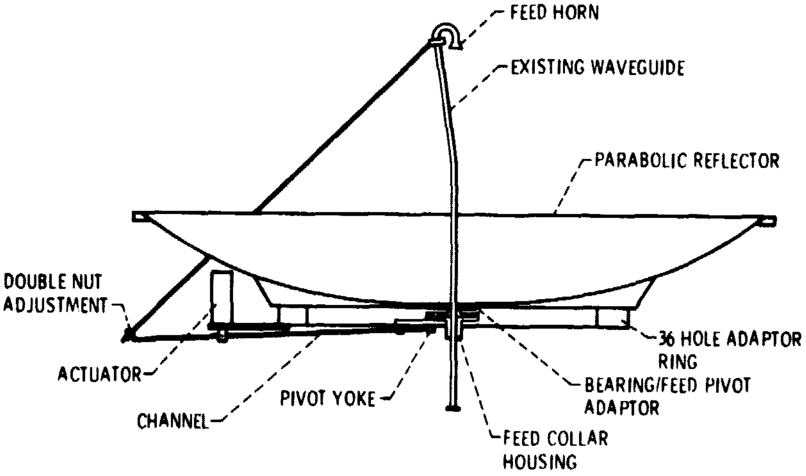

Figure 10. - Sketch showing mechanical design of nodding feed antenna.

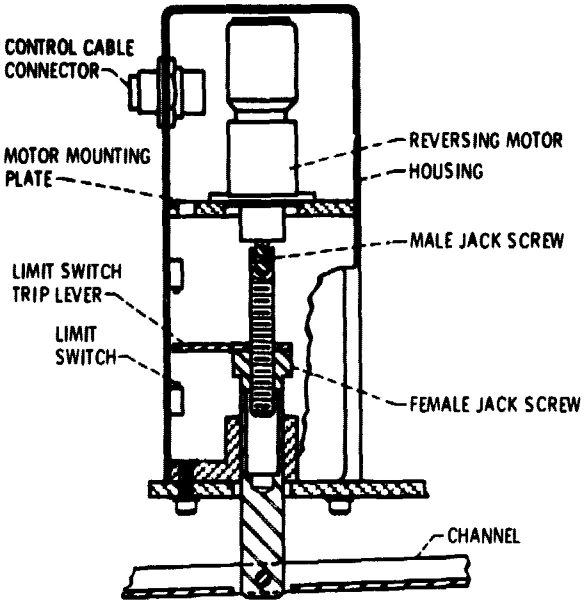

Figure 11. - Detailed sketch of actuator assembly.

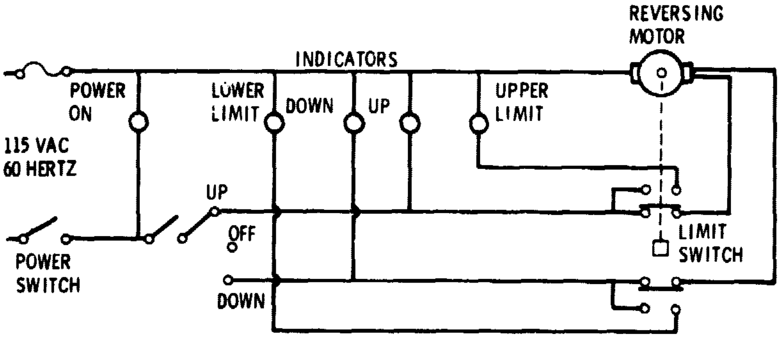

Figure 12. - Schematic diagram of nodding feed antenna control unit.

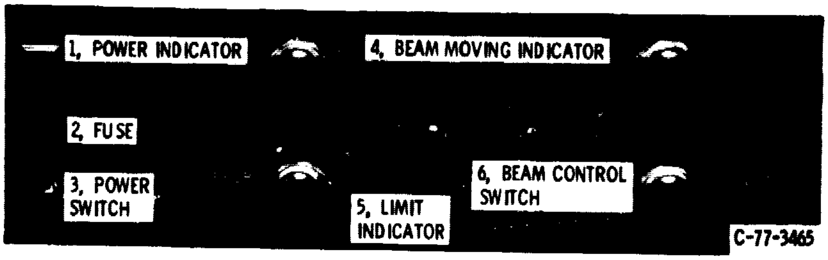

Figure 13. - Front panel of antenna control box.

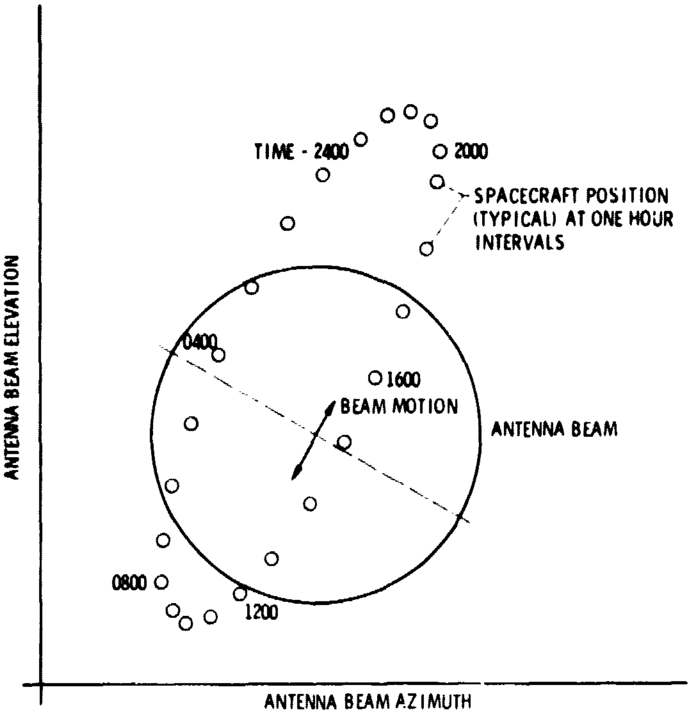

Figure 14. - Relationship between antenna beam pointing and spacecraft position.