COMBINING TECHNOLOGIES TO FOSTER IMPROVED TSPI ACCURACY AND INCREASE SHARING OF THE FREQUENCY SPECTRUM

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ABSTRACT

The loss of radio frequency (RF) spectrum for use in testing has steadily increased the likelihood that users of the few remaining frequencies available to test ranges will experience scheduling conflicts and interference with nontest users. A gradual increase in the base of test customers engaged in scientific, military, and commercial R&D, point toward a near term situation in which more test customers will be competing for fewer frequencies. The test ranges, often operating in close geographical proximity with other communications-intensive functions as well as with each other, will also encounter increasing out-of-band and adjacent-channel interference. This projected growth of R&D-related testing constrained to operate in a diminished RF spectrum (and a more confined test space), will undoubtedly stimulate the development of new products that make more efficient use of the RF spectrum. This paper describes one such innovative approach to spectrum sharing. The authors assess the operational need for an affordable miniaturized avionics instrument package based on a C-band radar transponder integrated with a Global Positioning System/Inertial Measurement Unit (GPS/IMU). The proposed approach would make use of frequencies already allocated for use by existing C-band aeronautical transponders. It would augment the format of the transponder output data to include the vehicle position obtained from an onboard GPS/IMU. Existing range instrumentation radars, such as the venerable AN/FPS-16, could be modified with low-cost upgrade kits to provide uniformly higher accuracy over the entire transponder coverage range.

KEYWORDS

Time-space-position-information (TSPI), Instrumentation radar, transponder, and GPS/IMU.

INTRODUCTION

This paper proposes an innovative approach to spectrum sharing by integrating an airborne Global Positioning System/Inertial Measurement Unit (GPS/IMU) with a G-band (5400 to 5900 MHz, formerly C-band) transponder to downlink time-space-position-information (TSPI) via an AN/FPS-16 instrumentation radar. This approach is an improvement over current telemetry links and the RAJPO data link for downlinking TSPI because the inherent long-range advantage of the radar. Our goal is to demonstrate continuous 15 meters or better position accuracy over the entire flight envelope out to slant ranges of 1,000 km or more. The outcome of this demonstration will determine the feasibility of a novel approach for improving safety coverage for wide-area flight testing. With integrated GPS/IMU transponder approach, the TSPI data from the vehicle would degrade gracefully. This approach would lead to a significant improvement in range safety using existing range assets.

A brief comparison between our approach and the GPS-Squitter approach will be discussed.

OPERATIONAL PHILOSOPHY

The primary requirement driver is the need for improved range safety systems to support flight test of future manned and unmanned air/space vehicles. Test of this type are characterized as follows:

- The systems under test operate at very high altitudes and speeds in the Mach 5-10 region.
- The vast operating spaces required for conducting open-air flight test drive the need for radars capable of tracking the systems under test at very long ranges.
- The systems under test perform high-dynamic maneuvers.
- These factors drive the need for high update rates for measurement systems such as tracking radars.

This project will perform advanced test technology development directed at satisfying a test and evaluation requirement for safe testing of future manned and unmanned aerospace vehicles. These include endo- and exo-atmospheric aerospace vehicles (such as the X-33, X-34, X-38, and future X-Vehicle) and surface to air missiles for theater missile defense (such as PAC-3, THAAD, and Navy Lower and Upper Tier). Flight termination decisions are based on TSPI obtained from multiple acquisition systems. The primary TSPI source could be a GPS receiver on board the vehicle. The GPS receiver data could be downlinked from the vehicle to the ground stations via (either or both) telemetry and radar transponder links. For the scenarios we are considering, the radar link is the primary source and telemetry is secondary. The GPS receiver data could be imbedded in the telemetry stream (this has already been demonstrated), and it could also be modulated onto the radar transponder output signal (this has yet to be demonstrated). The TSPI from the onboard GPS receiver would provide 15-meter or better positional accuracy over the entire flight envelope. This would satisfy the range safety requirement for high-quality TSPI from the vehicle in real time via two independent paths. When test instrumentation fails to go according to plan, the radar data will degrade more gracefully than the telemetry data. If the GPS receiver drops lock on the satellite constellation, the accuracy of the GPS/IMU will degrade slowly allowing time for reacquisition. Also the radar can continue to track the vehicle using the transponder return without the position data from the GPS/IMU. If the transponder fails to respond then the radar can still skin-track the vehicle.

Operation of the integrated radar/GPS system will not vary greatly from standalone radar operation. During the acquisition phase for an orbiting vehicle, there is usually vehicle position data available from another source in the tracking network, either radar or GPS. If this is not the case, a manual acquisition can usually be made using orbital parameters generated by the local-site computer.

Upon radar acquisition of the vehicle transponder, raw stand-alone GPS vehicle-position data will be available to the ground station in (WGS) earth-centered coordinates. GPS vehicle position data is always processed in the WGS coordinate system to present a consistent system to all users. If corrections are available from a local differential GPS ground station in the same frame of reference, these can be summed with the raw data to enhance GPS position accuracy both at the ground-tracking site and in the airborne vehicle. Several scenarios exist as to how these signals are used. Since the transponder provides a two-way link to the ground, with the proper choice of GPS data and differential signals on the link, it is obvious that the summing of signals could take place either on the ground or in the vehicle. Both methods have been used. However accomplished, the end result is at least a three-fold improvement in vehicle position accuracy.

An active track requires interrogation of the transponder on the airborne vehicle by the local-site radar transmitter, and that the transponder reply, with embedded GPS data, be received by the local-site receiver. Valid GPS data can be received with either an active or a passive radar track. Passive tracking is not a normal acquisition mode, but can be used when no other form of acquisition data is available. During a passive track, the local-site transmitter does not interrogate the transponder. Replies are received from interrogation of the transponder by a ‘host’ radar. In this mode of operation, a full radar lock can be maintained on the host radar's transponder reply pulse or 'rabbit.' This will provide valid angles, but the range data will not be valid. With a valid angle track, WGS vehicle position data imbedded in the transponder reply will provide valid vehicle position, even though the reply was initiated by another radar. When these WGS coordinates are converted to local site range, azimuth and elevation, the range can be used to supplement the azimuth and elevation track already acquired to return to a full automatic radar track. Either type of track requires a line-of-sight view between the radars and the vehicle. In the passive mode, after WGS vehicle position data has been translated to local site coordinates, valid local site range data will be available to help the radar reacquire and return to the active tracking mode.

When tracking in the active mode, after conversion to local site coordinates, GPS data can provide long-term corrections to the radar data that will compensate for short-term signal fade caused by aircraft maneuvering, multipath, and other causes. Whether GPS coordinates can be processed expediently to act as aiding signals to the radar tracking loop will require further study of signal processing technique.

TECHNICAL APPROACH

Our proposed system is illustrated in Figure 1. It consists of two segments. They are the airborne segment and the ground segment. The airborne segment consists of a GPS receiver, a G-band transponder, and a decoder/encoder module to interface the GPS receiver with the transponder. The ground segment will include a single object tracking radar, and a modified kit.

The key to the development of the airborne segment will be the design of a radar transponder with an integral GPS receiver. The transponder will function as a two-way data link for uplink GPS request messages and downlink GPS vehicle position data. The transponder must be capable of receiving the radar interrogation and an encoded GPS request message. After decoding, this message will enable the encoder and initiate the transfer of GPS position data through the encoder to the transponder transmitter for transmission to the ground radar receivers. All timing and synchronization of the received and transmitted codes must be accomplished within the transponder.

The GPS/IMU system for the airborne set is currently in development under an Air Force Small Business Innovative Research Phase II contract with Waddan Systems, Torrance, California. Waddan's task for Phase II is to develop and demonstrate a prototype modular, affordable, embedded GPS/IMU TSPI capability for support aircraft. The system design combines a commercial 12-channel GPS receiver with a miniaturized IMU developed by Waddan using micro-electro-mechanical system technology. By executing a preplanned contract option the chip-set can be interfaced to a commercial transponder unit.

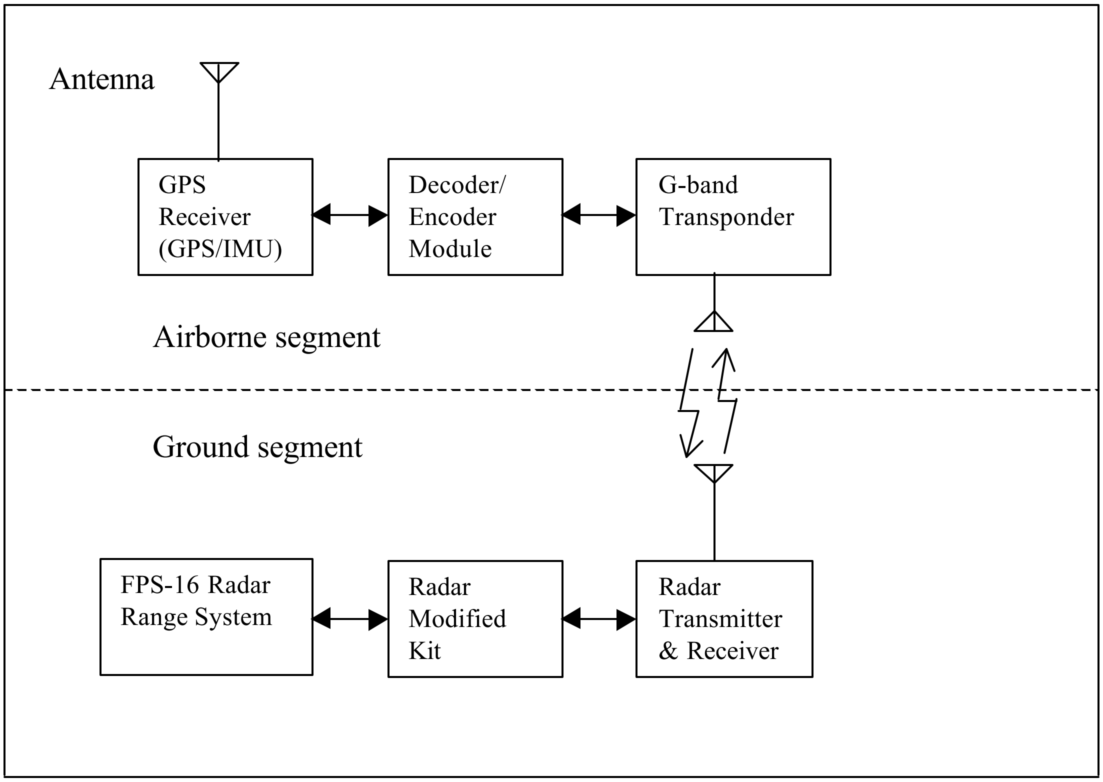


Figure 1: Integrated GPS Transponder System

Combining on-board IMU and GPS data will always result in improved vehicle position data. IMU provides good short-term data during periods of interrupted GPS reception, while GPS provides IMU with good long-term references to compensate for IMU long-term drift. Most of the remaining GPS error is the result of atmospheric and tropospheric effects on the RF transmission from the GPS satellite constellation. This error is cancelled in the differential GPS mode when differential corrections are summed with raw GPS data. During the takeoff and landing phases of a mission, an AN/FPS-16 radar is more accurate than differential GPS out to 27 km, unless multipath is a problem for the radar. Then GPS will be more accurate.

A conformal antenna system for G-band radar has been available since the X-15 program. A similar antenna for GPS will no doubt be available soon. Both these developments are recommended for use by exo-atmospheric vehicles.

For the ground segment, a modified kit will synchronize the radar interrogation pulses and GPS request message to the radar pretrigger. This unit will provide the coding and generate the radar transmitter triggers for both functions. It will also extract the GPS message and present it as GPS position data for range use. Modification to the basic FPS-16 system will be 90 percent wiring additions. Designs for integration of GPS with other radars will have to be on a case by case basis, but no insurmountable problems are anticipated.

Vehicle tracking systems, in their present form, use a combination of autonomous systems externally linked together to provide real-time vehicle position. These systems consist primarily of radar, telemetry, GPS, and optics (visual, infrared, and laser). The approach described in this section will attempt to integrate GPS and radar. This will eliminate the requirement for other forms of vehicle position-determining systems.

The radar GPS integration will provide for both the two-way links required by GPS for differential operation and for the normal functions of the radar system. This approach will provide an alternative for using telemetry to receive downlink GPS vehicle position and a separate data link channel to transmit uplink GPS differential correction signals. Economic savings will result not only from the elimination of system hardware, but also from the cost of transporting and manning the additional systems at remote sites.

The venerable FPS-16 is an old-style, high-power radar that provides a highly precision track out to long ranges. But these systems date back to the Apollo program and are becoming costly to operate and maintain. As a result, several modification kits have been developed to upgrade them. One vendor quoted a budgetary estimate for updating an AN/FPS-16 to an RIR-716 at 4 to 5 million dollars; not a small investment. This modification replaces almost everything but the pedestal. A sensitivity increase to –120 dBm, from -106 dBm for the original AN/FPS-16, is obtained through the use of a 16-foot reflector, in place of the original 12-foot dish, and a 5-microsecond transmitter pulse width, as opposed to 0.8 microsecond. This is an increase of 14 dB over the original FPS-16 specification. The pay-off is quadruple range capability.

If radar and GPS are integrated, the vehicle must carry a transponder. A 400-watt transponder will add 43 dB to the return signal from the vehicle; this will obviate the need for the old high-powered skin-tracking radar. Any new radar systems built in the future, if they make use of a GPS beacon for tracking, would not have to be as powerful or as precise mechanically as the current single object tracking radars. This would cut their life-cycle cost considerably.

Table 1 illustrates the tracking range to be expected from an original FPS-16 radar with improved receiver sensitivity (-113 dBm as opposed to –106 dBm originally). For installation in small vehicles, the primary power requirement and transponder weight become limiting factors to transponder RF power output, which limits the tracking range. In this case, 400 watt has been arbitrarily chosen as a common level used by exo-atmospheric vehicles.

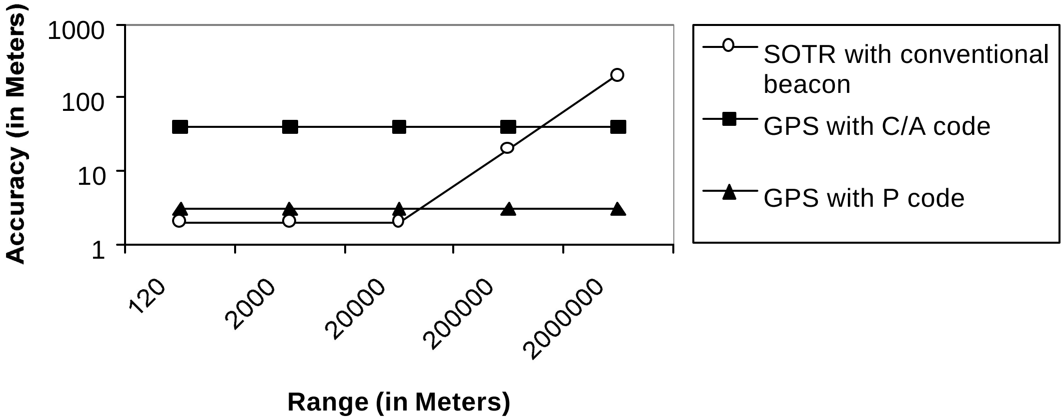
The transponder sensitivity most commonly provided by the vendor for radar tracking is –70 dBm, which is not adequate to meet the 2,000-km tracking range requirement as shown in Table 1. However, as determined from a conversation with the transponder vendor, the sensitivity can be increased to –80 dBm at the request of the customer. This would make the uplink and downlink margins nearly equal and provide a track to nearly double the required range.

Table 1. RF Budgets for FPS-16 / C Band Transponder, Range 2,000 km, Frequency 5,600 MHz

Uplink		Downlink	
Transponder sensitivity	-80 dBm	FPS-16 radar sensitivity	-113 dBm
Tx pwr. ERP	90 dBm	Tx pwr. ERP (400 W)	56 dBm
Gain, Tx ant	43.0 dB	Gain, Tx ant	0 dB
Lsp, 2,000 Km	-173.4 dB	Lsp, 2,000 Km	-173.4dB
Gain, Rx ant	0 dB	Gain, Rx ant	43.0dB
L line	-1.5dB	L line	-0.5dB
Fade	-20dB	Fade	-20 dB
BER	-13dB	BER	-13dB
Radar RF margin	6.6 dB	Xponder RF margin	5.6 dB

For single-object tracking radar (SOTR) with beacon tracking capability, we have the following specifications: azimuth and elevation drive accuracy is ±0.0056 degree, and range accuracy is ±2 m. From these specifications, the predicted accuracy for SOTR using beacon tracking at 1000 km is about ±100 m. With GPS receiver using C/A code at 1000 km, the predicted accuracy is about ±40 m. For GPS receiver using P code the predicted accuracy reduces to ±3 m. Figure 2 illustrates the accuracy of SOTR with and without GPS augmentation. Optionally, if an integrated GPS transponder has an uplink to receive differential corrections for GPS data from ground stations, then differential GPS (DGPS) can be used. With DGPS, the predicted accuracy reduces to ±4 m for C/A code.

Figure 2: Accuracy Comparison of Beacon Tracking SOTR with C/A Code and P Code GPS Receiver.



COMPARISON TO GPS-SQUITTER APPROACH

The Federal Aviation Administration (FAA) proposes to use GPS-Squitter technology in its future ‘free flight’ Air Traffic Control concept. Squitter is the random firing, intentional or otherwise, of a transponder transmitter in the absence of interrogation. There are several differences between GPS-Squitter and our approach. GPS-Squitter randomly broadcasts GPS data without receiving any interrogation, but our project requires an integrated GPS/IMU transponder, which transmits GPS data only when it receives interrogation pulses from a SOTR. The GPS-Squitter integrates only GPS data with Mode S transponders, while our approach integrates IMU and GPS data with G-band beacon transponders. With IMU, our approach will provide good short-term data during periods of interrupted GPS reception. Also with frequency differences between Mode S (at 1,090 MHz) and G-band (5,400 to 5,900 MHz) transponders, ranges which have G-band single- object-tracking radars can’t use GPS Squitter without significant costs in investments for new ground stations, communication links, additional radio frequency allocations, and mission support personnel. In addition, the GPS-Squitter system has a maximum range of 185 km. In contrast, our approach requires a maximum range of 1,000 km or more. Also, GPS-Squitter sends pressure altitude, while our approach sends GPS altitude. For range safety, GPS altitude is preferred over pressure altitude.

ASSESSMENT OF COSTS

Table 2 shows the types and quantities of SOTRs currently in use at various government agencies. For this assessment, we assumed that all FPS-16s and MPS-36s would be modified. MPS-36s are mobile FPS-16s.

This project will attempt to develop and demonstrate a working prototype capability for a cost of about $500,000. This proof of concept will be funded as a DoD R&D project. Based on the data in Table 1, we estimated the number of units to be produced as follows: The number of ground units was assumed to be 33, and the number of airborne units was assumed to be 66. We estimate the cost to go from a working prototype to production units at about $500,000 for a ground unit and $500,000 for an airborne unit. We assumed this non-recurring engineering (NRE) cost would be amortized over the total number of units produced. Also, the vender profit was assumed to be 15 percent.

Estimate cost to produce one ground unit is $25,000.

Procurement cost to government customer for one ground unit is
$\$25K + (\$500K / 33) + (0.15 \times \$25K) \cong \$44K$

Estimated cost to produce one airborne unit is $10,000.

Procurement cost to government customer for one airborne unit is
$10K + ($500K / 66) + (0.15 x $10K) ≅ $19K

Table 2: Population of Single-Object Tracking Radar.

Agencies	Type of Radar									
	FPS-16	MPS-25	MPS-36	RIR-716	TPQ-18	TPQ-39Z	FPQ-6	FPQ-14	FPQ-15	Total
Army, White Sands Missile Range	10	1	5	0	0	0	0	0	0	16
Navy, Pt. Mugu	5	0	0	0	0	0	0	0	0	5
Air Force, Eglin AFB	4	0	0	0	0	0	0	0	0	4
Air Force, Edwards AFB	1	0	0	0	0	0	0	0	0	1
Army, Kwajalein Missile Range	0	0	2	0	0	0	0	0	0	2
Air Force, Hill AFB	0	0	1	0	0	1	0	0	0	2
NASA, Dryden Flight Research Center	0	0	2	2	0	0	0	0	0	4
Air Force, Vandenberg AFB	1	0	1	0	1	1	1	1	0	6
Air Force, Patrick AFB	1	0	0	0	1	0	0	3	1	6
Total	22	1	11	2	2	2	1	4	1	46

FINDINGS AND RECOMMENDATIONS

Integrating radar and GPS is both technically and economically feasible. There is no requirement for the development of new and untested technology; only new application of tried and proven technologies is necessary. This project will produce positive benefits. It will improve range safety, improve system accuracy and reduce equipment and operational costs. Some existing equipment will no longer be required and the number of operational personnel will be reduced. Most sites will require no major new assets for transition to the integrated GPS radar system. Also, by improving position accuracy for both terrestrial and orbital tracking at extended ranges, it is applicable to the testing of future aerospace vehicles.

We anticipate our project will be widely applicable to test and evaluation of unmanned combat air vehicle, unmanned reconnaissance vehicle, manned air/space craft, tactical missile, and theater missile defense.

Based on our findings, we have the following recommendations:

- Develop a prototype system and assess its capability to reduce risk associated with production.
- Explore low cost solutions to leverage mass market commercial solutions.
- A follow-on project should investigate the GPS-Squitter technology for future range applications.

REFERENCE:

1. Bayliss E., Boisvert R., Burrows M., & Harman W., "Aircraft surveillance based on GPS position broadcasts from Mode S beacon transponders," Proceeding of the 7th International Technical Meeting of the Satellite Division of the Institute of Navigation, Salt Lake City, UT, Sept. 20-23, 1994. Pt. 1, Alexandria, VA, Institute of Navigation, 1994, p. 939-950.

2. Proctor P., "ADS-B Displays Versatility in Tests," Aviation Week & Space Technology, Apr. 26, 1999, p. 68-73.

3. "GPS Squitter Technology," www.faa.gov.

4. "Dictionary of Technical Terms for Aerospace Use," http://sulu.lerc.nasa.gov/dictionary.