A TELEMETRY TRANSMITTER CHIP SET FOR BALLISTIC APPLICATIONS

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ABSTRACT

The U.S. Army's Hardened Subminiature Telemetry and Sensor Systems (HSTSS) program has engaged the M/A-COM Corporation to work in the development of a highly accurate, crystal controlled telemetry transmitter chip set to be used in Army and other U.S. military munitions. A critical factor in this work is the operating environment of up to 100,000-g launch accelerations. To support the Army in this project, M/A-COM is developing integrated Voltage Controlled Oscillators (VCO) for L and S band, a silicon synthesizer/phase locked loop (PLL) IC, and a family of power amplifiers. Lastly, the transmitter module will be miniaturized and hardened using M/A-COM's latest chip-on-board mixed technology manufacturing capabilities. This new chip set will provide the telemetry engineer with unprecedented design flexibility. This paper will review the overall transmitter system design and provide an overview for each functional integrated circuit.

KEY WORDS

Transmitters, telemetry, munitions, high-g, voltage controlled oscillators, phase locked loop, power amplifiers

INTRODUCTION

In order to provide for the test and evaluation of smart munitions, the U. S. Army's Hardened Subminiature Telemetry and Sensor System (HSTSS) program is developing a new generation of devices for in-flight instrumentation. Gun launched systems experience high accelerations (high-g) during launch and are difficult to instrument. Rockets, although they experience less acceleration at launch, also have a severe environment due to vibration. Both are a challenge to instrument with today's commercial products due to volume constraints, system performance requirements, and budgetary issues. The HSTSS program is developing the basic building blocks of a telemetry system utilizing technological advancements from the wireless/portable commercial sector. The program is developing sensors, data acquisition components, power sources, electronic packaging techniques, and transmitter chip-sets. With this family of products the telemetry engineer will have the design flexibility needed to instrument gun launched projectiles and other advanced munitions of the future.

In October 1998, the M/A-COM Corporation was awarded a development contract for a very rugged, small, low cost, transmitter chip set for ballistic telemetry applications. Although some commercial transmitters exist for these types of applications, they typically are large in size, expensive, and limited in performance. In order to provide greater packaging and system flexibility, a highly integrated transmitter chip set is required. The chip set is comprised of three major subsystems. They include a phase locked loop (PLL) chip, voltage controlled oscillator (VCO), and family of power amplifiers (PA). A block diagram of the transmitter system is shown in Figure 1. The design of each component along with the manufacturing concept for miniaturization, environmental requirements and a typical munition application will be discussed.

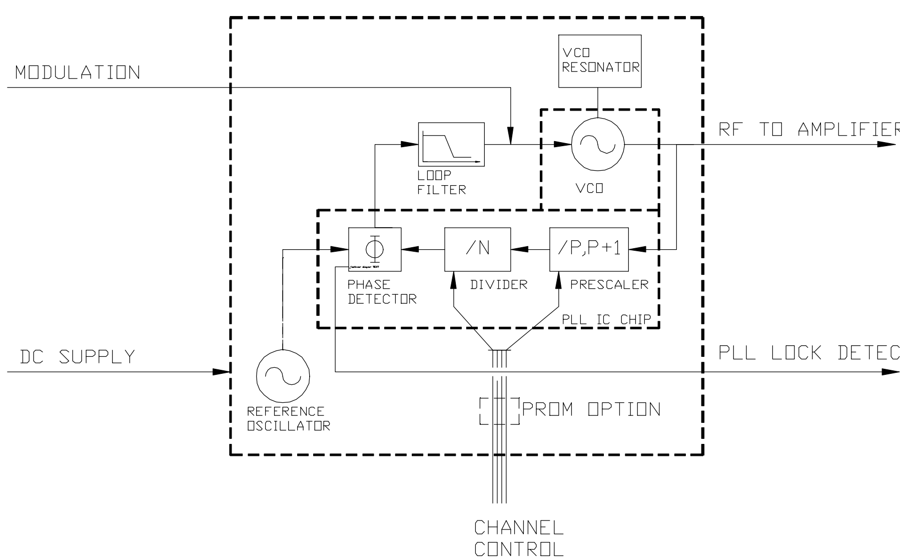


Figure 1. Frequency Source Block Diagram.

HIGH G SHOCK ENVIRONMENT

The operating environment for ballistic munitions is severe. The payload of an artillery projectile can experience setback accelerations as high as 30,000 g. An artillery projectile can have spin rates greater than 300 rps yielding radial accelerations as high as 25,000 g depending on payload location. Both maximum acceleration and spin are achieved in less than 15 milliseconds. The range of a typical artillery projectile is 20 kilometers.

For this transmitter development effort the munitions have been divided into four categories; missile/rockets, Large caliber (i.e. artillery), small caliber, and kinetic energy (KE) projectiles. Table 1 summarizes the typical environment experienced by these munitions. On-board instrumentation for all these munitions is required by the Army and other branches of the military. This transmitter development will enable the designer to make smaller and more reliable telemetry packages. This will allow for a greater number of measurements to be made, as well as the realization of measurements that were previously impossible due to size limitations.

	Missile/Rocket	Large Caliber	Small Caliber	KE
Setback Acceleration	500 g	30,000 g	100 k-g	100 k-g
Spin	100 rps	300 rps	400 rps	50 rps
Range	2 km	20 km	.5 – 2 km	2-3 km
Volume (typ)	820 cm^3	147 cm^3	8 cm^3	8 cm^3

Table 1. Summary of Typical Environmental Conditions.

THE TELEMETRY SYSTEM

The transmitter system design is driven from the contract specifications that were developed by a team of tri-service engineers. General specifications come from the IRIG 106-96 Telemetry Standards. Listed in Table 2 are some of the major parameters requested by the government team.

PARAMETER	UNIT	MINIMUM VALUE	NOMINAL VALUE	MAXIMUM VALUE
Frequency Stability	%	0.002		
Turn on Time	ms	20		30
Frequency (L Band)	MHz	1435.5		1525.5
Frequency (S Band)	MHz	2200.5		2290.5
Modulation Type			FSK, FM	
Data Rate (digital)	Mbps	0.065		10
Deviation Sensitivity (selectable)	MHz/V	.250		5
Supply Voltage	Volts	3		12
Temperature	Degrees C	-40		+85
Acceleration	g	500		100k
Output Power	W	.010		2
Package Type			Die & SMT	

Table 2. Partial Table of HSTSS Telemetry Specifications (Low Power Systems).

OPERATIONAL OVERVIEW

The transmitter chip set is comprised of a PLL, VCO, and a family of PA's. The PA's are available in 100 mW, 250 mW, 1W, and 2W ratings. The VCO is the primary frequency source and can be used in two configurations. The first is a simple free running VCO. By selecting the appropriate resonator, the VCO can operate across both the L and S bands. When coupled with a PA, this free running VCO provides a very small and inexpensive transmitter. This type of configuration can be used for extremely limited volume applications. In the free running mode, the 0.002% stability specification is not expected to be met, though the VCO has been carefully designed for the best stability across temperature.

The second configuration is the phase locked frequency source, with reference oscillator and phase locked VCO. For this configuration, the operator can program the carrier frequency using a four-wire bus. Programming can be accomplished by hardwiring the control lines or by using a micro-programmer. Sixteen steps are available in increments of

0.5 MHz steps in the L-band and both the lower and upper S-bands. The PLL chip is being designed with an on-board oscillator that can be used along with an external resonator. It can also be bypassed for use with an external reference oscillator for greater stability. This configuration is expected to easily meet the 0.002% stability specification as stated in IRIG 106-96. To make the chip set even more versatile, the components are going to be available in both die form and surface mount packages. With this type of architecture the telemetry engineer can optimize the transmitter based on the system requirements.

MODULATOR/PLL

The PLL circuit to be used is shown in Figure 2. It uses a fairly standard topology that phase locks the VCO to a reference oscillator using a phase detector and frequency divided signal from the VCO. The use of a programmable divider allows the change of the division ratio N, resulting in a new VCO frequency.

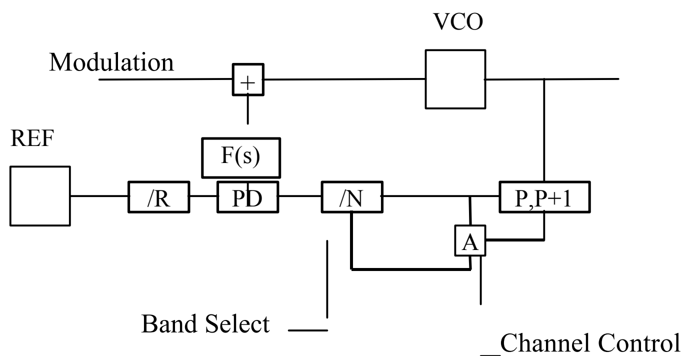


Figure 2. Topology for Phase Locked Loop Circuit.

PHASE DETECTOR/LOOP FILTER: The IRIG and HSTSS specifications require frequencies centered on 0.5 MHz. This requirement determines the phase detector (PD) frequency as 500 kHz. The PD is to be a phase-frequency type detector, which allows for fast acquisition (high bandwidth) and narrow bandwidth tracking. The loop filter is shown in Figure 2 as F(s). Determination of the bandwidth of this filter is driven by conflicting needs of fast acquisition and low data rate modulation. In order to quickly acquire lock, the loop bandwidth must be high. At the same time, the modulation to be added to the VCO must be added outside the loop filter bandwidth, or it will be nulled by the PD. The tracking bandwidth was chosen to be 1 kHz and the acquisition bandwidth to be10 kHz. The acquisition time is calculated by:

$$Tacq \leq 3.5\frac{\Delta f^2}{{B_{COARSE}}^3} + \frac{2}{B_{FINE}}$$

Given the bandwidths chosen, and ~10 milliseconds relaxation time for the crystal reference oscillator, the overall system is expected to acquire lock in less than 20 milliseconds.

Dividers /Channelization: The topology in Figure 2 uses a dual modulus prescaler. In order to divide from L or S band, a prescaler would be needed; in order to allow for maximum frequency selection, a dual modulus prescaler is preferred. By controlling both the A register and the N register, the three bands of operation and 16 required channels in each band (minimum) can be synthesized. Table 3 shows one channel scheme using 1 MHz channel spacing on 0.5 MHz channel centers to meet the IRIG and HSTSS channel specifications for 16 channels. Some applications do not have external logic or controllers. Programming is then accomplished by hard wiring the registers for a specific frequency.

The PLL IC will be fabricated using a silicon process. At the time of this writing, a foundry has been chosen, the design architecture has been agreed upon, and transistor level design is in progress. The loop filter will use externally loadable components for maximum flexibility in integration for various applications. As with all other components, the high g acceleration requirement must be kept in mind. Components with similar construction have been tested at ARL for ability to withstand high shock, and have been found to be reliable (Ref 3).

Channel	**PD freq. (MHz)**	**P**	**N**	**N binary**	**A**	**A binary**	**VCO freq. (MHz)**
1	0.5	12	240	11110000	1	00001	1440.5
2	0.5	12	240	11110000	3	00011	1441.5
3	0.5	12	240	11110000	5	00101	1442.5
4	0.5	12	240	11110000	7	00111	1443.5
…	…	…	…	…	…	…	…
14	0.5	12	240	11110000	27	11011	1453.5
15	0.5	12	240	11110000	29	11101	1454.5
16	0.5	12	240	11110000	31	11111	1455.5

Table 3. Channelization for L Band, 1 MHz Steps.

VOLTAGE CONTROLLED OSCILLATOR (VCO)

The VCO will be constructed separate from the PLL IC. This again allows for maximum flexibility in integrating frequency sources for various applications. At the time of this writing, a VCO ASIC is undergoing fabrication using an heterojunction bipolar transistor (HBT) process. The specifications that drive the VCO are shown in Table 4. The VCO is required to have 100 MHz bandwidth. In order to have a design capable of operating in either L or S band, a broadband active device is used with external resonator and internal or external varactor tuning diode. Loading options for varactor and resonator allow the VCO to operate in either L or S band. Based on spice simulations the free running stability of the VCO is expected to be better than 0.5% over the operating temperature range. The die and packaged part can be seen in Figure 3.

Specification	Unit	Value	Comment
Frequency Range	MHz	1435 – 1535 2200 – 2300	Tune with external resonator elements. Internal varactor may be bypassed.
Tuning Voltage	volts	0.5 - 3.0	
RF output power	dBm	10	
Supply Voltage	volts	3	Allow 20 % drop while operational
Operating temperature	degrees C	-40 to +85	

Table 4. Partial Table of VCO Specifications.

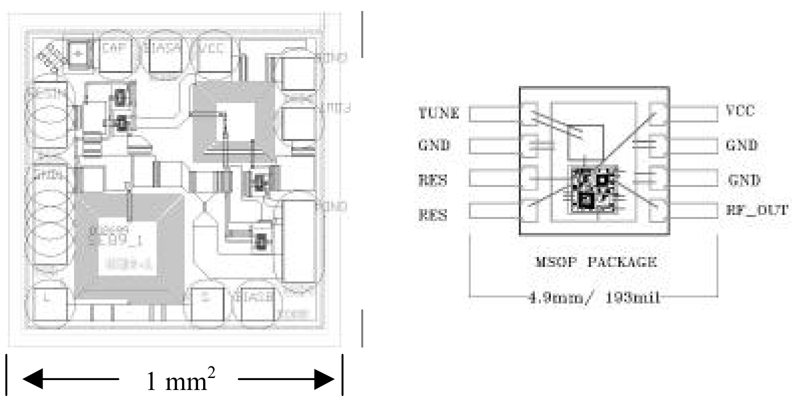
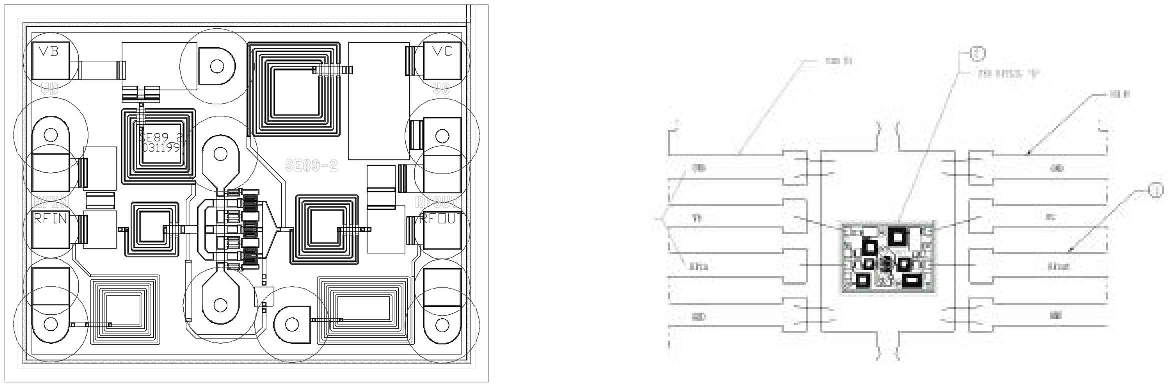


Figure 3. VCO Die Layout and MSOP-8 Package.

POWER AMPLIFIERS

The nominal power output of the frequency source is 10 milliwatts. In addition, a family of cascadable power amplifiers is being developed to provide 100mW, 250mW, 1W and 2W output power. The 100 and 250mW amplifiers are to operate from 1.4 to 2.4 GHz at 3V. At the time of this writing, both the 100mW and 2W components are in fabrication. The 250mW component is still in the design phase.

100mW Low Power Amplifier: The die outline and package layout for the 100mW low power amplifier is shown in Figure 4. This amplifier is matched to 50 ohms at input and output (<2:1 VSWR) and is designed to use the 10mW output from the VCO as its input drive. The PA operates across the 1.4 to 2.4 GHz band, and is expected to operate in a saturated mode at >20dBm output. The driver amplifier is fabricated from a GaAs HBT process, which allows for single supply operation with good efficiency. It will be available as bare die for chip-on-board operation or as SMT in an MSOP8 package.



(1.3 x 1.0 mm)

Figure 4. 100mW PA Die Outline and MSOP-8 Package.

2 Watt Power Amplifier: The 2W power amplifier will be two separate chips for L and S band and operate at 8 volts. The 2-watt amplifiers are being constructed using standard M/A-COM FET processes. When operated at 5 volts the 2-watt amplifier provides 1-watt of output power. The 2-watt power amplifier is expected to operate at better than 35% efficiency. As with the other components, the amplifiers will be tested for survivability in high acceleration environments. Puck packages similar to those to be used have been mechanically tested under high g accelerations at ARL and were evaluated by the M/A-COM Reliability Lab. The package showed no signs of damage (Ref 4).

QUARTZ REFERENCE OSCILLATOR

The key to meeting the IRIG 106-96 frequency stability specification of 0.002% over temperature is in the reference oscillator. Providing small, reliable, and affordable quartz crystal reference oscillators for high-g applications has been an on-going challenge. The challenge involves finding a crystal fabrication process and a mounting structure that can withstand the extreme accelerations without a permanent frequency shift or severe damage. A less rigid mount can dampen acceleration effects on the crystal; unfortunately this also affects the high Q which is the crystal's most important parameter.

In May of 1999, the Statek Corporation was put under contract to the HSTSS program to develop both a quartz crystal resonator and quartz crystal oscillator specifically for high-g telemetry applications. These components will provide frequency control for the HSTSS transmitter and clocking for the HSTSS data acquisition chip set. The quartz resonator will be packaged in a surface mount ceramic package. It's target size is 0.197"L x 0.072"W x 0.045"H. The oscillator, which employs the crystal resonator is to be less than 0.35"L x 0.27"W x 0.13"H. The oscillator will have both sine and square wave outputs, at 20MHz, with 20 PPM stability over a –40 °C to +85 °C temperature range. Both components are being designed to survive the ballistic and missile environments.

TYPICAL APPLICATION

There are many applications where a telemetry system is needed, but available volume is extremely limited. A prime example of this is instrumenting a kinetic energy (KE) rod as shown in Figure 5. This long, thin solid rod has very little volume for a telemetry system. The only locations available are in the tracer-well of the fins and possibly in the nose. The environment for this projectile is extreme with launch accelerations over 60,000 g and propellent flash temperatures greater than 2500 °C. Because of the volume limitation and extreme environmental conditions there have been very few telemetry systems built and successfully flown on this munition.

Figure 5. Kinetic Energy Rod.

The ARL has been tasked to put a telemetry module into the nose of an advanced KE rod. The telemetry system will be used to monitor on-board electronics. The volume available is 28cm^3 (2cm d x 9cm h). This virtually eliminates all presently available commercial telemetry transmitters. ARL has designed and is fabricating a single channel system using a hybrid transmitter and an HSTSS battery. This single channel system requires all of the available volume as seen in Figure 6. The transmitter alone requires more than 1/3 the total volume. The M/A-COM transmitter, along with other HSTSS components, will make it possible to build a multi-channel system in less than 1/3 the present total volume.

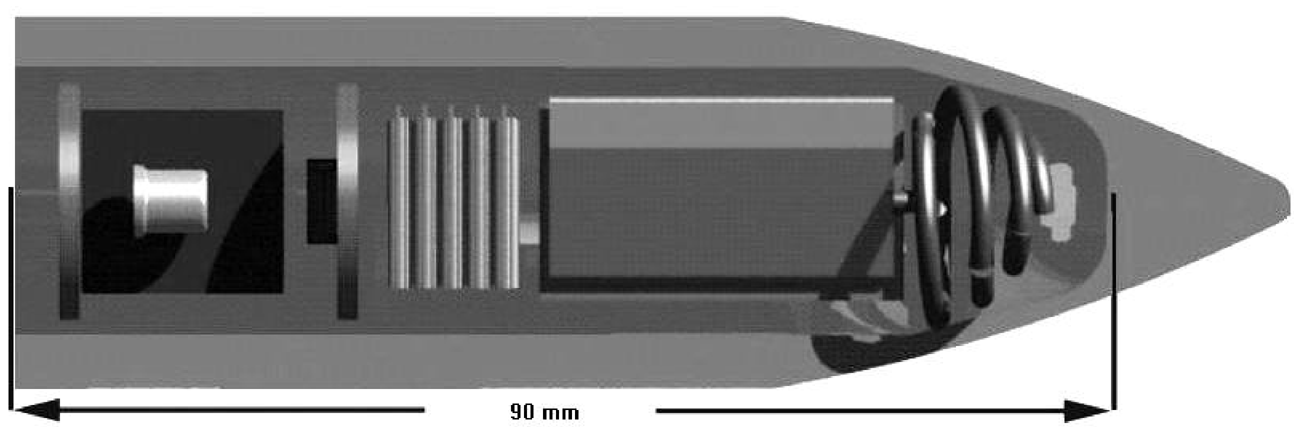


Figure 6. Advanced Kinetic Energy Telemeter.

SUMMARY

The M/A-COM transmitter chip set is going to provide the telemetry engineer with unprecedented design flexibility. It has a frequency response better than 10 MHz, programmable deviation sensitivity, in-band channel selectivity for both L and S bands, and a choice of power amplifiers. When used with a 20-ppm resonator the transmitter is IRIG 106-96 compatible. All integrated circuits for this chip set will be available in both die form and surface mount packages. The estimated die sizes and supply requirements for each component are summarized in Table 5.

	Size (mm)	Supply Voltage (Vdc)	Supply Current (mA)
VCO	1.0 x 1.0	3	30
PLL	3.3 x 1.9	3	25
100 mW	1.3 x 1.0	3	150
250 mW	1.0 x 1.5	3	330
2 W	3.0 x 2.5	8 (2W) & 5 (1W)	800

Table 5. Summary of Chip Sizes and Power Requirements.

Prototypes of the VCO, PLL, and PA devices are to be evaluated during the summer of 1999. Final product delivery for these components is expected in November of 1999. In addition to the components, M/A-COM is producing fully integrated transmitter modules using their proprietary MCM-L technology. The modules are going to be configured for S-band operation and will utilize the Statek quartz crystal reference oscillator. These modules are currently scheduled for a March 2000 delivery.

Under the HSTSS program M/A-COM is working directly with the Army Research Lab on qualifying the components and microelectronic assembly techniques for high-g environments. The most challenging design and manufacturing concern is the 100,000 g acceleration survivability requirement. In order to meet this requirement, both robust design practice and extensive reliability testing are being used.

In this paper, the operation and configuration of the chip-set was discussed. Details of the PLL, VCO, and PA integrated circuits were reviewed. Plans for obtaining the reference oscillator, and manufacturing the complete module, have been outlined. This work represents a major advancement in the area of ballistic telemetry. This new transmitter chip set, when coupled with other HSTSS products will allow for unique measurements, which in the past were considered impossible.

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