

AN X-BAND TELECOMMUNICATIONS TRANSMITTER FOR THE MID-COURSE SPACE EXPERIMENT

An X-band (8475 MHz) telecommunications transmitter has been designed for use on the Mid-Course Space Experiment spacecraft. The transmitter is designed for an output power of 5.0 W and operates at a data rate of 25 Mbits/s. The transmitter construction uses a two-level modular approach, allowing for easy adaption to other programs. In addition, adjustable tuning is absent to minimize time and cost during the fabrication and test phases. Two flight units have been built, qualified, and integrated as redundant units on the Mid-Course Space Experiment spacecraft.

INTRODUCTION

Background

During early 1988, the Applied Physics Laboratory was involved in early planning for the Mid-Course Space Experiment (MSX) program. That planning included a high-data-rate microwave downlink for transmitting recorded scientific data to the APL ground station. As part of the planning, an industry survey was made to determine the availability of an existing telecommunication transmitter suitable for spacecraft applications. None was found in either the X (8475 MHz) or Ku (13.6 GHz) space research frequency bands; S-band (2200 MHz) was not a choice because of its limitation on data rate. The task of developing the required transmitter was addressed in the last quarter of 1988. Since an off-the-shelf transmitter did not exist, a decision had to be made either to subcontract its development or to develop it at APL. During the same period, the Microwave and RF Systems Group at APL was working on an independent research and development effort involving the insertion of microwave integrated circuit (MIC) and monolithic microwave integrated circuit (MMIC) technology into microwave applications. Included in the effort were both a subsystem integration task and a microwave power amplifier task. The development of the telecommunication transmitter for MSX was a natural next step. Thus, the decision was made to develop the transmitter at APL.

A conceptual design for a proposed APL development was undertaken and documented in January 1989.¹ Either X- or Ku-band could have been used. X-band was chosen to minimize programmatic risk associated with cost and schedule as well as technical risks associated with efficiency, power and power conditioning, thermal considerations, weight, and availability of parts.

Design Requirements

The space research frequency band for spacecraft-to-ground communications at X-band has a total bandwidth of 50 MHz centered at 8475 MHz. After some early iterations, the required downlink data rate for MSX was

fixed at 24.99 Mbits/s. To minimize the transmitted signal bandwidth, quadriphase shift keying (QPSK) modulation was chosen. In addition, the data were differentially encoded to eliminate the inherent phase ambiguities of QPSK. The system link analysis showed that the minimum power necessary to provide the theoretically required bit energy-to-noise ratio (E_b/N_0), including an allowance for minimum margin, was about 1.3 W (W. T. Gray, pers. comm., 1989). To provide a comfortable margin over this minimum requirement, the output power of the transmitter was set at a minimum of 5.0 W.

Weight and power were concerns for the MSX spacecraft, although minimizing the size was not a requirement. Thus, the initial ground rule was to minimize the risk by taking advantage of available MMIC circuit blocks, but not to design dedicated MMIC circuits. A summary of the design requirements for the transmitter is given in Table 1.

Table 1. Transmitter design requirements.

Output frequency	8475 MHz
Long-term frequency stability	±20 ppm
Output power	5.0 W (min)
Data rate	24.99 Mbits/s
Modulation	Differentially encoded QPSK
Modulation amplitude balance	0.5 dB (max)
Modulation phase balance	±5° (max)
Spectrum	Filtered to meet NTIA requirements
Spurious and harmonics	<-60 dBc
Size ^a	11.1135 × 19.0500 × 8.8900 cm
Weight ^a	2.268 kg (max)
DC input power ^a	35.0 W (max)

Note: QPSK = quadriphase shift keying; NTIA = National Telecommunications and Information Administration.

^aFigures do not include the DC/DC power conditioner.

TRANSMITTER DESIGN

Electrical Design

A functional block diagram of the transmitter is shown in Figure 1. Briefly, it operates as follows: The output frequency is derived from the crystal oscillator shown at the left center, which is first multiplied to the source frequency of 847.5 MHz. The signal is then split into three paths. One is a continuous-wave reference used for test purposes, the second is the RF input to the QPSK modulator, and the third is multiplied to 7627.5 MHz for use as the local oscillator signal for the up-conversion mixer. The upper sideband out of this mixer, 8475 MHz, is amplified for radiation by the antenna.

The first consideration in the design approach to the transmitter was overall power efficiency. The bandwidth of the output spectrum of a transmitter must be controlled to meet the requirements of the National Telecommunications and Information Administration.² (The requirement for this transmitter is superimposed on the plot of its output spectrum shown later in Fig. 5.) If the relatively narrow bandwidth filter necessary to satisfy this requirement was placed at the transmitter output, excessive losses would occur. Consequently, the design approach was to perform the modulation and spectrum control filtering at a lower frequency where the losses would be lower because of the relatively wider bandwidth of the filter. In addition, it is more power efficient to make up the losses at a lower power level. The modulated signal would then be translated to the output frequency, and all subsequent gain would be provided by linear amplifiers. The frequency chosen was 847.5 MHz, one-tenth of the output frequency.

The 847.5-MHz source frequency was chosen in anticipation of using an off-the-shelf fundamental-mode surface acoustical wave oscillator. A survey of the indus-

try indicated, however, that a surface acoustical wave oscillator could not be guaranteed to meet our long-term frequency stability requirement. That finding dictated the use of a relatively simple purchased crystal oscillator, operating at 105.9375 MHz, and a $\times 8$ multiplier to generate the desired 847.5-MHz source frequency.

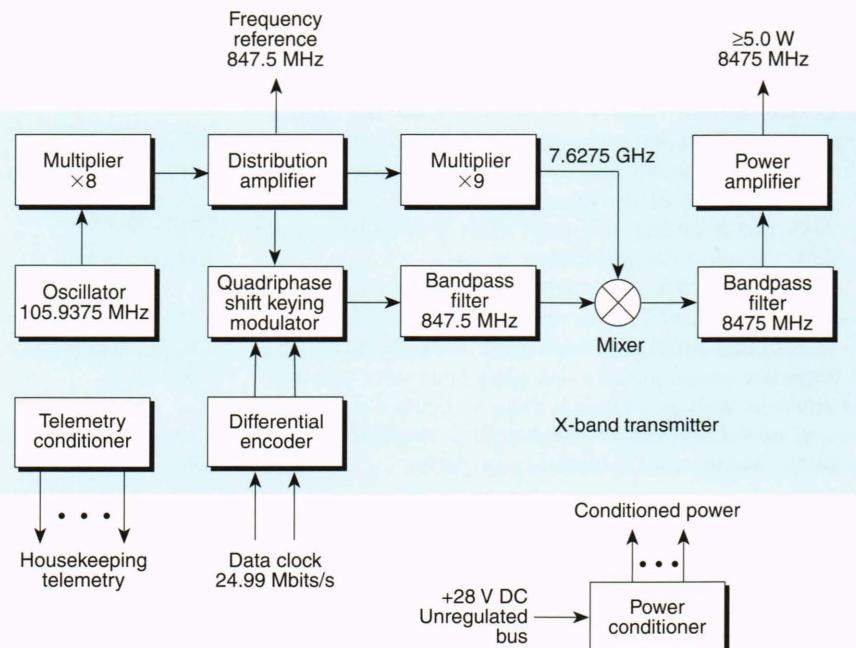
Also shown in Figure 1 are two support functions. One is an external DC/DC power conditioner, which is a necessary part of the transmitter subsystem. It provides the required regulated voltages and sequences them on and off in the proper manner to prevent damage to the gallium arsenide (GaAs) field-effect transistors (FET's) used in the transmitter. The other support function is conditioning circuitry for the housekeeping telemetry monitors.

Mechanical Design

Whereas minimizing the size of the transmitter was not a critical issue in itself, it was important in maintaining low weight. This design goal indicated the need for reasonably dense packaging techniques. Also, it was desirable to place as much of the design, fabrication, and test effort as possible in parallel since the schedule was relatively short. Therefore, a modular design was selected. In addition, adapting the transmitter for use on other programs is easier if a modular design is used. The assigned channel frequency, output power, modulation format, and so on, are usually program-unique. The transmitter can be adapted to new programs by modification only to those modules affected.

The functional blocks of the transmitter were partitioned into four parts representing stand-alone functions that could be implemented with about equal amounts of circuitry. The four parts became the modules and were given names appropriate for their prime functions: source, modulator, translator, and power amplifier. The transmitter consists of the four modules stacked and

Figure 1. Functional block diagram of the X-band transmitter.



bolted together as a single unit. All connections between the modules are on one face and are enclosed within the transmitter package by a dust cover. All connections with other spacecraft subsystems are on another face of the transmitter package. The housing of each of the modules is an open-top tray with its own electromagnetic-interference-tight cover. The fully assembled transmitter is shown in the center of Figure 2 surrounded by the four modules with their covers removed.

Each of the four modules was further partitioned into definable circuit functions and constructed using a submodule approach. Individual circuits were patterned onto microstrip circuit boards that were then broad-area soldered ("sweated") to mounting plates. After being populated with piece parts and tested, the mounting plate submodule was mounted into its module housing. The number of submodules in each module varied, depending on the circuit requirements. This construction technique is illustrated in Figure 3.

To keep the weight low, the metal of choice for use throughout the transmitter was aluminum, both for the module housings and the submodule mounting plates. The mounting plates used in high-power dissipating circuits were solid for better heat conduction, whereas all others had their back sides recessed to reduce weight. The mounting plates were gold-plated because the circuit boards were soldered to them, but the housings were not plated. Soft circuit boards made of Duroid 6010.5 (a trade name of the Rogers Corp.) were chosen. This material has a thermal coefficient of expansion very closely matched to the aluminum mounting plates and a relative dielectric constant of 10.5. Ceramic circuit boards made of alumina were avoided for fear of cracking problems arising from the mismatch in thermal coefficient of expansion between them and the aluminum mounting plates over the design temperature range of -30 to $+65^{\circ}\text{C}$.

The thermal design of the transmitter is an integral part of the package design. Because of the vacuum environment and the thermal design of the MSX spacecraft, the heat transfer is predominantly by way of conduction through the transmitter's mounting surface. Thus, the largest power-dissipating module, the power amplifier, was placed on the bottom of the stack. The location of the other three modules in the stack was not important for thermal considerations, so they were arranged in order of descending frequency above the power amplifier to minimize the length of the connections between the modules. At the submodule level, piece parts requiring heat sinking were attached directly to the mounting plates through cutouts in the Duroid microstrip circuit boards.

Source Module

The primary function of the source module is to multiply the output of a 105.9375-MHz crystal oscillator to a frequency of 847.5 MHz. This function is shown as the $\times 8$ block in Figure 1. The source module also provides buffered outputs of the signal to the other modules (distribution amplifier in Fig. 1). Finally, the source module houses the conditioning circuitry for the housekeeping telemetry monitors (telemetry conditioner in Fig. 1).

The frequency multiplication method chosen for the $\times 8$ was direct multiplication in a single step using a step recovery diode (SRD), a device whose output is extremely rich in harmonics. The $\times 8$ block contains a driver amplifier followed by a network for matching power going into the SRD, which is, in turn, followed by a bandpass filter used to select the desired harmonic. Although computer-aided engineering (CAE) programs were used extensively in the design of the transmitter, models for highly nonlinear devices such as SRD's do not currently exist. Thus, this design was performed in a largely empirical manner. Generally, SRD's are driven into hard saturation. In keep-

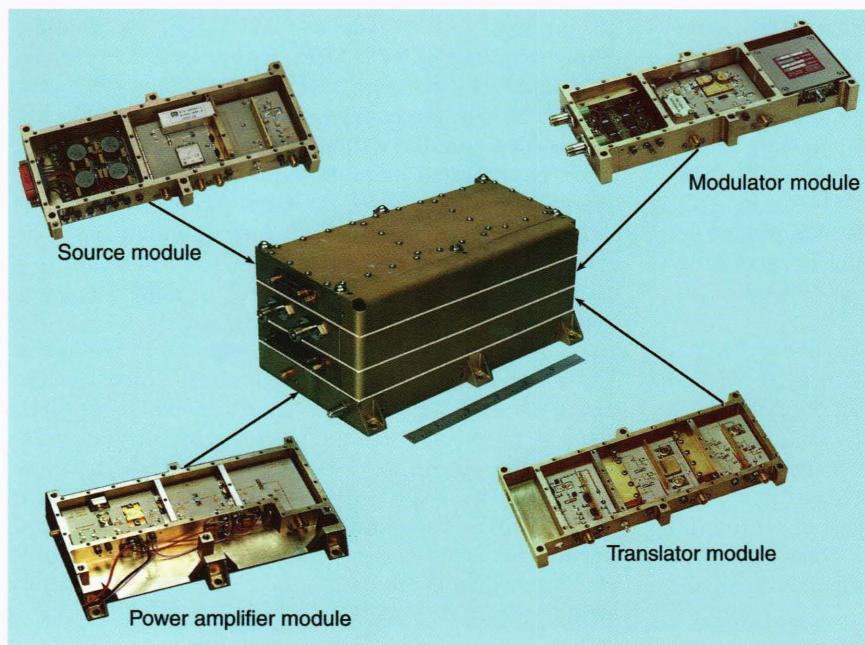


Figure 2. Fully assembled X-band transmitter and each module with its cover removed.

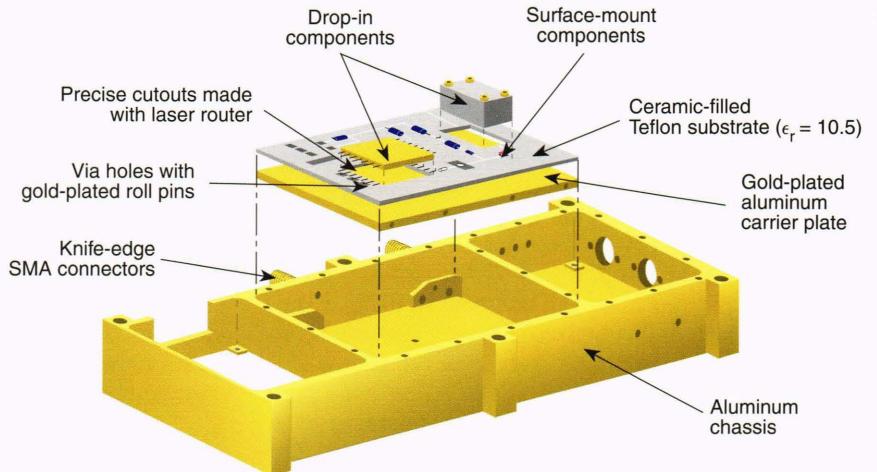


Figure 3. Open view of the typical module construction (ϵ_r = relative dielectric constant).

ing with the desire to hold the DC power low, however, this circuit was designed at a power level that provides stable and consistent performance but operates well below hard saturation.

Various technologies were used in the source module, consistent with the design goals. Packaged drop-in silicon MMIC amplifiers were used in both the SRD driver amplifier and the distribution amplifier. The matching network was a combination of patterned microstrip lines and chip components. The 847.5-MHz bandpass filter was a miniature drop-in component. The telemetry conditioner was implemented with integrated circuit instrumentation amplifiers and chip components on a standard printed wiring board. The source module can be seen in the upper left corner of Figure 2.

Modulator Module

The modulator module performs three of the functions shown in Figure 1. They are the differential encoder including the data and clock interfaces with the spacecraft, the QPSK modulator, and the spectrum control bandpass filter. Although not shown, an RF gain versus temperature compensation network is also included. Finally, the crystal oscillator is housed in the modulator module.

The differential encoder formats the input data so that bit pairs 00, 01, 11, and 10 will produce RF phase changes out of the QPSK modulator of 0° , 90° , 180° , and 270° , respectively. With this encoding scheme, the ground receiver can unambiguously determine the bit pattern by observing the transmitted phase changes instead of absolute phases.

The RF input to the modulator module is at 847.5 MHz. The input circuits consist of the gain compensator and an isolation amplifier. The gain compensator provides open-loop compensation for transmitter gain variations due to temperature, thereby maintaining a relatively constant power level out of the transmitter. It consists of a PIN diode (a current-controlled RF resistance) in series with the signal path. The diode current is controlled by a thermistor network that senses the temperature of the modulator housing.

Next in the chain is the QPSK modulator that interfaces with the encoder with a simple, high-speed driver circuit.³ A bandpass filter following the QPSK modulator provides a 24-dB per octave roll-off with a 3-dB bandwidth of 36 MHz for spectral shaping of the modulated signal.

Several technologies are used in the modulator module. The encoder is implemented with emitter-coupled logic and with Fairchild advanced CMOS (complementary metal oxide semiconductor) technology logic, both of which are high speed and radiation resistant. The devices are in a flat-pack configuration installed on a polyimide multilayer printed wiring board. The crystal oscillator is a purchased item packaged in its own connectorized enclosure. The remaining RF components are a combination of miniature drop-in, chip component, and silicon MMIC technology installed on a patterned microstrip board. The modulator module can be seen in the upper right corner of Figure 2.

Translator Module

The translator module contains all the circuitry necessary to translate the modulated 847.5-MHz signal to the output frequency of 8475 MHz. This process is illustrated by three blocks in Figure 1: the $\times 9$ multiplier, the mixer, and the 8475-MHz bandpass filter.

The local oscillator frequency for the up-converter mixer is generated by multiplying the 847.5-MHz continuous wave input to 7627.5 MHz. Again, this multiplication is performed in a single step using an SRD. The design procedure for this multiplier was similar to that used for the multiplier in the source module. The $\times 9$ is followed by an amplifier used to increase the level of the 7627.5-MHz signal to 10 dBm, as required by the mixer. The intermediate-frequency input to the mixer is the modulated 847.5-MHz signal from the modulator module. The mixing process produces a replica of the intermediate-frequency input signal at both 847.5 MHz below and above the 7627.5-MHz local oscillator frequency. The 8475-MHz bandpass filter selects the upper sideband signal. The signal is then amplified to a level of nearly 20 dBm, which is required to drive the power amplifier module.

It was necessary to implement the 7627.5- and 8475-MHz amplifiers in MIC circuitry using discrete GaAs FET's and chip resistors in their bias circuits, since no suitable MMIC's were available. The objective of this design was to eliminate all post-fabrication tuning and adjustments. Thus, all matching was fixed and was accomplished with microstrip transmission lines patterned on the Duroid circuit board. The design procedure began with the measurement of commercial FET S-parameters. From these data, a set of average S-parameters was generated for use in the design process. When the screened flight FET's arrived, their S-parameters were also measured. Individual flight FET S-parameter data were then used in the CAE simulation to select FET's with acceptable performance in the fixed tuned design. By using this procedure, better than 75% of the flight FET's gave acceptable performance. Agreement between the measured and simulated performance was good. The translator module can be seen in the lower right corner of Figure 2.

Power Amplifier Module

The power amplifier module is shown in Figure 1 as a single block. Its size and importance should not be diminished by the lack of space given it in the block diagram. The function of the power amplifier is to increase the level of the modulated signal out of the translator module to 5.0 W. The output of the power amplifier is protected with an isolator. A dual directional coupler follows the isolator to provide monitoring of the transmitted and reflected power.

The technology and design methodology used in the power amplifier module were similar to those used in the translator module. The power amplifier module included discrete GaAs metallic Schottky barrier (MES) FET's and chip components because of the unavailability of power MMIC devices.

A three-stage power amplifier was required to provide the necessary gain. Because a design objective for the transmitter was to keep the DC power low, and since the three stages are the largest power consumers, it was important to operate them at their most efficient point. At the same time, near-linear operation had to be maintained so that significant sidelobe regrowth of the modulation spectrum would not occur. In satisfying these conflicting requirements, the power amplifier was designed to operate at a compression level of about 1 dB and has an efficiency between 19% and 23%.

The final stage in the power amplifier was implemented with an internally matched MESFET; matching networks had to be provided for the first two stages, however. Linear S-parameter data were not sufficient for synthesizing the networks, because of the nonlinear characteristics of the power MESFET's when operated near or into compression. The Cripps Method⁴ was used to generate a large-signal equivalent circuit model of the output of the MESFET devices, thereby allowing for synthesis of optimum output matching networks.

Because of their construction, microwave power MESFET's exhibit high gain at low frequencies. As a result,

they are highly susceptible to low-frequency oscillations, which are suppressed in this design by using appropriate filters in the bias networks. The power amplifier module can be seen in the lower left corner of Figure 2.

MEASURED PERFORMANCE

This section covers the results of performance measurements made on the two units built and integrated onto the MSX spacecraft. The measurements showed that the requirements listed in Table 1 were either met or the noncompliances were small enough to be acceptable. Some of the key performance parameters are highlighted in the following discussion.

The output power of each transmitter is listed in Table 2, indicating an output power of 4.2 to 5.0 W over the required temperature range. At the outset, it was believed that the FET selected for the final stage would be sufficient to produce the required output power. Several things, however, caused the realized output power to drop below 5.0 W, such as the level of compression at which the amplifier was operated, the increment in setting the drive level to the power amplifier module, and variations between the desired and actual gain compensation curves. As stated in the "Design Requirements" section, the specification of a minimum output power of 5.0 W came about in part by selecting a round value that provided more than the minimum required margin. Although the measured minimum power of 4.2 W did not meet this level, the link margin was deemed adequate, and the flight transmitters were not further optimized to increase the output power.

The typical bit error rate performance of the X-band link, using a flight transmitter, is shown in Figure 4. It shows a degradation from the theoretical value of just 1.1 dB at a bit error rate of 10^{-8} . A large portion of this degradation (half or more) is known to be a result of the receiving equipment and not of the transmitter.

Output spectral plots are shown in Figures 5 and 6. Figure 5 shows the spectrum when modulated with random data. This plot was chosen to show the worst-case compressed performance of the two transmitters. The maximum envelope requirement for the spectrum specified by the National Telecommunications and Information Administration is superimposed. Figure 6 shows the broadband unmodulated spectrum. Again, it was chosen to show the worst-case performance of the two transmitters. The -60 dBc spurious requirement is

Table 2. Transmitter DC input and RF output powers.

Temperature (°C)	Transmitter S/N001		Transmitter S/N002	
	P_{DC} (W)	P_{RF} (W)	P_{DC} (W)	P_{RF} (W)
-30	31.34	4.55	28.87	4.31
-10	31.73	4.83	28.66	4.48
+10	31.76	4.69	28.72	4.47
+25	31.71	5.00	29.57	4.88
+45	30.97	4.71	29.53	4.71
+60	30.97	4.37	29.40	4.20

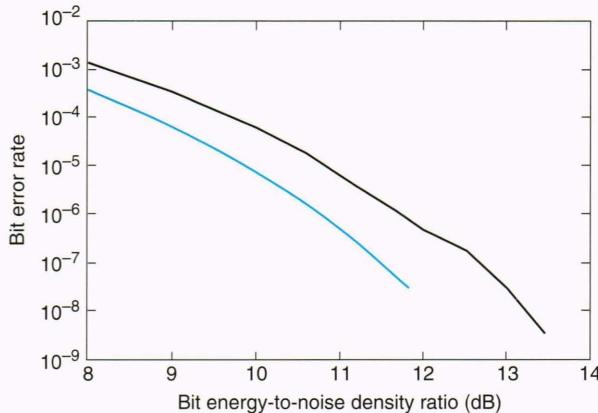


Figure 4. Typical measured (black) and theoretical (blue) bit error rate of the X-band telecommunication link.

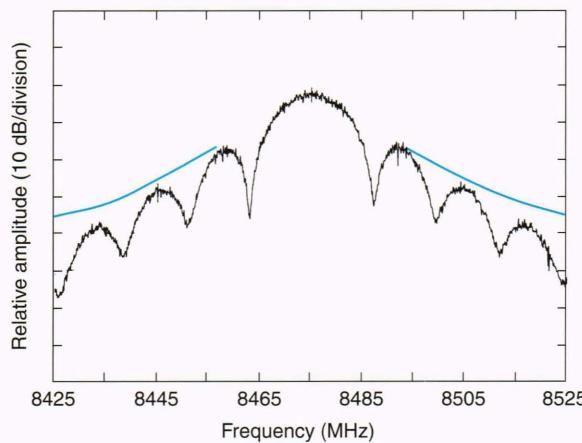


Figure 5. Typical output spectrum for random modulation (black) with the spectral limit of the National Telecommunications and Information Administration superimposed (blue).

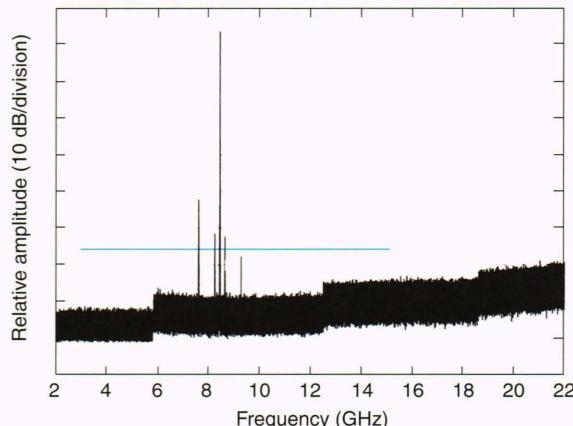


Figure 6. Broadband unmodulated output spectrum (black) with -60-dBc spurious and harmonic specification limit superimposed (blue).

superimposed, showing that three of the four subharmonic responses centered about the center frequency are in noncompliance. The noncompliances were deemed acceptable to the system design and were subsequently waived.

FUTURE APPLICATIONS

The X-band transmitter design represents a technology and capability base at APL that can be drawn upon for future spacecraft missions. A version of the transmitter, modified for very low data-rate operation (5 to 10 bits/s), is already slated for use on the Advanced Composition Explorer program. That unit will be used to transmit advanced warning of solar flare activity from an orbit at the L1 Sun-Earth libration point.

Numerous concepts have been developed at APL for modifying the transmitter design for a variety of other spacecraft missions. A small, very high data-rate (325 Mbits/s) transmitter concept has been developed for small satellite applications. In addition, a concept for scaling the frequency of the design to 15 GHz for return link applications of the Tracking and Data Relay Satellite System (TDRSS) has been developed. And the addition of a second translator to the transmitter will permit Ka-band (27-32 GHz) operation. Applications in this frequency range include deep-space communications and low-Earth orbit-to-ground users via future TDRSS satellites.

In addition to the applications just discussed, the power amplifier module can be used in deep-space probes that require X-band solid-state power amplification.

CONCLUSION

An X-band telecommunication transmitter for use on the MSX spacecraft has been designed. Two units have been built, tested, qualified, and integrated onto the MSX spacecraft. From an applications viewpoint, the transmitter is an important and useful design that can be adapted to future missions. From an engineering viewpoint, this work has provided a broad base of microwave design experience and an enhancement in the use, understanding, and availability of CAE tools at APL. Also, key MIC/MMIC packaging techniques were developed that can be applied to future solid-state microwave designs.

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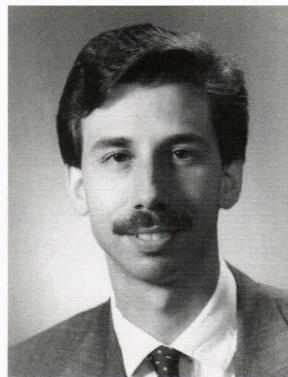
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