IMPROVING PERFORMANCE OF SINGLE OBJECT TRACKING RADAR WITH INTEGRATED GPS/INS

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ABSTRACT

A novel approach combines GPS receiver technology with micro-electromechanical inertial sensors to improve performance of single object tracking radar. The approach enhances range safety by integrating an airborne Global Positioning System/Inertial Movement Unit (GPS/IMU) with a C-band transponder to downlink time-space-position information (TSPI) via FPS-16 instrumentation radar. This improves current telemetry links and the Range Application Joint Program Office (RAJPO) data link for downlinking TSPI because of the inherent long-range advantage of the radar. The goal of the project is to provide distance independent accuracy, and to demonstrate continuous 15-meter or better position accuracy over the entire flight envelope out to slant ranges up to 1,000 Km with at least 50 updates per second. This improves safety coverage for the wide area flight testing. It provides risk reduction for the Air Force Flight Test Center (AFFTC), Edwards Air Force Base, California and other ranges planning TSPI system upgrades.

KEY WORDS

Tracking Radar Accuracy, Transponder, Data Link, MEMS, TSPI, GPS/IMU, Range Safety

INTRODUCTION

While testing an aerospace vehicle, many different parameters including its TSPI, stresses, deformations, temperature, and pressure at various locations are monitored. The test data is stored on board or telemetered down for analysis. Future aerospace vehicles (X-33, X-34, X-38, and Future X-Vehicles) and surface-to-air missiles for theater missile defense (PAC-3, THAAD, and Navy Lower and Upper Tier) will not only be fast but also highly maneuverable. Safe testing and proper evaluation of these vehicles will require almost real-time knowledge of their TSPI at distances exceeding thousands of kilometers. Occasional flight termination decisions of these test vehicles are made based on TSPI obtained from multiple acquisition sources including optical systems, skin-tracking radar, transponder reply, and audio radio links. To meet these requirements, a TSPI encoded radar transponder concept, illustrated in Figure 1, was developed.

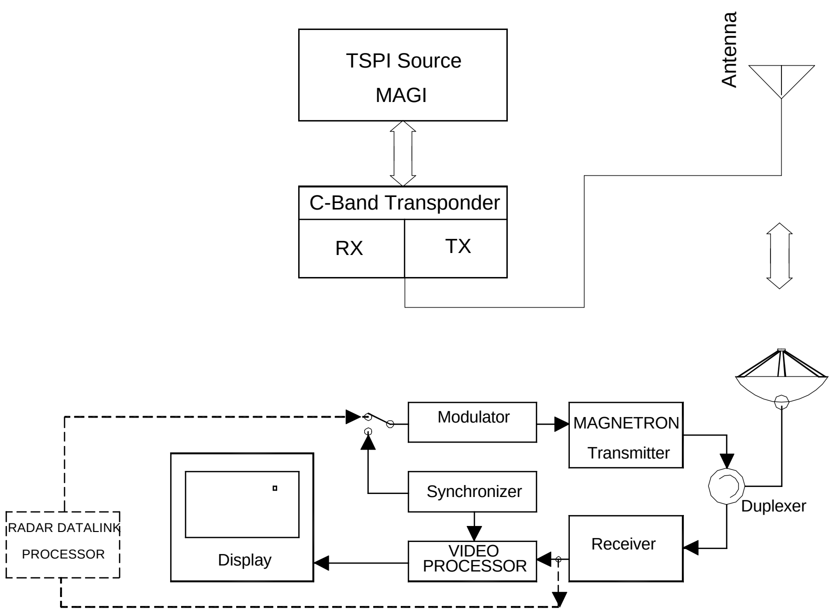

Figure 1: TSPI Encoded Radar Transponder Concept

The primary TSPI source onboard the vehicle is a system called Modular Affordable GPS/INS (MAGI). Currently, Waddan Systems is developing such a system by integrating GPS technology with micro-electromechanical inertial sensors. A modified transponder module attached to the MAGI downlinks the TSPI via a modulated signal to the radar station. At the radar station a radar datalink processor attached to the receiver decodes the TSPI. The system also has the capability to uplink digital information from the radar to the MAGI via the transponder receiver. The datalink is designed to transfer information in 32 byte long data packets. The structure of these packets is predefined for 256 types of messages that include TSPI and status information for downlinking, commands, and differential GPS corrections for uplinking.

The TSPI encoded radar transponder provides a graceful TSPI degradation scenario. In general, it is the primary source of TSPI. If the GPS receiver drops lock on one of the satellites, the TSPI degrades slowly because the IMU still provides the TSPI. When GPS/INS degrade, the conventional transponder replies will be sufficient to track the vehicle, and finally if the transponder itself dies, the radar can still skin-track the vehicle.

The design of the transponder is modular to keep it flexible for mods to accommodate future technologies. Although the system is designed for C-Band, a radio frequency (RF) module change will accommodate the future X-Band utilization. Since the efficient use of frequency spectrum is becoming increasingly more important [1], alternative signal modulation approaches or spread spectrum will be employed to provide such spectral efficiency.

OPERATIONAL OVERVIEW

The MAGI normally carries three types of TSPI solutions in its solid-state flash memory. It saves the raw GPS data, the strap-down INS solution and the integrated GPS/INS solution - all referenced to GPS time. A most recent copy of each of the three TSPI solutions is placed in a memory buffer on the transponder module.

The radar begins tracking the vehicle either by skin tracking or by the use of conventional transponder replies to radar's interrogation pulses. Once the radar locks to the vehicle, the radar datalink computer takes over and uplinks a message requesting the TSPI. The datalink works concurrently with radar tracking. Since the approximate range of the vehicle is known, an algorithm determines where to place the data packets so they are not interfered by the conventional radar pulses. If a differential correction of the GPS data is desired onboard the vehicle, then the correction information is also uplinked. The transponder downlinks the appropriate type of TSPI data after making any corrections. The TSPI, thus obtained, stays primary until at shorter vehicle ranges one switches to optical or skin tracking as they become relatively more accurate.

SYSTEM DESIGN

The system has two segments. The flight segment consists of MAGI and a tunable C-band transponder designed to be capable of transmitting conventional pulse-code replies as well as TSPI data packets upon interrogation by a ground radar. The ground segment consists of upgraded radar. Initially, FPS-16 instrumentation radar is chosen because of its long-range capability. The compact PCI based radar datalink processor is designed so that it is capable of producing TSPI command-data packets, as well as deciphering the transponder TSPI reply data packets. The tracking positional accuracy of the system is independent of the range of the vehicle, because the TSPI data packet is derived from the solutions provided by GPS/INS modules of MAGI. It is estimated that the time-tagged accuracy of the vehicle position will be ±4m [2].

FLIGHT HARDWARE

The transponder is being developed as a module of MAGI—a flexible GPS/INS-based test platform. As a MAGI module, it meets all the 3U compact PCI specifications – dimensions 100mmX160mmX22mm, plug-and-play compatibility, a peripheral identification, a manufacturer ID, calibration data etc. The MAGI architecture including the transponder is illustrated in Figure 2. The MAGI is being developed to provide the GPS/INS solution at the rate of 50 updates per second.

The transponder has all the reply modes available in currently fielded C-Band transponders so that it can respond to all existing interrogation modes. In addition to these modes, a new pulse interrogation mode T is introduced to trigger a general TSPI broadcast by the MAGI transponder. This allows the transponder to be triggered by less sophisticated radars or transponders.

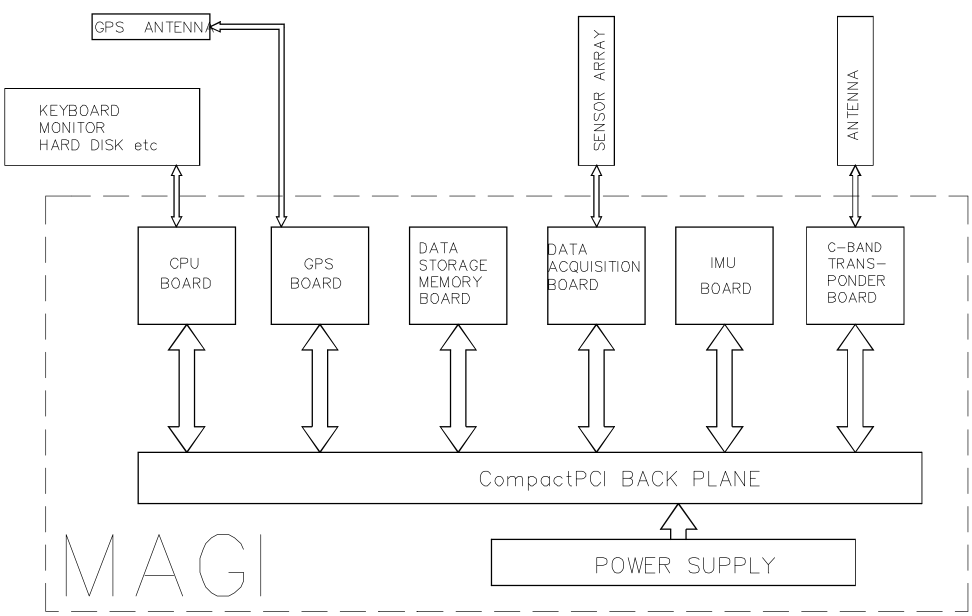

Figure 2: Transponder as a module of MAGI

A modular design of the MAGI transponder is shown in Figure 3. When the ground radar transmits the interrogation pulses or the data packet, they arrive at the transponder antenna. Here, the RF front-end filter serves to remove out-of-band energy and rejects image band signals. The LNA amplifies the entire signal spectrum, including the unwanted levels in the image band. The subsequent filter further attenuates the unwanted image band signal. The wide-gain block provides the gain required by the filtered signal. An RF oscillator tunes the desired band to a fixed IF channel. Irrespective of the carrier channel to which the transponder is tuned, at the output of the first down-converting mixer, the desired received channel is always at the same IF frequency. Again, a filter is used to attenuate the out of channel energy and a wide-gain block is used to provide the necessary gain for the following steps. Since the IF is fixed, an I/Q demodulator translates the signal to the baseband. The demodulated analog signal is digitized prior to processing by a DSP.

The DSP is connected to a PCI I/O controller chip. It acquires the three TSPI solutions via the PCI bus. The most recent replica of these solutions is saved at the local memory. When the digitized signal received by the transponder arrives, the DSP decodes the signal. The decoding algorithms identify the incoming signals as conventional radar trigger modes (including Mode T) or as data packets to be unpacked. Other tasks such as side-lobe suppression and house keeping are also performed in time slices. If the interrogation pluses are coded with a request for transmitting the TSPI, the DSP formats the appropriate TSPI info in data packets for transmission by the transponder.

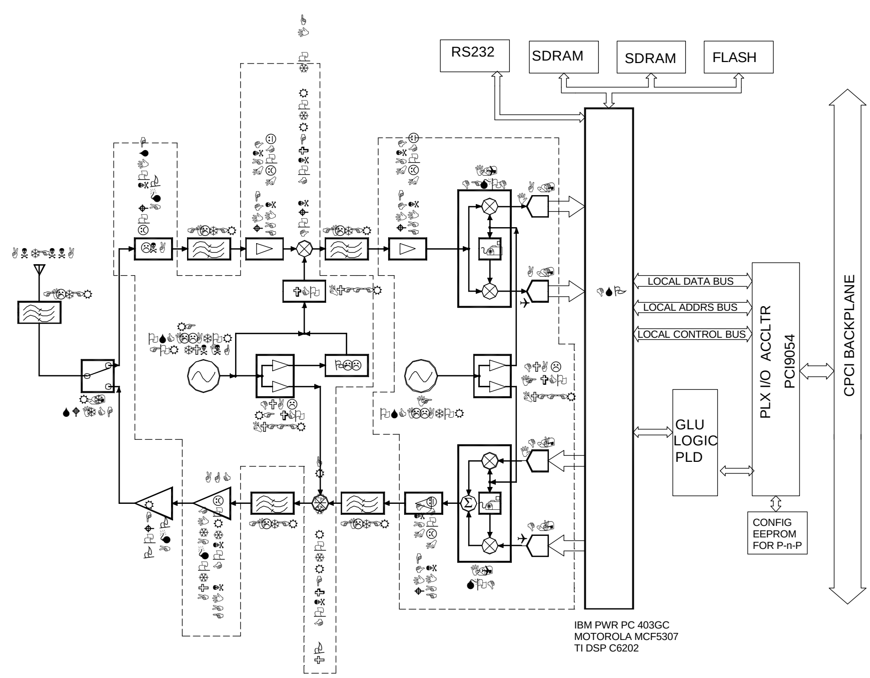

Figure 3: Modular MAGI Transponder Design

The coded digital data, first passes through D/A converters. It is then translated to a fixed IF by the I/Q modulator, after that it is summed together. The wide-gain block adjusts the amplitude of the analog signal. The harmonics of the fixed IF and the distortion caused by the D/A converters may cause problems in the power amp later on, these anomalies are filtered out. The signal is then up converted to the RF by a mixer and an RF channel select oscillator. The following filter removes the distortion caused by the up converter. An automatic gain control (AGC) amplifier provides the drive signal for following power amp. Finally, a band-pass filter removes the energy outside the transmission band. The resulting signal radiates power through the transponder antenna.

In Figure 3, a number of blocks are shown within two different dashed boundaries. Each boundary represents a commercially available chip in QSOP packages. On the right side of these blocks, a DSP and a PCI controller are shown. A hardware kit to design a compact PCI board using these is also available. Alternatives to the TI DSP C6202 include IBM PWR PC 403GC or Motorola MCF5307. To minimize development costs and design risks, only the silicon ICs currently available for wireless and industrial applications were employed. No ASICs were considered at this stage. Thus, the five main chips used on the transponder board are:

- Digital signal processor (DSP)
- PCI controller chip
- I/Q modulator and demodulator
- Up and down converter
- Power amplifier

GROUND RADAR HARDWARE UPGRADE

A block diagram representation of the current ground radar system and the upgrade required is shown in Figure 4. In current FPS-16 radar, a synchronizer controls the operation of the modulator and the receiver by generating precise clock pulses. It is used to time the various events on both the transmitter and the receiver sections of the radar. Upon receiving a timed trigger, the modulator generates a high-power DC pulse of operator selected duration (0.25 μs, 0.5 μs, 1 μs or up to 5 μs). When the pulse generated by the modulator is applied to the transmitter, it generates high power RF energy at a chosen frequency between 5.4 and 5.9 GHz. Currently, the peak power of the transmitter is one MW. The duplexer guides the high power RF energy to the antenna for radiation.

On the other hand, when the antenna receives a signal, the duplexer guides it to the receiver side where it goes through a protection device (which removes any power coupling from the transmitter side). After passing through an LNA and filter, it gets down converted to the fixed IF frequency (30 MHz). The IF signal is amplified and filtered before being used by a video detector. The video detector detects all the echoes including the clutter. An automatic range tracker (employing range gate, early and late gates) centers the gate window on the pulse centerline. Time difference between the centerlines of the transmitted pulse and the echo is used to determine the range. A video display of the range gate and the pulse are provided to the operator.

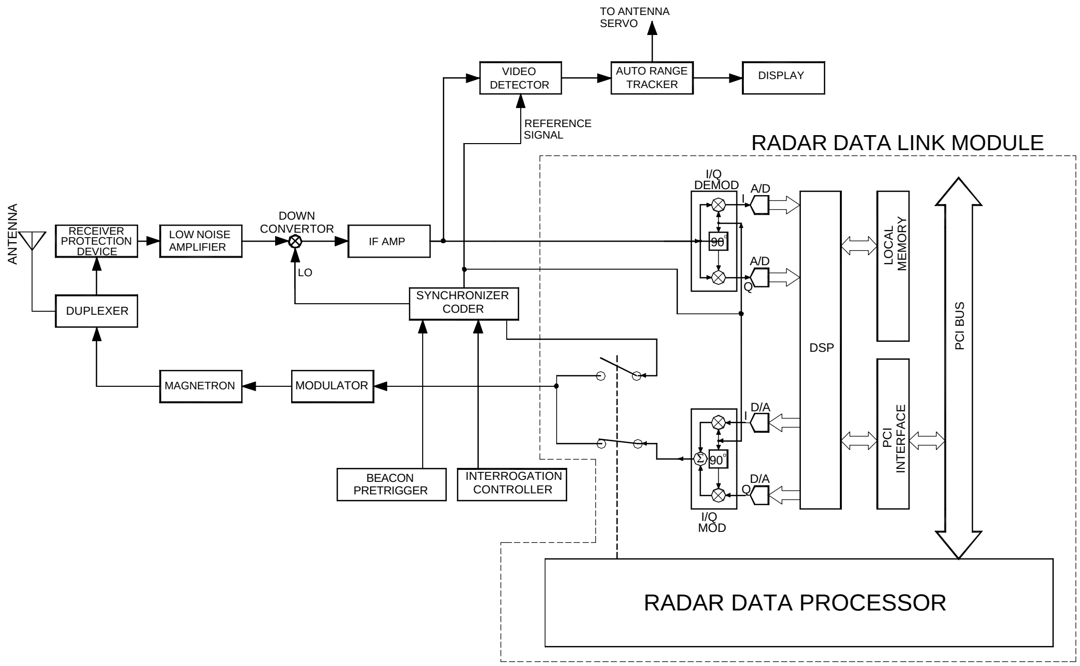

Figure 4: Ground Radar System Upgrade

The system upgrade, also shown in Figure 4, uses a methodology, which keeps the current radar hardware intact. On the receiver side, the IF signal coming off the IF amplifier and filter is tapped, and then I/Q demodulated. Then both I and Q components are digitized for decoding by the DSP. The decoded data packet information is sent to the radar data processor (RDP) via the PCI bus. The RDP is also a 3U compact PCI computer that hosts a radar data link (RDL). The RDP itself becomes an AFFTC measurement data node.

The data packet to be uplinked is provided by the RDP to RDL. The coded digital data, first passes through D/A converters. It is then translated to the fixed IF by the I/Q modulator, and after that it is summed together. The amplitude of the analog signal is adjusted and any anomalies caused by the D/A converters are filtered out. The modulated signal is used on the transmitter side to radiate RF energy at two minimum shifted orthogonal frequencies.

A switch controlled either by the RDP or RDL determines when the radar would work in its conventional tracking mode, and when it would work in its datalink mode.

DATA FORMAT

The data link between the radar and the transponder is designed to be a flexible one. The data packet is 32 bytes long. The basic message structure employed is the same for uplink, downlink or interlink (between two transponders). However, depending upon the message type, it could contain specific data and/or command fields.

The data packet contents are presented in Table 1.

PACKET STRUCTURE		
ORDER	DATA FIELD DISCRIPTION	NO OF BITS
1	Synchronization	16
2	Start	8
3	Transmitter (Originator) ID	8
4	Receiver (Destination) ID	8
5	Message ID	8
6	Message Packet Chain Count	4
7	Message Packet Chain Sequence	4
8	Header Checksum	16
9	Message (18 Bytes)	144
10	Message Checksum	16
11	Stop	8
12	Pause	16
Total Number of Bits in the Packet		256

Once the Synchronization marker is found, the receiver assumes that it has found a valid packet. The Start flag signals the beginning of the message. Generally a transponder or a radar site will have a pre-assigned 8 Bit long ID. The Transmitter ID uniquely identifies the transponder or the ground radar site originating the message packet. The Receiver ID announces the transponder or the ground radar site for which the message is intended. It is possible to originate the message for all those who could listen. In the case the message is intended for a specific receiver, other listeners simply ignore the rest of the packet contents.

The next field labeled Message ID identifies the type of the message. The number of message types can be as high as 256. A few examples of the message types available are as follows:

Message Type ID	DESCRIPTION
1	Command for Airborne System Status Report
2	Command for TSPI Report from Transponder Local Memory
3	Command for Continuous TSPI Broadcasts
4	Command for Raw GPS Data Report

5	Command for INS only Data Report
6	Command for DGPS based TSPI Data Report
7	Command for Encrypted Continuous TSPI Broadcasts
..	……..
65	Reference Data Uplink for DGPS correction
..	……..
..	……..
..	……..
129	Reply to Message Type 1
130	Reply to Message Type 2
131	Reply to Message Type 3
132	Reply to Message Type 4
133	Reply to Message Type 5
134	Reply to Message Type 6
135	Reply to Message Type 7
..	……..
193	Analog and/or Digital Sensors Outputs
..	……..
200	Contents of 16 Memory Bytes from Address beginning at $$$$$$0
201	Contents of 16 Memory Bytes from Address beginning at $$$$$$1
	Etc.

The Message Packet Chain Count indicates the number of packets that are chained together. This allows transmission of general messages that are longer than 18 bytes. Up to 16 packets can be chain-linked together. The next field in the packet shows the location of the current packet in the chained sequence. The Header Checksum transmits an error check code for the receiver to determine if the routing and header transmission were accomplished correctly.

The next 18 bytes of the data field contain the packet information. Following that is the Data Checksum to determine if the information in the proceeding 18 bytes was transmitted correctly. A Stop flag indicates the end of the transmission. A two byte long pause provides the separation between consecutive packets transmitted.

MODULATION

The TSPI and other information available in MAGI are numeric in nature. It is stored and transmitted in binary form (1's and 0's). These 1's and 0's have to be some how transmitted to another site correctly. An efficient way to accomplish this is to convert the 1's and 0's into a continuous time waveform and embed it into a carrier. This process is referred to as digital modulation. The modulated carrier is what is transmitted.

An exactly reverse operation takes place on the receiving end, where the embedded information is extracted from the carrier to reconstruct the 1's and 0's. This process is referred to as digital demodulation. The three different types of modulations under consideration are briefly described here.

PULSE POSITION MODULATION

In pulse position modulation (PPM), the position of the pulse in the bit period identifies its binary value. For example, if the bit period is 1 μs then a 0.5μs wide pulse in the first half of the bit period represents a binary 1, and a 0.5μs wide pulse in the second half of the bit period represents a binary 0. It is the most common modulation scheme utilized in radar interrogation modes.

QUADRATURE PHASE SHIFT KEY

In quadrature phase shift key (QPSK) modulation, the phase of the carrier is modulated to impress the digital information. The carrier phase is quantized at four equally spaced angles ($\pi/4$, $3\pi/4$, $5\pi/4$, and $7\pi/4$ radians). A serial data stream is used to generate the four possible combinations of the 2 bit logic pairs – 00, 01, 10, and 11. From the original serial stream, another stream phase shifted by 90° is derived. By combining various sums and differences of these two streams, the signals related to binary combinations are derived. The binary data stream to be coded is split into two channels. For example, the bits occupied in the odd positions are sent to the I-side, and those occupied in the even positions are sent to Q-side. Corresponding carrier modulations are automatically generated by proper sums and differences of the I and Q components.

MINIMUM SHIFT KEY

It is a special case of FSK. It utilizes the minimum tone spacing that allows two frequency states to be orthogonal. The minimum tone separation for orthognality is $1/T_b$ (=bit frequency). If bit frequency were 1 MHz, then the minimum tone separation between the two frequencies would be 1 Hz. It is spectrally efficient, can be easily generated by stretching the odd and even bits over two-bit duration. The phase transitions between the frequencies are smooth unlike the QPSK where 90° transitions are involved.

A variant of MSK, where a pre-modulation Gaussian low pass filtering and MSK are involved, is referred to as GMSK. It has excellent power efficiency due to constant envelop. This method is preferred over the others as it provides Spectrum Efficient data transfers.

FINDINGS AND CONCLUDING REMARKS

In this paper the designs of a transponder and the radar ground equipment upgrade were presented. It shows the feasibility of a high-speed data-link between the radar and vehicles operating at long ranges employing current and proven technologies. The technology platform chosen for these designs is plug-and-play compatible to accommodate hardware based on future technologies. To minimize the development costs, no ASIC designs were included. Only board level designs using proven ICs and technology was utilized. The transponder design is modularized to allow easy upgrade for frequency spectrum changes (from C-Band to X-Band). As new coding and decoding schemes are developed, modifying I/Q MOD and DEMOD module could incorporate them.

The ground radar system mods are non-invasive for FPS-16 SOTR. Although the current focus of the effort is to improve the performance of such radars, the design is flexible enough to incorporate future enhancements. The data packet structure is such that it also allows data-links between transponder-to-transponder. Even the data transported is quite general to accommodate data other than TSPI.

REFERENCES

[1] "Spectrum Efficient Modulation," Document 705-98, Range Commanders Council.

[2] Earl R. Switzer et al, "Combining Technologies to Foster Improved TSPI Accuracy and Increased Sharing of the Frequency Spectrum", ITEA 1999.