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GPS Translator
Record and Interface System (TRIS)

James Danaher
Structured Systems & Software, Inc. (3S)
23141 Plaza Pointe Drive
Laguna Hills, CA 92653
(714) 830-3777

ABSTRACT

Global Positioning System (GPS) translator signals have been used to track U.S Navy Trident missile test launches for the past 15 years. Absolute position accuracies of better than 20 meters in real-time and 8 meters in post mission have been consistently demonstrated. Flight qualified GPS translators 40 cubic inches in size have been developed for the U.S. Army Exoatmospheric Re-entry Vehicle Interceptor Subsystem (ERIS) program and are currently available for use by U.S. and allied government test ranges.

More widespread use of GPS translators is constrained, however, by the great expense and size of the custom ground equipment currently used to acquire GPS translator signals and compute the position and velocity of the vehicle. To address this problem, the U.S. Air Force Western Space and Missile Center (WSMC) placed 3S under contract to design a lower-cost GPS translator processor based mainly on using commercial telemetry equipment.

This paper describes how a working prototype was constructed to demonstrate the feasibility of the Translator Record and Interface System (TRIS). This prototype shows that TRIS can be built from a combination of commercially-available telemetry equipment, GPS equipment developed for the U.S. Air Force Range Applications Joint Program Office (RAJPO), and a few elements of custom equipment.

Key words: translator, transdigitizer, TSPI, GPS, tracking, navigation, TRIS.

VEHICLE TRACKING USING GPS

GPS navigation systems will offer considerable advantages for determining time, space, position information (TSPI) for flight vehicles at US and allied government test and training ranges. When the full GPS constellation becomes operational in the early 1990’s, GPS will offer practically 24 hour world-wide coverage, provide rapid access to estimated trajectory, and allow trajectory estimating accuracy that does not degrade with elapsed time or distance from the vehicle to the tracking site. The benefits of GPS can be further enhanced when a ground transmitter (GT) is used to broadcast GPS-like signals to reduce periods when the geometry of the GPS satellites results in decreased trajectory estimation accuracy [1].

On-board GPS receiver. There are two distinct ways to use GPS to track flight test vehicles. The obvious way is to use an on-board GPS receiver to acquire GPS signals and estimate the position and velocity of the vehicle (Figure 1). The position and velocity values are then either transmitted to the ground via a telemetry link or stored on-board a recoverable vehicle for later readout. The raw pseudo-range and range-rate measurements made by the on-board GPS receiver can also be stored and later used for post-mission computation of the vehicle trajectory, as is done in the RAJPO Method 3 software developed by 3S for Interstate Electronics Corporation (IEC).

Translated GPS. Translated GPS is a fundamentally different way to use GPS signals to estimate the position and velocity of a flight vehicle [2]. In this case, a GPS translator is carried on the vehicle to be tracked. The translator receives the GPS coarse acquisition (C/A) code spread spectrum signals, adds in a pilot carrier. translates these signals to a frequency in S-band (2200 to 2400 MHz) and transmits the resulting signal (Figure 2). A GPS translator processor receives the translated GPS C/A code signal in S-band and estimates the position of the vehicle. It is the design of a low-cost GPS translator processor that is the topic of this paper.

The advantages of translated GPS as compared to an on-board GPS receiver have been described elsewhere and are briefly summarized here [2, 3]. First, an on-board GPS translator is considerably simpler than an on-board GPS receiver. Second, translated GPS has a 6 dB signal-to-noise advantage due to the “data wipe” of telemetry data within the GPS translator processor. Third, more powerful tracking and navigation methods are possible when computations are not done on-board the vehicle. Finally, the GPS translator processor can record the GPS C/A code spread spectrum signals prior to detection and thus allow post-mission computation of the estimated vehicle trajectory using truly raw data.

Translated GPS has the disadvantage of more frequent signal dropouts as the GPS signal passes through both receive and transmit vehicle-mounted antennas. A second problem is that the available GPS translator does not provide downlink of inertial aiding data. This paper shows how these problems are mitigated in the design of a low-cost GPS translator processor. Also, this design will support future GPS translators that provide inertial data downlink. A third disadvantage is the 2.5 MHz bandwidth used to downlink the translated GPS signal. This frequency allocation issue is not discussed herein. A final disadvantage is the perception that the GPS C/A code used in translated GPS provides lower accuracy than the GPS precision (P) code. There is no real disadvantage here: a coherent carrier tracking C/A code receiver can achieve accuracy comparable to a P code receiver.

Transdigitized GPS. Transdigitized GPS is a variation of translated GPS [4, 5], In this. case, a vehicle-borne GPS transdigitizer converts the GPS C/A code spread spectrum signals to baseband and performs in-phase and quadrature-phase (I&Q) sampling at a rate of about 2 MHz. Inertial measurements are multiplexed with the I&Q samples, and the combined data are transmitted to a GPS transdigitizer processor. A GPS transdigitizer was developed for the Deep Ocean Transponder/Sonobuoy Missile Impact Location System [DOT/SMILS), but it is not suitable for flight use [6]. Processing transdigitized GPS signals is similar to processing translated GPS signals. Both types of signals will be supported by the system described in this paper.

THE TRANSLATOR RECORD AND INTERFACE SYSTEM (TRIS)

Origin of TRIS. IEC developed the Flight Test Support System (FTSS), which was first used to track GPS translator signals from U.S. Navy Trident missile test flights in 1974 (7). An assessment of more than fifty flights shows a consistent post-mission root sum square (RSS) accuracy of better than 8 meters in position and 0.09 feet per second in velocity [8]. A 40 cubic inch GPS Ballistic Missile Translator (BMT) has been developed by IEC for the RAJPO at Eglin AFB. IEC has also developed a Translator Processing System (TPS) for real-time and post-mission vehicle trajectory calculation [2,9]. The BMT and TPS will be used to track U.S. Army Exoatmospheric Re-entry Vehicle Interceptor Subsystem (ERIS) interceptors and targets in the 1990's [10].

The U.S. Air Force Western Space and Missile Center (WSMC) at Vandenberg AFB recognized that recent advances in technology have made possible a reduction in the complexity and cost of the equipment required to receive and process GPS translator signals [11]. 3S was placed under contract by WSMC in June 1989 to study to the feasibility of using commercially-available equipment to provide these improvements. The remainder of this paper describes the 3S design for a Translator Record and Interface System (TRIS) that offers a simpler, lower-cost alternative for processing GPS translator signals.

TRIS architecture. TRIS consists of commercial, custom and RAJPO equipment (Figure 3). The RAJPO BMT mounted in the vehicle receives all signals in a 2 MHz wide GPS C/A code pass band centered at 1575.42 MHz. Signals in this pass band are translated to a pre-flight selected S-band frequency in the range of 2200 to 2400 MHz. A pure-tone pilot carrier is added at 1.92 MHz below the translated center of the GPS C/A code pass band and the combined signal is transmitted to TRIS.

Ideally, L-band receive and S-band transmit antennas on a vehicle would exhibit a flat phase response, provide omnidirectional coverage, have fixed polarization, and not introduce nulls. Practical antennas do not approach these goals, thus there are dropouts in the GPS signal received by TRIS. These dropouts are the reason for the TRIS diversity combiner and fast reacquisition features.

The S-band signals transmitted by the BMT are received by a dual polarization autotrack antenna that is locked to the pilot carrier. Typically, both right and left hand circular polarization are used. The dual polarization signals are input to two standard commercial S-band telemetry receivers, tuned 1.5 MHz above the pilot carrier frequency. A 20 MHz second IF is used with a bandwidth of 3 MHz, which is wide enough to encompass both the pilot carrier and the GPS pass band.

Signal conditioning unit (SCU). The 20 MHz IF output from the dual S-band telemetry receivers is processed by a signal conditioning unit (SCU) that performs diversity combining, signal delay, and GPS carrier doppler correction functions. The SCU diversity combining function performs phase alignment of the pilot carrier in the dual polarization inputs and selects the signal with the stronger pilot carrier. Hysteresis in reacting to differences in pilot carrier levels prevents unnecessary switching. Optimal ratio combining is not used because it provides little practical benefit over switched combining.

The SCU signal delay function serves three purposes. First, in some configurations, multiple receive locations are connected to a centralized navigation processor, as shown in Figure 4. In this case, each SCU applies a fixed signal delay to cause the total ground signal delay to be the same for all ground stations, The second purpose of the SCU signal delay function is to remove most of the C/A code range rate variation caused by the S-band downlink. Third, the GPS signal is delayed so that it can be aligned with inertial measurements taken from a separate telemetry stream.

Remote signal combiner (RSC). The TRIS architecture supports real-time reception of Translated GPS at multiple tracking sites, as shown in Figure 4. The remote signal combiner (RSC) at the TRIS master station is a network of SCU's that perform hierarchical switching of pairs of signals until the strongest signal is selected. Hysteresis is used to prevent unnecessary switching.

Airborne TRIS. TRIS can also be used for airborne reception of Translated GPS signals. A minimal airborne configuration consists of dual S-band telemetry receivers, an SCU, a pre-detect recorder, and a local GPS receiver that computes the tracking aircraft trajectory. For real-time tracking, either all of the equipment shown in Figure 3 can be carried on board the tracking aircraft or the SCU output can be transmitted to the ground via a wideband communications link. The second alternative is somewhat similar to the proposed Airborne Platform/Telemetry Relay (AP/TM) [12].

GPS C/A code receiver. The SCU output is a baseband GPS C/A code signal as it would appear inside a GPS receiver aboard the vehicle. A GPS C/A code receiver must overcome frequent GPS signal dropouts to track this signal. TRIS has two mechanisms to aid in bridging GPS signal dropouts. When inertial data are available, the TRIS SCU delays the GPS signal so that it can be aligned with the inertial data. In this case, a standard inertial-aided GPS receiver can be used. When inertial data are not available, the selected GPS receiver must be capable of rapidly reacquiring the GPS signal. This reacquisition can be quite difficult, because TRIS is intended for use in vehicles that can accelerate at up to 200 meters per second squared.

The RAJPO High Dynamics Instrumentation Set (HDIS) GPS receiver has been selected for TRIS use when inertial data are available [13]. For the case where no inertial data are available, we found no existing GPS C/A code receiver that could reacquire the GPS signal fast enough. We did, however, determine that the fast acquisition tracker (FAT) board within the RAJPO TPS performs the rapid C/A code reacquisition required. WSMC has accepted the 3S proposal to develop a Fast Acquisition HDIS (FA-HDIS) that would integrate the FAT board with the RAJPO HDIS receiver. The resulting FA-HDIS will both resolve the difficulty of tracking the translated GPS signal without inertial data and will effectively use inertial data in the navigation solution when such data are available.

Pre-detection record/playback alternatives. An important advantage of the TRIS architecture is that commercially-available hardware is used to perform pre-detection recording of the GPS signal. The playback of the recorded GPS signal through TRIS provides a signal for post-mission analysis and for TRIS functional testing. For highly accurate post-mission analysis, pre-detection recordings can be processed outside of TRIS. By using computationally intensive filters and all available sources of position and velocity measurements, a considerable improvement in the estimated vehicle trajectory can be accomplished post-mission [3, 8]. Table I summarizes the recorder requirements for each of the three points in TRIS where pre-detection recording of the spread-spectrum GPS C/A code signal can be performed.

TRIS PHASE I PROTOTYPE

3S developed a working prototype of TRIS under a Phase I Small Business Innovation Research (SBIR) contract with WSMC. The TRIS Phase I prototype consisted of the equipment shown in Figure 5. The purpose of the prototype was to demonstrate that commercial off-the-shelf equipment can be used for processing GPS translator signals.

In real-time operation of the TRIS Phase I prototype, live GPS satellite signals were received by an antenna at a fixed location and translated to S-band by a RAJPO BMT. The resulting S-band signal was the input to a commercial S-band telemetry receiver. The receiver's 20 MHz intermediate frequency (IF) output was converted back to L-band. This L-band GPS signal was then input by a GPS C/A code receiver, which estimated the position of the GPS antenna on the roof of the 3S facility.

The fixed location BMT provided an S-band signal similar to that expected during an operational mission in terms of signal bandwidth and relative strength of the pilot carrier vs. translated GPS signals. This allowed realistic tests of the ability of commercial S-band telemetry receivers to handle the BMT signal. Successful real-time GPS navigation was achieved with both telemetry receiver models that were tried (Scientific Atlanta SA-930 and Microdyne 1400). The three different GPS receivers (IEC Astrolabe II, IEC Astrolabe III, and Magellan GPS-NAV-1000) were successfully used in the prototype. These are all one-channel C/A code receivers oriented toward static or low dynamic navigation. This was adequate for the Phase I prototype because a stationary BMT was being "tracked".

The combination of a SA-930 telemetry receiver, a GPS-NAV-1000 GPS receiver, and a Kodak/DataTape DTR-70 wideband (8 MHz bandwidth) analog recorder were used for quantitative measurements of TRIS Phase I prototype performance. The 169 real-time measurements that exceeded minimum thresholds for signal strength and dilution of precision are summarized in Table II. Simultaneous with the real-time measurements, a pre-detection recording was made. Later playback resulted in the 26 measurements summarized in the first part of Table III. The final test setup involved simulation of digital recording and playback with 1-bit samples at a 9 MHz sampling rate, which resulted in the 17 digital playback measurements in the second part of Table III. A plot of the data (Figure 6) demonstrates good agreement in results across a number of different test setups. Thus the TRIS Phase I prototype demonstrated that effective navigation using GPS C/A code signals received by commercial S-band telemetry receivers and recorded in both analog and digital formats. This validated the fundamental TRIS concept of using standard telemetry processing equipment to handle translated GPS signals.

TRIS PHASE II

The next stage in the development of TRIS is to demonstrate its use in tracking moving vehicles. This will require two pieces of equipment are not available off-the-shelf. First, a prototype SCU must be built to perform dual polarization channel combining and removal of downlink effects. Second, a prototype FA-HDIS must be developed to provide both rapid GPS signal reacquisition as well as effective use of any available inertial data. These developments will be performed by 3S during 1991 under contract to WSMC. This TRIS Phase II contract also includes use of a TRIS prototype to track signals from simulated and actual moving vehicles carrying BMTs. By early 1992 we expect TRIS to be ready for a trial field installation.

ACKNOWLEDGEMENTS

The activities described in this paper were partly funded under US Air Force WSMC contract number F04703-89-C-0912. Bob Greenberg, of WSMC, and Bob Pickett, of ITT Federal Electric Corporation, were the key customer representatives for TRIS Phase I. ViaSat, Inc. and JB Systems are 3S subcontractors and team members for TRIS. Mark Miller, of ViaSat, is the designer of the SCU. Jacques Bescr, of JB Systems, performed navigation software analysis and simulation that helped demonstrate the feasibility of TRIS. Interstate Electronics Corporation (IEC) provided extensive support for TRIS Phase I and is a 3S subcontractor on TRIS Phase II. Companies that supplied equipment for the TRIS Phase I prototype are: AMPEX, Burr-Brown, IEC, Kodak/DataTape, Marconi UK, Microdyne, Odetics. RACAL, and Scientific Atlanta.

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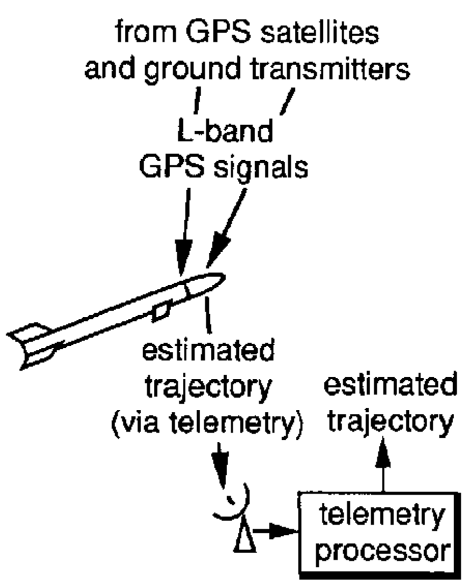

Figure 1. On-board GPS Receiver.

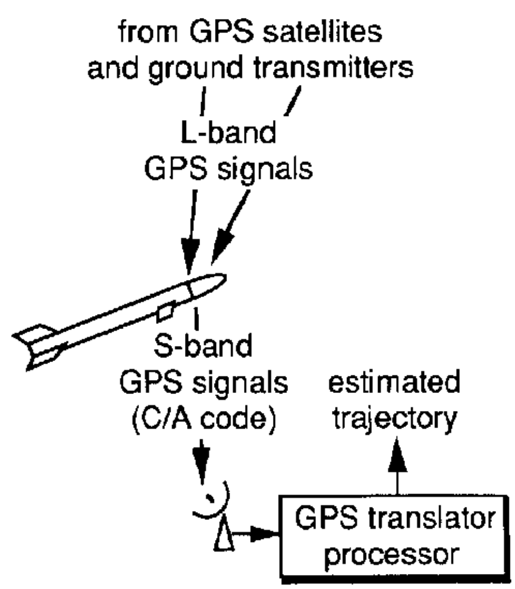

Figure 2. Translated GPS.

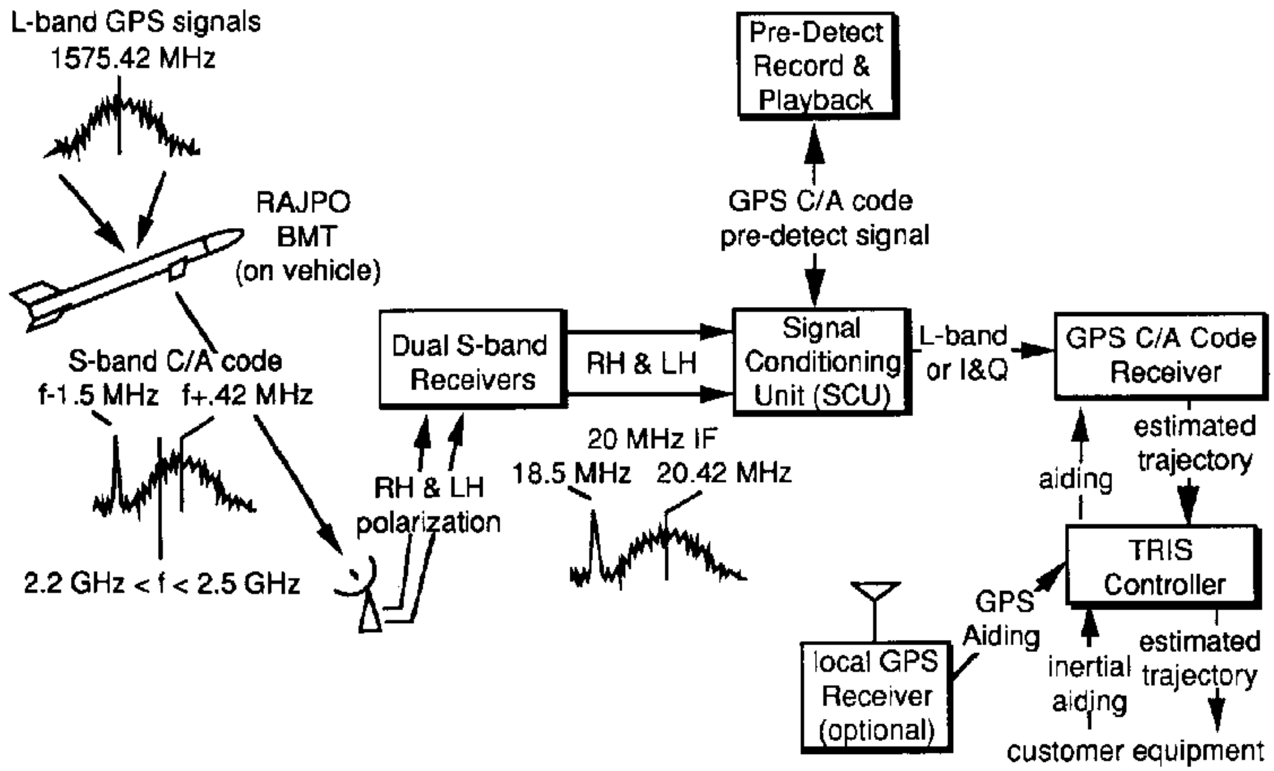

Figure 3. TRIS architecture.

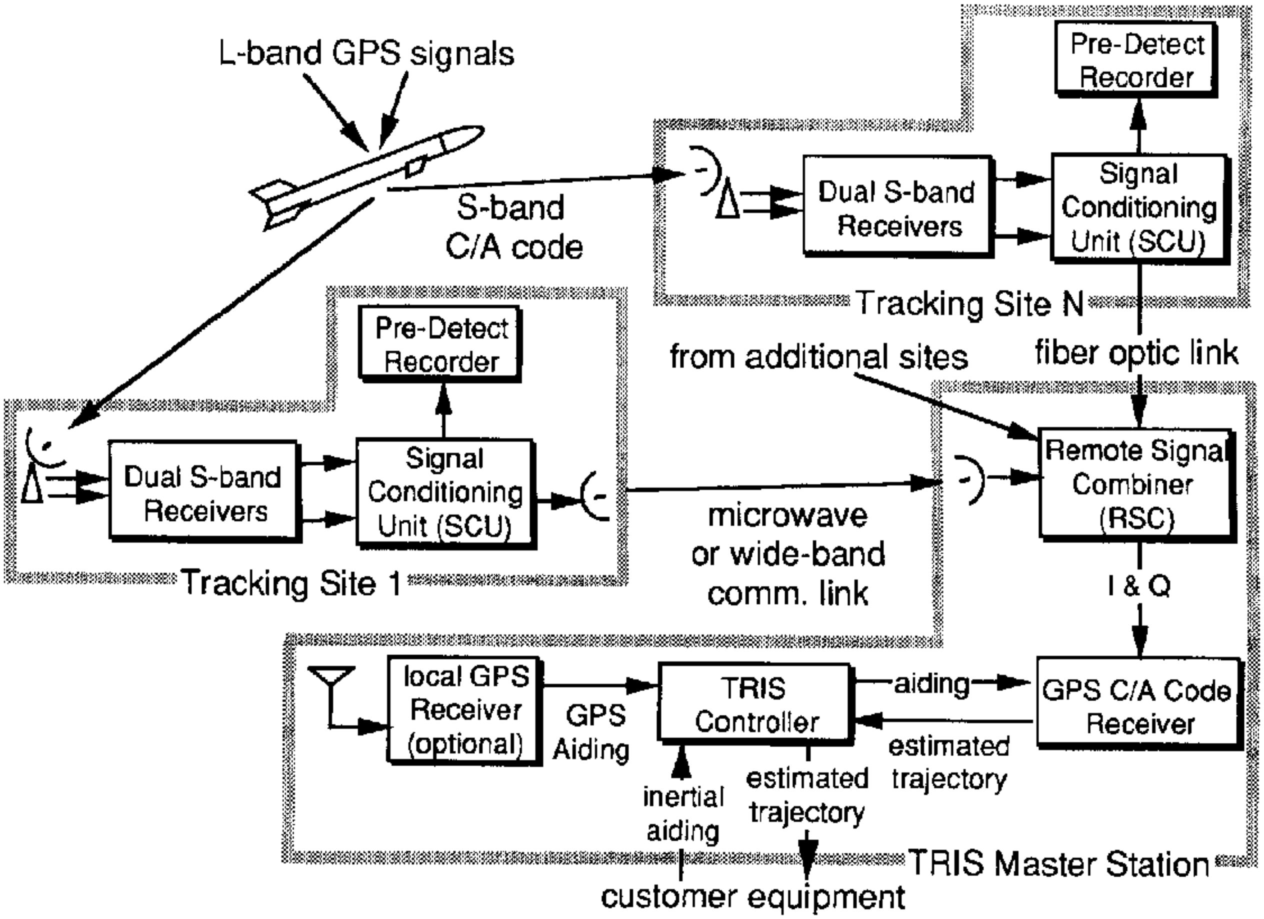

Figure 4. Multiple TRIS Receive Sites

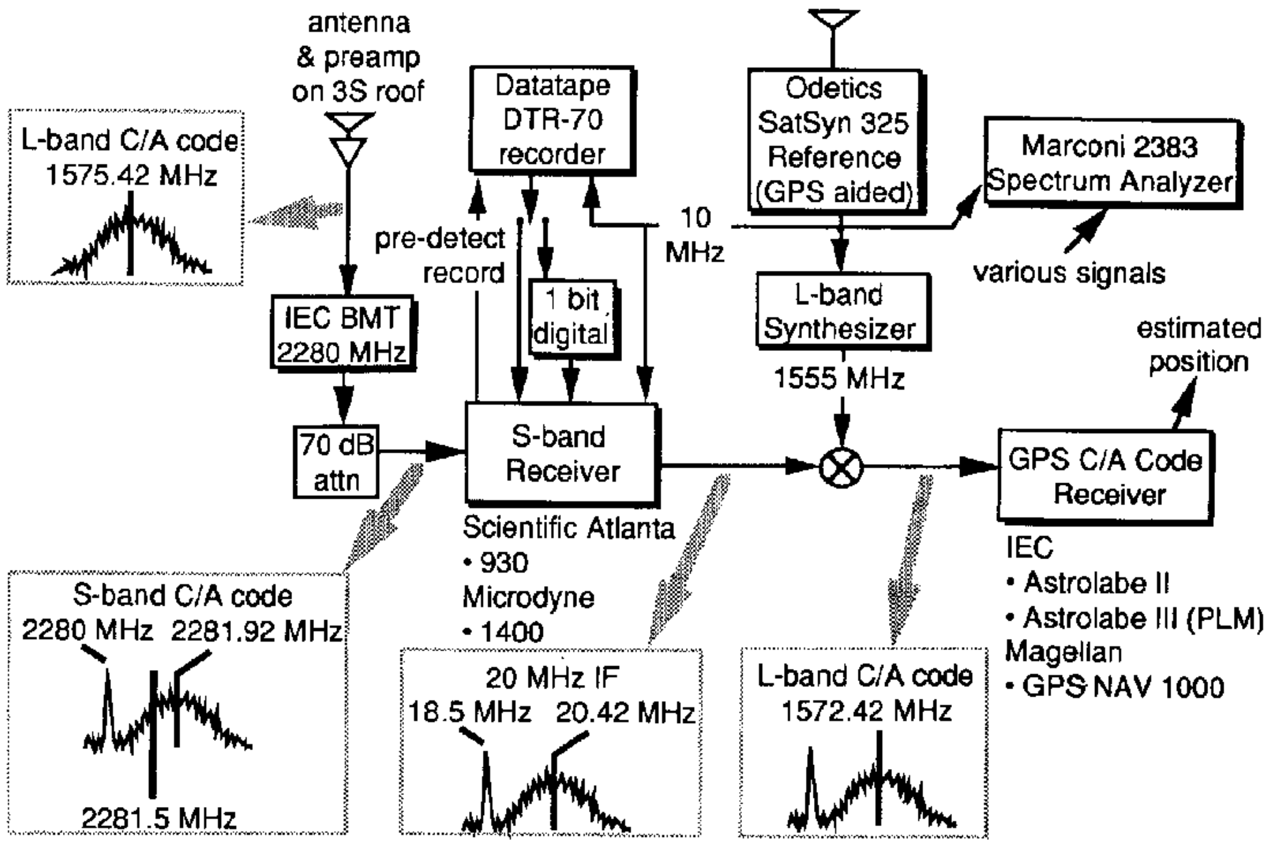

Figure 5. TRIS Phase I Prototype

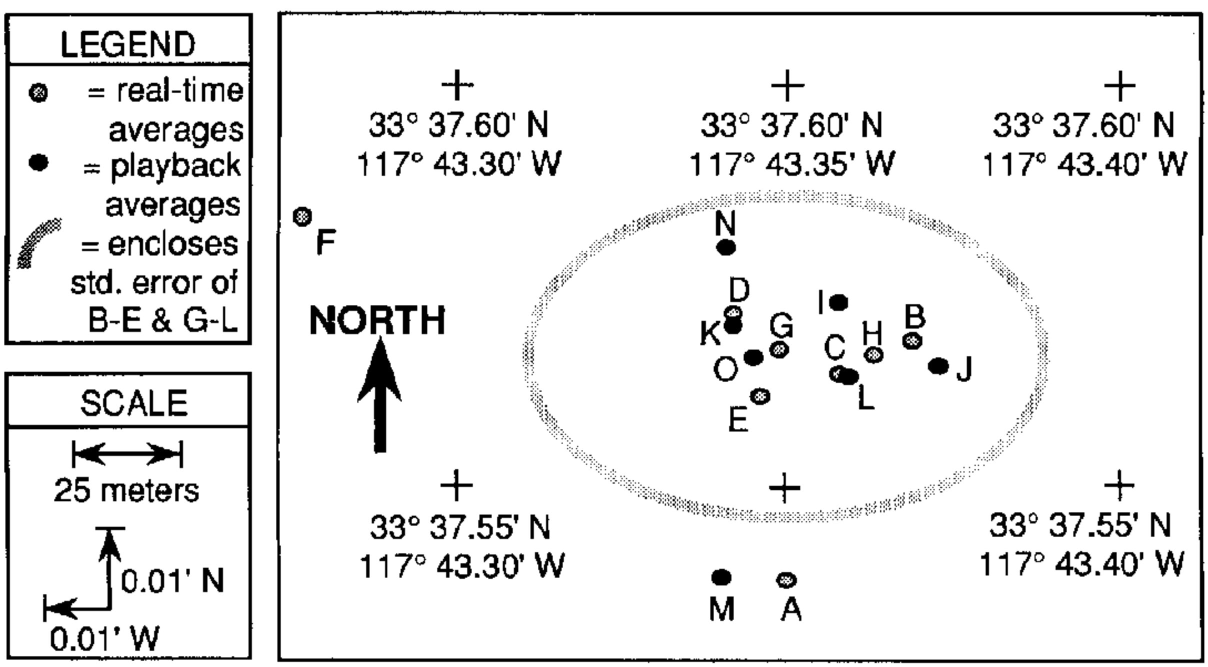

Figure 6. TRIS Phase I hardware prototype results.

Table I. TRIS Pre-detection Recorder Requirements.

signal source	channels	analog	digital		
		bandwidth per channel (MHz)	bits/sample	samples/sec (x 10^6)	total bits/sec (x 10^6)
receiver pre-D	2	4.0	2	10.0	40.0
SCU pre-combiner	4	2.0	2	5.0	40.0
SCU combined	2	1.3	2	2.5	10.0

Table II. Real-time Tests.

	2nd IF b/w (MHz)	2D/3D	# of meas
A	1.0	2D	12
B	1.0	3D	12
C	1.5	2D	81
D	1.5	3D	19
E	4.0	2D	16
F	4.0	3D	12
G	12.0	2D	10
H	12.0	3D	7

Table III. Playback Tests.

	setup	Pre-D freq. (MHz)	2nd IF b/w (MHz)	2D/3D	# of meas.
I	analog	0.9	1.0	2D	6
J	analog	0.9	1.0	3D	4
K	analog	2.4	1.5	3D	11
L	analog	3.6	4.0	2D	5
M	digital	0.9	1.0	2D	2
N	digital	2.4	1.5	3D	9
O	digital	3.6	4.0	2D	8