Developments Related to the Future Use of the 32-GHz Allocation for Deep Space Research

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This paper was prepared for presentation at the third annual meeting of the Space Frequency Coordination Group (SFCG), held in Bangalore, India, at the invitation of the Indian Space Research Organization. SFCG is an informal organization consisting of the European Space Agency and agencies of 16 countries interested in space research. The purpose of the paper was to inform the SFCG of JPL/NASA activities that will lead to use of the 32-GHz allocations for deep space telecommunication. The paper discusses the advantage of 32-GHz links, the estimated link performance, and developments in the fields of antennas, low noise preamplifiers, radiometry, and propagation studies. A description of ways to demonstrate 32-GHz link capability concludes the discussion.

I. Introduction

In preparation for the 1979 WARC, the United States examined the need for new space research allocations. As a result of that examination it was proposed that a pair of bands near 32 GHz be allocated for space research, deep space only. At the WARC, 31.8-32.3 GHz was allocated for space-to-earth links, and 34.2-34.7 GHz for earth-to-space links.[1]

Operation at 32 GHz offers particular advantages, as compared to the lower frequency bands. To realize these advantages, there must be improvements in equipment and techniques. A substantial amount of analysis, design, and development is needed to achieve the improvements.

In this report we explain the advantages to be gained by operating at 32 GHz. Improvements needed to realize these advantages are identified. Several related study programs and hardware developments are then described.

II. Advantages of 32-GHz Links

There are two principal advantages offered by operation at 32 GHz as compared to lower frequencies: charged particles along the propagation path have less adverse effect, and link performance under clear weather conditions is generally higher.

For purposes of spacecraft navigation, and certain scientific measurements, it is important that the velocity of radio wave propagation be known very accurately. Interplanetary or atmospheric charged particles (electrons) alter the velocity to a degree proportional to the total number of particles along the

[1] These are footnote primary allocations that apply to Australia, Spain, and the United States.

path. To the extent that the number of particles is unknown or imperfectly modelled, the velocity will be correspondingly uncertain. The charged particle effect on propagation velocity is inversely proportional to the square of the frequency ratio. The velocity uncertainty at 32 GHz is thus 14 times smaller than that at 8.4 GHz, a clear advantage in favor of the higher frequency.

Another effect, particularly of dense plasmas (high concentrations of electrons), is the spectral broadening of signals passing through the plasma region. The broadening is noisy and limits the ability of an earth station to track weak radio signals that have passed through such a region. The sun is surrounded by an especially dense plasma. As the propagation path from a spacecraft in deep space comes closer and closer to the sun, the received signal on earth finally becomes too noisy for successful reception, and communication is interrupted. Operation at 32 GHz would allow reception of signals along paths passing closer to the sun, minimizing the time of interruption. This is important because the data obtained when a spacecraft enters and leaves occultation is of particular scientific value.

The second advantage to deep space links that is offered by 32 GHz is the potentially higher link performance, as compared to the 2- and 8-GHz bands currently used. The performance increase can be used to provide higher data rate or to allow communication using smaller and lighter antennas and transmitters.

III. Estimated Performance Advantage of 32 GHz

In free space, and with ideal fixed aperture antennas, link performance increases as the square of the frequency ratio. A 32-GHz link is thus 11.6 dB better than an 8.4-GHz link. Practical antennas, transmitters, receivers, and the propagation characteristics of the atmosphere reduce this potential advantage.

Table 1 presents the results of two analyses of the performance improvement that might actually be achieved.

The 1978 estimate is shown as historical background. It was made before the WARC, used data available at that time, and provided the justification for further development aimed at utilizing 32 GHz for deep space links. The 1982 estimate makes use of more recent weather data as described later in this paper.

Five factors were considered in each analysis: spacecraft efficiency, earth station efficiency, tropospheric loss, system noise temperature, and frequency. Spacecraft efficiency refers to the variation of e.i.r.p. caused by frequency-dependent changes in antenna gain and transmitter output power. Earth station efficiency refers to the performance of the 64-m antennas. Each factor was evaluated at 8.4 GHz and at 32 GHz. The ratio of the factors at the two frequencies gives the estimated relative gain or loss in performance that would be obtained by operation at 32 GHz.

For the analyses summarized in Table 1, spacecraft efficiency is assumed to be constant with frequency except for the traveling wave tube power amplifier. For deep space applications, the combined requirements of high efficiency and long life are particularly difficult goals to satisfy, and somewhat less efficiency is expected at 32 GHz.

The earth station efficiency is estimated on the basis of improvements to the existing 64-m antennas. Aperture phasing errors caused by the atmosphere are taken into account. For purposes of a conservative comparison, the ground antenna improvements assumed for the 32-GHz case are also applied to the 8.4-GHz case.

The third factor is the tropospheric loss that will not be exceeded at the Goldstone tracking station for 90% of the time. The fourth factor, system noise temperature, includes maser noise temperature and the estimated antenna temperature that will not be exceeded at Goldstone for 90% of the time. Cooled waveguide is assumed for the 32-GHz case.

The fifth factor is that of link improvement due to frequency increase under ideal conditions, as mentioned earlier.

IV. Comparison of the Two Analyses

The 1978 analysis in Table 1 shows a potential performance improvement between 5.8 and 1.4 dB. This unacceptably wide range of estimated performance improvement was principally caused by uncertainty in the tropospheric loss factor and its corresponding influence on system noise temperature.

To allow successful deep space missions using 32 GHz, it is necessary to substantially reduce the uncertainty in predicted performance. The alternative of providing excess link margin to cover the uncertainty is simply too expensive.

The 1982 estimate that is also shown in Table 1 includes more recent figures for tropospheric loss and system noise temperature. Not only is the uncertainty in estimated performance reduced from 4.4 to 1.2 dB, but the maximum potential benefit is higher than before.

V. Improvements Needed to Allow Deep Space Communications at 32 GHz

A number of improvements in earth station technique and equipment are necessary in order to realize the potential benefits of communicating at 32 GHz:

(1) Higher mechanical precision and pointing accuracy of earth station antennas.

(2) Wider bandwidth maser preamplifiers.

(3) More complete knowledge of 32-GHz attenuation and sky noise temperature at all three DSN (U.S. Deep Space Network) sites: Goldstone, Canberra, and Madrid.

Work on these is discussed in the following paragraphs.

A. Antenna Improvement

Earth stations of the U.S. Deep Space Network include 64-m reflector type antennas with Cassegrain feed. Table 2 shows their characteristics at 8.4 GHz. Designed 20 years ago, these antennas begin to lose efficiency at 10 GHz, and the gain limit is reached at 20 GHz. To achieve the estimated performance advantage of communication links at 32 GHz, it will be necessary to make a number of improvements to the antennas.

1. **Antenna precision.** The gain of a reflector antenna depends on its size and the degree to which the received wavefront can be collected and focussed without appreciable phase errors. There are several sources of these, and when the standard deviation of all the phase distortions approaches 1/12 wavelength, there is a 4-dB loss in gain. One-twelfth wavelength at 32 GHz is 0.78 mm. Since a 4-dB loss would appreciably reduce the advantage of 32-GHz links, it will be necessary to limit the phase distortions to the equivalent of a fraction of 1 mm.

Ideally, an antenna would have smooth and exact reflector and subreflector shapes, the correct alignment of these elements with respect to the feed, and would be so rigid that wind, gravity, and thermal effects could not disturb the total structure. In practice, this perfection does not exist, and the mechanical errors result in phase distortions that degrade the antenna performance.

Some phase distortions are caused by imperfections in the manufacture and installation of the mechanical parts of the antenna: the panels that make up the reflector, the subreflector, and the feed assembly. In addition, structural deflections caused by gravity and wind result in phase errors that are a function of elevation angle, pointing direction, and wind speed and direction.

To appreciate the difficulty of making an antenna that is suitable for 32 GHz, observe that the area of a 64-m reflector is approximately equal to one-half of a soccer field. Imagine keeping half a soccer field smooth and level to a tolerance of less than a millimeter!

2. **Antenna pointing.** In order to realize the gain offered by an excellent antenna, it is necessary to point it in the correct direction. The beamwidth of a given size of reflector antenna decreases with increasing frequency (up to the frequency where phase distortion limits the gain). The pointing at 32 GHz must be four times more accurate than the pointing at 8.4 GHz, because of the decreased bandwidth.

Antenna pointing error is the difference between the intended and actual direction of the electrical boresight. The pointing error is a composite of phasing errors and mechanical imperfection in positioning the antenna structure with respect to the desired direction. Referring again to the 8.4-GHz characteristics of the 64-m antenna (Table 2), notice that the beamwidth at 32 GHz will be 4 times smaller, or approximately 0.01 deg. The existing pointing accuracy of 0.02 deg must therefore be improved so that there will not be excessive loss during initial acquisition of spacecraft signals.

Improving the pointing accuracy of an existing large antenna is difficult and costly. One technique that circumvents this problem is to experimentally create a table of actual pointing direction as a function of mechanical position. To point in a particular direction, the antenna is then caused to take the corresponding position as read from the table.

Once a signal has been acquired, it is necessary to follow the movement of the spacecraft with respect to the earth station. Directional control by means of conical scan or monopulse techniques can result in electrical or mechanical beam steering that maximizes the received signal strength.

It is estimated that acquisition pointing accuracy of ±0.005 deg and active tracking accuracy of ±0.001 deg can be achieved with the 64-m antenna under calm or light wind (6-m/sec) conditions. An important reason for the possibility of such accuracy is that the 64-m antennas include a special optical alignment system. Called the master equatorial, the system closes azimuth and elevation servo drive loops in a way that ensures that the mechanical axis of the main reflector is driven to the desired direction. In this way, the imperfections in the drive and support mechanism do not introduce pointing errors. The master equatorial reference system is a key element in the ability to use the 64-m antennas at 32 GHz.

(Note: The foregoing discussion of antenna pointing is in the context of receiving signals from known spacecraft by a process of acquisition and tracking. There also is a need to receive signals that are so weak as to be detectable only after minutes, or perhaps hours, of signal integration. In this case, active tracking is not possible. Echoes from planetary radar exploration, and signals from some distant natural sources, are examples. Pointing that is needed to satisfy these requirements is beyond the scope of this paper.)

3. **Performance of improved antennas.** Table 3 lists the factors discussed above along with estimates of the phase distortion and corresponding loss that could reasonably be achieved with improved antennas. Also shown is the loss associated with atmospheric turbulence that affects phase across the incoming wavefront.

The estimated performance depends upon a number of improvements to the existing 64-m antennas. Structural stiffening to reduce the deformation of the main reflector due to gravity and wind has been designed and installed on the Goldstone antenna. Improved panel manufacturing has been demonstrated. Based on work in the United Kingdom, improved methods for measurement of surface precision are being developed to allow more accurate panel setting. Motor-driven axial adjustment of subreflector position has been installed to allow focus correction for structural deflection as a function of elevation angle. Similarly, an adjustment to compensate for vertical beam shift is planned. A subreflector surface that could be slightly changed in shape is being considered as a further means of correcting for gravity-induced deformation of the main reflector surface.

Through a continual program of measurement, analysis, design, and implementation, the useful life and frequency range of the existing antennas at deep space earth stations can be extended, and the practical application of 32 GHz made possible.

4. **Clear aperture antenna development.** A more fundamental improvement in antenna performance is also under development. The typical reflector antenna with Cassegrain feed (Fig. 1) suffers from a loss of efficiency because the feed and the subreflector support structure block a part of the wavefront. Additionally, microwave thermal radiation from the surface of the earth is coupled into the antenna by reflection from these structures, increasing the system noise temperature. An offset feed and subreflector (Fig. 2) achieves a clear aperture.

The reflector and subreflector of a conventional Cassegrain antenna are circularly symmetric surfaces with approximately parabolic and hyperbolic curvature. An offset feed requires that the surfaces be modified accordingly in order to provide proper phasing. Modern analytic techniques allow the calculation of reflector and subreflector shapes that complement each other and result in unusually high antenna efficiency. A 1.5-m-diameter antenna has been constructed using these principles. Analysis and tests at 32 GHz show an aperture efficiency of 85%, believed by the designers to be a world record. The high efficiency is accompanied by sidelobe levels that are comparable to those of conventional antennas. By tapering the aperture illumination, unusually low sidelobes are possible by using the clear aperture principle.

B. Maser Improvements

1. **Receiver preamplifiers.** Maser preamplifiers have been used with multiple conversion superheterodyne receivers to provide system noise temperatures of 16 kelvins at 2.3 GHz and 24 K at 8.4 GHz. These downlink bands are relatively narrow, 10 and 50 MHz respectively, and are well served by 40 and 100 MHz, the bandwidths of masers operating at these frequencies. To take advantage of the higher link performance that is possible at 32 GHz, and to provide for the use of the 500-MHz allocation width, new masers are needed.

The gain-bandwidth product of a maser amplifier depends upon the nature of the maser material, the size and configuration for the maser structure, and the operating frequency. Operation of a given length of ruby maser material at 32 GHz would yield higher performance than the same length operating at 8 GHz. Compared to the bandwidths of existing 2- and 8-GHz amplifiers, a much wider bandwidth can be achieved in a 32-GHz amplifier of the same size.

2. **Maser operating cost and a new multiple frequency amplifier.** An important limitation to maser design is the need for cryogenic (very low temperature) cooling. The high gain and extremely low noise temperature of a maser amplifier are achieved by cooling it to a temperature (4.5 K) near absolute zero. The energy cost of providing this cooling for the 2- and 8-GHz maser, located at the DSN tracking sites, is substantial. Adding the 32-GHz capability would add more cost. Fortunately, the development of a wideband 32-GHz maser provides an opportunity to construct a new multiple-frequency low-noise amplifier that uses a single maser. This new amplifier is possible as a result of improvements in microwave solid-state upconverters.

An upconverter is a special kind of mixer. Utilizing a semiconductor diode, it transforms an incoming signal to a higher frequency by means of a local oscillator called a pump. The input and output frequencies differ by the pump frequency. A unique characteristic of the upconverter is the power gain associated with the frequency increase. Low noise operation comparable to a maser is possible with cryogenic cooling. The upconverter can also have a wide bandwidth.

Figure 3 shows a block diagram of a multifrequency low noise amplifier being developed for the Deep Space Network. A single 32-GHz maser is used for that band. 2.3- and 8.4-GHz upconverters provide for those bands by translating the input frequencies to 32 GHz for amplification by the maser. The bandwidth of the maser allows separate 2.3- and 8.4-GHz signals to be simultaneously amplified and then sent to different receivers for further amplification and detection.

It is expected that the multifrequency upconverter-maser amplifier will have a noise temperature of approximately 3 K and a bandwidth of 300-500 MHz.

C. 32-GHz Propagation Characteristics

Adverse weather in the form of clouds and rain can degrade or interrupt the reception of weak signals from deep space. Clouds and rain increase the attenuation and sky noise temperature, both of which reduce the signal-to-noise ratio. To successfully design and operate a telemetry link, it is necessary to know the effect of weather on link performance.

The 1978 estimate of performance, Table 1, included a consideration of weather effects at Goldstone, based on knowledge available at that time. Since then, a program of measurement and analysis has given a more complete understanding of atmospheric effects on signal-to-noise (SNR) that might be expected with 32-GHz operation at the Goldstone earth station. Future work at the Canberra and Madrid stations will complete the information that is needed for mission planning and operation.

1. **Propagation measurements and modeling.** To understand the relationship between weather and link performance, it is necessary to have a model of the statistical variation of attenuation and noise temperatures with time. It will then be possible to know the fraction of time that a particular SNR can be exceeded. Since attenuation and sky noise temperature are related by a simple expression, it is only necessary to measure sky noise temperature over time.

Although a model of 8.4-GHz noise temperature has existed for several years, it cannot be successfully extrapolated to 32 GHz. This is because the modelling errors tend to be multiplied by the square of the frequency ratio. For example, 1 K uncertainty at 8.4 GHz becomes a 14.2 K uncertainty at 32 GHz. Since this magnitude of uncertainty makes useful analysis and prediction impossible, it was necessary to make measurements directly at approximately 32 GHz, and this has been done.

Early in 1981, a water vapor radiometer at the Goldstone station measured the increase in sky noise temperature caused by the atmosphere. A simplified diagram of the instrument is given in Fig. 4. A square law detector produces a voltage proportional to the noise power received from the antenna or from hot and ambient temperature loads. These loads at known temperatures allow calibration of the radiometer and calculation of the sky noise temperature as seen by the antenna. Figure 5 is an example of the measurement made by a radiometer.

By correlating the radiometer data with other meteorological observations of temperature, pressure, humidity, rain rate, and cloud cover, it is possible to model the attenuation and noise temperature that may be expected over time. For example, at 32 GHz, the model indicates that the Goldstone sky noise temperature will be 29 K or less 90% of the time, at an elevation angle of 30 deg. Atmospheric attenuation is directly related to the sky noise temperature. Each 6.45 K of noise temperature indicates approximately 0.1 dB of attenuation.[2] The attenuation that corresponds to a 29 K sky noise temperature is therefore 0.45 dB.

It was mentioned earlier that 8.4-GHz models cannot be extrapolated to 32 GHz because of the manner in which errors are multiplied at the higher frequency. A 32-GHz model may, however, be applied to 8.4 GHz by calculation. Table 4 is an example of the steps involved. The computation uses the square of the frequency ratio with respect to the noise temperature contribution of water vapor, cloud, and rain. The contribution from the dry oxygen component of the atmosphere is drawn from other data.

Returning to Table 1, the 1982 estimate of performance advantage uses the new 32- and 8.4-GHz models of attenuation and noise temperature. The net advantage of operation at 32 GHz will equal or exceed a value of 5 to 6.2 dB at Goldstone for 90% of the time.

2. **Prediction of link performance.** We have seen how radiometer and other measurements are combined to permit a more complete understanding of the effects of weather on the performance of a 32-GHz link. By knowing the probability that a particular link degradation may take place, the spacecraft designers can plan how to meet mission requirements. Figure 6 shows an example of the predicted ratio of received signal power to noise spectral density as a function of time. Curves are given for each of the three earth station locations and for four different weather assumptions. (The curves in this example are for a particular 8.4-GHz telemetry link for the Galileo mission to Jupiter. The values shown may *not* be extrapolated to 32 GHz without serious error. A 32-GHz example of link prediction was not available for this paper.)

[2]This simple relationship is only valid for small (0 – 0.5 dB) values of attenuation.

Thus we see that radiometer measurements taken to improve the estimated telemetry performance advantage at 32 GHz may also be used as part of the data needed for more accurate navigation. Knowledge of atmospheric delay is also applicable to the 2- and 8-GHz bands used for current deep space missions.

VI. Working Toward a 32-GHz Capability

In the foregoing paragraphs we have discussed antenna improvements, maser development, and data collection for propagation models. These are just a beginning in the development of an operational capability at 32 GHz. The development will take several years and involve some important steps that will be described next.

A. Uplink Requirement for 32-GHz Downlinks

Coherent two-way communication is needed for the doppler tracking that is an essential part of spacecraft navigation. Two-way communication requires an uplink, a coherent frequency change in the spacecraft transponder, and a downlink. In principle, the current 2.1-GHz uplink transmitter could be used in conjunction with a 32-GHz downlink from a spacecraft. A 32/2.1 turnaround ratio would be required in the transponder. That ratio is too large and would result in excessive downlink phase jitter. Fortunately, a higher frequency uplink will be available in time for the 32-GHz requirement.

Uplink capability at 7.2 GHz is being developed for the Galileo mission to Jupiter. For a future spacecraft with a 32-GHz downlink, a 7.2-GHz uplink would allow an acceptable transponder turnaround ratio.

B. Capability Demonstration

In order to convince mission planners that 32-GHz downlinks are practical and offer advantages, it is necessary to demonstrate a reliable capability. In the absence of 32-GHz transmissions from spacecraft, another way must be found to show that the necessary receiving system development has been accomplished. There are three possibilities. First, a combination of an improved antenna and maser, plus the associated receiving equipment, could be operated over a protracted period without any received signal. Measurement of system noise temperature would allow demonstration of reliability and predicted performance. Correlation of the measured temperature with weather models would show the degree to which claimed performance advantage could be realized in practice.

Second, the receiving system capability could be demonstrated by listening to radio star emissions. Important data about antenna pointing would be gathered also.

Third, and most comprehensive, a 34-GHz radar experiment would provide valuable experience with both up and down links. The weak echoes from objects in space would test the receiving system. The radar experiment would also give experience with the equipment and techniques for needed high power transmissions in the 34-GHz deep space uplink band.

The eventual achievement of communication capability at 32 GHz is thus seen to be the result of laboratory analysis and development, field testing and experimentation, and careful planning to ensure that the necessary steps are taken according to a schedule that meets the future requirements of space exploration.

VII. Conclusion

In this paper we have seen that a 32-GHz telemetry link from a spacecraft in deep space could have a performance advantage of 5 to 6.3 dB, as compared to the 8.4-GHz band currently used. This advantage depends upon a number of improvements in equipment and technique. Some of these were discussed: antennas, low noise amplifiers, and propagation modelling. Ways of demonstrating readiness for 32-GHz operational links were also considered. In addition, we have seen how the study of needed 32-GHz improvements sometimes yields information that is also useful in the lower frequency bands.

The long and challenging process of developing the capability of using 32 GHz for deep space research has begun.

Table 1. Estimated 32-GHz performance advantage that will be equalled or exceeded for 90% of the time at Goldstone, as compared to 8.4 GHz

Parameter (See text)	1978 estimate, Elevation angle, 30 deg			1982 estimate, Elevation angle, 30 deg		
	Value at 8.4 GHz, X	Value at 32 GHz, K_A	K_A/X ratio, dB	Value at 8.4 GHz, X	Value at 32 GHz, K_A	K_A/X ratio, dB
Spacecraft efficiency	0.17	0.17 – 0.13	0.0 to –1.2	0.17	0.17 – 0.13	0.0 to –1.2
Ground efficiency	0.61	0.36	–2.3	0.61	0.36	–2.3
Tropospheric loss factor	0.97	0.85 – 0.69	–0.6 to –1.5	0.99	0.9	–0.4
System noise temperature, K	34 – 38	66 – 127	–2.9 to –5.2	24	45	–2.7
Frequency, GHz	8.45	32.0	+11.6	8.45	32.0	+1.6
Total, dB	–	–	+5.8 to +1.4	–	–	+6.2 to +5.0

Table 2. Characteristics of DSN 64-m antenna, 8.4 GHz

Gain	72.1 dBi
Beam width	0.036 deg (3 dB)
Polarization	RCP, LCP
Ellipticity	1.0 dB
Pointing accuracy	0.02 deg (master equatorial reference)
Pointing precision	0.002 deg
Efficiency	51%

Table 3. Estimated pathlength errors and associated losses for improved 64-m antenna

Error mechanism	Elevation angle: Zenith, σ, mm	Zenith, X-band loss, dB	Zenith, K_a band loss, dB	30 deg, σ, mm	30 deg, X-band loss, dB	30 deg, K_a band loss, dB	10 deg, σ, mm	10 deg, X-band loss, dB	10 deg, K_a band loss, dB
Gravity (structure)	0.42	-0.10	-1.38	0.038	-0.00	-0.01	0.19	-0.02	-0.28
Wind, 32 km/hr (20 mph)	0.28	-0.04	-0.61	0.28	-0.04	-0.61	0.28	-0.04	-0.61
Subreflector manufacturing	0.25	-0.03	-0.49	0.25	-0.03	-0.49	0.25	-0.03	-0.49
Panel manufacturing	0.25	-0.03	-0.49	0.25	-0.03	-0.49	0.25	-0.03	-0.49
Panel setting	0.25	-0.03	-0.49	0.25	-0.03	-0.49	0.25	-0.03	-0.49
Tropospheric turbulence	0.12	-0.01	-0.11	0.18	-0.02	-0.25	0.30	-0.05	-0.70
Antenna pointing	0.15	-0.01	-0.17	0.15	-0.01	-0.17	0.15	-0.01	-0.17
Totals	0.69	-0.25	-3.74	0.57	-0.16	-2.51	0.64	-0.21	-3.23

Table 4. Example of 8.4-GHz sky noise temperature computation using data from 32-GHz model

	Parameter	Value K	Comment
(1)	Total 32-GHz tropospheric noise	29.0	From statistical model
(2)	Contribution from oxygen only	9.8	From other data for clear dry atmosphere
(3)	Contribution from water vapor, cloud, and rain	19.2	(1) − (2)
(4)	8.4-GHz contribution from water vapor, cloud, and rain	1.4	$(3) \div (32/8.4)^2$
(5)	8.4-GHz contribution from oxygen only	3.5	From other data for clear dry atmosphere
(6)	Total 8.4 GHz tropospheric noise	4.9	(4) + (5)

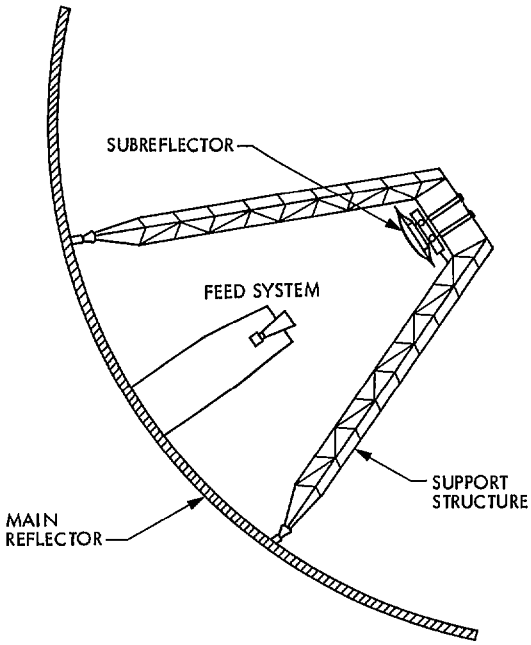


Fig. 1. Cassegrain fed dual reflector antenna

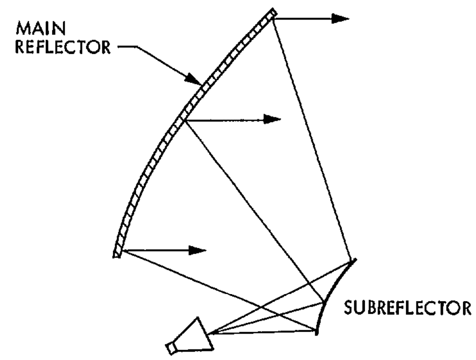


Fig. 2. Offset fed dual reflector antenna

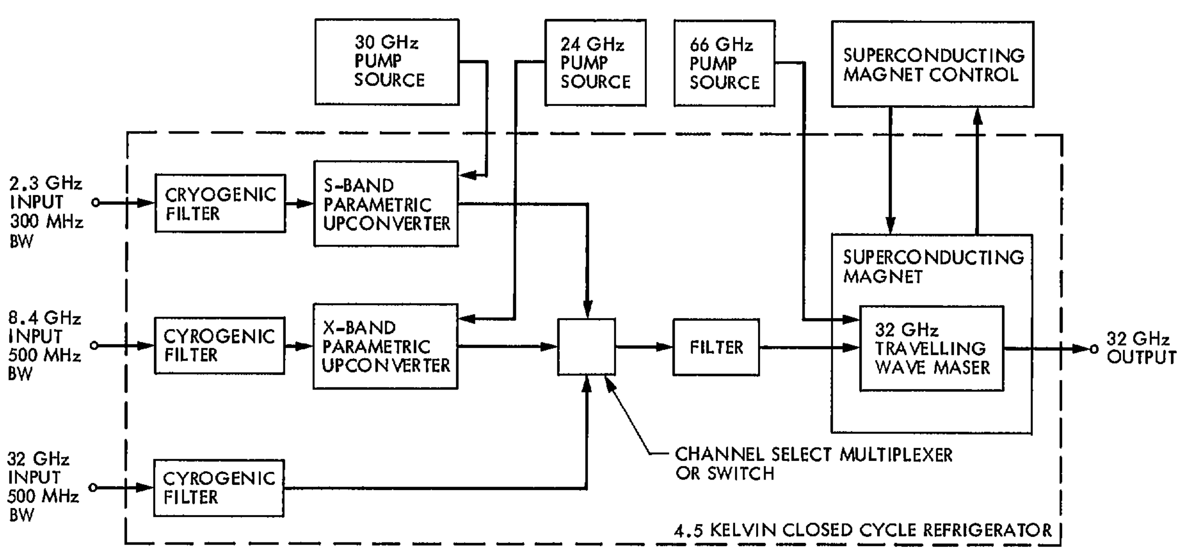


Fig. 3. Multifrequency low noise amplifier

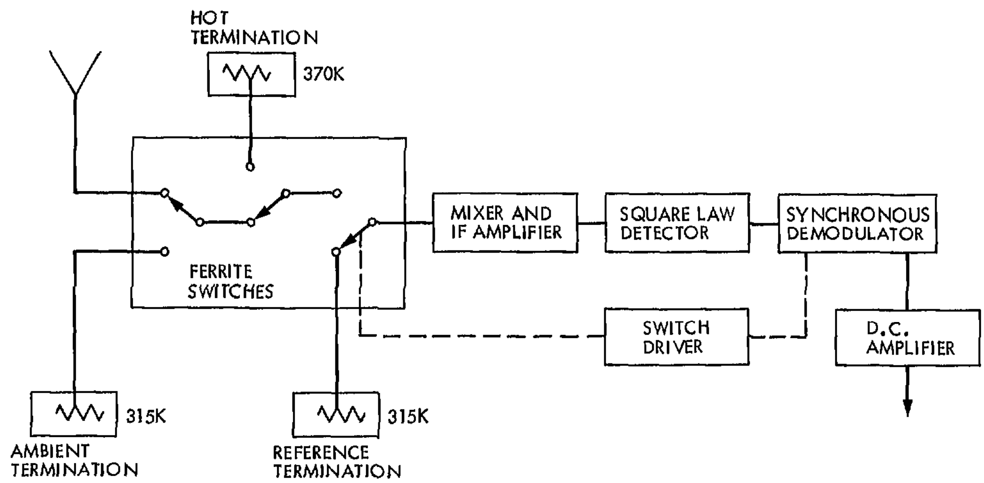


Fig. 4. Block diagram of radiometer

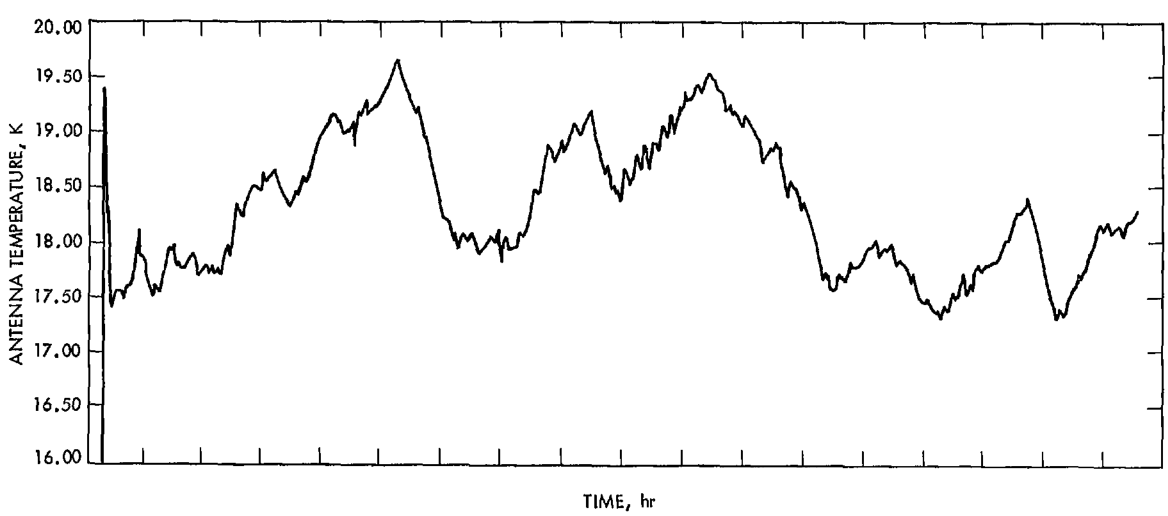
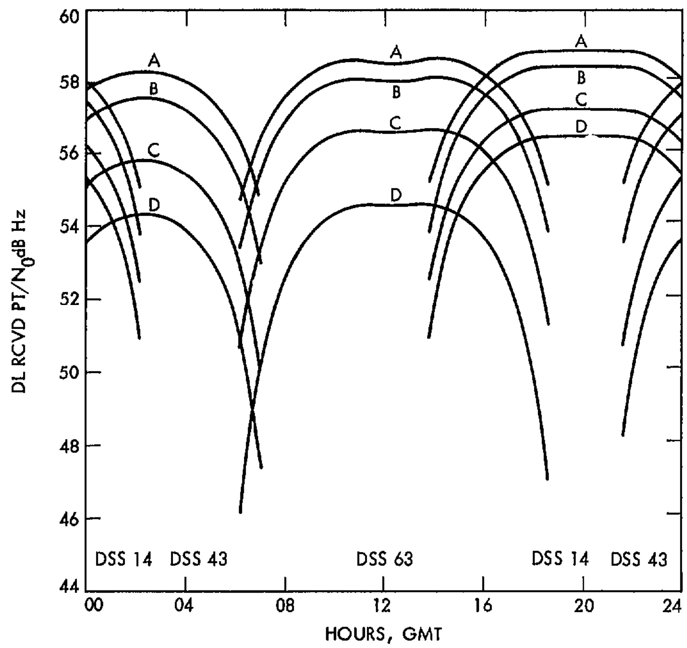


Fig. 5. Example of antenna temperature measurement made by radiometer at 31 GHz



A CLEAR DRY WEATHER, MEAN LINK

B STATISTICALLY DERIVED EXPECTED VALUES OF PERFORMANCE, COMBINED WEATHER AND LINK

C PERFORMANCE THAT WILL BE EXCEEDED 90% OF THE TIME, COMBINED WEATHER AND LINK

D EXPECTED VALUE OF LINK PERFORMANCE MINUS 2σ LINK TOLERANCE, MINUS 90th PERCENTILE WEATHER LOSS

PT TOTAL RECEIVED POWER, dBm

N_0 NOISE SPECTRAL DENSITY, dBm/Hz

DSS 14 GOLDSTONE, CALIFORNIA

DSS 63 CANBERRA, AUSTRALIA

DSS 43 MADRID, SPAIN

Fig. 6. Downlink PT/N_0 for Galileo mission vs time on 14 August 1991, 8.4 GHz