Ka-Band Tiny Transmitter for the New Millennium Program

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ABSTRACT

The size, mass and cost of telecommunications systems on deep space missions have increased at almost an exponential rate over the last thirty years. Great cost and size reduction of these systems can be achieved by reducing the cost and size of the transponder component of the radio subsystem. An advanced technology X- and Ka-band (8 and 32 GHz) Tiny Transmitter is being developed at JPL for the New Millennium program and is described in this paper. The Tiny Transmitter is the first phase of development of the Tiny Transponder which will incorporate recent advancements in miniaturization and flexibility of radio systems by utilizing digital radio techniques. These techniques incorporate digital technology and algorithms to perform many functions which have traditionally been performed by analog circuits and allow the complexity of the RF portion of the radio to be minimized. The Tiny Transponder will be able meet the needs of almost all deep space missions presently being planned for launch after the year 2000.
Keywords: telecommunications, transponder, microwave systems, microwave monolithic integrated circuit, multi-chip module, digital

1. OBJECTIVES OF THE DEEP SPACE TINY TRANSPONDER DEVELOPMENT

While deep space communications performance has increased dramatically over the last three decades, the size, mass and cost of spacecraft telecommunications subsystems have also increased. Present subsystems will not meet the needs of many future missions which will have much lower budgets and mass, volume and power capability, However, the telecommunications performance requirements of these future missions are not substantially different from those of present larger deep space missions. The most expensive and complex component of the spacecraft radio electronics is the deep space transponder. The transponder includes the radio receiver which receives and demodulates commands from NASA's Deep Space Network (DSN) and the transmitter which provides telemetry and ranging communications from the spacecraft to the DSN. In addition, the transponder provides navigation capability to enable the measurement of the spacecraft range, range rate, and radio science functions to enable measurement of the propagat ion path.

A recent JPL study concluded that the greatest cost and size reduction of deep space telecommunications systems can be achieved by reducing the cost and size of deep space transponders The Tiny Transponder is designed to achieve these goals. Figure 1 shows a comparison of the Tiny Transponder with other recently developed transponders. The Cassini transponder will be used on the Mars Pathfinder and NEAR missions, as well as the Cassini mission. The Small Deep Transponder will be flown on the New Millennium Deep Space 1 mission and represents an interim effort to reduce costs and sire. The Tiny Transponder will further reduce cost and it will

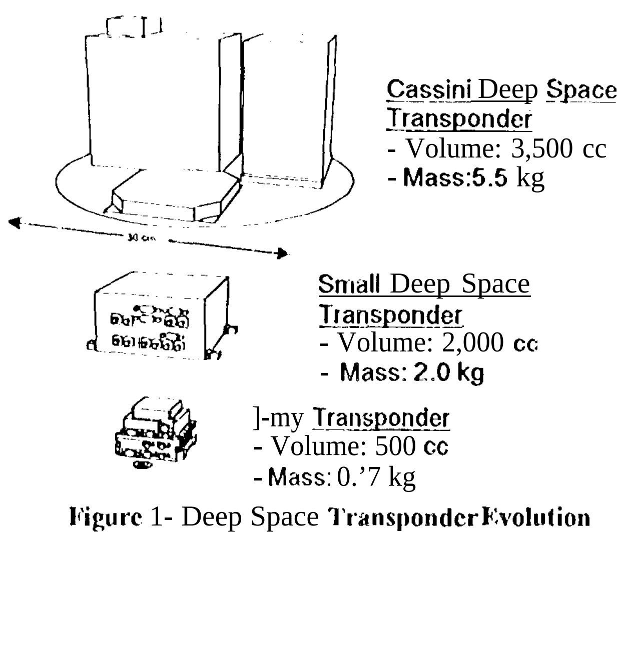

Figure 1- Deep Space Transponder Evolution

reduce mass and volume by almost an order of magnitude relative to the Cassini transponder. The Tiny Transponder will be developed in two phases, the first of which is the development of the Tiny Transmitter which is presently underway. This Transmitter will be used as building block in the Tiny Transponder. The Transponder will be developed during the second phase and will be flown on a later New Millennium flight. The Tiny Transponder will meet all the telecommunications needs of most deep space missions presently planned for launch after the year 2000.

2. TRANSPONDER ARCHITECTURE DESIGN APPROACH

The Tiny Transmitter architecture was derived from a the architecture design of the Tiny Transponder. The key design goals of the Tiny Transponder are:

- Minimize cost, mass and volume
- Make telecommunications the key function, with navigation and radio science secondary functions
- Meet performance requirements of the majority of deep space missions in the next decade
- Use a modular design to enable initial development of a miniature downlink transmitter for potential use on autonomous missions or for downlink redundancy

The top level approaches selected for implementing the Tiny Transponder arc:

- Minimize the number of components and utilize commercially available components where possible

Table 1- Tiny Transponder Specifications

Parameter	Design Requirement
Receiver Specifications	
Frequency	7,145 MHz to 7,190 MHz
Carrier threshold	-15S dBm
Dynamic range	70 dB (threshold to -85 dBm)
Up-link no damage level	>10 dBm (>10 mW)
Acquisition and tracking rate	500 Hz/s @ -110 dBm
Tracking range	±100 kHz
Tracking error	<1° /40 kHz @ -110 dBm
Command demodulation	
Data rate	7.8125 bps to 2,000 bps
Bit error rate	10^{-5} @ E_b/N_o 10.5 dB
Ranging demodulation	
Signal bandwidth	t MHz
Noise bandwidth	1.5 MHz
Exciter Specifications	
X-band down link.	
Frequency	8,400 MHz to 8,450 MHz
Power	12 dBm (16 mW)
Ka-band down-link	
Frequency	31,909 MHz to 32,171 MHz
Power	>10 dBm (>10 mW)
f'base Noise	Compatible with 31 Hz tracking
Telemetry modulation	
Subcarrier frequencies	22.5 kHz to ?.88 MHz (factors of 2)
Mod indices	40° to 80°
Data rates	10 bps to 2.2Mbps
DOR tone frequency	19 MHz
Beacon tone frequencies	20 - 200 kHz

- Maximize the number of transponder functions performed with digital circuits and implement these in ASICs

- Simplify the analog and RF circuitry and implement with microwave integrated circuits (MMICs) in high density packaging

- Minimize overall package design volume, consistent with requirements for power dissipation, shielding, modularity, testability and cost of assembly.

To perform the communications functions, a deep space transponder provides tracking of the uplink carrier transmitted from the DSN, demodulation of the command data, generation of a downlink carrier and modulation of spacecraft data on this carrier for transmission to the DSN. For navigation measurement of spacecraft range, the receiver demodulates ranging tones and then modulates these tones on the downlink. For navigation range rate and radio science measurements, a very stable downlink carrier is required which may be generated from either the uplink carrier or from a separate ultra stable oscillator (USO). Recent studies at JPL have defined the requirements of future deep space telecommunications systems and the key requirements to be applied to the Tiny Transponder arc summarized in Table 1.

To meet these design challenges the Tiny Transponder will take advantage of a revolution in radio system miniaturization and flexibility which is referred to as digital radio. Digital radio makes usc of the small size, flexibility, case of design and stability of digital systems and algorithms to perform functions which have traditionally been performed by analog circuits. Digital radio enables unprecedented reductions and size, power consumption and cost, This architecture is enabled by low cost application specific integrated circuits (ASICs) and ncw classes of efficient algorithms. The Tiny Transponder will bc designed to take advantage of recent innovations in these technologies. Also, the complexity of the RF portion of the radio will bc minimized. Highly integrated microwave monolithic integrated circuits (MMICs) and advanced packaging will also bc used to produce significant reductions in transponder recurring costs, size, mass and power consumption.

A block diagram of the Tiny Transponder is shown in Figure 2 and a similar block diagram of the Tiny Transmitter is shown in Figure 3. The key elements of the Tiny Transponder design arc the Receiver Module, the Transmitter Module and the Power Module. The Tiny Transmitter will utilize only

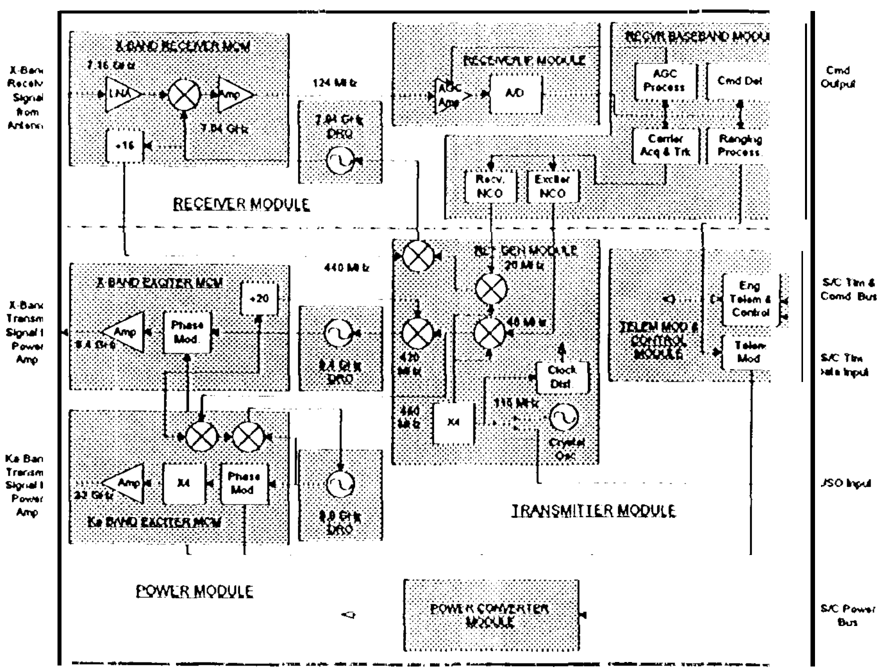

Figure 2- Tiny Transponder Block Diagram

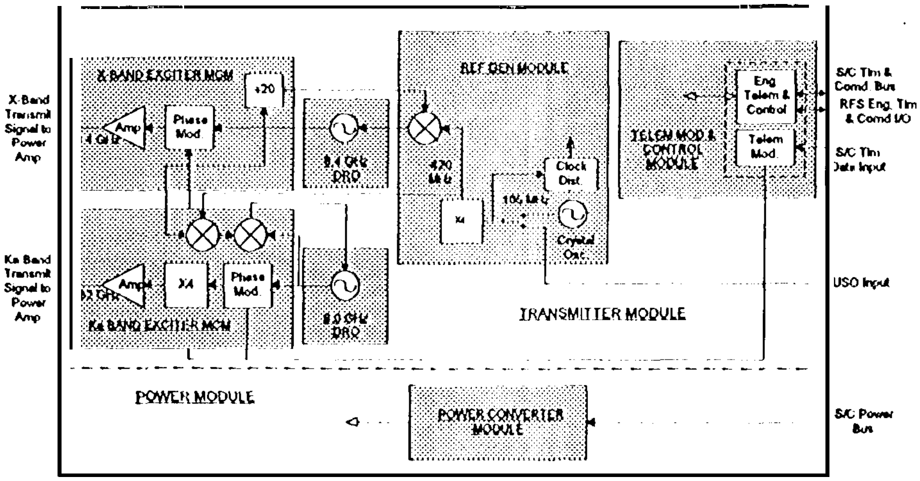

Figure 3- Tiny Transmitter **Block** Diagram

the Transmitter Module and the Power Module. Note that the Reference Generator Module in the Tiny Transponder and Tiny Transmitter are slightly different, but these two versions of the Reference Generator will have the same package design and will have the same interfaces.

The Receiver Module consists of the X-band Receiver Multi Chip Module (MCM), the 7.04 GHz Dielectric Resonator Oscillator (DRO) Module, the Receiver Intermediate Frequency (IF) Module and the Receiver Baseband Module. The X-Band Receiver Module down-converts the received X-band signal to an IF of 124 MHz and provides a low frequency (4? 1 MHz) coherent sample of the 7.04 GHz local oscillator. The 7.04 GHz DRO provides a coherent local oscillator to the receiver. The Receiver IF Module provides automatic gain control (AGC) and 3-bit over sampling analog to digital conversion with a 60 MHz sampling rate. The Receiver Baseband Module provides carrier acquisition and tracking, command detection to produce a digital command data stream to the space.aaft, ranging modulation processing and AGC processing. The carrier acquisition and tracking processor produces a digital data stream which drive low complexity, low spur level numerically controlled oscillators to produce reference signal which may be selected to be coherent with the uplink carrier frequency. In this design the number of RF functions and analog components are minimized by using one analog down conversion stage and by implementing digital processing algorithms using CMOS ASICs. In order to meet the stringent down-link spurious signal requirement the receiver and exciter numerically-controlled oscillators (NCO) will use amplitude and phase dithering followed by one-bit delta-sigma digital-to-analog converters.

The Transmitter Module consists of the X-Band Exciter MCM, the Ka-Band Exciter MCM, the 8.4 GHz DRO Module, the 8.0 GHz DRO Module, the Reference Generator Module and the Telemetry Modulation and Control Module. The two exciter modules perform similar functions in that they provide two signal paths for the carrier signals generated by the DROs. One path provides phase modulation and signal level adjustment, and in the case of the Ka-Band Exciter Module provides frequency multiplication to Ka-band. The second earlier path provides a sample of the of the DRO frequency for feedback to phase lock the DRO to a reference frequency from the Reference Generator Module. The Reference Generator Module, as mentioned, will have two designs for the Tiny Transponder and the Tiny Transmitter. In the Tiny Transmitter design a reference signal of 420 MHz is generated from the fourth harmonic of 105 MHz from either an internal crystal oscillator or external Ultra Stable Oscillator (USO). The Transponder variant of this design enables generation of reference signals which are phase coherent with received uplink carrier. In this scheme a 115 MHz internal crystal oscillator or external USO is used and the fourth harmonic of this signal is off-set by the coherent signal generated by the NCOs The chassis of the Transmitter Module will be designed to accept either variation of the Reference Generator module. The Telemetry Modulation and Control Module provides the interface to the spacecraft data bus for commands to change transponder operating modes and for sending engineering telemetry from the radio subsystem to the spacecraft. In addition, this module provides an interface to the spacecraft telemetry data to be sent to the Earth. This module will produce either a modulation signal to directly modulate the carrier or a modulated subcarrier of selected frequency for subcarrier modulation of the carrier. This module will also have the capability of convolutionally encoding the data and adding ranging and beacon tones to modulate the carrier.

3. TINY TRANSMITTER MICROWAVE AND DESIGN

3.1 Microwave Multi Chip Modules (MCMs)

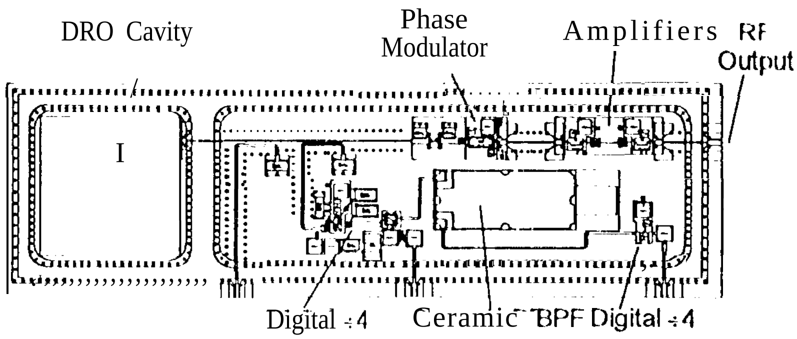

Figure 4- The Physical **Layout** of the **X-Band** MCM

The microwave circuitry of the Tiny Transponder will be packaged in multi chip modules (MCMs) to enable substantial size reduction. The Tiny Transmitter will utilize IWO of these modules, one for the X-band and the other for the Ka-band transmitter frequency. The functions of these modules are two-fold: to provide an integral package for the voltage controlled dielectric resonator oscillator (DRO) circuit and remaining exciter circuitry and to provide the interconnecting traces, isolation, and support structure for the various MMICs and other components within the exciter. In both X and Ka-band modules, the DRO signal is sampled and frequency divided or translated to produce an error signal used 10 phase lock the DRO to the reference frequency. In a second path, the DRO output is modulated with the telemetry and science data, filtered, and amplified to an output level of+ 12 dBm (16 mW). This signal is then output to external power amplifiers (to produce power levels of the order of 2-20 W) for transmission, through the spacecraft antennas, 10 the DSN. In the case of the Ka-band module, this phase locked, modulated signal at 8 GHz is multiplied by 4, filtered, and amplified to produce the 32 GHz output.

The X-band exciter microwave MCM layout is shown in Figure 4 and the Ka-band MCM is of similar design, The planned approach to the design of these MCMs is to utilize multi-layer low temperature co-fired ceramic (LTCC) substrate with a seal ring brazed to the top surface. A hermetically sealed cover is then welded to the seal ring. The lower surface of the MCM will be bonded to a heat spreader of either kovar or aluminum silicon carbide metal matrix material. Microwave transmission lines in the substrate will consist of buried stripline with microstrip transmission line interface pads where the signal connects to the active devices. The MMICs will be bonded with traditional eutectic solder or silver epoxy. Wedge and/or ball bonding techniques will be used to complete the electrical connections. Traces to external connections will be buried within the. substrate as stripline conductors then transition to co-planar waveguide in the LTCC structure once the signal is outside the hermetic seal ring.

The Tiny Transmitter X-band MCM will contain seven MMIC chips, a miniature ceramic microwave filter, and two power dividers. These devices will be placed in cavities in the LTCC structure with access from the top for mechanical and electrical bonding. Internal DC regulator chips, mounted on the top surface above the upper stripline ground plane, will provide the low ripple, low noise DC Power to the active MMICs. Via holes to lower layer interconnects will distribute the DC power to the lower layers where the active MMICs are mounted. The overall size of the X-band MCM including DRO cavity is 65.6 by 19.6 mm and is shown in Figure 2. The height of the completed MCM is 10.4 mm over the DRO cavity stepping down to 6.5 mm over the rest of the MCM.

3.2 Miniature Dielectric Resonator Oscillators **(DROs)**

The Tiny Transmitter uses two voltage-tunable DROs which will generate the transmitter's two downlink signals at X-band (8.4 GHz) and Ka-band (32.0 GHz). The voltage controlled DRO in the Ka-band exciter is generated from an X-band signal (8.0 GHz) which is quadrupled to produce the final 32 GHz Ka-band downlink signal. The DROs are part of two phase-lock loops, each of which is frequency-locked to a 421 MHz signal.

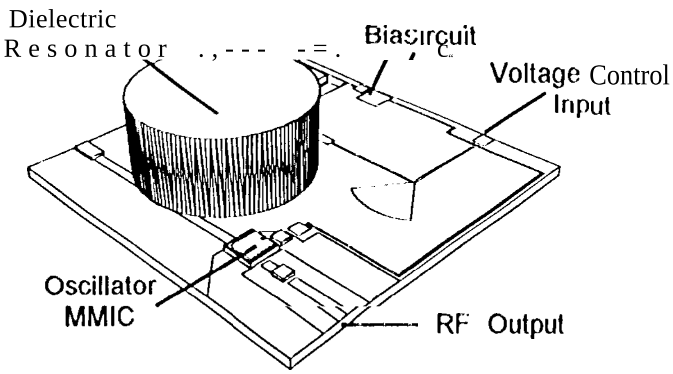

Figure S - **Layout** of Typical Voltage Cent rolled DRO

The design of the DROs is based on a Pacific Monolithic OTIOSO MMIC voltage controlled DRO design. It uses a 1 by 1 mm Pacific Monolithic VA1712 MMIC amplifier chip which provides, at its input, the negative resistance conditions necessary for oscillation. The oscillation frequency is stabilized by a high-Q dielectric resonator which is magnetically coupled to a 50-ohm line connected to the negative resistance input of the MMIC amplifier chip. The output frequency can be adjusted within a O.1% tuning bandwidth by varying the voltage applied to a silicon abrupt varactor diode. This varactor diode is connected to a 50-ohm half-wave resonator which is magnetically coupled to the resonator. A change in the varactor voltage changes its Capacitance, which changes the resonant frequency of the half-wave resonator. The capacitance change "pulls" the resonant frequency of the resonator, which, in turn, adjusts the output frequency of the oscillator. High impedance DC bias lines with quarter-w'ave shorting stubs and DC-decoupling chip capacitors are used to distribute the required 8 Volt supply to the MMIC amplifier chip and the tuning voltage to the varactor diode. The overall size of the resulting DRO layout, shown in Figure 5, is 1.3 by 1.3 mm. This board will be bonded into the MCM board illustrated in Figure 4.

3.3 **Reference Frequency** Generator

A block diagram of the Reference Frequency Generator is shown in Figure 6. The Reference frequency Generator wilt be designed in two versions. For the Tiny Transmitter the Reference Frequency Generator takes a 105.3 MHz output signal from the crystal oscillator and multiplies its frequency by a factor of four to produce a 421 MHz signal. This signal is then filtered, amplified and divided into three equal power signals which are distributed to other modules of the Tiny Transmitter. One of the 421 MHz signals is used to down convert the 8.4 GHz voltage controlled DRO output signal to 8.0 GHz. The output of the 8.0 GHz DRO is quad rupled to provide the 32.0 GI 17. downlink signal and is phase-locked to this reference signal. The loop filter of this PI.1. is also part of the Reference Frequency Generator. The second of the three421 MHz signals is mixed with the fourth subharmonic of the 8.4 GHz DRO (2. 1 GHz), produced by a digital frequency divider, to a 1.68 GHz signal. This signal is then divided again by four and provides a421 MH7. signal which is fed back into the Reference Frequency Generator. This is represented by a divide by 20 in Figure 2 and Figure 3. There it is compared to the third Reference Frequency Generator 421 Ml Iz signal, using an on-board phase detector. The output of this phase detector provides the input to the 8.4 GHz PLL loop filter, also a part of the Reference Frequency Generator.

The frequency quadrupler is implemented with two cascaded MMIC mixers which are connected with the same frequency feeding both their RF and LO ports to act as doublers. The filter that follows the quadrupler is a four pole band pass filter which uses lumped capacitors and inductors. The amplifier is a MMIC amplifier and the three-way power splitter is implemented as a simple resistive network, to minimize its size. The two loop filters are implemented with single op-amps. The phase detector is a standard double-balanced design that uses diodes and miniature inductor-transformers. This circuit is planed to be implemented using a LTCC circuit board containing hermetically sealed die.

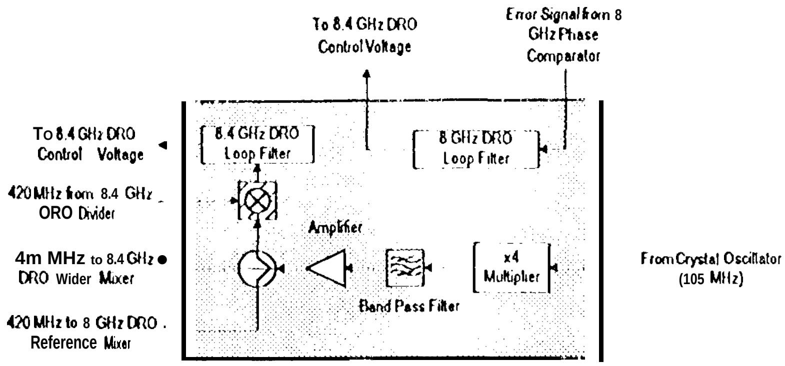

Figure 6- Reference Frequency Generator Block Diagram

3.4 Crystal Reference Oscillator

A low phase noise quartz crystal oscillator will provide the reference frequency and timing signal for the circuits. For the Tiny Transmitter the Reference Crystal Oscillator frequency will be 105 MHz and for the Tiny Transponder it will be 115 MHz. The primary temperature compensation of the oscillator will be achieved by selection of the crystal cut during the manufacturing process. This process will provide adequate frequency stability performance over a reasonable operating temperature range for the transmitter (±4 ppm over temperature range of + 10 C to +40 C, with a goal of ± 2 ppm). A greater frequency variation with temperature will be accepted for the oscillator outside the normal operating range. This will help to reduce oscillator costs and still provide adequate system performance. The oscillator will be packaged in a 2.5 x 1.4 x 0.5 cm flat pack. Required oscillator phase noise performance (single sided) is given in Table 2.

Table 2- Phase Noise versus Frequency

Frequency	Phase Noise(single sided), dBc/Hz
1 Hz	-61
10 Hz	-91
100 Hz	-119
1 kHz	134
10 kHz	136
100 kHz	136
1 MHz	-136
10 MHz	-136

3.5 Power Converter

A miniaturized DC-DC power converter will be utilized to convert the spacecraft primary bus voltage to the required Tiny Transmitter secondary voltages (+5V for digital circuits, ± 10V, and ± 6V for RF circuits). The power converter chopper frequency will be greater than 200 kHz. Distributed active regulators will be utilized in the transmitter design to regulate and reduce power converter spikes and ripple to acceptable levels. The power converter mass and size goals are to be less than 70 grams and 5.6 x 3.4 x 1.3 cm respectively.

4. TINY TRANSMITTER DIGITAL DESIGN

4.1 Telemetry Modulator and Control Module Design

The Telemetry Modulator and Control Module (TMCM) is the main interface between the Tiny Transponder and the spacecraft computer. The TMCM and the spacecraft computer communicate via the spacecraft data bus. The TMCM functional block diagram is shown in Figure 7 and will bc implemented in a CMOS ASIC chip. 7hc TMCM receives all the mode control commands to the transponder and transmitter and its own internal circuits from the spacecraft computer. It then routes these mode control commands to their destinations. The TMCM also collects analog and digital engineering telemetry from the radio subsystem, other transponder modules and from TMCM internal circuits, and routes them to the spacecraft computer.

A second major function of the TMCM is to generate the composite modulating signal for both the X- and Ka-band down link carriers. This modulating signal is composed of spacecraft telemetry data, regenerated ranging signal, one-way ranging signals, and status signals. The telemetry modulator encodes the spacecraft telemetry data and modulates a telemetry subcarrier with the encoded data. The TMCM functions will bc implemented in a full custom ASIC chip which will usc a macro ccl] library developed at JPL.

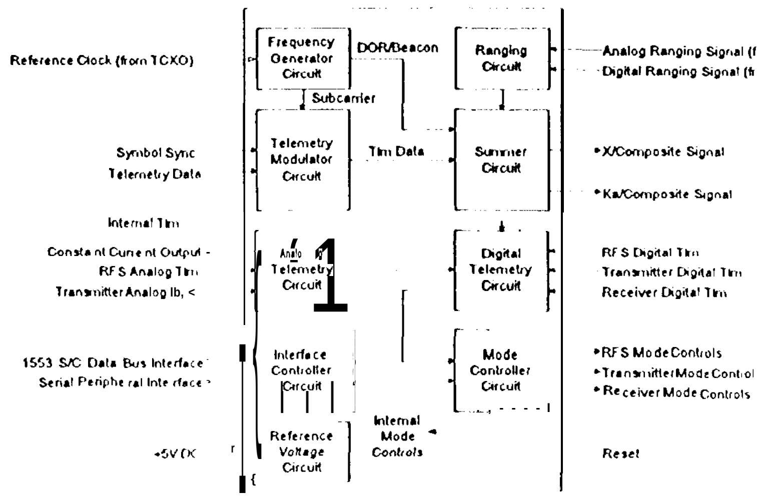

Figure 7- TMCM Block Diagram

5. TINY TRANSMITTER PACKAGING DESIGN AND PHYSICAL CHARACTERISTICS

5.1 Packaging Approach

The word "Tiny" implies major packaging constraints. The volume goal is < S00 cm^3 and the mass goal is < 700 g. Competition with other spacecraft subsystems for surface area on the spacecraft heat sink leads to a goal of minimizing the area of the base of the Transponder. Footprint size was traded with the need to dissipate of the order of 10 W of power through this foot print area. It was a goal that all connectors bc mounted on one surface to minimize the volume required for cabling. This requires that the connectors bc in close proximity creating challenges in shielding and isolation of signals. The transponder will operate at both X-band (8.4 GHz) and Ka-band (32 GHz) requiring special handling of a number of high frequency signals with low loss, controlled impedance connections. The dual port MIL-STD-1553 interface bus requires significant current outputs and bulky transformers. To minimize cost, a goal was set to minimize the need for custom connectors, heat straps, exotic materials or special machining techniques.

The chassis will be made of 6061 aluminum, using steel inserts for threads. The design , shown in Figure 8 has a 9.3 cm by 9.9 cm mounting area. The package has three layers of circuitry with a total height of 5.2 cm. The power converter, which is 5.0 cm x 6.3 cm x 1.25 cm, is mounted on the top of the stack. The total module outside dimensions are 9.3 cm wide x 9.9 cm long x 6.5 cm height. The power converter is mounted external to the module to save volume and mass. The trade off for this mounting scheme meant that the thermal path 10 the heat sink is relatively long. To keep the thermal resistance as low as possible the module mating surfaces are enlarged and fastened with a number of surface mating screws, while minimizing mass and volume. A thermal analysis has been carried which indicates that the thermal rise between the power converter mounting surface and the spacecraft heat sink is less than 23 C, which is within acceptable limits. Much of the telemetry and control circuitry is in a full-custom ASIC and the RF circuits utilize multi-chip modules (MCMs) using low temperature co-fired ceramic (LTCC) substrates. Digital and analog input and output signals will use standard micro 'D' connectors, while the RF connectors are low leakage SMA and 2.4 nun types, placed for best isolation. A 1553 data bus interface will be integrated into a micro 'D' shell. The completed module will have a mass of approximately 500 grams.

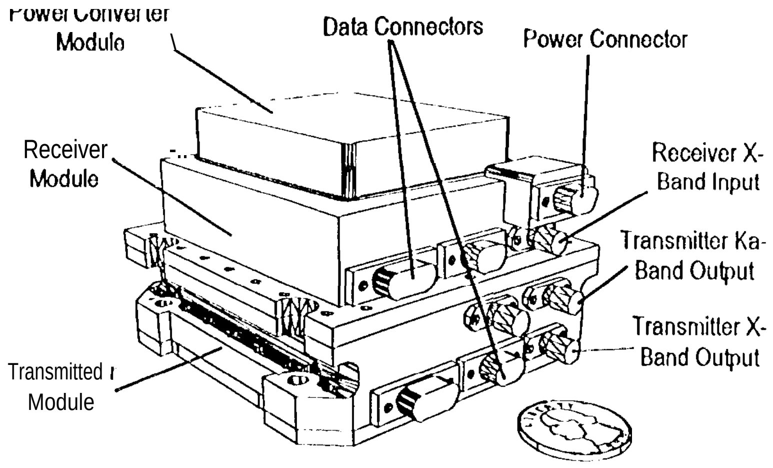

Figure 8- Tiny Transponder Package Concept

6. SUMMARY

The Tiny Transponder and the Tiny Transmitter will meet the challenging requirements for lower cost, small size and mass of future small deep space missions. These designs will aggressively utilize simplified design architectures, state of the art digital techniques, miniature microwave techniques and advanced packaging. Low cost will be achieved by minimizing the number of parts, utilizing custom ASICs for implementing, the major transponder functions. It is anticipated the Tiny Transponder have an order of magnitude lower mass and volume compared with the Cassini Deep Space Transponder at a recurring cost of less than one-fifth of Cassini. The Deep Space Tiny Transponder will be able to meet the needs of the majority of deep space missions and is planned to be available for operational mission in the year 2000 time frame.