The NASA Spacecraft Transponding Modem[1]

Jeff B. Berner
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
818-354-3934
jeff.b.berner@jpl.nasa.gov

Selahattin Kayalar
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
818-354-2872
selahattin.kayalar@jpl.nasa.gov

Jonathan D. Perret
Jet Propulsion Laboratory
California Institute of Technology
4800 Oak Grove Dr.
Pasadena, CA 91109
818-354-5438
jonathan.d.perret@jpl.nasa.gov

Abstract—A new deep space transponder is being developed by the Jet Propulsion Laboratory for NASA. The Spacecraft Transponding Modem (STM) implements standard transponder functions and some of the command and telemetry channel service functions that have resided in spacecraft Command/Data Subsystems.

The STM tracks an X-band uplink signal and provides both X-band and Ka-band downlinks, either coherent or non-coherent with the uplink. A command detector is integrated into the STM, along with a codeblock processor and a hardware command decoder.

The STM provides Reed-Solomon coding, convolutional coding, and Turbo coding for downlink telemetry. The downlink symbol rates can be linearly ramped to match the G/T curve of the receiving station. Data rates range from 5 bits per second (bps) to 24 Mbps, with three modulation modes provided: subcarrier, biphase-L direct on carrier, and Offset-QPSK.

Standard turn around ranging, regenerative pseudo-noise ranging capability, and Differential One-way Ranging (DOR) tones are provided.

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1. INTRODUCTION

A new deep space transponder is being developed by the Jet Propulsion Laboratory (JPL) for NASA. Traditionally, deep space transponders provide uplink carrier tracking, command bit detection, ranging signal turn around, telemetry convolutional encoding, and downlink carrier generation and modulation. The new Spacecraft Transponding Modem (STM) provides these features, along with capabilities that previously were in the domain of the spacecraft Command/Data Subsystem (CDS): codeblock processing, hardware command decoding, telemetry block time tagging, and Reed-Solomon encoding. New features include linear ramping of the telemetry symbol rate (increasing data return by matching changes in the ground receiver's gain to system temperature (G/T) ratio), turbo encoding on the telemetry, ranging signal regeneration (to significantly reduce the noise degradation on the downlink

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ranging signal), and offset quadrature phase shift keying (OQPSK) modulation of the downlink carrier (for a more spectrally efficient signal).

The STM receives an X-band uplink (7147 MHz to 7189 MHz) signal and can generate downlink carriers at either X-band (8397 MHz to 8440 MHz) or Ka-band (31,909 MHz to 32,096 MHz), or both simultaneously. To provide compatibility with both current spacecraft architectures and those planned for the future, two different avionics interfaces to the CDS are included: a MIL STD 1553B bus and an industry standard PCI interface. In either case, the data passed between the STM and the CDS are frames of data, as opposed to the bit interfaces used in the past.

Through the use of custom Application Specific Integrated Circuits (ASICs), Monolithic Microwave Integrated Circuits (MMICs), and Multi-Chip Module (MCM) packaging, the STM is able to reduce the active device parts count to 70, the mass to 1 kg, and the volume to 524 cc. The STM will be radiation hardened to a level of 100 krad. The first STMs will be flown on missions launching in the 2003 time frame.

This paper is presented in three parts. The first part provides a functional description of the STM functions and capabilities. The second part describes the components and the construction of the STM. Finally, a brief discussion of the STM schedule milestones is provided.

2. FUNCTIONAL DESCRIPTION

A high level functional block diagram of the STM is given in Figure 1. The various functions are described in the following subsections.

2.1 X-band Uplink Tracking

Figure 2 provides a diagram of the X-band uplink tracking. The X-band frequency is represented as 749Fo + fk, where the Fo is the base clock of the STM and the fk is any frequency offset, due to uplink tuning or doppler shifts. Currently, the Fo is selected to be 9.56502525 MHz, which sets the STM for X-band deep space channel 23 [1], which corresponds to a frequency of 7172.715276 MHz. The carrier power (Pc) input range is less than –162 dBm (defined as the threshold) to –70 dBm [2]. The 1.7 dB noise figure of the STM gives a noise spectral density (N0) of -177 dBm/Hz, which means that the input carrier power-to-noise spectral density ratio (Pc/N0) is 15 dB-Hz to 107 dB-Hz.

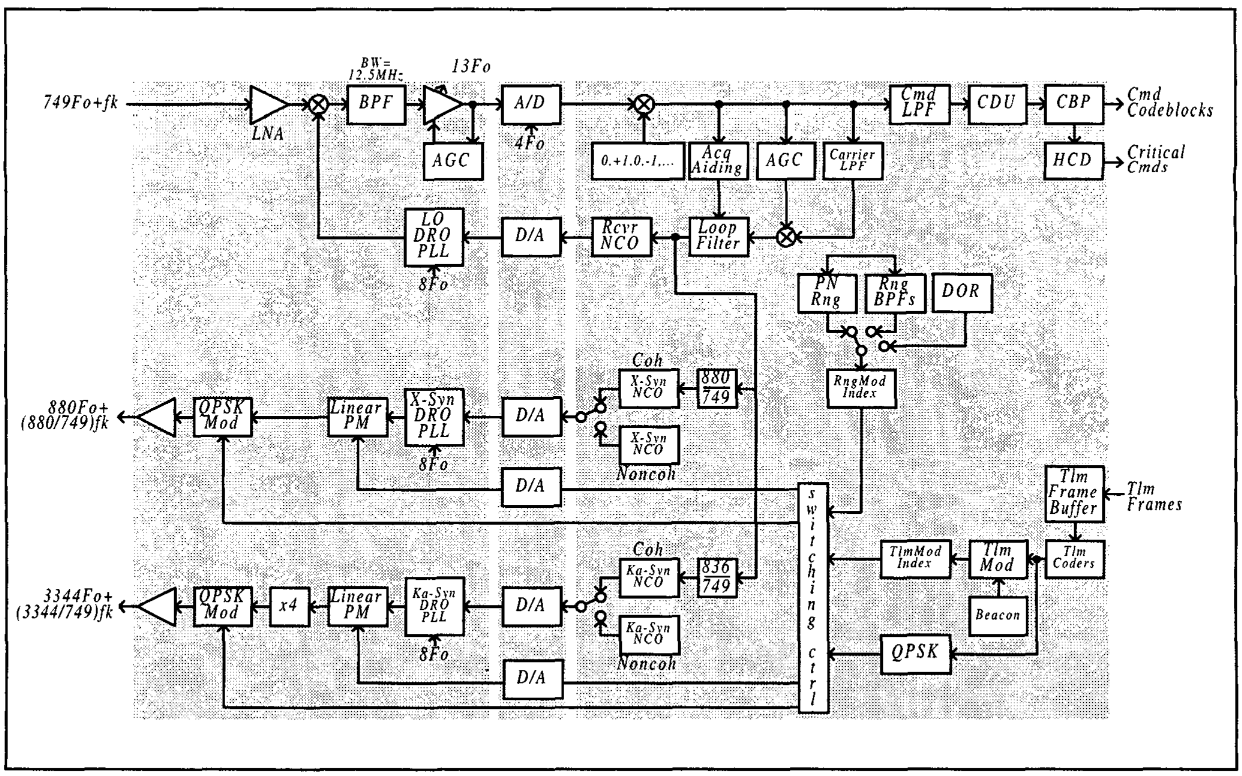

Figure 1 STM Functional Block Diagram

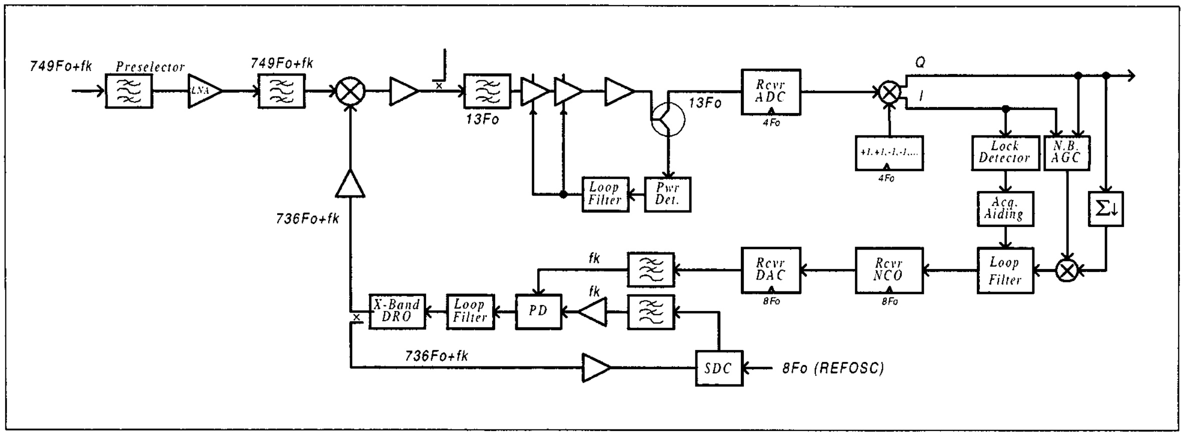

Figure 2 X-band Uplink Tracking

After pre-select filtering is done, the uplink signal undergoes a single downconversion stage. The signal is mixed with 736Fo + fk; the 736Fo is generated by multiplying the reference oscillator and the fk is the feedback from the carrier tracking loop. After this mixing, the resulting 13Fo intermediate frequency (IF) is filtered to a 12.5 MHz bandpass and input to a total power automatic gain control (AGC) loop. The AGC is designed to scale the signal plus noise so that the four sigma point of the output is equal to the saturation point of the Analog-to-Digital Converter (ADC).

The 13Fo input to the ADC is at approximately 124.3 MHz. The 8-bit ADC is clocked at 4Fo (approximately 38.26 MHz). The undersampling downconverts the carrier to a frequency of Fo. The ADC has an aperture jitter of 12 psec, which means that, due to the undersampling of the higher frequency, the phase jitter on each sample is approximately 1.5 mcycles. This puts a maximum on the Pc/N0 seen by the following tracking of 112 dB-Hz (i.e., this is the point where the phase quantization noise is equal to the thermal noise).

Since the input frequency is now at one-fourth of the sampling frequency, the separation of the Inphase (I) and Quadrature (Q) channels is simply done by multiplying the ADC output by the sequence (+1, 0, -1, 0, ...) for the I channel and by the sequence (0, +1, 0, -1, ...) for the Q channel. The multiplication by 0 is implemented as a down sample operation, reducing the data rate of the I and Q channels to 2Fo.

The Q channel is used as the phase error estimate, since it is proportional to the sine of the carrier phase error. The phase error estimate that we get from the Q channel is also proportional to the square root of the carrier power. Normally, we would perform a coherent AGC function on the carrier power to remove this factor, providing a normalized error signal. However, the STM has the requirement to provide a two-sided phase-locked loop (PLL) bandwidth that varies with signal strength from 20 Hz to 200 Hz [3]. The varying bandwidth is required to allow the STM to track weak signals, with low rate of change of the frequency due to doppler, and strong signals, with large frequency rate of change. To implement this feature, a narrow band total power AGC is implemented. The I and Q channels are filtered to 4.7 kHz and then squared. The square root of the inverse of this power measurement is used for the scaling of the error signal. This allows the bandwidth to expand until the point where the carrier power dominates the noise power in the 4.7 kHz bandwidth. From that point on, the scaling value varies with the square root of the carrier power, keeping a constant effective loop bandwidth.

The filter output is summed with a base frequency value for the system and input to the frequency register of the Numerically Controlled Oscillator (NCO). The update rate of the loop is Fo/128, approximately 74 kHz; the NCO is clocked at 8Fo. The NCO has 40-bit phase and frequency registers. The output of the NCO, the sine of the phase, is a very clean signal, with spurs no greater than -80 dBc. This is achieved without using large phase-to-amplitude look-up tables, but by using a novel phase and amplitude dithering technique that spreads the spur energy across the entire spectrum; the noise floor raises slightly, but spurs are significantly reduced [4]. The 6-bit output of the NCO is converted to analog by a Digital-to-Analog Converter (DAC) clocked at 8Fo. This signal, fk, is used to close the loop at the first downconversion stage.

A feature of the digital implementation is that the loop bandwidth and loop damping are determined by coefficients, not physical hardware. This means that the loop parameters can be changed easily if requirements change. The coefficients that set the loop parameters are stored in a configuration ROM. Thus, the tracking performance of the STM can be changed by updating the configuration ROM.

One advantage a digital PLL has over its analog equivalent is that the loop filter can be implemented with perfect (non-lossy) integrators. A second order PLL with a perfect integrator in the loop filter will track out a frequency offset (due to doppler) with no steady state phase error; a PLL with a lossy integrator (an imperfect loop) will have a steady state phase error that is proportional to the frequency offset [5]. This performance advantage is not for free, however. When there is no signal input to the PLL (i.e., when there is no uplink to track), the loop tends to drift significantly (up to 10 kHz in 24 hours) [6]. The STM implements the best of both worlds: when the PLL is searching for a signal, an imperfect loop filter is used; when the loop has locked to a signal, the loop filter is switched to a perfect integrator. This is implemented by using the same filter structure and just changing one coefficient with the lock status.

Previous transponders require the ground transmitter sweep the uplink carrier in frequency to lock the transponder to the signal. This is to ensure that the signal passes through the PLL's pull-in range (the sweep is necessary due to uncertainties in the rest frequency of the transponder and doppler offsets due to spacecraft and Earth motion). This limits the capability of multiple spacecraft in the uplink antenna's beamwidth to share the uplink, since each spacecraft would be independent (for example, if one spacecraft were a lander on Mars and the other an orbiter of Mars, the orbiter may appear from behind the planet after the lander is locked to the uplink). The STM provides a way to manage this problem. The STM simulates the uplink sweep by ramping the base frequency of the PLL, using the same pattern that the uplink would use. This causes the same acquisition results as if the STM frequency were fixed and the uplink were ramped. This allows multiple spacecraft to share the same uplink.

The I channel is proportional to the cosine of the phase error, so this is the natural choice for a PLL lock detector. Lock detection is performed by integrating the I channel for 1.3 seconds and comparing the result with a threshold that is computed from measurements of the mean and variance of the I and Q channels. By using this computed threshold instead of a fixed reference, the STM avoids problems that previous transponders have had with variations in the DC gain degrading the lock detection performance.

2.2 *Command Detection*

When the STM is locked to the uplink carrier, the uplink signal is checked for the existence of a command signal. The commands, if present, are modulated onto a 16 kHz sine wave subcarrier. The ratio of the subcarrier frequency and the command bit rate is a factor of 2, with the highest command bit rate being 2000 bps and the lowest being 7.8125 bps [2].

Figure 3 shows the block diagram of the command detection processing. The Q channel, clocked at 2Fo, is filtered by an fifth order elliptical low pass filter, whose 3 dB bandwidth is 27.4 kHz. This filter is implemented using an all-pass lattice structure method [7], which reduces the number of

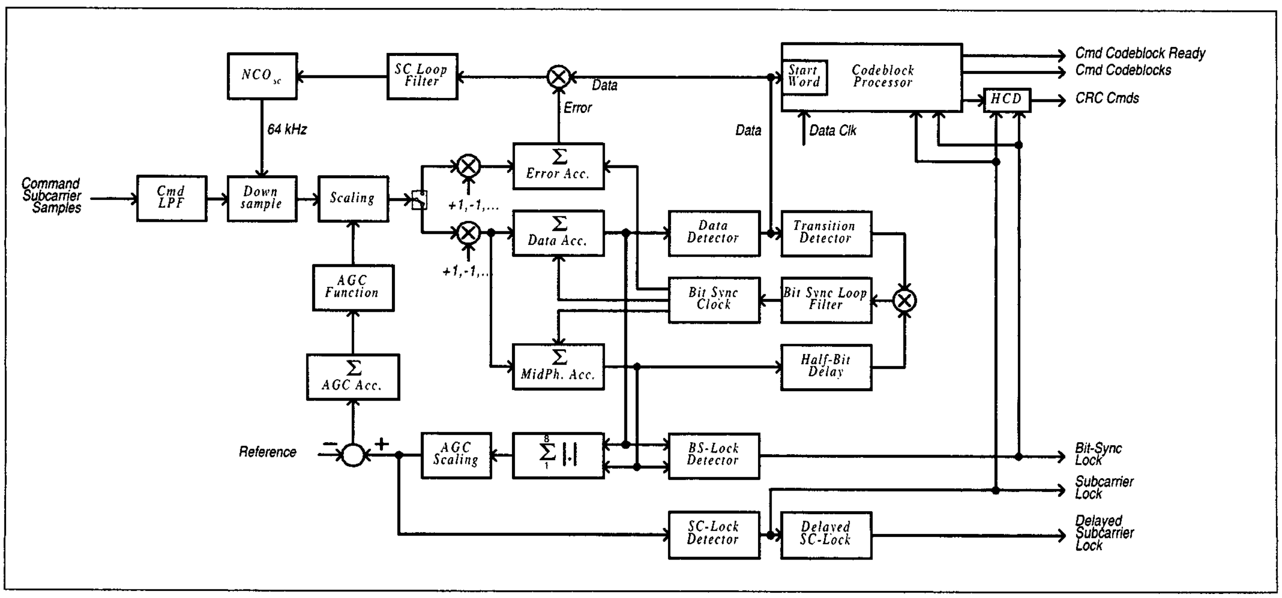

Figure 3 Command Detection Processing Block Diagram

multipliers to five (Figure 4 shows the structure of the implementation). After filtering, the sample rate is reduced to 64 kHz (four times the subcarrier frequency); this sample reduction is achieved by the subcarrier tracking loop controlling the timing of the sample decimation. Bit synchronization is achieved by using a standard Data Decision Tracking Loop (DDTL), which uses integrations from mid-bit to mid-bit and the detected bit's sign to generate the error signal [8].

false command locks when there is no uplink carrier, which was a problem in previous transponder designs.

2.3 Downlink Carrier Generation

Figure 5 shows the block diagram of the downlink carrier generation. There are two independent carriers that can be generated by the STM, an X-band and a Ka-band. Each downlink has two modes that must be supported: coherent with the uplink and non-coherent with the uplink. To achieve this, two sets of NCOs are used for each downlink. The first NCO generates the non-coherent downlink. The frequency word is a ROM parameter that is set based on the assigned downlink channel and is not changed over the life of the mission. The second NCO generates the coherent downlink. The frequency word that is always a scaled version of the frequency word used in the uplink carrier tracking NCO. The scaling is based on the coherent turn around ratio (880/749 for X-up to X-down and 3344/749 for X-up to Ka-down). The X-band output is 880/749fk; because the Ka-band output gets frequency multiplied by a factor of 4 after it is converted to analog, its value is 836/749fk. The resets of the uplink NCO and the two coherent NCOs are tied together, so the downlink coherent NCOs are always phase synchronous with the uplink NCO.

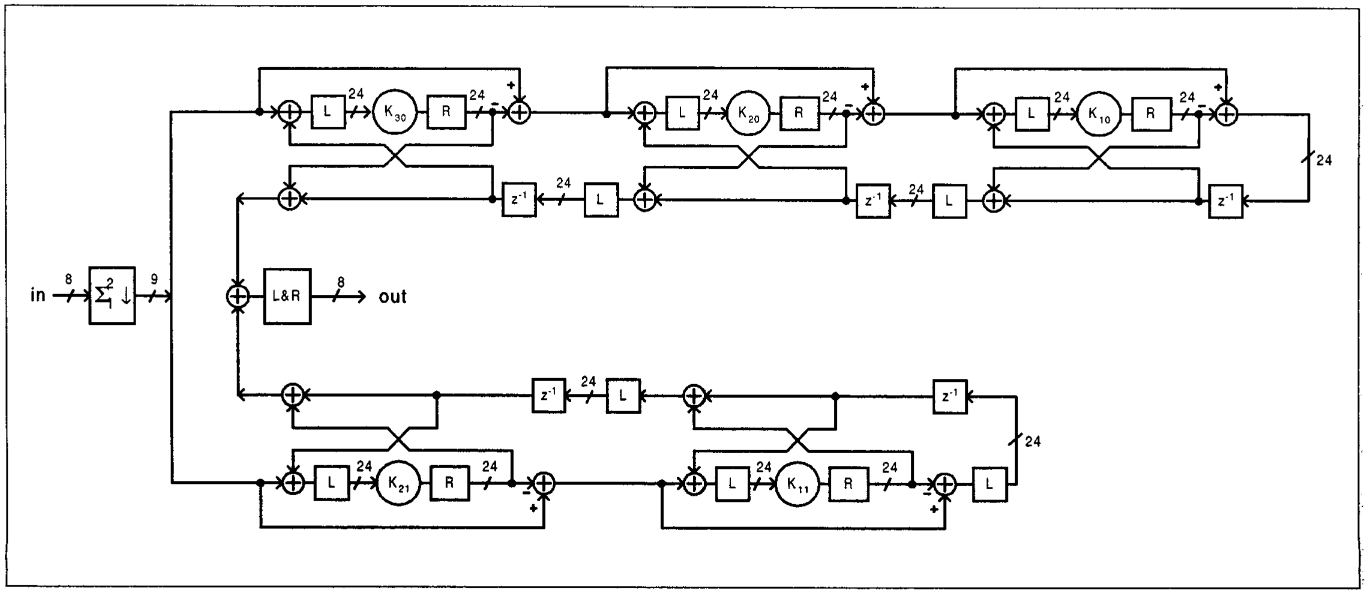

Figure 4 Command Detector Low Pass Filter Structure

Once the subcarrier and bit tracking loops are locked, the detected bits are searched for the 16 bit command start sequence. Once the command start is detected, the command codeblock processing begins. First, the codeblocks, which were encoded with a (63, 56) BCH code, are decoded; the decoding can correct a single bit error and detect two bit errors. If the codeblock cannot be decoded, codeblock processing stops. Once the codeblock is successfully decoded, the codeblock processing checks the block's header to see if it is a Virtual Channel 0 (VC-0) command. If not, the command codeblock is forwarded to the CDS. However, if the codeblock is a VC-0 codeblock, the processing checks the spacecraft ID in the header to verify that this codeblock is for the spacecraft; if so, the hardware command decoder processes the command and outputs it as one of eight critical controller commands. The critical controller commands are specified by the spacecraft designers, but generally will include commands such as a hardware reset for the CDS.

Note that the command detection processing only operates when the STM is locked to the uplink carrier. This prevents

The NCOs used by the downlink carrier generation are the same design as the NCO used by the uplink tracking: 8Fo clocking, 40 bit frequency word, 40 bit phase register, and 80 dBc minimum spur generation in the phase to amplitude conversion. The 6-bit outputs are converted to analog by

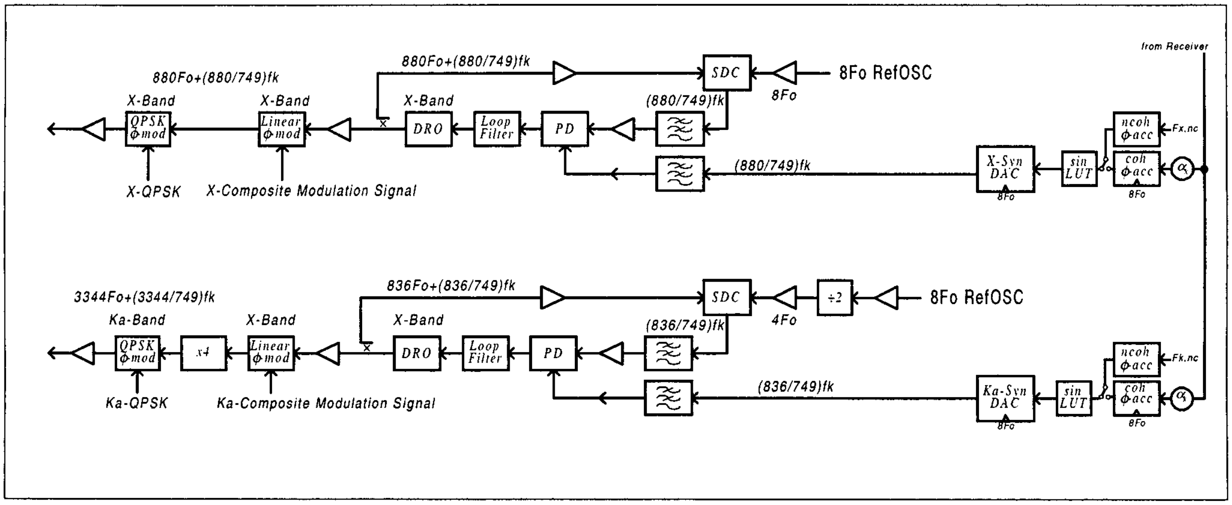

Figure 5 Downlink Carrier Generation Block Diagram

the DACs and then filtered. The X-band signals are upconverted and then modulated with the data and sent to the amplifier for transmission to Earth. The Ka-band signals are upconverted, modulated with the data, frequency multiplied by a factor of four, and then sent to the amplifier.

2.4 Telemetry Modulation

The STM receives the telemetry as frames from the spacecraft CDS. It provides several telemetry coding and modulation capabilities.

The standard Deep Space Network (DSN) rate ½, constraint length 7, and rate 1/6, constraint length 15 convolutional encoding are provided. Consultative Committee for Space Data Systems (CCSDS) standard Reed-Solomon (255, 223) encoding is included, for interleave depths of one and five, with respective frame sizes of 1784 and 8920 bits. The Reed-Solomon encoding can be concatenated with either of the convolutional codes.

Also, capability to code the data with the new turbo codes is provided. Turbo coding for rates 1/3 and 1/6 is provided, with two frame sizes allowed for each rate (1784 and 8920 bits). Turbo codes provide better coding performance than even the long constraint length convolutional code concatenated with Reed-Solomon coding [9].

Once the data is encoded, it is ready for modulating the downlink carriers. There are three modes of carrier modulation supported: data modulated square wave subcarrier, direct (no subcarrier) on the carrier, and OQPSK. For the subcarrier mode, the subcarrier is selected by the CDS to be one of three allowed values, nominally 22.5 kHz (low rate), 360 kHz (high rate), and 2.88 MHz (very high rate); the actual values are selected in the configuration ROM of the STM and also depend on the actual frequency of the 8Fo clock. The allowed data rates are integer factors of the subcarrier, generated by dividing down the subcarrier by an integer. This ensures that the subcarrier and symbol frequencies are coherent, which the ground receivers can take advantage of to reduce the tracking losses. The allowed telemetry rates for the subcarrier modulation mode are:

5 bps to 2.5 kbps for the low rate
2 kbps to 40 kbps for the high rate
30 kbps to 320 kbps for the very high rate

The subcarrier is multiplied by the symbol, scaled by a 5-bit number that sets the modulation index (each step is 4.5 degrees, giving a maximum modulation index of 139.5 degrees, though a modulation index of 90 degrees is the largest that would used), and converted to analog by a DAC. The analog signal is input to a linear phase modulator, which modulates the downlink carrier. The transfer function from digital to analog for the Ka-band DAC is one-quarter of the transfer function for the X-band DAC, due to the times four frequency multiplication that is done after the phase modulator in the Ka-band downlink path.

For the direct on the carrier mode, the symbols are converted to a biphase-L format (level transition in the middle of the symbol) and then follow the same process as the modulated subcarrier data does. The maximum symbol rate is 12 Mega-symbols per second (Msps) for this mode.

The OQPSK mode is a little different. The data stream is alternated into I and Q streams. These streams feed the IQ phase modulator directly, with no scaling (the IQ modulator suppresses the carrier). The maximum symbol rate is 24 Msps (12 Msps per arm) for this mode.

A new capability that the STM provides is to linearly ramp the symbol rate. This allows the STM to attempt to match the change in the ground system's G/T ratio, keeping a constant received symbol SNR (SSNR). By doing this, the amount of data received in a pass can be increased by up to 1.5 dB for X-band and 1.9 dB for Ka-band, as opposed to a pass with a fixed data rate [10, 11]. The STM allows the CDS to change the ramp rate at the beginning of each telemetry frame, providing enough granularity to match the changes in G/T. Note that these rate changes must be pre-programmed into the CDS before the transmission begins. Since the subcarrier and symbol frequencies are coherent, using this method means that the ground receivers need to be able to track the subcarrier and symbol using third order phase locked loops, a capability that exists in the DSN.

In addition to the standard telemetry modulation described above, the STM also provides the capability to generate one of four non-harmonically related subcarrier tones, based on an input from the CDS. These unmodulated subcarriers (also known as beacon tones) are applied to the downlink carrier with a modulation index of 90 degrees. This allows the spacecraft and ground to implement a simple spacecraft monitoring scheme for cruise phases of missions, when there may not be enough SNR to support normal telemetry.

2.5 Ranging

The STM provides three types of ranging modes: turn around ranging, regenerative PN ranging, and Differential, One-way Ranging (DOR). The functional block diagram of the ranging processing is provided in Figure 6.

The first type of ranging, turn around ranging, is the standard method of ranging. The ranging signal is extracted off of the Q channel, filtered, scaled to set the downlink modulation index and summed with the telemetry modulation for input to the linear phase modulator. The filter bandwidth is selectable between two values, 1.8 MHz and 6.1 MHz. The wider bandwidth is provided for strong signal conditions (such as early after launch), when the ranging power dominates the noise power in the 1.8 MHz bandwidth. The ranging signal that is currently used is a series of square wave tones, each one being half the frequency of the previous one. The frequency of the initial tone is normally 1 MHz; this means that the higher harmonics of this tone are cut off by the 1.8 MHz bandwidth. However, the harmonics of the subsequent tones (500 kHz and lower) are not attenuated as badly. When the ranging power dominates the noise power, the missing harmonics affect the strength of the signal that modulates the downlink, causing a variance in the downlink carrier power that changes with the cycle time of the ranging signal. By increasing the bandwidth to 6.1 MHz in this case, the harmonics of the 1 MHz tone are not attenuated significantly, preventing the variation in the carrier power.

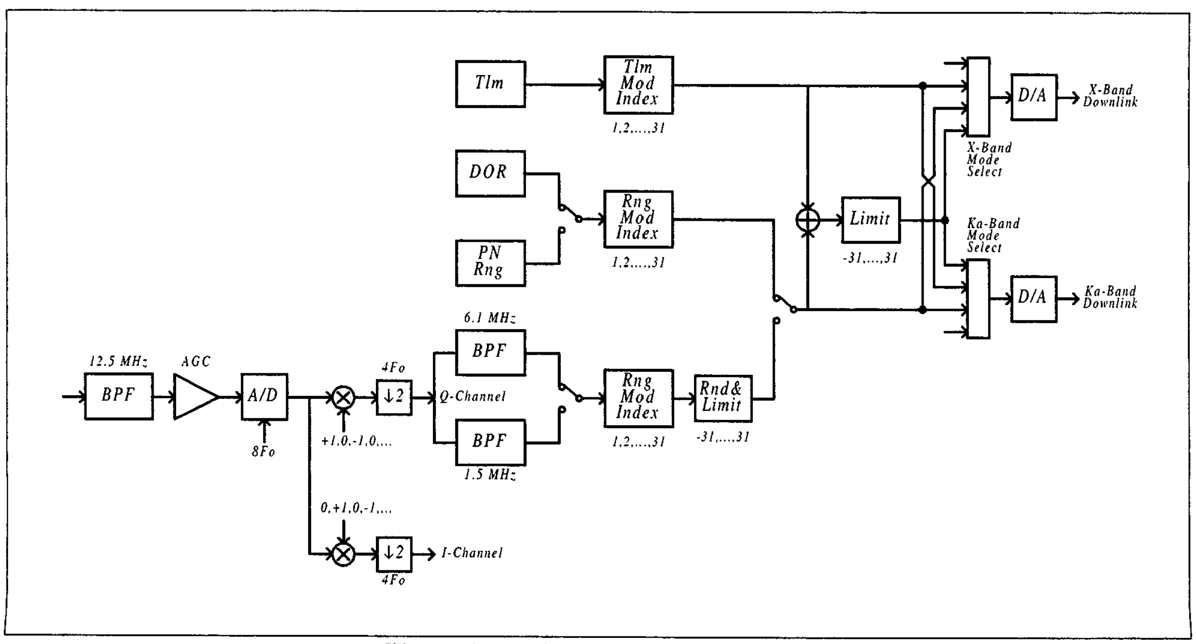

Figure 6 Ranging Processing Block Diagram

The second ranging mode is regenerative pseudo-noise (PN) ranging. When using standard turn around ranging, the downlink carrier is modulated with the ranging signal and 1.8 MHz (or 6.1 MHz) of noise. Normally, the noise dominates. This significantly degrades the received ranging signal on the ground, wasting precious transmission power for sending down noise. If the original ranging signal is generated by a combination of PN sequences, the STM provides circuitry to acquire and track the ranging signal [12]. To lock to the signal, the STM must first lock to the PN chips and then correlate them against the PN sequence. Deep space ranging signals are frequency coherent with the uplink signal, so the frequency of the chips is known just by scaling the frequency generated by the uplink carrier tracking loop. A first order chip tracking loop is implemented, using the fact that the sequence as generated looks like a square wave, with a few errors (details are provided in [12]). Once the chips are locked, correlations are done to lock to the PN sequence itself. Only 75 different correlations (the sum of the lengths of the PN sequences) are needed, since the final sequence is based on just six subsequences. Once the signal is locked, the output of the correlators is scaled by the modulation index scalar and summed with the telemetry. Depending on the strength of the uplink signal, the regeneration has the capability to increase the received ranging SNR by up to 30 dB.

The final method of ranging provided by the STM is the generation of a DOR tone. The Fo clock (approximately 19 MHz) is scaled by the ranging modulation index scalar and summed with the telemetry signal. The ground equipment uses this mode when spacecraft Very Long Baseline Interferometry (VLBI) measurements are desired.

2.6 *Time Keeping*

The STM divides down the 8Fo clock to 0.25 μsec pulses. The time keeping function provides 54 bits for counting these pulses. This gives a counter that counts from 0 to 2^{32}-1 seconds, with a resolution of 0.25 μsec. The counter rolls over once every 136.2 years. The stability of the 8Fo clock gives the time keeping an error, due to clock drift, of less than 1 psec.

The time feature is used in several ways. First, any VC-0 telemetry frames that are transferred to the STM from the CDS are time tagged with the STM time. Secondly, the state of the regenerative ranging PN correlators and the chip NCO phase are periodically time tagged and sent to the CDS, for on board navigation processing. Finally, STM engineering telemetry is time tagged when it is delivered to the CDS.

2.7 *Interfaces*

The STM provides three external interfaces, two for communicating with the spacecraft CDS and one for controlling external devices.

The first is the implementation of the MIL STD 1553B interface. In this configuration, there are three connections to the CDS. There is a Serial Peripheral Interface (SPI) devoted to the telemetry frames from the CDS. There is a SPI devoted for the command codeblocks from the STM to the CDS. And finally, there is a 1553 Low Power Serial Bus (LPSB) that commands from the CDS to the STM and STM engineering telemetry to the CDS are transmitted.

The second CDS interface is an industry standard PCI bus. All data (telemetry frames, command codeblocks, CDS commands, and STM engineering telemetry) are transmitted across this interface. This provides an interface to the next generation of spacecraft architectures.

In addition to the CDS interfaces, the STM provides an interface to control antenna functions, such as switching antennas or controlling antenna pointing. The interface is implemented as a bi-directional SPI.

3. CONSTRUCTION

The STM is approximately 10 cm wide, 10 cm deep, and 6 cm high, with 1.5 cm mounting tabs on each side of the front. Its total volume is 524 cc and its mass is 1 kg. Figure 7 shows a layout of an assembled STM. Due to its use of custom ASICs, MMICs, and MCMs the active device parts count is 70. It has a radiation hardness of 100 krad. The STM has the following power usage:

Uplink tracking only -	8.1 W
Uplink and X-band downlink -	11.7 W
Uplink and Ka-band downlink -	13.5 W

The following three subsections describe some of the key construction elements of the STM.

3.1 *Slices*

The STM is constructed in four self-contained slices: the X- and Ka-band synthesizer slice, the digital processing slice, the downconverter slice, and the power converter slice. Figure 8 shows interconnections between the slices.

The design decomposition of the STM into the four slices considered several criteria, including component RF shielding, ease of slice testing, manufacturability, and upgradability. For example, since the uplink-to-downlink turnaround ratios are ROM values that can be changed, to change the STM from an X- and Ka-band transponder to a dual Ka-band transponder would just require manufacturing a new synthesizer slice and changing the ROM. This design gives maximum flexibility for future modifications. Additionally, the slice configuration allows for new functionality via the addition of a new slice. This would be used for things such as an open loop signal processor, for Radio Science purposes, or an Ultra-Stable Oscillator

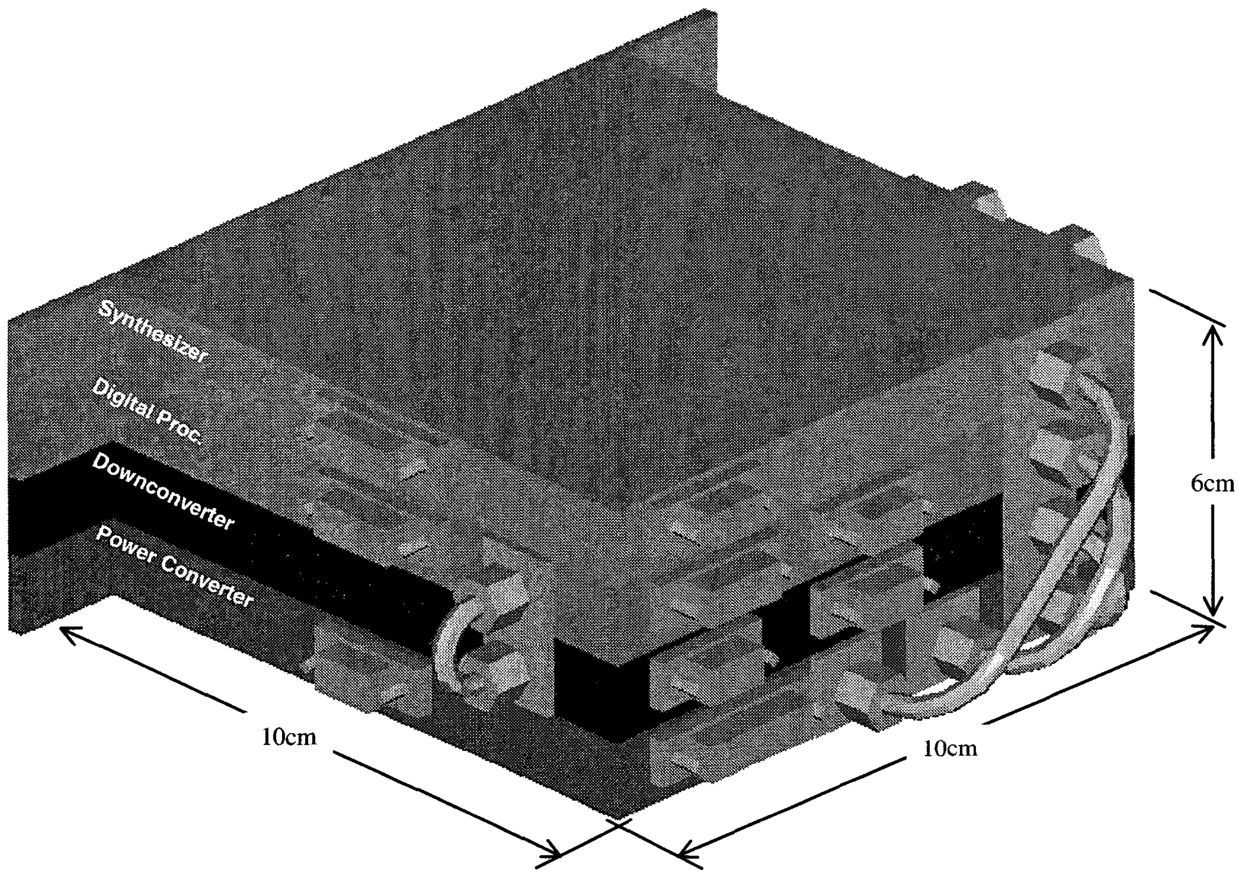

Figure 7 Assembled STM

(USO), for missions that require higher stability for non-coherent operation.

Each slice is 10 cm wide, 10 cm deep, and 1.5 cm high, with mounting tabs on the front and the connectors on the back and sides. The slice containers are aluminum. The lid of each slice will be laser welded to the container, forming a hermetic enclosure.

3.2 MCM

There are three MCMs in the analog section of the STM: the uplink downconverter, the X- and Ka-band synthesizers, and the power converter. The two RF MCMs are fabricated on low temperature co-fired ceramic 15-layer substrates, with a 3.75 mil thickness per layer. The power converter MCM is fabricated on a standard ceramic substrate. The MCMs also provide raised RF shielding covers for cavities, to decrease the susceptibility to component-to-component interference. Both GaAs and Silicon MMICs are used on the MCMs.

The downconverter module is shown in Figure 9 (Gallium-Arsenide components are colored green; Silicon components are in white). The downconverter module takes an input RF signal in the range of –162 dBm to –70 dBm and outputs the downconverted signal to the digital processor slice at a level of 0 dBm. It also accepts the feedback signal from the digital processor, which it uses to close the tracking loop. It has an on-module crystal reference generator, which generates the 8Fo main reference signal for the STM. It will also allow switching to an external 8Fo reference signal, for cases when a USO is desired. A Dielectric Resonator Oscillator (DRO) is used, along with the fk signal from the digital processor and the output of a multiplier of the 8Fo, in a phase locked loop to generate the 736Fo + fk signal needed to mix with the input signal. The DRO amplifier is a MMIC that was developed by Hittite Microwave for JPL as part of a NASA Small Business Innovation Research (SBIR) program.

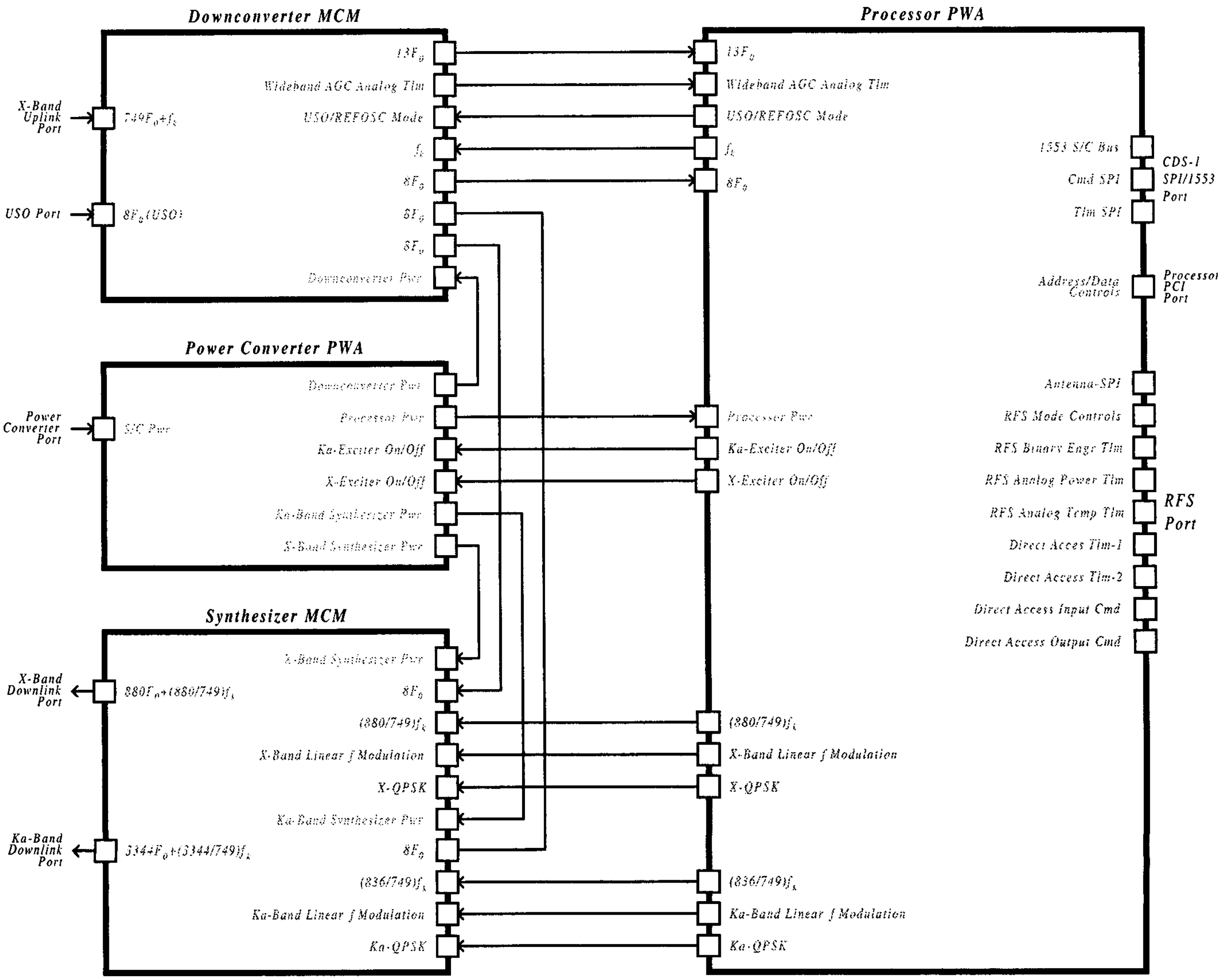

Figure 8 Interconnection Diagram

The X-band synthesizer is shown in Figure 10. The synthesizer generates the downlink signal by multiplying up the 8Fo reference signal to 880Fo and mixing it with the 880/749fk input from the digital processor module. As with the downconverter, a phase-locked loop, with a DRO as the oscillator, is used to generate the signal. The signal is then input to the linear phase modulator (for the ranging and non-OQPSK telemetry modulations) and then to the OQPSK modulator. The 880Fo + 880/749fk signal is then amplified to +12 dBm and output to the downlink amplifier. The DRO amplifier and the two modulators are MMICs developed by Hittite Microwave under the NASA SBIR program.

The Ka-band synthesizer is shown in Figure 11. The synthesizer is basically identical in operation to the X-band synthesizer operation, with the following exceptions: the signal from the digital processor is 836/749fk and the signal generated by the phase-locked loop is 836Fo + 836/740fk. After the linear phase modulation, the signal is frequency multiplied by four, to arrive at the desired output frequency of 3344Fo + 3344/749fk. After the times four multiplication, the signal is input to the OQPSK modulator, then amplified to +12 dBm and output to the downlink amplifier. As with the X-band synthesizer, the DRO amplifier and the modulators are MMICs developed by Hittite Microwave under the NASA SBIR program.

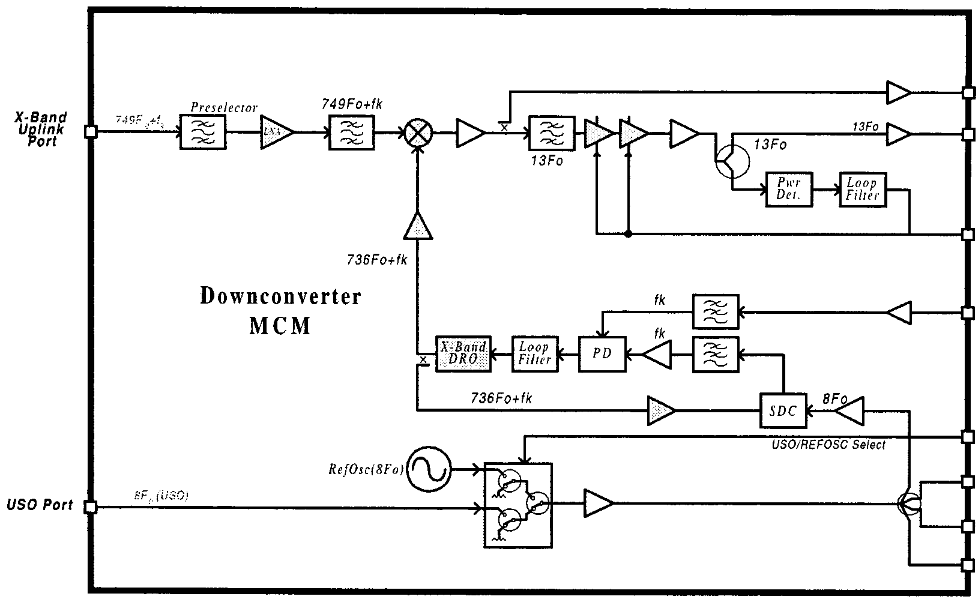

Figure 9 Downconverter MCM

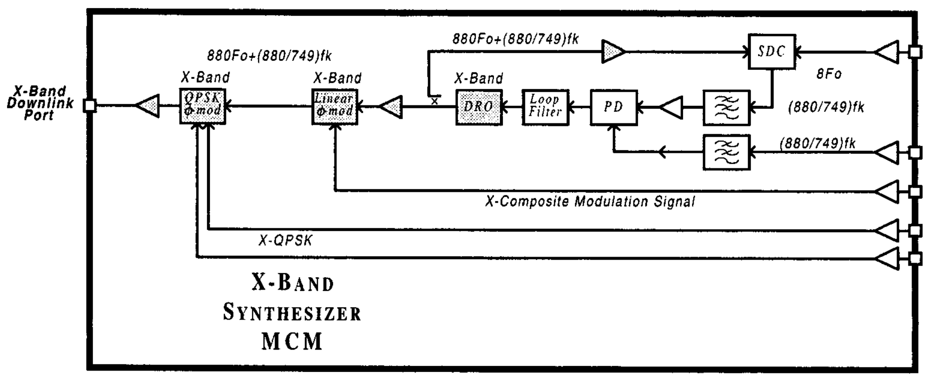

Figure 10 X-Band Synthesizer MCM

The power converter MCM generates the 10 independent voltages needed by the STM from a single 28 V input. The power converter also locks to a synchronization reference signal that is provided by the spacecraft. This is used to keep the noise spectrum generated by the power conversion process in a controlled region, protecting the spacecraft instruments from Radio Frequency Interference (RFI).

3.3 ASICs

There are two ASICs designed for the STM, a mixed signal ASIC and a digital ASIC. The mixed signal ASIC provides the interface between the analog downconverters and synthesizers and the digital processing of the digital ASIC. Figure 12 shows the signal connections between the two ASICs. The red lines indicate the Input/Output bus and the blue lines indicate the control bus.

The mixed signal ASIC consists of one 8-bit ADC that operates at 4Fo (uplink carrier tracking), five 6-bit DACs operating at 8Fo (uplink carrier tracking feedback, X-band downlink carrier, X-band telemetry data, Ka-band downlink carrier, and Ka-band telemetry data), and one 8-bit ADC that operates at a low rate (STM analog engineering telemetry sampling). The analog engineering telemetry

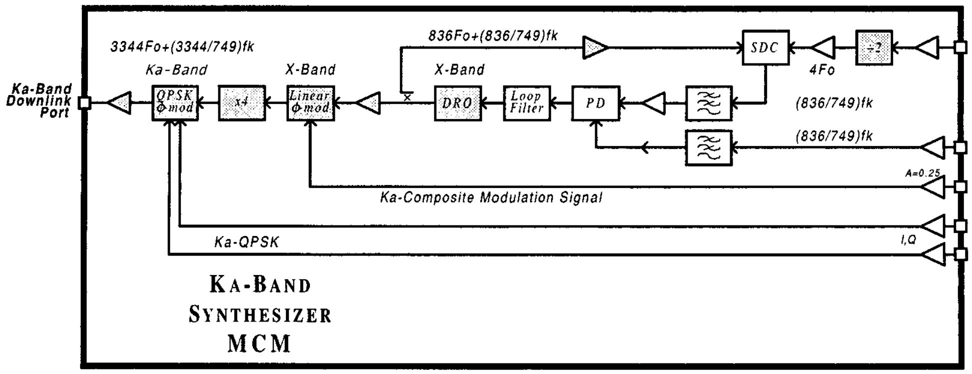

Figure 11 Ka-Band Synthesizer MCM

ADC selects between 13 analog signals (such as supply voltage sensors and temperature sensors) and sends the samples to the digital ASIC, which forwards the samples to the spacecraft CDS.

The mixed signal ASIC was implemented in the National 0.35 μm process for the Engineering Model (EM) and will be fabricated in the Honeywell 0.35 μm radiation hardened process for the Flight Unit. There are 43,000 transistors on a 10.1 μm by 10.1 μm size die. This ASIC was designed for JPL by Boeing Solid State Electronic Development.

The digital ASIC consists of all of the digital processing done by the STM, including the carrier loop filtering, the narrow band total power AGC, the X- and Ka-band downlink generation, the command detection and code block processing, the ranging processing, the telemetry frame processing and encoding, and the interfacing to the spacecraft CDS via the two buses. The clock rate is 8Fo. Based on user requirements and needs, certain parameters that modify the configuration and performance of the digital processing are stored in a ROM that is external to the ASIC. These parameters include the following items: carrier loop filter parameters, subcarrier frequencies, telemetry beacon tone frequencies, uplink-to-downlink turnaround ratio scalars, self acquisition parameters, X- and Ka-band noncoherent frequency values, PN ranging parameters (bandwidth and integration time), and open loop frequency value.

The digital ASIC is being implemented in the National 0.35 μm process for the EM and will be fabricated in the Honeywell 0.35 μm radiation hardened process for the Flight Unit. There are 1,934,363 transistors on a 13,619 μm by 13,959 μm size die. This ASIC was designed by JPL.

4. Development Schedule

Currently, the EM is in the process of being built. The mixed signal ASIC has been fabricated and is undergoing stand alone testing. The digital ASIC is in the process of being sent to National for fabrication. The EM will be assembled and tested in the summer of 2000, with the completion of compatibility testing with the DSN uplink, downlink, and tracking equipment scheduled for the fall of 2000.

The Flight Unit parts procurement process is currently on-going. As part of the Flight Unit development, the two ASICs will be transferred to the Honeywell radiation hard process. The ASICs will complete fabrication in April, 2001. The first Flight Units will be assembled and tested in July, 2001, with delivery to the first project in October, 2001, for a launch in 2003.

5. Conclusion

A description of the Spacecraft Transponding Modem has been presented. The STM is a new transponder being developed by JPL that uses digital signal processing to implement both the standard transponder capabilities and some capabilities previously done by the spacecraft CDS. The X-band up, X- and Ka-band down STM provides new downlink telemetry and ranging capabilities, which will increase mission data return, while decreasing the power and mass requirements. The STM will be used on missions launching in 2003.

6. References

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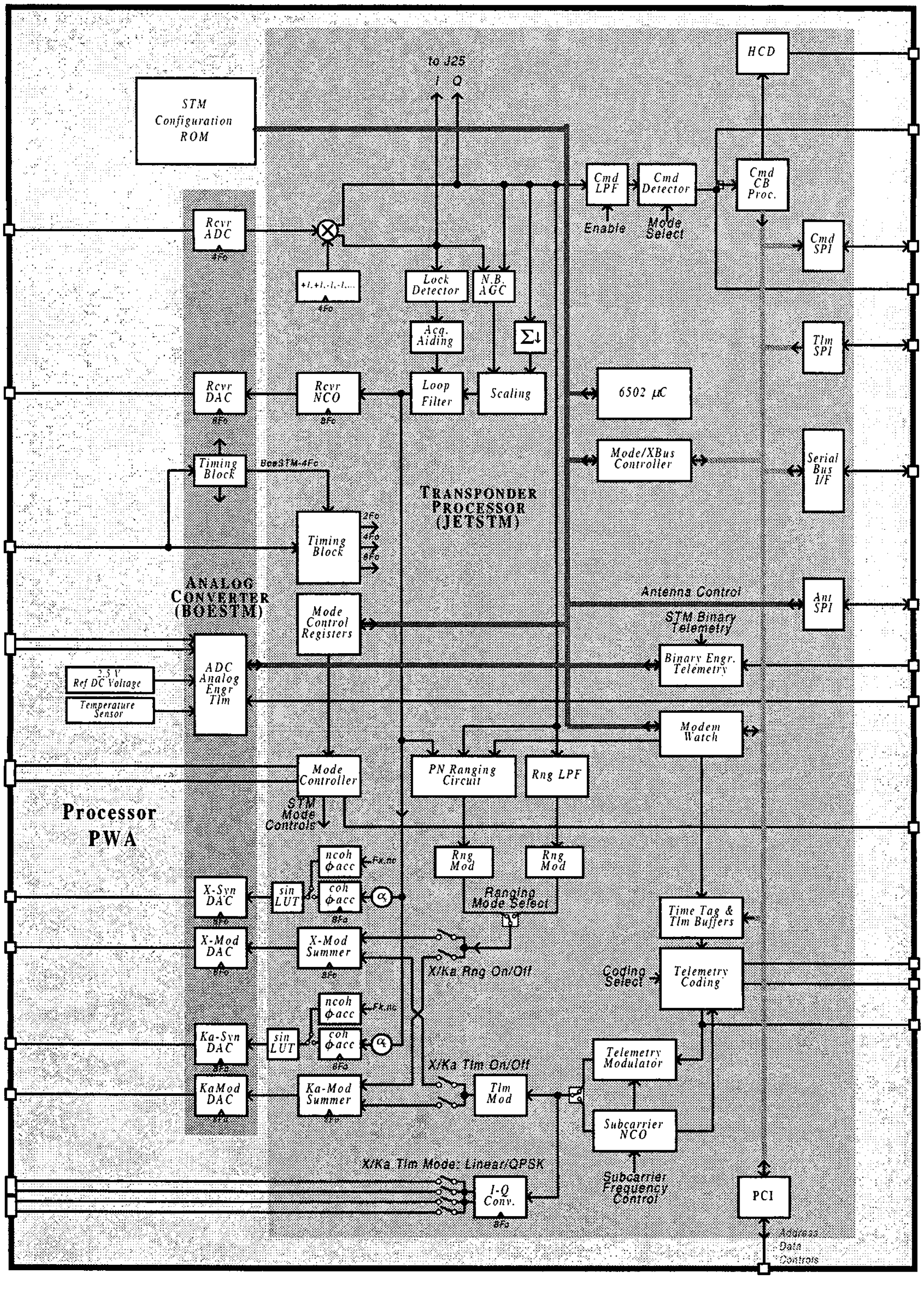

Figure 12 ASIC Interconnect Diagram

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7. ACKNOWLEDGEMENTS

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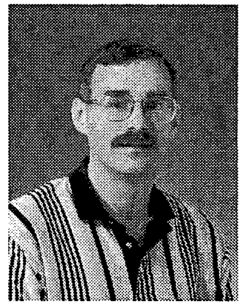
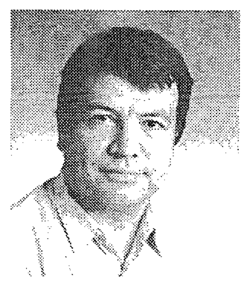


Jeff B. Berner (S'82, M'84, SM'98) earned his B.S. (with honors) in Electrical Engineering in 1983 and his M.S. in Electrical Engineering in 1984, both from the California Institute of Technology. With the exception of a six-month period in 1984, he has been at the Jet Propulsion Laboratory since 1982. Early in his career, he worked on projects such as the Galileo and Mars Observer spacecraft, and the Mobile Satellite Experiment (MSAT-X). More recently, he was the Cognizant Development Engineer of the Block V Receiver, the tracking and telemetry receiver of the Deep Space Network. In 1996, he was awarded the NASA Exceptional Service Medal for his work with the Block V Receiver for the Galileo project. Currently, he is the Telecommunications and Mission Operations Directorate Telecommunications Services System Development Engineer, where he is responsible for the uplink, downlink, and tracking equipment design and performance, and for the STM signal processing architectural design.



Selahattin Kayalar (M'87) received the B.S. degree in electrical engineering from Bogazici University, Turkey, in 1977, M.S. degree in electrical engineering from Purdue University, Indianapolis, in 1980, M.S. degree in engineering and Ph.D. degree in electrical engineering from The Johns Hopkins University, Baltimore, in 1982 and 1986, respectively.

In 1991, after teaching at Purdue University for four years, he joined the Technical Staff of Jet Propulsion Laboratory in Spacecraft Telecommunication Equipment Section. He worked in the development of the Cassini Transponder and Command Detector Unit. He is currently working in the development of Spacecraft Transponding Modem. His main fields of interest are telecommunication systems and signal processing. Dr. Kayalar is also part-time faculty at the California State University at Fullerton.

Jonathan D. Perret earned a B.S. in Electrical Engineering at California State University Polytechnic, Pomona in 1980, and a M. S. in Electrical Engineering at California State University, Los Angeles, in 1982. He has been developing spacecraft radio hardware at JPL since 1980, producing hardware for Galileo, Cassini, New Millenium DS2 Mars Microprobe and future mission spacecraft. Currently, he is the task manager for the Spacecraft Transponding Modem and the RF spacecraft equipment work area manager for the Telecommunications and Mission Operations Directorate Technology office.