EARTH TERMINAL DESIGN CONSIDERATIONS FOR BIOMEDICAL COMMUNICATIONS VIA CTS

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Summary

This paper describes the earth terminals in the Biomedical Communications Experiment via the Communications Technology Satellite (CTS). Important analyses performed in the selection of the earth terminal parameters are summarized. In particular, analyses of the link, inter-modulation products, and rain attenuation are presented as rationales for selecting ground transmitter power, receiver G/T, frequency spacing, that are optimum for TASO Grade 1 video quality, full-duplex color video/audio and an audio order-wire capability.

1.0 Introduction

In recent years satellite systems have provided the capacity for, meeting many social needs by greatly expanding and improving communications. The Communications Technology Satellite (CTS), launched in January 1976 as a joint U.S.-Canadian venture and placed in synchronous orbit at 116° West Longitude, is an important element in the continuing development of such capability to fill a variety of social needs in an efficient and cost-effective manner. A number of experiments with CTS will be coordinated by the National Library of Medicine's Lister Hill Center in the areas of medical education, health care delivery and medical research dissemination.

The goal here is to document the analyses, assumptions, design considerations and tradeoffs which establish the feasibility of operation. First, a description of CTS is presented, highlighting those relevant characteristics assumed in the design of the communications system. This is followed by a frequency plan, operating points, signal parameters, link analyses, performance analyses and rain margin considerations.

2.0 CTS Spacecraft Characteristics

2.1 Communications Transponder

The CTS communications subsystem consists basically of two steerable antennas, a high-power traveling wave tube amplifier (TWT) capable of a maximum output of 200 W, redundant 20 W TWT's, and a highly sensitive high-gain parametric amplifier receiver with a Tunnel Diode Amplifier (TDA) backup. A schematic of the transponder switched to its primary mode, is shown in Fig. 1. The transponder has two 85 MHz passband channels, two transmit bands (TB1 and TB2) in the 11.7 - 12.2 GHz range, interfaced with two receive bands (RB1 and RB2) in the 14.0 - 14.3 GHz range.

To describe duplex operation, briefly, in the primary operational mode the transponder will receive 14 GHz signals (RB1) via antenna No. 1, and amplify and re-radiate the signals through antenna No. 2 as TB1. In this mode the 20 watt TWT is used as a driver amplifier for the 200 watt TWT which drives antenna No. 2. The transponder can simultaneously receive other 14 GHz signals (RB2) via antenna No. 2, amplify and frequency translate them to 12 GHz, then send them through antenna No. 1 as TB2.

2.2 Communications Antenna System

The characteristics of the antenna system for communications are summarized in Fig. 2. The transponder has two, gimballed, 28-inch diameter antennas with parabolic reflectors. Each antenna provides a 2.5 degree beam of circular cross-section for the simultaneous transmission and reception of orthogonal, linearly polarized signals. Isolation between the two polarizations is expected to be at least 25 dB. The electrical boresight of each antenna can be positioned anywhere within a 14.5 degree cone about the normal to the satellite forward deck. Transmit and receive gains are approximately equal with minimum transmission values of 36.2 dB along the electrical axes. First and second sidelobe levels are expected to be -14 dB and -25 dB respectively.

The antennas can be steered to cover different parts of Canada and the United States (including Alaska and Hawaii) to support various CTS communications-oriented experiments. Three boresight pierce points typical for the Biomedical Communications Experiment were selected and the corresponding footprints appear in Fig. 3. The dotted contour represents the 2.5° beam. The solid inside contour is the "effective" coverage accounting for the satellite's attitude uncertainty of ± 0.25°.

2.3 Beacon Signal

A crystal-controlled reference oscillator for the receiver of the CTS transponder system provides, after suitable multiplication, the drive for a continuous-wave, circularly polarized, 200 mW beacon. The beacon signal is transmitted at 11.7 GHz through an earth-coverage horn antenna. Its primary use is as an antenna tracking aid.

In addition, it can reduce operational uncertainty in a situation where a received signal is seen to suffer a power loss which may be caused by a problem in either the uplink or the downlink. The beacon signal received at a transmitting station provides an indication of uplink quality independent of the downlink at the receiving station.

3.0 Communications Link Considerations

To specify the nature of the signals to be transmitted, since each of the two passband channels is 85 MHz wide, no difficulty is encountered in fitting into each one a color video signal with four audio subcarriers, each composite signal using up no more than 30 MHz of bandwidth. Simultaneous two-way (full-duplex) communication is accomplished by sending signals in one direction that are amplified by the 20 W amplifier, and in the other direction signals amplified by the 200 W amplifier. In addition to these broadband signals, it is intended to include an audio "order-wire" channel in TB2, a carrier frequency-modulated by an audio baseband. The purpose of this order-wire will be clarified by describing one possible scenario. Imagine a "central station" A in one footprint transmitting to a set of "field stations" B, C, D, etc., in the other footprint. Assume A and B are in a duplex video mode, that is, B's transmission is being received at A while A is transmitting. Should another field station, C for instance, want to request permission to talk to A, it can do so via the order-wire without interfering with the existing communications. This feature would conceivably be useful in an application involving, for example, a lecturer at A and a set of remote classrooms at the field stations, since it permits each classroom access to the lecturer for questions or comments without interrupting the proceedings.

As a result of analyses summarized in the following section, figures for ground transmitter power, margins, typical outages and video signal quality, are shown in Figure four to provide some idea of system capability in relation to the selected system parameters.

3.1 Link Analyses

Since the satellite characteristics are fixed quantities within the system, performance is ensured only by selecting earth terminal parameters such as ground transmitted power P_t, system noise bandwidth B_{IF}, antenna gain G and system noise temperature T. Of these parameters a 10 foot antenna is selected because any increase in gain available with a larger antenna would be offset by the operational difficulties caused by the increase in size, weight and the more rigorous tracking requirements of the larger antenna.

Various transmitter-receiver combinations were considered in order to give an indication of the range of system performance. As an example, it was clear that an FM threshold of 11 dB cannot be exceeded on the 20 W downlink by using an 865°K mixer in the receiver front-end. However, some margin will always be available for both downlinks by using a 220°K parametric amplifier.

Although the parametric amplifier seems to be a good choice for any location, it is an absolute necessity for a station receiving the 20 W downlink, since the basic limitation of the 20 W operation is the weak downlink. The transmitter power that determined this conclusion ranged from 200 W to 1.25 kW. The transmit power P_t should be selected so that under ideal operating conditions for a power limited satellite communication system the downlink, rather than the uplink, becomes the limiting portion of the overall link C/N. This requires that uplink C/N be several dB greater than downlink C/N, provided that the protective overdrive limits on the traveling wave tubes are not exceeded.

In the link budgets shown in Figure 5 and 6 , the parameters P_t,G/T and B_{IF} have been left as variables in the link budget calculations because these are design parameters. The rain attenuation losses at 14 GHz and 12 GHz, L_R^{14} and L_R^{14} respectively, are treated separately. Although the satellite transmit Power could have been left as a variable, the assumption is made that both amplifiers are operated about a dB below saturation. This is a reasonable compromise resulting from the suppression of the weaker signal by the stronger in the common 20 W amplifier and the need to maximize power in both downlinks.

Practical considerations in the uplink budget include the use of 10 ft. of WR 75 waveguide (at 0.05 dB/ft.) and six couplers (at 0.1 dB apiece). For a longer path, which at some locations will be necessary, a proportionately higher loss is assumed. Since it is most likely that the parametric amplifier will be used in the spacecraft, it appears in the link budget with a system temperature of 1315°K. This figure results from the spacecraft antenna system (25°K), earth albedo (290°K), and transponder (1000°K). Should the parametric amplifier be replaced by the TDA in the satellite the system temperature is assumed to increase by 1000°K resulting in a 2.5 dB degradation in the uplink carrier-to-noise ratio. The estimates of needed ground transmitter power in this event would increase by 2.5 dB to result in the same system capability.

The uplink budget results in general expressions for the uplink carrier-to-noise ratio $(C/N)_u$ and the received power at the satellite. These expressions lend themselves to varying P_t, B_{IF} and the uplink rain attenuation at 14 GHz, L_R^{14}.

The "nominal" received power at the satellite accounts for all the expected losses in a typical link. While the lossless received power which is 4.1 dB greater applies in a situation where feedline loss is 0.6 dB (only one coupler), no pointing losses exist in either the ground transmit antenna or the satellite receive antenna and the earth terminal is located at beam center. This "lossless" power is useful to determine the maximum permissible P_t to avoid tripping off the 200 W TWT when the link quality is exceptionally favorable.

In achieving a compromise between tripping off the amplifiers by allowing too much power in the uplink and not having adequate power for the desired signal quality, an important consideration is the previously mentioned suppression effect in the transponder: the suppression of weak signals by stronger signals in the same amplifier. The spacecraft transponder is configured such that both received signals, RB1 and RB2, are amplified by the 20 W TWT. After amplification, TB2 leaves from the antenna through which RB1 arrived. The other signal is amplified by the 20 W TWT and leaves from the antenna through which RB2 arrived. The 20 W TWT thus acts as a driver amplifier for the 200 W TWT. Since both signals share the power of the 20 W TWT an increase in the stronger suppresses the weaker. For equal strength signals arriving at both antennas, at the input to the 20 W TWT, the RB2 signal is 19 dB stronger than RB1 (they follow different paths from the input multiplexer). Should either of the incoming signals change in strength resulting in an increase in the level differential at the input of the 20 W, the smaller signal could be suppressed to the point that it cannot adequately drive the 200 W for the desired output power. On the other hand should the level differential decrease, the smaller signal could rise to the point that it overdrives the 200 W TWT, thereby tripping a switch and cutting off all output power. The problem of not having enough power to drive the 200 W TWT could be caused by an increase in RB2 (rain stops in its uplink) or a decrease in RB1 (rain starts in its uplink). The alternate problem of having too much power so that the 200 W TWT is turned off, could arise when RB2 decreases (rain starts in its uplink) or when RB1 increases (rain stops in its uplink).

To avoid either of these situations some control has to be exercised at the transmitter end. Since the problems are due to too much or too little uplink power most probably caused by a change in propagation conditions, output power could be varied in inverse proportion to the change. The beacon signal which is being tracked for antenna pointing purposes, indicates by its strength the quality of the link. This signal strength could be monitored and the uplink power manually adjusted by an operator. Alternately, a servo-mechanism arrangement could be activated by the beacon signal strength to control an attenuator at the output of the transmitter. However, this is not considered as an option at the present.

It has been stated previously that in a downlink-limited satellite communications system the uplink C/N should ideally be several dB greater than downlink C/N. However, uplink power to CTS is limited by the protective overdrive limit mentioned previously on the input to the 200 W tube which could result in tripping a switch that turns off the amplifier at overdrive levels of 3 dB or more above the input needed for saturation. The 20 amplifier is designed to withstand a 6 dB overdrive level. In light of this fact and since the net saturated gain of the 200 W path in the transponder is specified to be 122 dB, the input power, at antenna #1, receive band #1 (RB1), cannot exceed 23 - 122 + 3 or -96 dBW, unless the 20 W tube, operating into antenna #1 in transmit band #2 (TB2) is also operating near saturation. If the 20 W tube is driven to saturation, the drive signal for the 200 W tube, which is taken from the 20 W tube output, will be suppressed and uplink power in RB1 (to the 200 W tube) could safely be increased correspondingly. It should be noted that the suppression of the signal in the 20 W path is not a problem since it is much larger than the other signal in the common 20 W TWT.

In estimating the ground transmit power for nominal operation in the 200 W (RB1/TB1) signal path the following considerations apply:

In the absence of a signal in RB2, the input power $P_{in\ (RB1)}$ required to saturate the 200 W tube is 23 - 122 or -99 dBW , and to operate the tube 1 dB below saturation, a 4.5 dB input backoff applies, giving $P_{in\ (RB1)}$ = -103.5 dBW. With a signal in RB2 driving the 20 W tube close to saturation the drive to the 200 W tube is suppressed 5 dB approximately, from measured transponder suppression data. To provide -103.5 dBW, a ground terminal must transmit P_t = -103.5 + 126.2 or 186 watts. To make up for the suppression P_t in the 200 W path has to be increased by 5 dB to 588 watts.

Ignoring suppression, it may be noted that with an overdrive limit of 3 dB, the maximum input possible is -99 + 3 or -96 dBW. The corresponding maximum P_t on the ground is -96 + 126.2 or 30.2 dBW (1050 watts).

Similarly for the 20 W (RB2/TB2) signal path with the specified saturated gain of 109 dB, the input power $P_{in\ (RB2)}$ required to saturate the 20 watt TWT is 13 dBW - 109 dB = -96 dBW. With the required input backoff of about 5 dB in $P_{in\ (RB2)}$ needed to obtain 16 watts output is -96 - 5 = -101 dBW. The corresponding nominal ground transmitted power P_t is -101 + 126.2 or 25.2 dBW (331 watts) for a clear uplink. The 20 W TWT will not be tripped off till P_t exceeds 1324 W.

The uplink carrier-to-noise ratios that correspond to the values of P_t under nominal conditions can be obtained from the equation $(C/N)_u = P_t - L_R{}^{14} - B_{IF} + 71.2$. Assuming B_{IF} = 30 MHz, the $(C/N)_u$ for the downlink $(C/N)_d$ obtained for G/T = 24 dB/°K are 24.2 dB and 14.2 dB for the 200 W and 20 W signal paths respectively, and the corresponding total clear weather $(C/N)_t$ available from the 200 W and 20 W paths are 21.1 dB and 13.5 dB as appear in Fig. 4.

3.2 Figure of Merit and System Noise Temperature

The results of the previous section assumed a figure of merit G/T for the earth station of 24 dB/°K. This follows from a receive gain for the 10 foot antenna of 49.2 dB and a system noise temperature of 337°K. The selection of the antenna is a compromise between wanting a large enough antenna for good signal quality and one that is small enough to avoid making the tracking requirements a serious problem.

The total system noise temperature referred to the receiver input is given by:

$$T = \frac{T_a}{L_L} + T_L + T_R$$

where T_a is the antenna noise temperature

L_L is the antenna ohmic loss (including diplexer and feedline).

T_L is the feedline noise temperature (at feedline output)

T_R is the receiver noise temperature (at receiver input)

An antenna noise temperature T_a of 45°K results from assuming a clear-sky medium loss of 0.2 dB, source temperature (space, sun, etc) of close to 0°K, and a worst case ground temperature contribution of 35°K (for a 10-foot antenna at a 5° elevation angle).

Assuming antenna ohmic losses of 1.5 dB, T_L = 85°K $T_a/L_L \simeq$ 32°K. and T_p is typically 220° K, which add up to a system noise temperature T of 337°K.

For a rainy path the antenna noise rises in proportion to the medium loss. For example, for a medium loss of 10 dB, T_a becomes 239°K, which increases the system noise temperature to 474°K. Under such foul weather conditions, with a receive antenna gain of 49.2 dB, the fair weather G/T of 24.0 dB/°K is degraded by 1.6 dB to the foul weather G/T of 22.4 dB/°K.

3.3 Frequency Spacing

Full-duplex video communications in this system requires that multiple signals be amplified by the 20 W TWT. Since this device is to be operated in a nonlinear region, near saturation, intermodulation (IM) products are generated that could potentially cause degradation in the message basebands. The selection of the exact frequencies for the two video carriers (designated as V_1 and V_2) and the audio order-wire (A_2) depends on the frequencies and magnitudes of the resulting IM's relative to the desired signals. 3rd order IM's are assumed to be the only significant interference, higher order IM's are not.

The two video signals, V_1 in the TB1 band and V_2 in the TB2, do not by themselves cause interfering 3rd order IM products. The CTS users who need full duplex video without the order-wire have placed the carriers at the center frequencies of the two bands, for the sake of convenience. The introduction in TB2 of the audio modulated carrier, generates 3rd order IM spectrums that overlap the V_1 spectrum to some extent. This occurs when the two video carriers are at band-centers and A_2 is placed as far away as possible and still within TB2. The IM can be prevented from overlapping the V_1 spectrum if V_2 and A_2 can be spaced further apart, and V_1 moved up somewhat in frequency. These three signals V_1, V_2, A_2 have been spaced sufficiently apart, about 48 MHz, to avoid any IM's within the RF bandwidths of either V_1 or V_2, but there are IM's at 11.7 GHz, the beacon frequency. However, these are not expected to interfere with the beacon signal received by ground stations since the pre-antenna output filters in the satellite will filter them out.

4.0 Signal Performance Analyses

Since an important measure of the success of the experiment is the quality of video and audio received at the participating earth terminals, signal parameters are selected to be consistent with widely accepted performance criteria.

4.1 Video Performance

The most commonly used indicator of video signal quality is S/N, the ratio of the nominal peak-to-peak amplitude of the picture-luminance to rms noise in the video frequency band. This is given by the expression:

$$S/N = 12m^2 (m + 1) (C/N)_t W$$

where

m = FM modulation index

$(C/N)_t$ = total carrier-to-noise ratio at the receiver input

W = noise weighting improvement factor (10.2 dB)

This expression includes FM discriminator improvement, a factor to convert rms signal to peak-to-peak signal, and noise weighting improvement. It omits a pre-emphasis improvement factor since in a frequency-modulation system operating near threshold the use of pre-emphasis does not appreciably improve the signal-to-weighted noise ratio, according to CCIR Report 215-2 (1974). For systems operated well above the threshold, the improvement is estimated to be about 3 dB.

The goal for the video performance to be obtained in this experiment is an S/N in excess of 45 dB. From subjective tests performed by the Television Allocations Study Organization (TASO), a median observer would rate a picture as "excellent" (TASO Grade 1) for an S/N of about 45 dB.

The selection of modulation index m is to be consistent with the available IF bandwidth B_{IF} and the desired FM discriminator improvement. Since the video baseband is 4.2 MHz, and B_{IF} is nominally 30 MHz, the peak deviation Δf is in the neighborhood of 10 MHz, and m lies around 2. Choosing Δf = 10.5 MHz, a modulation index of 2.5 is obtained to give an IF signal occupying a B_{IF} of 29.4 MHz. The expression for S/N with the above parameters becomes S/N = $(C/N)_t$ + 34.4, which requires $(C/N)_t$ to be 11 dB to give an S/N exceeding 45 dB. For operation above a threshold of 11 dB, therefore, the selected parameters will meet the video quality goal.

4.2 Audio Subcarrier Channel Performance

Four audio channels are associated with each video signal. Each of the four audio basebands frequency modulates a subcarrier ranging from 5.14 to 6.3 MHz; these modulated subcarriers and the video baseband are summed to give a composite signal which modulates the main carrier. When received, the composite IF signal passes through a discriminator yielding the video baseband and the four modulated subcarriers at its output. Each subcarrier then is passed through a second discriminator to give the audio baseband. This makes FM improvement possible at two places, though it is not worthwhile to require an improvement in the first discriminator when ample improvement is available in the second discriminator, especially when a higher deviation in the IF carrier by the subcarrier will be required for the first improvement.

The expression for improvement in the first discriminator in multiplex systems is given as:

$$(S/N)_{01} = (C/N)_{IF} (B_{IF}/2B_s) \quad (\Delta f/f_s)^2$$

where

$(S/N)_{01}$ = signal/noise at the output of the first discriminator

B_s = subcarrier channel bandwidth

Δf = peak channel-frequency deviation

f_s = mid-band subcarrier channel frequency

B_{IF} = IF bandwidth at the input to the first discriminator

If no improvement is desired, the minimum Δf requirement is given by:

$$\Delta f \geq f_s \, (2B_s/B_{IF})^{\frac{1}{2}}$$

For typical values of B_s = 150 kHZ, B_{IF} = 30 MHz, f_s = 6.3 MHz (the highest frequency and audio subcarrier), the minimum peak-to-peak deviation 2Δf must be 1.26 MHz. Any lower deviation will result in an S/N degradation and a corresponding loss in link margin.

The improvement in the second discriminator is given by the conventional FM equation which relates output signal/noise to the other parameters:

$$(S/N)_o = 3m_a^2 \, (m_a + 1) \quad (C/N)_{in} \, W_d$$

where m_a = audio modulation index
W_d = pre-emphasis improvement
$(C/N)_{in}$ = carrier-to-noise ratio at the input to the second discriminator which equals $(S/N)_{01}$ or $(C/N)_{IF}$

For an audio baseband of 15 kHz and a subcarrier channel bandwidth of 150 kHz, m_a = 4, giving an FM improvement of 23.8 dB. Adding this figure to the12.2 dB improvement available from pre-emphasis, the output signal/noise at a threshold of 11 dB is 47 dB, a figure that ensures excellent fidelity.

4.3 Audio Order-Wire Channel Performance

The audio order-wire that shares the 20 W TWT with one video channel is formed by the audio baseband directly modulating an IF carrier. The frequency and power level of this carrier are selected to minimize the effects of intermodulation products in the video channels and to ensure that sufficient downlink signal power exists to provide good audio quality.

Assume that the carrier undergoes a peak deviation consistent with a modulation index m_a of 4 as in the case of the audio subcarriers to give an IF bandwidth of 150 kHz. The previous considerations of FM discriminator and pre-emphasis improvements hold here and an adequate audio quality [$(S/N)_o \geq 47$ dB] results if the FM threshold is exceeded. The effort here is simply to estimate the output power required from the satellite and the ground transmitter to give an adequate $(C/N)_{IF}$ at the receiver input.

To estimate the satellite output power, assume a downlink margin of 10 dB over the 11.0 dB threshold so that this voice link comes through during rain that would wipe out the video. This minimum $(C/N)_t$ of 21.0 dB may be achieved by a combination of downlink $(C/N)_d$ and uplink $(C/N)_u$ of 22.0 and 28.0 dB respectively, although other combinations are possible.

For a G/T = 24 dB/°K, the 20 W TWT at a 1 dB backoff yields a carrier-to-noise density C/N_o of 89 dB-Hz on the ground. For B_{IF} = 150 kHz, a $(C/N)_d$ of 22 dB results if C/N_o = 74 dB Hz. This corresponds to a satellite power of half a watt. The required uplink power to result in $(C/N)_u$ of 28 dB is 7.6 W.

5.0 Conclusions

The rationales for the selection of system parameters in a biomedical communications experiment via CTS have been presented. The system features full-duplex color video by simultaneously sending a 30 MHz signal in each of the two satellite transponder channels. Although these channels are 85 MHz wide in this experimental system, it is more realistic to expect narrower bandwidths on the order of 30 or 40 MHz in future operational 12/14 GHz satellite systems. The peak frequency deviation is chosen as a tradeoff between the requirements for TASO Grade 1 video quality and the bandwidth constraint. The equipment will have the capability of varying the deviation from 5 to 13 MHz, a range within which the optimum value will be determined by trial. The deviation for the audio channels also has been optimized, although high signal quality is much easier to achieve in this case.

The suppression characteristics of the transponder and its tripoff limit have been traded off to give 588 W and 331 W for the ground transmitter power for stations accessing the 200 W and 20 W channels respectively. The two video channels and the order-wire have been frequency spaced to avoid third order IM products.

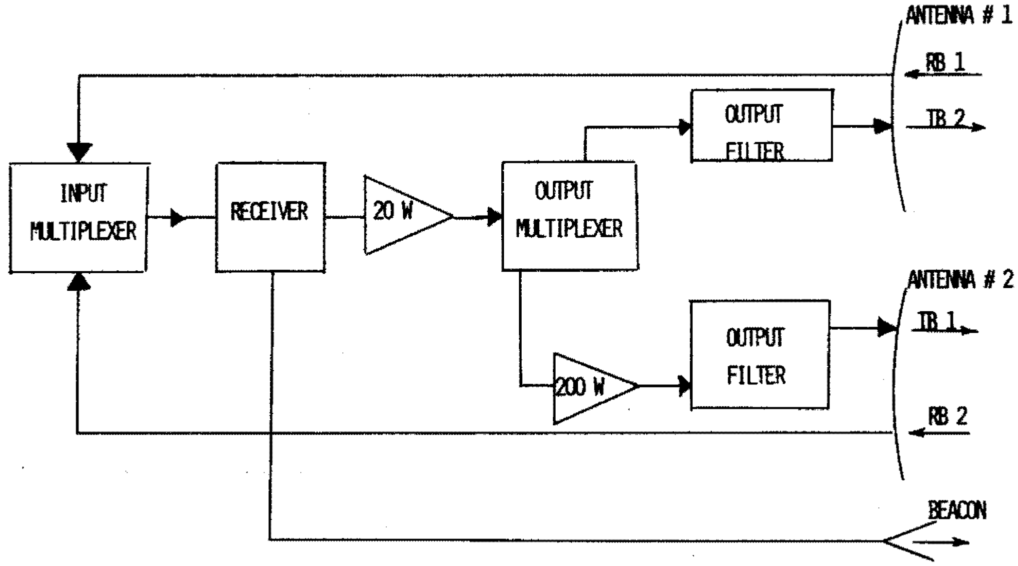

Fig. 1 CTS Transponder: Simplified Diagram

Diameter	2-1/3 ft.
Beam Width	2.5°
Gain on Axis-Transmitting	36.3 dB
-Receiving	36.2 dB
Boresight Pointing Accuracy	± 0.25°
Boresight Steering Range	± 8.5°

Fig. 2 CTS Communications Antenna Characteristics

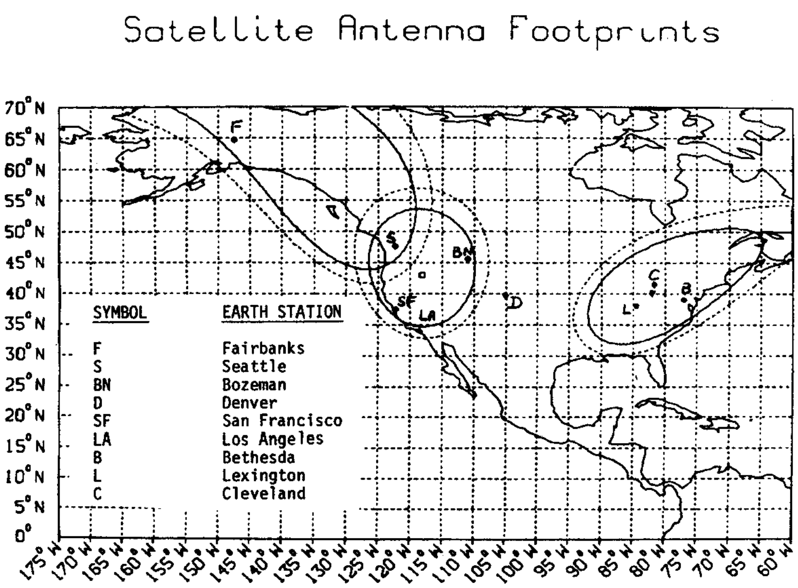

Fig. 3

Station Xmt	Station Rec	TWT (Watts)	P_T (Watts)	$(C/N)_U$ (dB)	Uplink Margin(1) (dB)	Typical Outage(2) (%)	$(C/N)_T$ (dB)	Overall Margin(3)	Typical Outage (%)	VSNR(4) (dB)
A	B	200	588	24.1	3.3	0.1	13.5	2.5	0.1 to 10	47.9
B	A	20	331	21.6	5.8	0.1	21.1	10.1	0.01	55.5

Notes: Typical parameters for full-duplex communications between stations A and B.

(1) Uplink margin is the excess of a maximum possible ground transmit power P_T of 1250 watts over the P_T required for full-duplex.

(2) "Typical outage" refers to the percentage of time the rain attenuation at some typical location exceeds the margins (0.1% corresponds to 9 hours per year).

(3) Overall Margin is the excess of total $(c/n)_T$ over 11 dB threshold.

(4) VSNR = Video peak-to-peak signal/rms weighted noise

Fig. 4 System Parameters

Uplink Power Budget

Earth Terminal Transmitter Output Power	P_T	dBW
Feedline Loss (10 ft. WR 75 + 6 couplers)	-1.1	dB
Antenna Gain (10 ft. diameter, 55% efficiency)	50.1	dB
Space Loss (CTS - Bethesda)	-207.3	dB
Clear Sky attenuation Loss	-.2	dB
Rain Attenuation	$-L_R^{14}$	dB
Transmit Antenna Pointing Loss	-.2	dB
Satellite Antenna Gain	36.2	dB
Satellite Antenna Pointing Loss	-.2	dB
Feedline Loss	-.5	dB
Beam Edge Loss	-3.0	dB
System Noise Temperature (Parametric Amplifier, 1315°K)	31.2	dB-°K
System Noise Power Density	-197.4	dBW/Hz
Bandwidth	B_{IF}	dB-Hz
Uplink Carrier/noise, $(c/n)_U$	$P_T - L_R^{14} - B_{IF} + 71.2$	dB
Nominal Received Power (with typical losses)	$P_T - L_R^{14} - 126.2$	dBW
"Lossless" Received Power	$P_T - L_R^{14} - 122.1$	dBW

Fig. 5

Figure 6

DOWNLINK POWER BUDGET

200 W TRANSMITTER POWER (1 dB BELOW SATURATION)	22.0 DBW (158.5W)
FEED LOSSES	-.9 DB
TRANSMITTER ANTENNA GAIN	36.3 DB
SPACE LOSS (CTS - BETHESDA)	-205.9 DB
CLEAR SKY ATTENUATION LOSS	-.2 DB
RAIN ATTENUATION	$-L_R^{12}$ DB
SATELLITE POINTING LOSS	-.2 DB
BEAM EDGE LOSS	-3.0 DB
ANTENNA GAIN	G DB
TRACKING LOSS	-.2 DB
FEEDLINE AND COUPLERS	-.5 DB
BAND PASS INSERTION LOSS (DIPLEXER)	-1.0 DB
SYSTEM NOISE TEMPERATURE	T DB^{O} - K
BANDWIDTH	B_{IF} DB-Hz
BOLTZMANN'S CONSTANT	-228.6 DBW/Hz- ^{O}K
$(C/N)_D$ IN THE 200 W DOWNLINK	G/T - L_R^{12} - B_{IF} + 75.0 DB
$(C/N)_D$ IN THE 20 W DOWNLINK	G/T - L_R^{12} - B_{IF} + 65.0 DB