BENEFITS OF A SPACE-BASED AUGMENTATION SYSTEM FOR EARLY IMPLEMENTATION OF GPS MODERNIZATION SIGNALS

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BIOGRAPHY

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ABSTRACT

The first space-based GPS augmentation systems were implemented using the L-band geostationary transponders launched on the Inmarsat-3 satellites. The Ground Uplink Station (GUS) hardware and software, which enables these “bent-pipe” transponders to broadcast pseudo-GPS signals, was developed by NAVSYS. The Ground Uplink Station equipment allows the Inmarsat-3 GPS augmentation signals to be precisely locked to GPS time and provide highly accurate, coherent pseudo-range and carrier-phase observations. This hardware and software is now the core of the Federal Aviation Administration’s (FAA) Wide Area Augmentation System (WAAS).

The adaptability of the transponder approach is attractive for supporting the development of next generation GPS capabilities as part of the GPS modernization effort. The geostationary augmentation earth station equipment developed by NAVSYS is reprogrammable. While the WAAS signals only use the Course Acquisition or Clear Access (C/A) code, NAVSYS’ Ground Uplink Station hardware can be configured to support C/A code, military encrypted Precision (P(Y) code and also the new Military-code (M-code) signals. This capability enables a geostationary transponder to be used to support development, test and qualification of new military signals using a space-based augmentation system.

In this paper, the geostationary augmentation earth station equipment being developed under contract to Air Force Research Laboratory (AFRL) to support the GPS Modernization signal structure is described and test results of the system operating in a loop-back test-mode are provided.

INTRODUCTION

The FAA has developed WAAS as an augmentation to the core GPS constellation operated by the US Air Force. WAAS uses geostationary satellites to provide additional GPS ranging signals and to broadcast integrity and differential GPS (DGPS) corrections. This system was developed to enable GPS to meet radionavigation performance requirements. Similar systems are being fielded internationally for the same purpose.

The WAAS system architecture is shown in Figure 1. This includes a network of ground reference stations that monitor the GPS satellites, a master station that processes and formats the data received, and a Ground Uplink Station that rebroadcasts the WAAS data to aviation GPS user equipment. WAAS provides the following services: integrity corrections which provide an alert when out of tolerance GPS errors are detected[1]; wide area DGPS corrections to improve the accuracy of the navigation solution to 1-5 meters[2]; and a pseudo-range observation, precisely synchronized to the GPS satellite constellation[3].

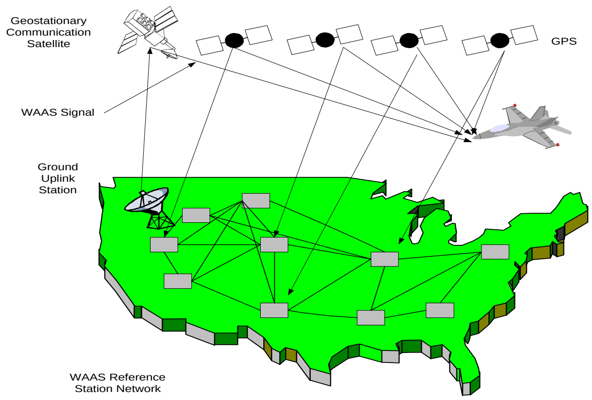

Figure 1 FAA Wide Area Augmentation System

NAVSYS produces the satellite ground uplink system hardware and licenses the signal control software that is used for the FAA's WAAS earth stations. The initial development effort was sponsored by Inmarsat where testing was done using the Inmarsat-2 satellite L-band communication transponder. This led to the development of the L1-transponders now carried on-board the Inmarsat-3 satellites Figure 2.

The core of the WAAS Ground Uplink Station is the NAVSYS SIGGEN 1200 which provides a synchronous GPS signal for transmission through a geostationary satellite transponder or as a local broadcast as a pseudolite. The automatic signal conditioning and calibration applied by the SIGGEN makes the broadcast geosynchronous earth orbit (GEO) satellite or pseudolite signal synchronous to that generated by a GPS satellite payload. The SIGGEN 1200 is used by the FAA for operation of the WAAS and is also being purchased by the Japanese CAA for use with their MT-SAT geostationary overlay.

One of the benefits of the bent-pipe approach adopted for the geostationary augmentation system used in the WAAS program was that the satellite payload was able to be defined and specified in advance of completion of the detailed WAAS signal specification. In fact, the first Inmarsat-3 satellites were used for qualifying the final WAAS signal format with prototype GPS user equipment. NAVSYS is currently developing a military version of the geostationary augmentation system hardware and software under contract to the AFRL. This equipment is capable of operating with the C/A code, P(Y) code and the new M-code in development. In this paper, the system operation is described, and applications of a military GPS augmentation system can be used to support early implementation and testing of the GPS modernization signals are described.

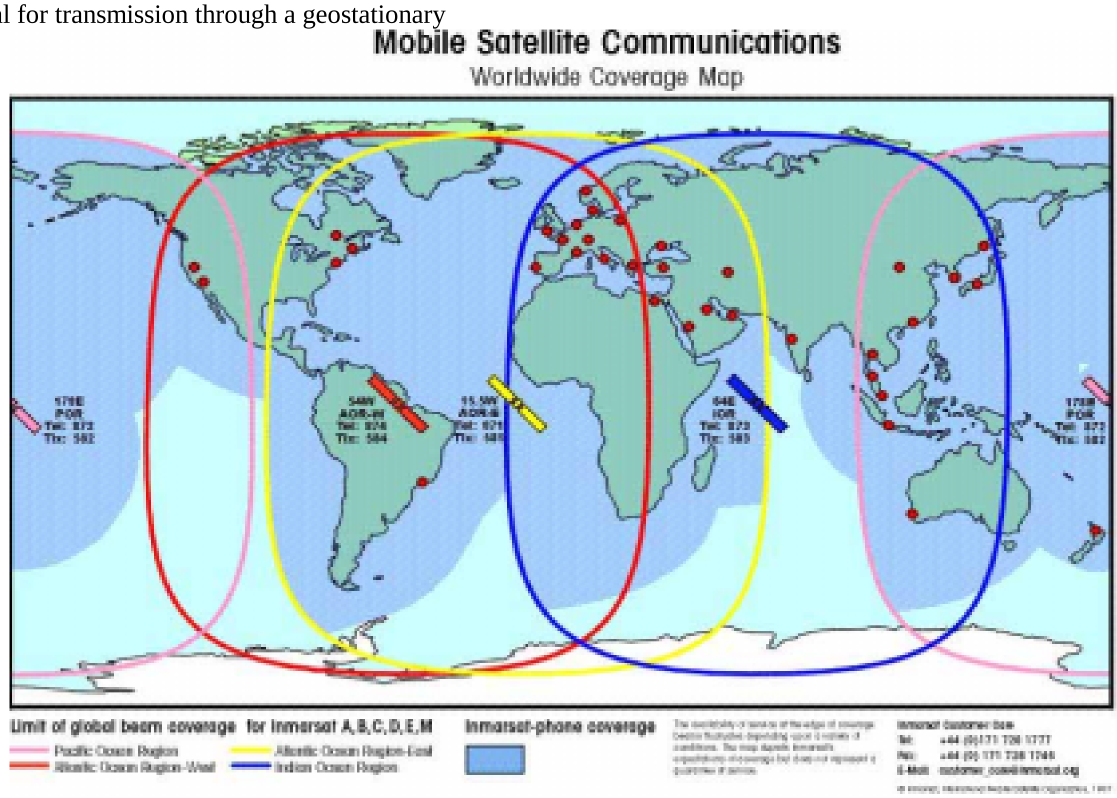

Figure 2 Inmarsat-3 Transponder Coverage

SPACE-BASED MILITARY GPS AUGMENTATION SYSTEM (MGAS)

The elements of a Military GPS Augmentation System (MGAS) are illustrated in Figure 3. This architecture leverages the same principles adopted by the FAA for their WAAS project. The encoded military GPS signal is generated at the Ground Uplink Station. This signal is then uplinked to a communication satellite and retransmitted at L-band for reception by a GPS receiver.

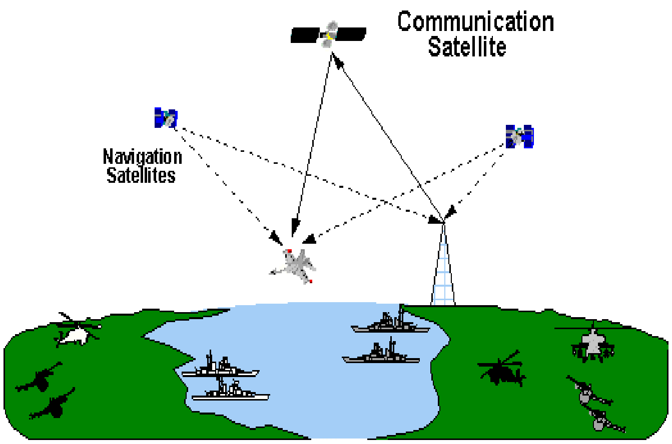

Figure 3 Military Geostationary Augmentation System (MGAS)

With a GPS geostationary transponder, the majority of the functions performed by the GPS satellite payload reside in the earth station instead. As shown in Figure 4, the signal code generation and data modulation are handled by the earth station signal generation hardware and are modulated on the satellite up-link. The precise time reference is also maintained at the earth station, instead of being carried on-board the satellite. This makes the transponder payload significantly simpler than the GPS satellite payloads, which allows it to be carried as a "piggy-back" onboard another communications satellite.

Since the signal encoding is performed at the earth station, the geostationary transponder architecture provides much more flexibility for modifying or dynamically reallocating the signals broadcast through the geostationary satellite. This means that both the current and next generation GPS modernization signals can be broadcast through the geostationary transponder. The next generation GPS satellites are planned to adopt improved military codes (M-codes) and also higher power signals to improve the GPS anti-jam (A/J) performance. The use of a GPS geostationary augmentation system to broadcast the GPS modernization signal provides the capability to test the new signal structure from space, and also offers an early opportunity to increase the over-all robustness of GPS in a tactical environment through the use of a DoD GPS augmentation system.

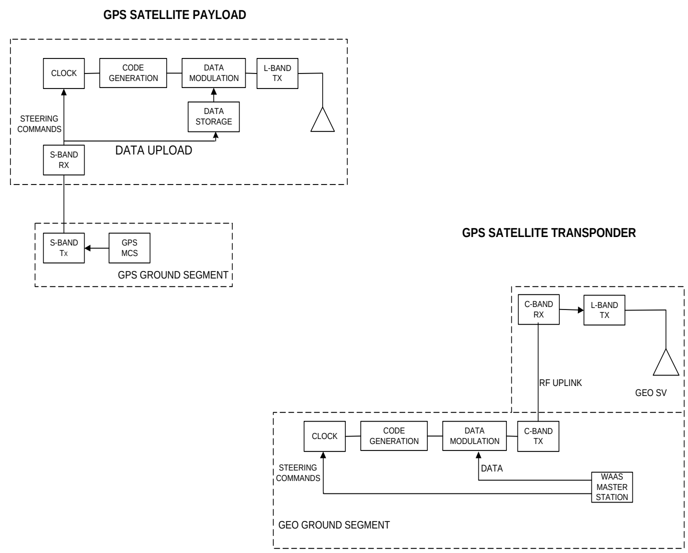

Figure 4 Payload/Transponder Comparison

The GPS transponders carried on-board the Inmarsat-3 satellites operate at the L-1 frequency (1575.42 MHz) and have a 2 MHz bandwidth. Since the full military spectrum covers a 24 MHz bandwidth, the existing GPS transponders are not well suited for use in testing with the military GPS signals. A design for a broad-band GPS transponder has been developed for the U.S. Navy and is being considered for launch on a DoD geostationary satellite within the next 3 years.

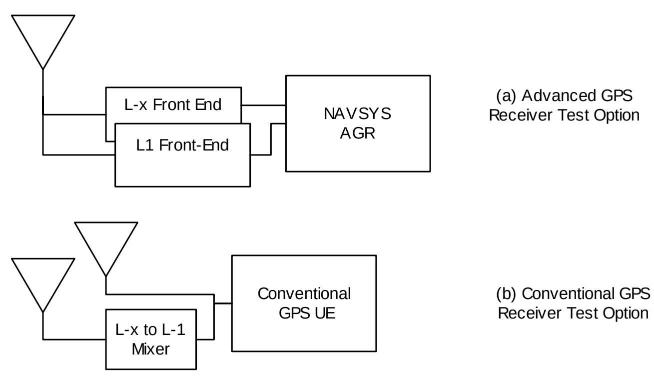

Figure 5 GPS User Equipment Test Options using SATCOM Bands

Another option for the next phase of our current MGAS program is to perform the satellite testing using a leased L-band channel operating in the SATCOM bands (e.g. 1530 to 1559 MHz). This option was used to support initial testing of the WAAS concept by NAVSYS using the Inmarsat-2 satellites. The initial trials of the WAAS system capability were performed using a 1542 MHz downlink. Testing was performed both with a NAVSYS' GPS receiver, with an RF front-end tuned to the 1542 MHz center frequency, and with a conventional GPS receiver using a mixer to convert the input signal frequency back to 1575.42 MHz, as shown in Figure 5.

MGAS SYSTEM ARCHITECTURE

The MGAS system architecture being produced by NAVSYS is illustrated in Figure 6. This includes the following subsystem components.

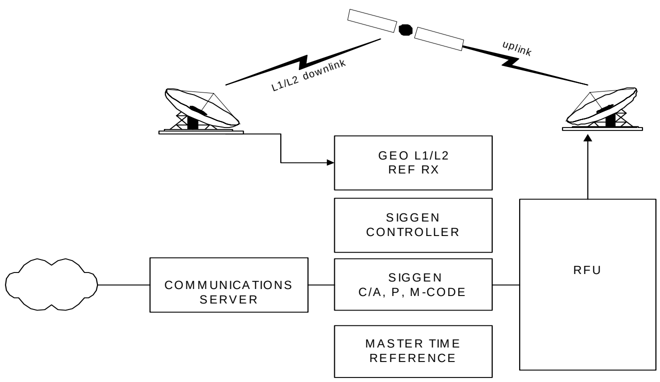

Figure 6 Military GPS Augmentation System Architecture

Communications Server. The communications server provides the network link for the data to be modulated onto the MGAS broadcast signal. In an operational architecture, this could include GPS corrections, integrity data (e.g. to provide a military WAAS capability), timing data, or messages to specific receivers (e.g. over the air re-keying). The communication server also provides the network access to support dynamic power allocation and M-code definition between the multiple signals being broadcast through the MGAS satellite transponder.

Reference Receiver. The MGAS architecture leverages the precise time synchronization and ranging capability provided by NAVSYS ground uplink equipment used for the FAA's WAAS system. A reference receiver is used to monitor the signals broadcast by the MGAS and send observations to the SIGGEN controller to allow it to adjust the encoding timing and uplink carrier to maintain the broadcast signals synchronized with the GPS constellation and at the correct power level designated for each signal.

SIGGEN Controller. The controller implements the control algorithms developed by NAVSYS to synchronize the broadcast code and carrier by the MGAS satellite transponder to the GPS master time reference maintained at the earth station.

Signal Generator. The Signal Generator generates the MGAS code structure for modulation on the satellite uplink. The FAA uses NAVSYS equipment to generate the C/A code WAAS signal. This equipment includes a reprogrammable code generator that will currently generate any of the 1023 codes in the C/A code family. The programming of the SIGGEN has also been modified for the MGAS to generate both the P(Y) codes and the M-codes so that multiple signals can be transmitted through the MGAS transponder.

Master Time Reference. The master time reference performs the same function as the master time reference on-board the GPS satellites, to precisely synchronize the broadcast signals to GPS master time. Since there is a dedicated network link to the MGAS ground equipment, the MGAS clock can be synchronized at a much faster rate than the GPS satellite clocks (which only receive 1-2 updates/day), enabling the MGAS time to be maintained to within 1 nanosecond of the GPS master time reference. This capability will allow the MGAS to provide a highly precise time signal, which is independent of the GPS broadcast satellite time.

Radio Frequency Uplink (RFU) Equipment. The uplink RFU equipment takes the SIGGEN IF output and uplinks it to the satellite transponder. The uplink frequency is dependent on the receive frequency of the satellite transponder. With the Inmarsat satellites, a C-band uplink is used. The hardware is also compatible with a Ka or Ku-band uplink.

Satellite Transponder
The basic design of the on-board satellite transponder is illustrated in Figure 7. The uplinked signal is mixed to a convenient LO for filtering to reject out-of-band components and then is mixed to L-band for retransmission. Since the on-board reference clock is not synchronized to the uplinked signal, the clock frequency offset introduced by the transponder has to be corrected as part of the earth station signal pre-conditioning. The band limiting and amplification of the signal also introduces effects on the GPS signal structure that have to be taken account in the system design.

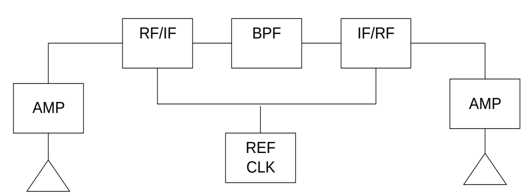

Figure 7 Analog Transponder Top-Level Design

GPS MODERNIZATION SIGNAL STRUCTURE

The current WAAS geostationary augmentation systems only transmit a single code, the C/A code. This is a 1.023 Mbps bi-phase shift key (BPSK) modulated signal. The GPS satellites currently broadcast both the C/A code and P(Y) code. The P(Y) code is a 10.23 Mbps BPSK signal modulated in quadrature to the C/A code. The combined spectrum occupied by the C/A and P(Y) code is shown in Figure 8.

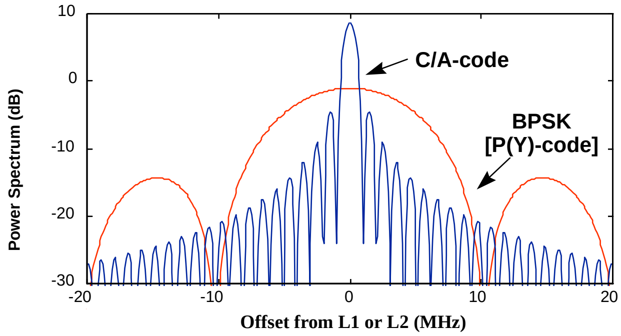

Figure 8 GPS BPSK C/A-Code and P(Y) Code Power Spectrum

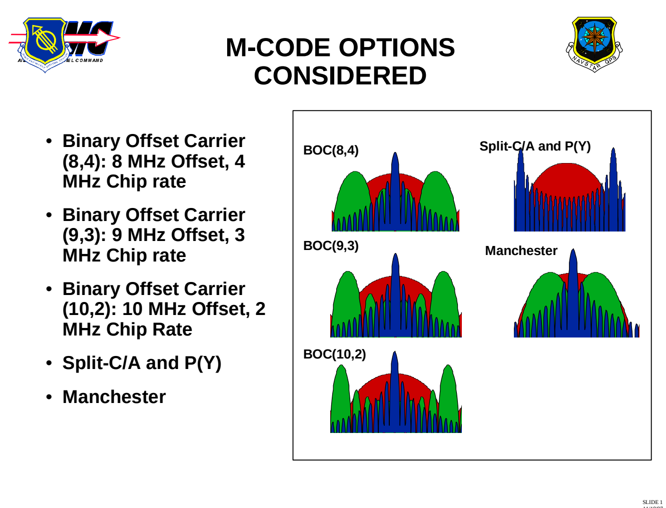

Figure 9 Alternative M-Code Waveforms

To improve the A/J performance of the GPS signals, the GPS JPO is planning to include an M-code. The various alternatives considered for this waveform are illustrated in Figure 9 and defined in their waveform development plan[4].

In a GPS jamming environment, depending on the type of jamming threat employed, there are advantages and disadvantages to all of the alternative M-code waveforms considered. The flexibility of the MGAS architecture raises the possibility of a concept of operations (CONOPS) for GPS, which includes the option for reprogramming the GPS broadcast codes to respond to a particular jammer threat. The MGAS system architecture would allow experimentation with this CONOPS and development of operational procedures with GPS users for how this could be employed.

MGAS TESTING

A satellite transponder emulator has been designed to allow closed loop testing of the system performance in the laboratory. The design of the transponder emulator was developed to includes the filtering, mixing and amplification stages shown in Figure 7, and also to model the effect of the uplink and downlink dynamics on the closed loop performance of the MGAS architecture.

The satellite emulator design is shown in Figure 10. The uplink and downlink effects on the code-phase group-delay and carrier Doppler offset are accounted for in the satellite emulator using logic control and a precision delay line to add the effect of a time delay between the SIGGEN transmitter and reference receiver.

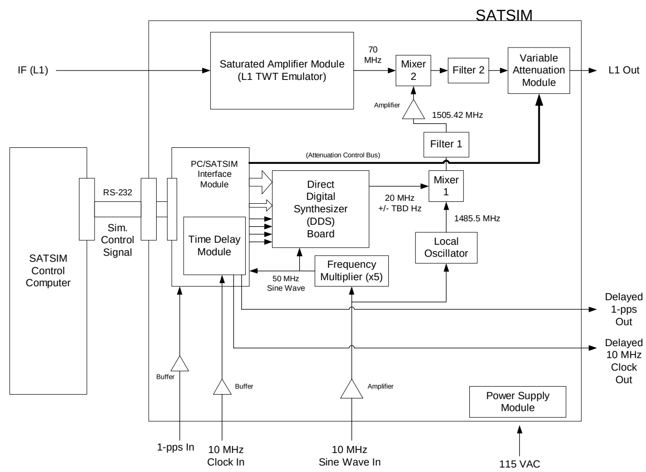

Figure 10 Satellite Simulator Functional Elements

Because spacecraft power amplifiers operate most efficiently in saturation, a high power traveling wave tube amplifier (TWTA) very nearly approaches the behavior of an ideal limiting amplifier. This can introduce significant distortions in the rebroadcast signal, particularly when a non-constant envelope signal structure is used[5]. Methods have been developed for modulating the C/A, P(Y) and M-code signals, creating a near constant envelope signal for the GPS satellites. However, NAVSYS has developed a method for compensating for the amplifier hard limiting effect in the Ground Uplink Station equipment allowing multiple signals to be transmitted through the MGAS transponder without requiring a constant envelope signal spectrum. Testing of this signal modulation method is being conducted with the satellite simulator shown in Figure 10

CONCLUSION

The use of a Military GPS Augmentation System has the following advantages for enhancing the existing GPS constellation and also the planned GPS-3 satellite constellation.

- MGAS can provide an early space-test capability for M-code operation either using a military geostationary overlay or by testing through an L-band SATCOM link.
- The MGAS reprogrammability provides additional flexibility over the GPS satellites enabling experimentation with new operational concepts for the GPS-3 constellation, including M-code reprogrammability or dynamic power allocation between codes.
- The geostationary overlay can support other military GPS needs such as over-the-air re-keying, precise time synchronization, or military WAAS messaging for approach and landing applications.

In a follow-on phase to our current contract with the Air Force, it is planned to demonstrate this capability using an L-band SATCOM transponder.

ACKNOWLEDGEMENT

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