Invited Paper

TRI·NAV™

Integrating LORAN, GPS, INS, and Timing for a Total Navigation Solution

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ABSTRACT: TRI·NAV™ (Triply Redundant Integrated Navigation & Asset Visibility System) is a fault-tolerant, tripartite navigation system combining an advanced low-power inertial navigation system (INS) [Sensor + custom ORNL electronics] with precision timing, a military-quality GPS receiver, and a robust wide-area RF location scheme designated as the ***Theater Positioning System (TPS)***. Both are derived from research at Oak Ridge National Laboratory (ORNL) sponsored by the U.S. DoD for military testing and training activities. The software-based TPS receiver can decode standard LORAN-C as well as the new spread-spectrum signals to provide a significantly more reliable (and faster) fix than GPS alone, especially in the presence of obstructions, multipath, noise, and jamming. For the rare intervals when neither RF signal is receivable, the INS subsystem takes over. Precise internal system timing aids in reducing acquisition times and in "smoothing" the fix data. The TRI·NAV™ unit, employing TPS/LORAN as a backup for GPS, can thus provide a truly reliable, cost-effective navigation solution for diverse applications and environments.

TRI·NAV™ OVERVIEW

The TRI•NAV™ system is a compact low-power fault-tolerant tripartite personnel/asset location system combining an advanced low-power Inertial Navigation System (INS) [inertial sensor with custom ORNL electronics] with precision internal timing, a military-quality GPS receiver, and a robust wide-area RF location scheme designated as the Theater Positioning System (TPS). The unit is suitable for remotely tracking individuals, vehicles, airborne platforms, containers, and the like, in a wide variety of environments when combined with an appropriate data link back to a central monitoring point.

The TPS makes use of a ***new spread-spectrum RF system,*** typically transmitting in the same LF range as the highly reliable and commercially proven LORAN-C (~ 80-120 kHz). In its initial configuration, TPS was implemented as a four-band spread signal, with two main components at the band edges (80-90 kHz and 110-120 kHz) to minimize their impact on existing LORAN signals and two lower power secondary components overlapping the principal 90-110 kHz region (where ≥99% of the LORAN power resides). Later versions, to fully maximize the compatibility with existing LORAN-C transmissions, have focused on a two-signal TPS format which uses only the two band-edge components; the overlapping in-band (90-110 kHz) signals are omitted. The novel TPS RF modulation scheme, although principally direct-sequence (DS) in nature, can also optionally be time-modulated to markedly reduce the usual near-far effects experienced with conventional CDMA systems.

The TPS portion of TRI•NAV™ will make use of modern solid-state modular transmitting hardware that can be deployed either within *or external to* the theater of operations. Transmit power levels would therefore be determined by the actual placement of the transmitters. Depending upon the transmit power levels (many tens of kilowatts or higher), ranges in excess of 1,000 km could definitely be obtained in the 100-kHz region. The LF TPS signals will be highly effective in foliage, rough terrain, and in urban areas. These ground-wave signals will complement GPS satellite signals and provide accurate position location in GPS-denied or degraded environments. These new signals will also permit the wide-area, real-time distribution of precision timing, tactical operational information and DGPS corrections via the embedded TPS navigation data stream. In addition, the TPS signals can be employed within the TRINAV system receiver to validate GPS position in order to dynamically detect multipath, jamming, or spoofing-induced errors in the GPS fix. The longer intrinsic RF wavelengths used in TPS will also facilitate more reliable position solutions in fast-movers and further serve to mitigate GPS carrier-cycle ambiguity errors, which are by design absent in the TPS signal structures.

The basic operation of the integrated TRINAV system is represented in the diagram (Fig. 1) below. In the usual operating mode, GPS serves as the principal positioning source. An ongoing internal TRINAV system software routine continually examines the received GPS and TPS signal qualities (as represented by signal-integrity data, tracking-loop error magnitudes and variances, loop lock states, continuity of position fixes, internal RF/IF AGC values, and front-end overload indicators). If for any reason the GPS receiver loses lock or exhibits sudden changes in loop tracking parameters [and thus the fix becomes suspect], the TRINAV software will automatically switch to tracking the TPS position solution (normally horizontal-plane only). Continuity of the fix is assured, since during the normal TPS tracking process, the TPS and GPS position data are continually compared. As long as the recent *and* current GPS signal quality is good, the displayed TPS fix will be automatically adjusted to overlay the GPS values; this is generally done to provide an ongoing *in situ* calibration of the TPS signal propagation delay figures and thus “drag” the TPS fix in to match the GPS. If GPS suddenly fails to provide a clean or continuous fix, the TPS value will track the last good GPS coordinates; thus, TRINAV will provide a “bumpless” transfer which will be transparent to the user. Once GPS signal integrity is restored for at least a few seconds and a new lock is satisfactorily obtained, the TRINAV unit will smoothly revert to the GPS fix and return to normal operation. In the event that GPS is jammed or otherwise unavailable for an extended period, TPS will be employed in a standalone mode to derive the unit’s fix, with a caution to the user that fix accuracies may be reduced. Since in virtually all instances the accuracy of TPS will be controlled by the estimates of the TPS signal propagation speed over varying paths (land/water), soil types and moisture content, and terrain features (mountains, hills, canyons, etc.), the TRINAV unit will carry stored constants for characterizing the area and thus optimally correcting these variations and, hence, the TPS accuracy. As previously mentioned, these constants will be continually and automatically updated for the area of use using the valid GPS fix data during times of normal operation. As cited earlier, another specific advantage of the TRINAV concept lies in the use of TPS as an anti-spoofing detector for GPS. For instance, if the TPS (presumed stable *and* in calibration) and GPS planar fixes do not essentially coincide (i.e., where the GPS solution is considerably off from the TPS fix), this could be an indicator of GPS receiver problems or of the presence of a spoofing signal. In Fig. 2, the potential solution zones are shown for both GPS and TPS, where the simplification is made that five transmitters’ signals are being processed for each system. On the right, it is assumed that the GPS and TPS solutions are consistent and thus overlay fairly well. If, however, the GPS indicates a much different position, as shown by the box on the left, it may be that a GPS spoofer or very strong multipath signal is present; in any event, the user is warned of the situation and that the confidence of the GPS fix may not be good. If either GPS or TPS loses lock, the position solution from the other can be used in TRINAV to speed the search and re-acquisition process, as shown by the two “search” arrows in the information-flow diagram of Fig. 1. Further, the succession of GPS and TPS fix data are also used by TRINAV to support the operation of an adjunct inertial navigation system (INS) unit which in the absence of *any* radiolocation data can provide timely location data to the user. Although for some critical applications a high-quality, low-drift INS will be needed, for the vast majority of users it is very desirable to utilize smaller, lower cost, but less stable devices such as quartz or MEMS accelerometers and gyros. Modern MEMS accelerometers are accurate and exhibit low drift, but typical inexpensive, low-power COTS MEMS gyros (e.g., the Analog Devices ADXRS150) are specified at ~70°/hour worst-case angular drift. To make such devices useful for navigation, the TRINAV system incorporates advanced device performance models in its software to more accurately predict the INS subsystem drift and other errors. As depicted in Fig.1, the lower arrows represent the trajectory-based calibrations applied to the INS readout derived from the GPS and TPS fix

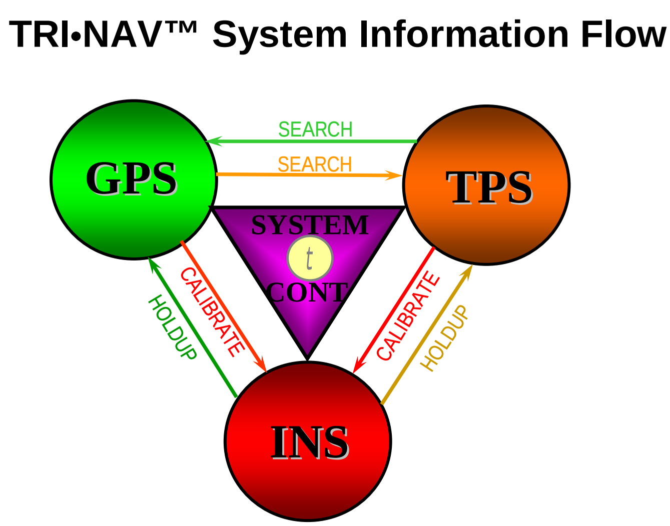

Fig. 1. TRINAV System Component Functional Interconnects

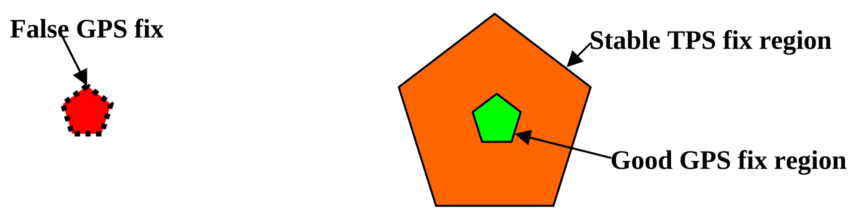

Fig. 2. TPS validation of GPS fix

data. Thus, the 3 independent trajectories are continually compared and the INS gains, drift factors, and linearities are dynamically adjusted to match the GPS (presumed best) and TPS path data sets. Either triple-input Kalman filtering, Allan filtering, multidimensional kernel techniques, or combinations thereof will be employed for the real-time GPS/TPS/INS integration processing. With appropriate temporal filtering, tracking the resulting displacements is relatively straightforward, but calculating the implied orientation angles is much more complex. Besides processing the coordinate transformations and compensating for the hysteresis, random-walk drift, and other parametric nonlinearities such as axis inorthogonality and acceleration-force compensation of the INS, the TRINAV system must also provide means of initially orienting the INS at startup and at reasonable intervals before substantial errors can accumulate. From previous experience, ORNL has found that flux-gate magnetometers can yield predictable north vectors (if well separated from ferrous objects), inexpensive tilt meters can provide the gravitational reference vector, and high-quality barometric altimeters for vertical position can serve as useful adjuncts to the INS components. We are also working with a private-sector firm in the early development of a novel multi-axis piezoelectric acceleration sensor which promises to be very cost-effective for the INS unit. In any event, the selection and optimization of INS components will obviously be largely dictated by the overall application's performance requirements. As an aid to the RF systems, the integrated INS position data is stored and used by TRINAV to provide holdup during rare intervals when neither RF locating system is receivable.

An overall block diagram of the complete TRI·NAV™ user unit is provided in Fig. 3 below. The integral GPS and TPS units feed their position data, status information (e.g., lock state, signal quality measurements, multipath detection, number of transmitters being tracked) and loop error signals back to the System Controller module. In addition, the Controller interfaces with the INS subsystem electronics, the operator interface/display unit, and any external sensors required by the application. The Controller also manages any required sensor telemetry (via RF link), handles the signal assessments (QoS monitoring), provides system power management, and performs all the computations needed to properly integrate the GPS, TPS, and INS subsystems and produce the fully integrated TRINAV outputs to the user. This includes the multiple, interacting Allan-filter based adaptive averaging and estimation routines used for position and time data integration. The TRINAV Controller also houses the EQUATE (Ensemble of Quartz clocks Adapting To the Environment) precision timebase and executes the internal oscillator controls and averaging software. The precise clock frequency of 10.000 MHz is also made available to the GPS and TPS receivers to assist in rapid re-acquisition after signal disturbances, as well as to any ancillary equipment (e.g., onboard sensors, data-reachback transmitters and radios).

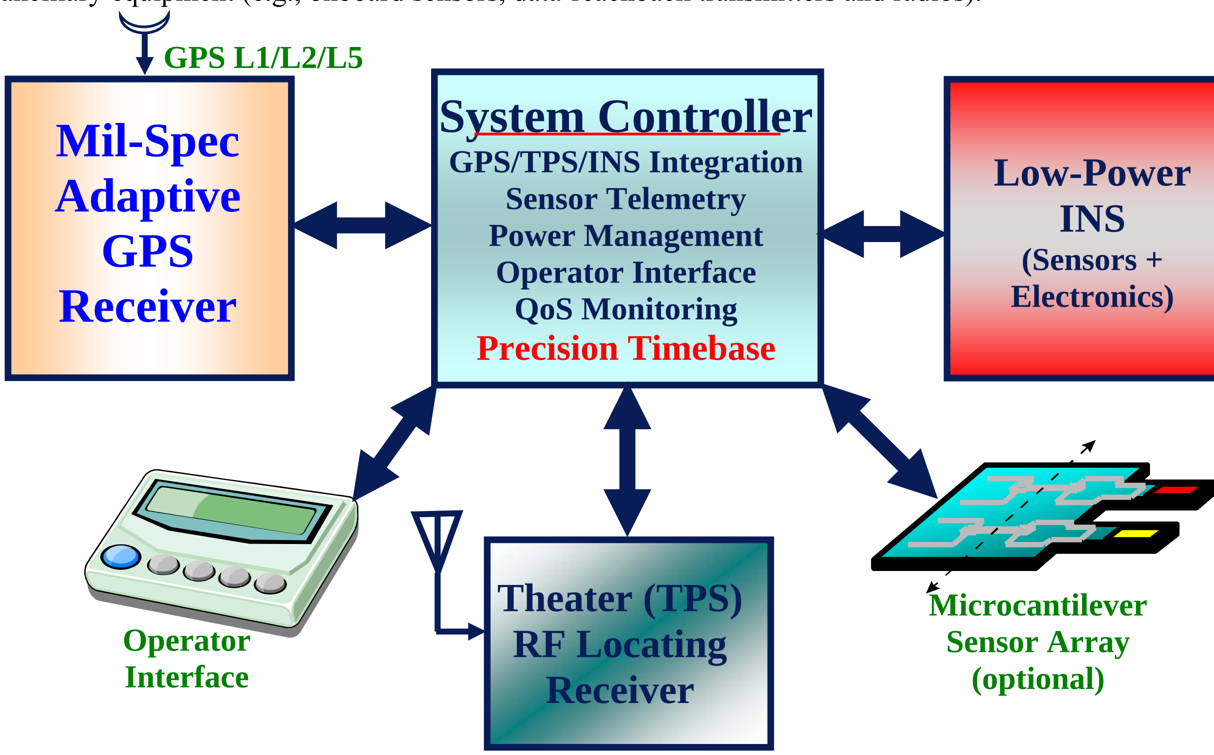

Fig. 3. TRINAV User Unit Block Diagram

THEATER POSITIONING SYSTEM (TPS) COMPONENT

TPS is a new frequency-agile, programmable-bandwidth radionavigation system being implemented for the U. S. Army's Operational Test Command to support soldier training and combat systems testing in GPS-denied environments such as dense forest areas and in urban terrain. Employing software-defined radio (SDR) techniques, the system is intended to be highly adaptive in order to rapidly adjust to different testing scenarios by changing its frequencies, coding bandwidths, and channelization as required by the specific application. The fundamental basis for the system is a direct-sequence spread-spectrum (DSSS) or hybrid spread-spectrum (HSS) signal which is launched from multiple widely-spaced, generally terrestrial transmitters. The radiolocating receiver acquires these largely continuous, overlapping code-division multiple-access (CDMA) transmitted signals, decodes them, and extracts the transmitter locations and times of transmission from data streams embedded in the respective DSSS signals, in a manner analogous to GPS units. The radionavigation solutions are then obtained by solving the usual systems of nonlinear pseudorange equations, but with downstream corrections for the spherical-earth geometry and RF propagation factors governing the groundwave signals. However, there are several significant features of this Theater Positioning System (TPS) which differentiate it from GPS, including its operating frequency range (~0.1-30 MHz), frequency- and modulation-agile capabilities, propagation modes (principally groundwave), and signal security mechanisms. In addition, the TPS signal structure is specifically designed to provide an effective back-up navigation source to GPS in difficult reception situations and afford maximal rejection of AC power-line noise to improve reception efficiency in urban areas. The use of special directional TPS receiving antennas can also enable orientation of the unit from the RF signals. A final feature of the TPS signals permits wide-area broadcasting of low-rate data for commands, DGPS corrections, status information, and the like.

To achieve rapid prototype development, fast reconfiguration, and highly flexible signal-processing architecture control, the vast majority of the TPS hardware has been implemented via highly reconfigurable software-defined radio (SDR) techniques. The platforms for most of the TPS subsystems are custom, small, low-power circuit boards using FPGAs as the core logic elements, augmented by high-performance A/D and D/A converters to convert the analog RF signals to and from the digital domain. A model-based design environment utilizing MATLAB® and Simulink® modeling tools, coupled with the Xilinx System Generator™ FPGA-design add-in module, was employed to permit an efficient, tightly coupled design/test/update system implementation cycle and to provide rapid system alterations as dictated by the sponsor's program needs.

TPS Technical Details

The TPS concept involves the use of a power-efficient, constant-envelope [1] direct-sequence spread-spectrum [2] RF transmission scheme which operates typically (***but not necessarily***) in the 80-120 kHz LF frequency range utilized in standard LORAN-C pulsed navigation transmissions. In Fig. 4 below, the basic TPS signal is split into two bands ("A" and "B") which lie outside the 99% power bandwidth of LORAN-C and thereby have essentially zero effect on conventional LORAN receivers due to the normal noise-rejection filtering already present. If desired, and for *future* data-bandwidth expansion, two additional in-band signals ("C" and "D") can be added. As noiselike, off-carrier spread-spectrum signals, they cause only a modest amount of interference to LORAN signals; in fact, at levels up to +7 dB relative to LORAN, in extensive tests with equal-level ABCD components they caused no observable degradation in LORAN positioning using both lab-grade and standard commercial-grade receivers. On the other hand, the band-edge A and B signals *alone* caused no ill effects to LORAN reception at levels up to 18 dB above the LORAN signals, thus emphasizing the excellent interoperability of the 100-kHz band A & B TPS signals with existing LORAN-C systems.

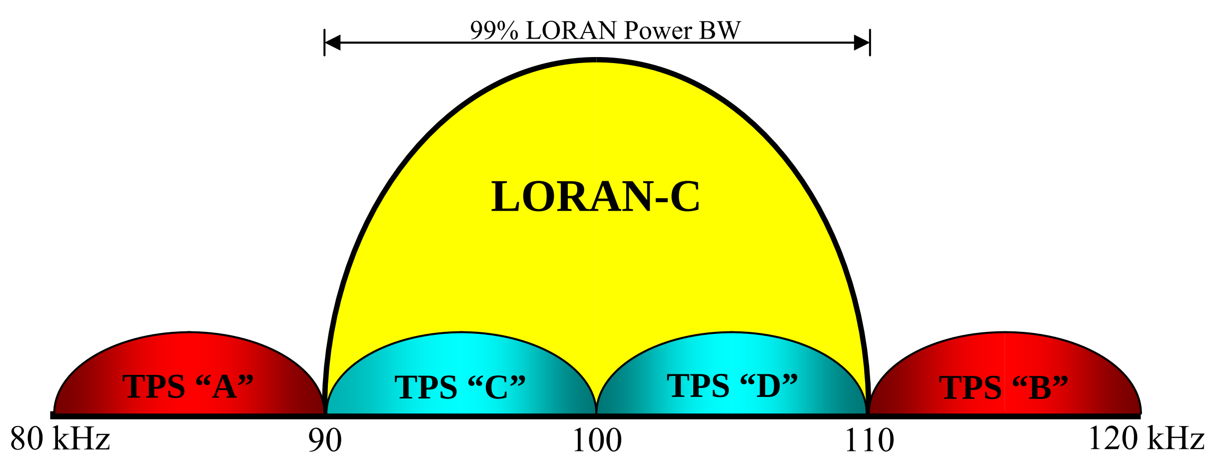

Fig. 4. Spectral Details of 100-kHz Band TPS Signals

The initial TPS deployment for the 80-120 kHz band would add the TPS “A” and “B” signals at the band edges, leaving the existing LORAN-C signals at each site intact. Besides affording a significant economic savings by sharing the LORAN transmitting plants, this scenario permits the addition of the much more robust TPS signals while maintaining full compatibility with current LORAN operations and field receivers (largely maritime and aviation users). The roughly 30-dB broadband and impulse-noise advantage of TPS, plus the additional 40-dB power-line related suppression (for a total of 70 dB) for the TPS data streams, will permit vastly more stable radiolocation performance, especially in noise-prone urban areas. Alternatively, other frequency bands or modulation formats may be employed for the TPS as application requirements dictate; the efficient translation of the transmitting and receiving hardware to new frequencies, bandwidths, formats, and data rates is accomplished via software-defined radio (SDR) techniques via modern reprogrammable FPGA devices which contain the digital signal processing hardware and even can include advanced on-chip software-controlled microprocessors.

In general, multiple, continuously broadcasting TPS transmitters are deployed around the desired coverage area (obviously using the existing LORAN sites) in an orthogonal code-division, multiple-access (OCDMA) scheme. Specialized spread-spectrum codes are employed to provide usefully high process gains (e.g., $\geq$ 30 dB) to provide effective rejection of impulse noise and other sources of RF interference, including standard LORAN-C signals or other types of in-band signals. The basic TPS data rates were chosen to provide very effective reduction of induced or intermodulated AC power-line noise components in the receiver; i.e., at 50/60 Hz or sub-multiples thereof (5 Hz for each component [A/B] of the LF version). The potential net gain is then about 40 dB of *additional* power-line noise rejection. The LF signal is of course already inherently optimized for 50-Hz power grids; thus, the system could certainly realize its full noise-rejection advantage even in 50-Hz regions of the world.

A navigation data stream of precisely 20 bits/s (in aggregate for the A & B signals) is encapsulated within the spread-spectrum signal; this data is used for TPS parameters, signal propagation prediction correction data (much as the GPS concept provides ephemeris corrections via the 50-bits/s GPS navigation stream), and for other signaling functions. An additional key feature of the system involves the active, automatic locking of the multiple, remotely located TPS transmitters to a common frequency/timing reference source such as that obtainable via specialized GPS receivers and highly stable local clock oscillators. The extremely tight frequency/phase lock (usually to better than 1 part in 10^{11}) is required to provide stable relative phases between the various TPS transmitters’ signals and thus maintain good positioning accuracy and signal quality at the TPS receivers in the field. Again, TPS can benefit greatly from the already-installed cesium clocks and common-view GPS time references added in the recent U.S. LORAN upgrade program.

TPS SYSTEM OPERATIONAL CONCEPT

A major operational concern in the deployment of U. S. military, emergency, and law-enforcement personnel is the nearly exclusive dependence on the GPS satellite constellation for accurate position information in the field. Since GPS signals are comparatively weak (~10-15 dB below the typical background RF noise floor) and subject to significant degradation from multipath and RF interference (intentional *and* unintentional), the use of GPS is at times unreliable and even subject to deception (“spoofing”) by an adversary [3]. The obvious consequences of inaccurate position information can be severe, up to and including loss of life of both friendly forces and/or noncombatants (civilians). Although inertial navigation systems (INS) have been proposed as *short-term* backups to GPS reception during outage periods, these units are in general too costly, heavy, bulky, inaccurate, and/or power-hungry to be deployed except in a few specialized applications. For the dismounted soldier and most platforms, a much more robust, inexpensive, and reliable GPS augmentation technique is needed, especially where outages may be of extended durations. For broad application areas, an RF approach is desirable; in addition, the use of ground-wave LF- to HF-band transmissions (depending on range) is radically different in propagation characteristics from GPS and thus provides a significant measure of signal diversity between the two radiolocation schemes. Further, the use of the TPS signals as a backup to GPS navigation offers far more consistent coverage than with GPS alone, since the low-frequency TPS signals can easily penetrate into most buildings, heavy foliage, urban terrain, and other areas where GPS signals are weak, unreliable, or even unreceivable; such expanded coverage is essential for successful operations in urban areas, very rough terrain, or in tropical or heavily forested regions. Furthermore, due to the extremely low signal strengths of the GPS satellite beacon transmitters at the GPS receiver, GPS signals are virtually always unusable indoors because of the additional attenuation of the overhead satellite signals by building roofs, upper floors, and other overhead structures, as well as trees and dense foliage in general. In addition, in "urban canyons" and in very rugged terrain, often there are too few GPS satellites in direct line-of-sight view of the receiver to obtain a sufficiently accurate (or timely) position fix. Again, TPS provides a much-needed improvement in locating-system reliability.

The basic configuration of the TPS scheme is shown in the accompanying diagram of Fig. 5. The TPS transmitters are typically (*although not necessarily*) deployed outside the main area of operations, in a reasonably regularly spaced array to provide favorable angles of reception from the various transmitter locations (i.e., "good system geometry" or "cuts"). For a fairly flat terrain profile, the TPS system will provide useful two-dimensional location data; if special provisions are made to generate TPS transmissions at varying heights (e.g., via elevated balloons, aircraft, etc.), the system can produce 3-dimensional readings as well, although the accuracy in the vertical direction (due to the geometric dilution-of-precision effect) will typically be noticeably lower than in the horizontal plane, much as with GPS. [As for *any* navigation system, the geometric dilution-of-precision (GDOP), the factor of position-accuracy degradation due to the included angle θ between a pair of reference points, $\propto \csc \theta$, must always be considered]. The mathematical equations used to calculate the respective ranges from the TPS receiver to the transmitters in the area (which could easily exceed 1000 km in distance), called the *pseudorange equations* in GPS parlance [3,4], are similar to the GPS versions, except that the TPS transmissions are generally from stationary sources and, as such, do not need Doppler or relativistic corrections to the pseudorange values before computing the location solution in the receiver. They do, however, require great-circle distance corrections for the ground-wave signal paths on the earth's surface and adjustments to the propagation velocity values over the intervening terrain due to changes in the dielectric constant from varying soils, moisture content, etc. Like GPS, the TPS setup utilizes a precise common time base to provide highly accurate, stable time-of-day information for each transmitter; as in GPS, a stable clock in the TPS receiver permits faster initial signal acquisition and more accurate positioning via algorithms which incorporate strategic averaging among the various TPS signals.

TPS typically operates to determine the position of a user's receiver by acquiring signals transmitted by a group of TPS transmitters distributed in a region on the surface of the earth. The TPS transmitters employ direct digital synthesizer (DDS) hardware driven by the local precision timekeeping oscillators to generate highly stable spread-spectrum waveforms which will then be amplified to the required RF power levels and broadcast through specially characterized, vertically polarized antennas for greater coverage and ease of deployment. The user's position on the surface of the earth is calculated relative to the center of the earth [in 3 dimensions] or relative to the surface of the earth [for 2 dimensions] by triangulation based on signals received from multiple (usually 4 or more) TPS transmitters. The distance from the user to a transmitter is computed by measuring the propagation time required for a direct-sequence spread-spectrum "ranging code" signal transmitted by a given transmitter to reach the receiver. An extra (the 4th) transmitter is employed to permit a simultaneous solution of both the position and the system time; this avoids the need for a costly super-accurate clock in the TPS receiver. Additional transmitters add redundancy to the system for improved reliability and noise rejection.

A particularly useful feature of the TPS scheme is the ability to obtain unambiguous position fixes in much less time than is typically required for GPS. This is principally due to the presence of complete transmitter location and time data within the TPS navigation data stream. In the basic LF TPS system near

100 kHz, the overall data rate is 20 bits/s, requiring 12 seconds to transmit the entire data set. Allowing for a fraction of a second for processing in the TPS receiver, the time-to-first-fix (TTFF) figure for the LF version is thus about 12.5 s. Since the TPS chip rates are relatively short compared to the carrier frequencies (~ $^{1}/_{20}$), the usual delays encountered in GPS receivers due to the need for integer-cycle ambiguity resolution from multiple satellite signals are totally avoided. This is particularly useful in situations when due to jamming, shielding, or receiver shutdowns the navigation signals have been unavailable; in these cases, even from a receiver cold start, the user's TPS fix should be good within the specified 12.5-second time frame.

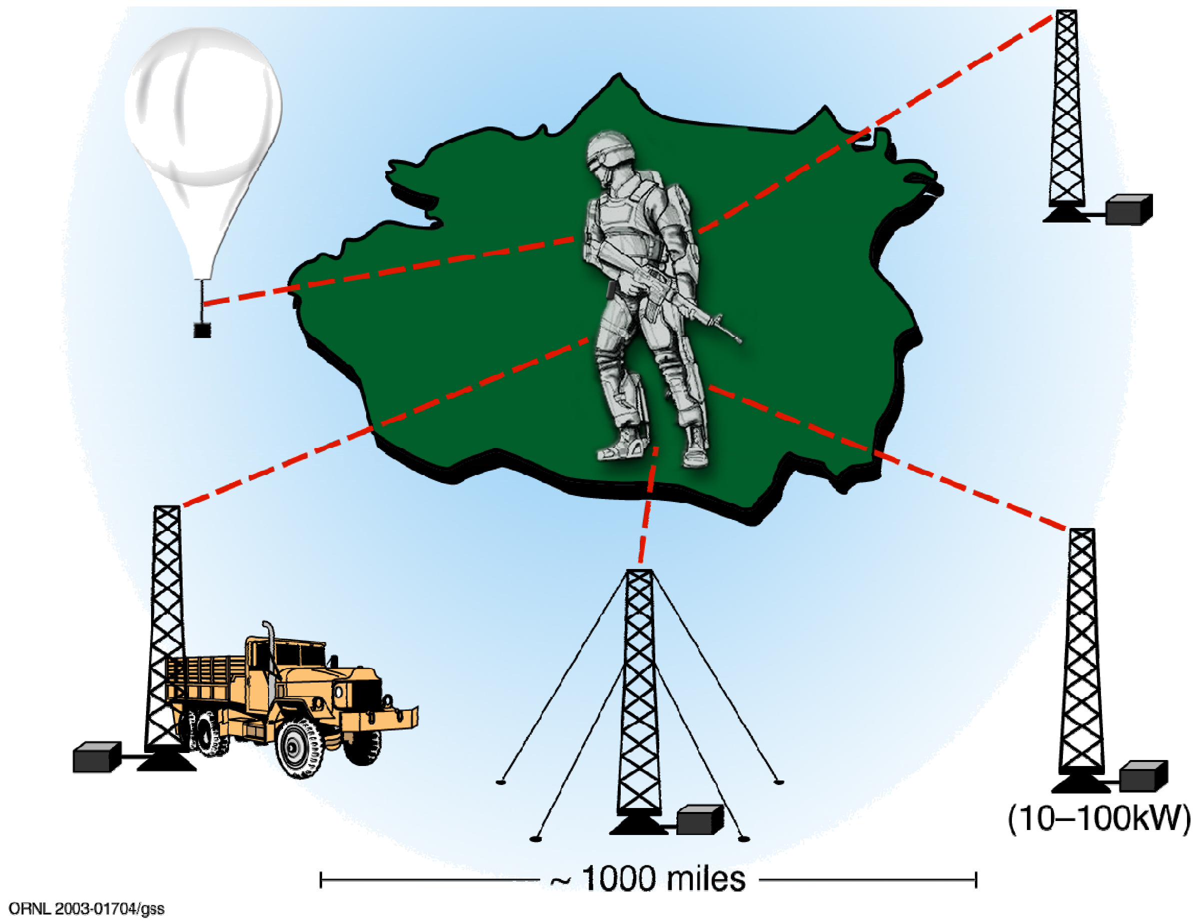

Fig. 5. Typical TPS Military Deployment in Large Operational Area

Transmitter Implementation

The representative TPS transmitter signal source, as shown below in Fig. 6, consists of a pair of PN code generators, nominally employing 1023-length Gold or Kasami code polynomials, which via an XOR operation (the ⊕ symbol) direct-sequence (DS) spread the TPS navigation data stream [emerging from the Packet Generator block]. Data contained in the packet consists of a total of 240 bits, including: **(1)** the 3-D transmitter location (32/32/16 bits for Latitude/Longitude/Height, for a total of 80 bits); **(2)** system time (64 bits); **(3)** system data (16 bits); **(4)** error-correction; **(5)** and sync bits. The separate in-phase (I) and quadrature (Q) continuous spread-spectrum data streams are shaped for bandwidth control and modulated (the "×" symbol) onto the respective phases of a programmable-frequency RF carrier generated by a numerically controlled oscillator (NCO). The two quadrature components are then summed (at the "+" sign) and smoothed by a low-pass filter (LPF) to form a composite output signal; all these steps are performed within a high-density FPGA chip. The 14-bit SOQPSK-modulated digital output from the FPGA is then applied to an external digital-to-analog converter (DAC); the resulting constant-envelope analog output is then fed to a high-gain, high-efficiency RF power amplifier (RF PA) and boosted to the desired drive level before being applied to the transmitting antenna. Obviously, the required transmitted power levels will vary according to the selected frequency band (80-120 kHz), desired coverage area, and available antenna configurations; near 100 kHz, the powers are projected to be in the 10- to 100-kilowatt range to cover long distances, compatible with the coverage of existing LORAN-C stations.

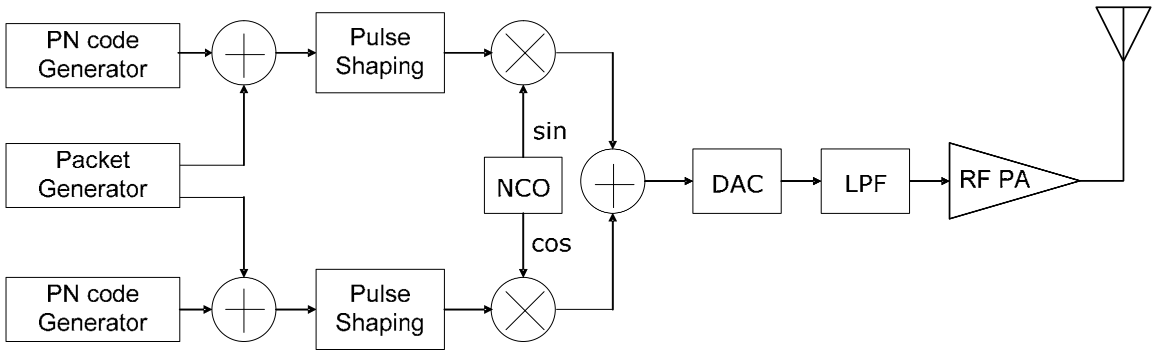

Fig. 6. Transmitting System Block Diagram.

Receiver Implementation

The front end of the basic dual-conversion TPS radiolocation receiver is shown in block diagram form in Fig. 7 below; Fig. 8 shows the downstream data-extraction circuitry. The received signal from the antenna is first bandpass filtered and amplified in a low-noise amplifier block with wide-range automatic gain control and integral, multistage limiting to reduce large impulse-noise spikes and minimize front-end/mixer overload. A second, tighter bandpass filter (BPF) precedes the analog-to-digital converter (ADC) to minimize out-of-band noise, spurious signals, and aliases. The ADC is a fast 14-bit unit to provide high signal resolution and good dynamic range for the subsequent FPGA-based signal processing chain. The digitized input signal is first downconverted to a very low intermediate frequency (IF) via the quadrature outputs of the first local oscillator (NCO1) and the two (I and Q) mixer/multipliers, denoted by the "×" symbols above and below the NCO block. The I and Q signals are then low-pass filtered (LPF) to remove mixer products and out-of-band noise and introduced to a low-frequency (near-DC) data demodulation and synchronization loop. These signals are also routed to other, parallel channel processors (one per transmitter); a typical channel is shown at right in Fig. 12, continuing into Fig. 13.

The low-IF signals are converted to baseband [via NCO2 and its associated multiplier/mixers] in an extended Costas-loop circuit that provides spread-spectrum chip demodulation, correlation, and synchronization. However, since chip-based ranging alone cannot achieve the required radiolocation accuracy at the relatively low carrier frequencies for TPS (as compared with GPS), the normal Costas demodulator is augmented with a secondary carrier-phase detection loop [the CDLL] which can lock to within better than 0.3° (within ±1 part in 1024 of the carrier cycle). In acquisition, the carrier phase is first estimated and an initial sequence of chips is correlated and demodulated. The tandem programmable delay registers [DLY] adjust the timing of the downsampling blocks [DS1, DS2] of the I and Q baseband signals, which in turn feed the respective channel correlators. To simplify the task of synchronization, the I and Q channels for each TPS transmitter are assigned different spreading codes, to distinguish which channel is I and which is Q. The normal Costas-loop data polarity (value) ambiguity is resolved by transmitting dedicated header sequences (much as in GPS); the receiver then selects the required sign to retrieve the correct chips. The outputs of the I and Q correlators (Fig. 13) feed back to the carrier delay-lock loop controller and also provide inputs to the rectangular-to-polar transformation logic, which takes the Cartesian I/Q sample values and converts them to polar (R, ϕ) magnitude and phase values. The magnitude signal [top] is sent to an early-late correlation detector, which reads out the fine PN code-phase values and also adjusts the timing delay-lock loop [TDLL] for convergence. Meanwhile, the respective chip-wise carrier phase values [bottom] are sent to a conventional QPSK-type data decoder to extract the TPS data stream, which includes transmitter IDs, locations, and the precise system time marks used in the subsequent navigation algorithms to calculate the user's position. Fig. 9 shows the lab TPS receiver system electronic hardware.

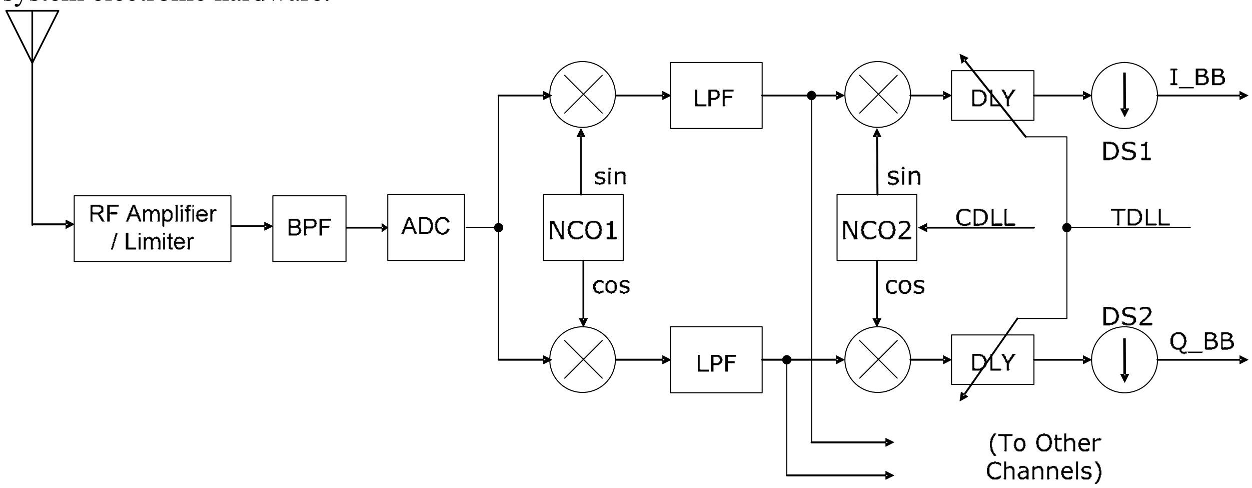

Fig. 7. Block Diagram of TPS Receiver Front-End Circuitry

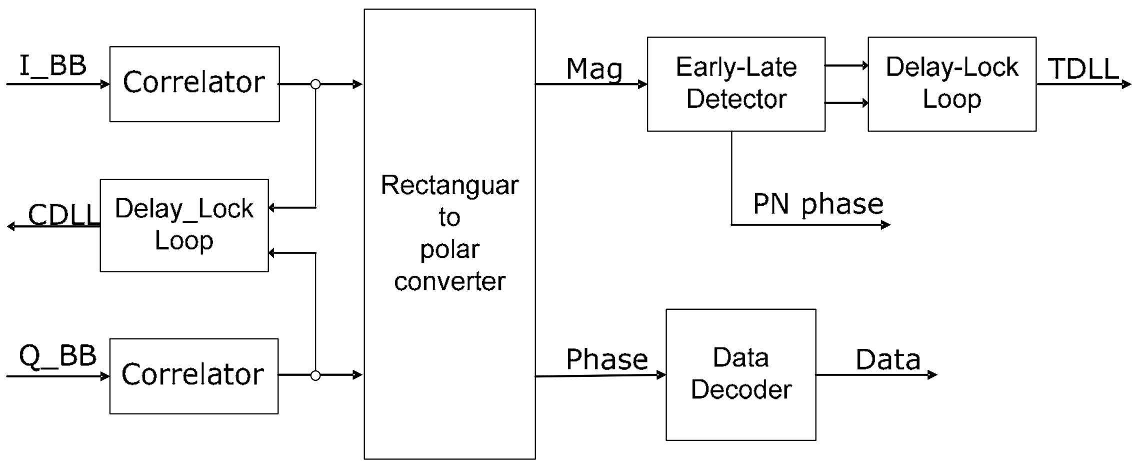

Fig. 8. Block Diagram of TPS Receiver Extended Costas-Loop Detector and Data Demodulator.

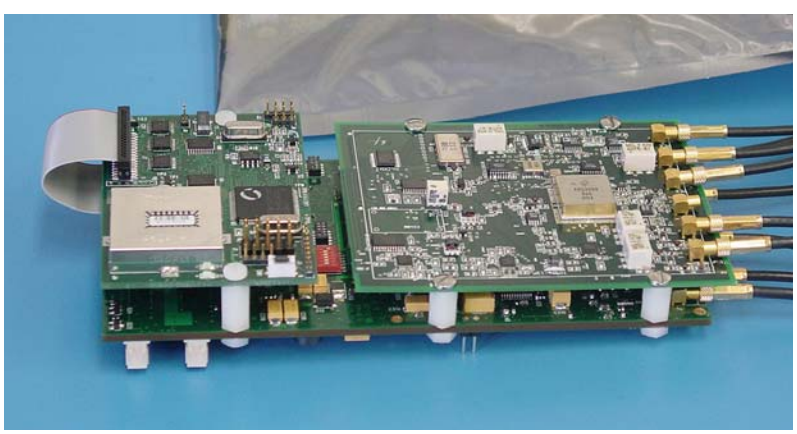

Fig. 9. Lab Prototype TPS Receiver Hardware with External Interfaces.

Navigation Algorithms

As mentioned above, the multilateration radiolocation algorithms for TPS are generally similar to those used in GPS [3, 4], except for the addition of great-circle corrections to accurately represent the lengths of the ground-wave propagation paths on the nearly spherical earth and (obviously) the deletion of the satellite almanac and ephemeris data. In most operational scenarios, the TPS transmitters will be locked to GPS time with very high-quality clocks; plus, their locations will be pre-surveyed and will be known to fractions of a meter. The respective TPS data streams will thus provide all the information needed by the receiver (except for onboard-stored local propagation-correction tables) to accurately compute its position. Due to the finite conductivity of the earth's surface, and local variations due to surface types (i.e., land or water), soil, moisture content, temperature, and (to a lesser extent) season, the *average* signal velocity must be reduced by *roughly* 0.15%; in addition, the curved path on the earth's surface requires generic great-circle distance computations, plus some additional corrections for local-area topographical irregularities. All these corrections are performed by the TPS navigation software.

Within each channel of a TPS receiver, an identical (replica) ranging code signal is generated and shifted in time (or phase) until it achieves peak correlation with the specific transmitter-generated ranging code being acquired. The magnitude of the time shift of the identical ranging code signal within the receiver relative to the transmitter transmitted ranging code provides a time differential that is related to the transmitter-to-user range. To determine user position in three dimensions, range measurements are made to multiple transmitters, resulting in at least four simultaneous ranging equations with four unknowns. These equations can be solved by computational algorithms to determine the values of x, y, z (the 3-dimensional location of the user's receiver), and Δt, which is a clock error. There are several closed-form solutions available for solving the equation to determine the unknown quantities. The positioning is in general accomplished by determining the time-of-flight of the signals from at least 4 TPS transmitters, and by careful processing of the real-time data from the multiple transmitter clocks (and other, small corrections) the actual distances are computed; the common solution to the set of simultaneous distance equations, coupled to the known transmitter locations, provides the TPS receiver's position. Thus, the *equivalent geometric range* is given by:

(1) $r = c(T_u - T_s) = c\Delta t$, where:

r = actual path distance (great-circle for groundwave signals)
T_s = system time when signal left the transmitter;
T_u = system time when signal reached the receiver;
δt = offset of transmitter clock from system time;
t_u = offset of receiver clock from system time;
$T_s + \delta t$ = transmitter clock reading when signal left transmitter;
$T_u + t_u$ = receiver clock reading when signal arrived;
c = speed of wave, corrected for path propagation;
(x_u, y_u, z_u) = position of the receiver in 3 dimensions; and
(x_j, y_j, z_j) = 3-dimensional position of the *j*th transmitter (j = 1 to 4).

For TPS, the usual rectilinear path computations used in GPS ranging have been altered to accommodate the ground-wave propagation and great-circle path distances; this is done by adjusting the equivalent speed of the wave for the slower propagation along the earth's surface; the curved-path distances may then converted to the equivalent chord distances to utilize the normal rectilinear distance equations. The ground wave follows the great-circle distance between two points on the earth's surface (assumed spherical), which can be computed by the following formula, where δ_1 and φ_1 are the latitude and longitude, respectively and *r* is the radius of the earth (approximately 6367 km on average), then the great-circle distance *d* is approximately:

$$d(\delta_1,\varphi_1,\delta_2,\varphi_2) = r \cos^{-1} [\sin \delta_1 \sin\delta_2 + \cos\delta_1\cos\delta_2\cos(\varphi_1-\varphi_2)],$$

or, in a form with smaller rounding errors,

$$d(\delta_1,\varphi_1,\delta_2,\varphi_2) = 2\, r \sin^{-1} \{\sin^2[(\delta_1-\delta_2)/2] + \cos\delta_1\cos\delta_2\sin^2[(\varphi_1-\varphi_2)/2]\}^{½}$$

In these terms, the *pseudorange* is given by:

$$\textbf{(2)}\quad \rho = c[(T_u + t_u) - (T_s + \delta t)] = c(T_u - T_s) + c(t_u - \delta t) = r + c(t_u - \delta t)$$

and the 4 pseudoranges are thus:

$$\textbf{(3)}\quad \rho_1 = [(x_1-x_u)^2+(y_1-y_u)^2+(z_1-z_u)^2]^{½} + ct_u$$

$$\textbf{(4)}\quad \rho_2 = [(x_2-x_u)^2+(y_2-y_u)^2+(z_2-z_u)^2]^{½} + ct_u$$

$$\textbf{(5)}\quad \rho_3 = [(x_3-x_u)^2+(y_3-y_u)^2+(z_3-z_u)^2]^{½} + ct_u$$

$$\textbf{(6)}\quad \rho_4 = [(x_4-x_u)^2+(y_4-y_u)^2+(z_4-z_u)^2]^{½} + ct_u$$

These nonlinear equations may be solved by either closed-form methods [5], iterative techniques based on linearization, or by Kalman filtering [6], Allan filtering, multidimensional kernels [7], or other equivalent estimation algorithms. Note that in the case where a good common-time reference exists between the transmitters and receiver, the various δt and t_u terms become vanishingly small. In the preferred TPS system implementation, highly stable rubidium or even cesium clocks would be employed at the distributed transmitter sites to maintain an extremely stable common time base, which will be augmented by periodic cross-checks with the GPS constellation via advanced common-view techniques to assure accurate wide-area time commonality (to perhaps a few nanoseconds).

The overall TPS locating algorithm (Fig. 10), unlike in GPS, may be either a 2-D or 3-D type, based on the available data sets. Since with all land-based transmitters TPS can only be used as a "planar" or 2-D locating system, often the data will only support 2-D calculations, since the normal 3-D algorithms will usually experience poor convergence (overly long solution times) when the data sets have little deviations in one dimension. This is the consequence of the high DOP conditions and can result in no solution at all if convergence of the computations fails. The first block in the algorithm thus selects the appropriate procedure (2-D or 3-D), and then performs the conversion to translate latitude-longitude-height (LLH) coordinates of the transmitters and initial receiver location estimate to earth-centered, earth-fixed (ECEF) format. Next, the straight-line point-to-point (chord) distances are determined from the standard

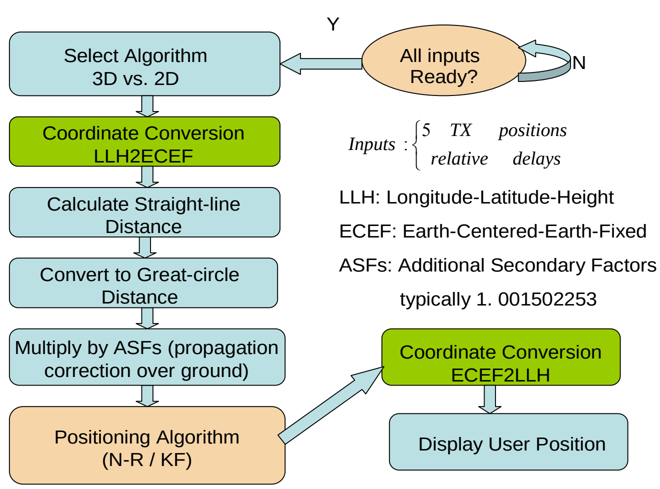

Fig. 10. Overall TPS Radiolocation Algorithm

geometric equations and corrected for the great-circle (arc) distances, assuming a near-spherical earth. Thus, the *effective* positions of the transmitters are shifted radially outward from the presumed receiver location to account for both the curvature of the earth's surface and the propagation speed of the RF signals over the earth's surface, including soil, water, and variations thereof. Once the effective distances have been determined, the positioning algorithm (either a Newton-Raphson routine, an extended Kalman filter, or other method) then is employed to solve the set of simultaneous linear (or linearized) equations to find the receiver's actual location in ECEF coordinates. Generally, these are re-converted to LLH format and displayed for the TPS user.

Some details of the Newton-Raphson and Extended Kalman filter methods are shown in the flow diagrams below (Figs. 11 and 12). The Newton-Raphson algorithm is typically used in the more basic linearization methodologies, whereas the Extended Kalman filter is modified from the standard Kalman approach to better handle the parametric nonlinearities inherent in the location-computation process. An additional, improved technique for solving the receiver's location from the group of pseudorange values is the use of adaptive, weighted averaging algorithms pioneered by David W. Allan of NBS/NIST for use in averaging the outputs of multiple atomic clocks to develop a weighted ensemble average for keeping standard time; a version of this technique is already being employed in the EQUATE oscillator ensemble mentioned previously. Similarly, the pseudorange values as a set can be manipulated via a form of the Allan algorithm to minimize overall errors and reduce dependencies on high-variance (noisy) parameters or pseudoranges where some redundancy exists in the data set. A recent further improvement in the Allan technique permits significant reductions in the random-walk (flicker) components of the data averages; this feature has been conclusively demonstrated in actual field time-transfer measurement data taken earlier this year [7]. Yet another general but powerful signal-processing technique involving kernel regression [8], developed by ORNL staff, is being studied for application into the TRINAV system where the data is particularly noisy.

The overall performance of TPS is, as with all radiolocation systems, determined by the precision (resolution) of the transmitter and receiver electronics [e.g., number of bits, sampling rates, internal clock frequency errors, and jitter] as well as systematic properties including transmitter clock errors, uncertainties in propagation-time predictions, and noise backgrounds. The basic positioning precision is dependent on the phase resolution of the receiver carrier-phase loop, which is from 0.35° down to 0.09° (10 to 12 bits). Expected noise variances in the system (assuming good signal-to-noise conditions and ~1-second averaging times) are in the range of 1° down to 0.3°; at 3.3 MHz, this yields an equivalent X-Y locating precision of roughly 0.3 to 0.1 m, depending on signal strengths. Lab measurements of the hardware have confirmed this number; assuming funding is available, field testing will be conducted over the next few months to establish overall system accuracies in a typical (noisy) RF environment and facilitate further system optimization efforts. A major benefit of the TPS signal format is the ability to achieve a rapid position solution; from initialization, the time-to-first-fix is designed to be in seconds, rather than minutes as is often the case with GPS.

As with GPS, multipath is a major limiting factor (and by nature the least well-defined error source) in the overall accuracy for field applications. In the 100-kHz LF groundwave version of TPS, the wavelengths are so long that multipath *per se* is not a real problem, though delayed skywave signals can be. Interestingly, the effects of skywave signal contamination for the LF version are almost identical with those of conventional line-of-sight multipath, in that a second, indirect signal (the skywave component) often arrives well within the period of a chip, thus distorting the ideally triangular correlation waveform and obscuring the true peak, which indicates the relative time-of-arrival of the main signal component. Several techniques to eliminate the effect of second-path (skywave) signals, adapted from GPS signal processing, have proven effective in simulations at LF. Examples of these include the use of special correlation waveforms and techniques and compensation via custom statistical processing software in the receiver.

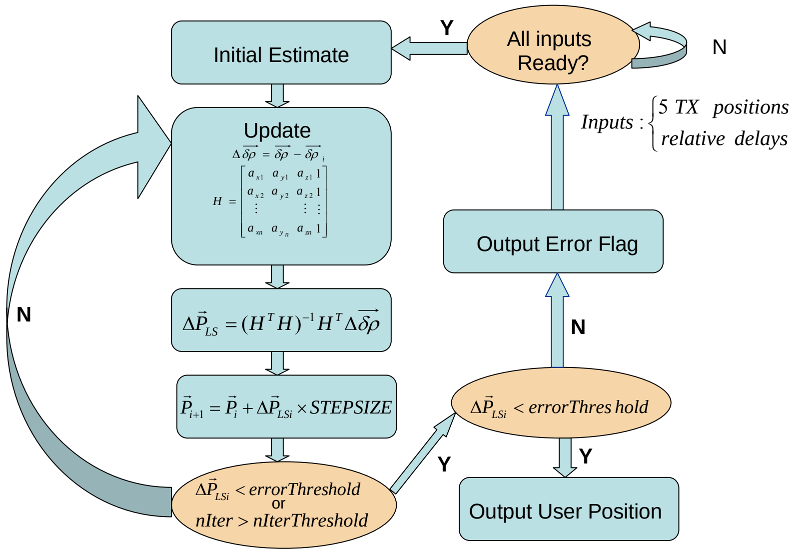

Fig. 11. Newton-Raphson Flow Diagram for TPS

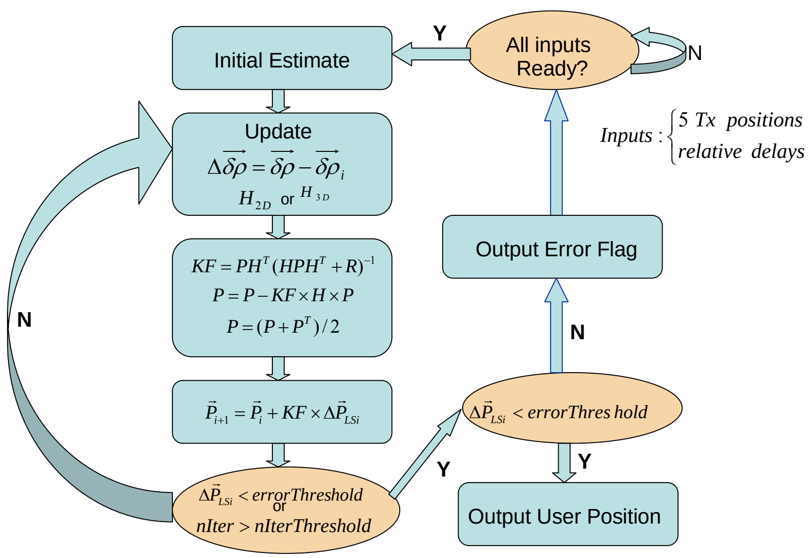

Fig. 12. Extended Kalman Filter Flow Diagram for TPS.

In addition, there are several other technologies which, when fully developed, can greatly enhance the performance of TPS systems in the field, even under adverse signal conditions. Since TPS is essentially a CDMA system, its ability to separate the various TPS signals, with their distinct spread-spectrum codes, is dependent on both the relative orthogonality of the transmitters' codes and the effective amplitude ratios among the TPS signals at the user's receiver. When relatively large (≤ 25-30 dB) signal-strength differences exist among the received TPS signals, an interference-canceling structure can be employed within the receiver to successively demodulate the larger signals, synchronize to them, reconstitute them using an internal remodulator, and then subtract them out one-by-one.

An additional aspect of TPS is the use of hybrid spread-spectrum (HSS) signaling in lieu of conventional DSS modulation. The added coordinated time-hopping component can significantly boost system dynamic range as well as improve the multiple-access properties of the TPS scheme, with a trivial change in transmitter hardware and only a small increase in receiver complexity. Additional protection from very strong locally transmitted signals (for receivers located rather close to one of the LORAN sites) is afforded by a staggered pulsing scheme which blanks (or greatly reduces) the power at each TPS site in a controlled, roughly periodic fashion to minimize the more severe near-far effects for users much closer to one site than the others.

TRINAV™ SYSTEM BENEFITS

TRINAV™ will provide greatly demonstrable advantages over GPS-only systems in urban areas, heavily forested regions, and inside most buildings, where the TPS signals can penetrate but GPS cannot, or when GPS signals are subject to jamming, spoofing, or unintentional RF interference. In addition, even in the few situations where the low-frequency terrestrial TPS/LORAN signals are difficult to receive, such as in structures heavily shielded against RF signals or principally metallic in construction, in underground areas such as mines, tunnels, and secure facilities, or in the internal areas of large buildings, high-rises, and the like, the INS portion of TRINAV will continue to provide accurate navigation information, from short to long intervals (depending on the drift rates — and thus, power and cost — of the INS/IMU component of TRINAV. In addition, TRINAV will permit greatly improved accuracy of the TPS/LORAN and INS data by providing continual cross-calibration of location and trajectory data with the corresponding GPS/TPS data (assuming, of course, that the GPS/TPS signal qualities are adequate). The TRINAV system will also permit effective automatic initialization and ongoing periodic recalibration of the unit's magnitude constants (sensitivities) and orientation vectors via the use of ancillary magnetometers, inclinometers, and barometers to enhance the setup, stability, and drift characteristics of the INS subsystem, without any user intervention. This recalibration process will also permit the effective use of much less costly, lower power INS components for a given level of overall TRINAV system performance. The TRINAV concept also provides faster GPS/TPS signal reacquisition times after loss of lock, GPS anti-spoofing detection, and better INS and overall navigation performance assessment. The use of the multiple-input Allan filter affords a level of flicker and random-walk-like noise rejection unattainable in conventional signal-averaging schemes and even Kalman filters. Furthermore, the TRINAV integration processing can derive an accurate fix even when too few GPS satellites are available for a good fix — often due to rough terrain, canyons, urban buildings, or foliage. In this case, TRINAV can concatenate vectors from the TPS/LORAN solution and thus form a hybrid GPS/TPS fix, even when neither system alone can provide a satisfactory fix accuracy; further, the TPS components permit much faster TTFFs after startup or prolonged RF signal disruptions.

A major advantage to the TRINAV concept is in the variety of its deployment scenarios, which can meet a wide range of performance and cost goals. For instance, TRINAV can typically be deployed on any of 4 levels of sophistication, size, power requirements, and cost, based on the intended application: **(1)** a "poor-man's" gyro-less TRINAV, which in addition to the standard GPS and TPS receivers, would use for the INS subsystem a simple pair of 2-axis MEMS accelerometers, orthogonally mounted, augmented with a modest-cost flux-gate compass and the inherent inclinometer obtained from the 2 accelerometer signal pairs; **(2)** a next-higher-grade TRINAV system, incorporating all the above INS components plus a trio of MEMS gyros, which would augment the flux-gate compass and the inherent inclinometer; **(3)** a still higher-grade TRINAV system, incorporating all the above INS components but with a trio of higher-quality MEMS gyros (drifts <<1deg/min, which would be augmented and recalibrated by the flux-gate compass and the inherent inclinometer obtained from the 2 accelerometer signal pairs; and **(4)** a top-grade TRINAV system, incorporating all the above INS components but using a trio of tactical- or full navigation-grade gyros [MEMS or optical] with drifts <<1deg/hr, which would be augmented and recalibrated/initialized by the flux-gate compass and the inherent inclinometer obtained from the 2 accelerometer signal pairs. The use of good-quality flux-gate magnetometers can provide a north heading accuracy of about ±1°, assuming a reasonably known magnetic environment (not much ferrous metal nearby); additionally utilizing the inclinometer function available from the 2 orthogonal accelerometers, within the TRINAV system context even typical automotive-grade MEMS gyros (e.g., the Analog Devices ADXRS150 with specified drift of 70°/hr or ~1.2°/min) can be held to overall orientation errors of roughly ±2° over time, which is more than adequate for most personnel and vehicular applications. All 4 configurations of TRINAV just described could also use the accelerometers or gyros for accurate north finding if sufficient stationary time is available (~20-30 min). In addition, the use of magnetic-north vector trajectory tracking can be used in conjunction with successive GPS/TPS fixes to back-calibrate the magnetic compass to true north and provide automatic magnetic declination corrections in the field. In addition, as mentioned previously, the EQUATE quartz-oscillator ensemble appears be able to function as both a very low-power clock and a mid-grade INS, which would be ideal for use with TRI·NAV ™.

The estimated overall accuracy figures for three distinct implementations of the TPS component of TRI·NAV are provided in Table 1 below. The nominal precision is based on the receiver's Costas loop establishing a phase error relative to the incoming RF carrier at lock of $^1/_{1024}$ of a cycle, or approximately 0.35°. The two lower bands utilize predominantly ground-wave propagation, whereas the highest band is definitely line-of-sight. The typical measurement method (for the LF and HF versions) is code-phase ranging, augmented by carrier-phase ranging. In the last case (the LOS version), the code-phase measurement is augmented by the phase of a difference signal derived from the two main TPS carriers. In all three bands, the ratios of code-to-carrier rates are configured ($^1/_{17}$ and $^1/_{23}$ respectively in the 80-120 kHz band) to avoid the inevitable problems of integer-cycle ambiguity encountered in GPS operation; since the basic TPS code-phase measurement can be resolved to well within a single cycle of the carrier (or difference-carrier) signals, the pseudorange value is always within the correct carrier cycle.

TPS Band	Nominal Precision *(Range)*	No. of Signals	Meas. Method	Timing Accuracy	Optimized Accuracy *(Standalone)*
80-120 kHz	± 2.93 m *(1000 km)*	2 – 4 (GW)	Carrier ϕ	<6 ns	3 m (H)

Table 1. Overall Estimated LF-TPS Navigation Accuracy

The horizontal accuracy figures are based on adequate site groundwave propagation delay calibrations, either from previously established benchmarks or via clean (multipath-free) GPS readings with suitably long averaging. The techniques have been mathematically verified, but substantial development and testing of transmitting and receiving hardware need to be completed before these figures can be realized in the field. The following TRINAV table shows the corresponding figures projected for the fully optimized TRINAV system, which by design cross-calibrates the GPS and TPS data as it determines the final fix. This permits the accuracy of GPS (when its received signals are of sufficiently good quality), to be combined with the well-known repeatability of TPS (and LORAN). The three different TPS bands in the chart include the groundwave LF, HF, and line-of-sight SHF versions developed at ORNL for use in the TRINAV context. The TRINAV user unit was originally intended to incorporate LORAN-C reception capability into the TPS receiving subsystem (both share the 80-120 kHz front-end) and would additionally utilize the recent e-LORAN enhancements. TPS, which could alternatively be dubbed "Terrestrial Positioning System" or even perhaps "LORAN-S", could possibly provide a basis for the next generation of precision LF systems. By maintaining full compatibility with all existing LORAN systems while simultaneously adding major improvements in noise rejection, rapid initial fixes, and data robustness, TPS technology appears to be an additional incentive for the U.S. Government to not only maintain current LORAN operations but also continue future system advancements, for the benefit of maritime, aviation, military, law-enforcement, and Homeland Defense users and the public at large.

TPS Band	Nominal Precision *(Range)*	No. of Signals	Meas. Method	Optimized Accuracy *(Standalone)*	Optimized Accuracy *(with GPS)*
80-120 kHz	± 2.93 m *(1000 km)*	2 – 4 (GW)	Carrier ϕ	3 m (H) 5-10 m (V)	1 m (H) 2 m (V)
3.23-3.40 MHz	± 8.8 cm *(20 km)*	1 (GW)	Carrier ϕ	0.3 m (H) 2-5 m (V)	0.3 m (H) 2 m (V)
2.400-2.4835 GHz	± 4.5 mm *(50 km)*	2 (LOS)	Differ. Carrier ϕ	0.1 m (H/V)	0.1 m (H/V)

Table 2. Overall Estimated TRI·NAV™ Navigation Accuracy

SUMMARY AND CONCLUSIONS

TRINAV™ has the potential to become a useful extension to GPS-only navigation to improve radiolocation performance and reliability in adverse RF environments where GPS reception is impaired or unavailable. The use of programmable SDR-based designs permits the rapid, adaptable re-tuning of TRINAV™ hardware to a wide range of operational frequencies to accommodate operational needs. Although the basic ground-based form of TPS provides only 2-D location information, the system can be deployed with elevated transmitters (e.g., balloons, aerostats) to obtain a vertical position as well. The integration of modern GPS, TPS, and cost-effective INS modules, coupled with a new paradigm in low-power, high-stability timebase technology (EQUATE), as represented in TRINAV™, will provide to U. S. military, emergency, and law-enforcement personnel a new level of dynamic locating-system accuracy, reliability, and availability, especially in adverse reception environments. Additional research is ongoing at ORNL to exploit more advanced signal-processing to provide higher accuracies and more efficient interoperation with GPS for applications to both vehicles and dismounted personnel.

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