TRI·NAV™

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

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TRI•NAV™

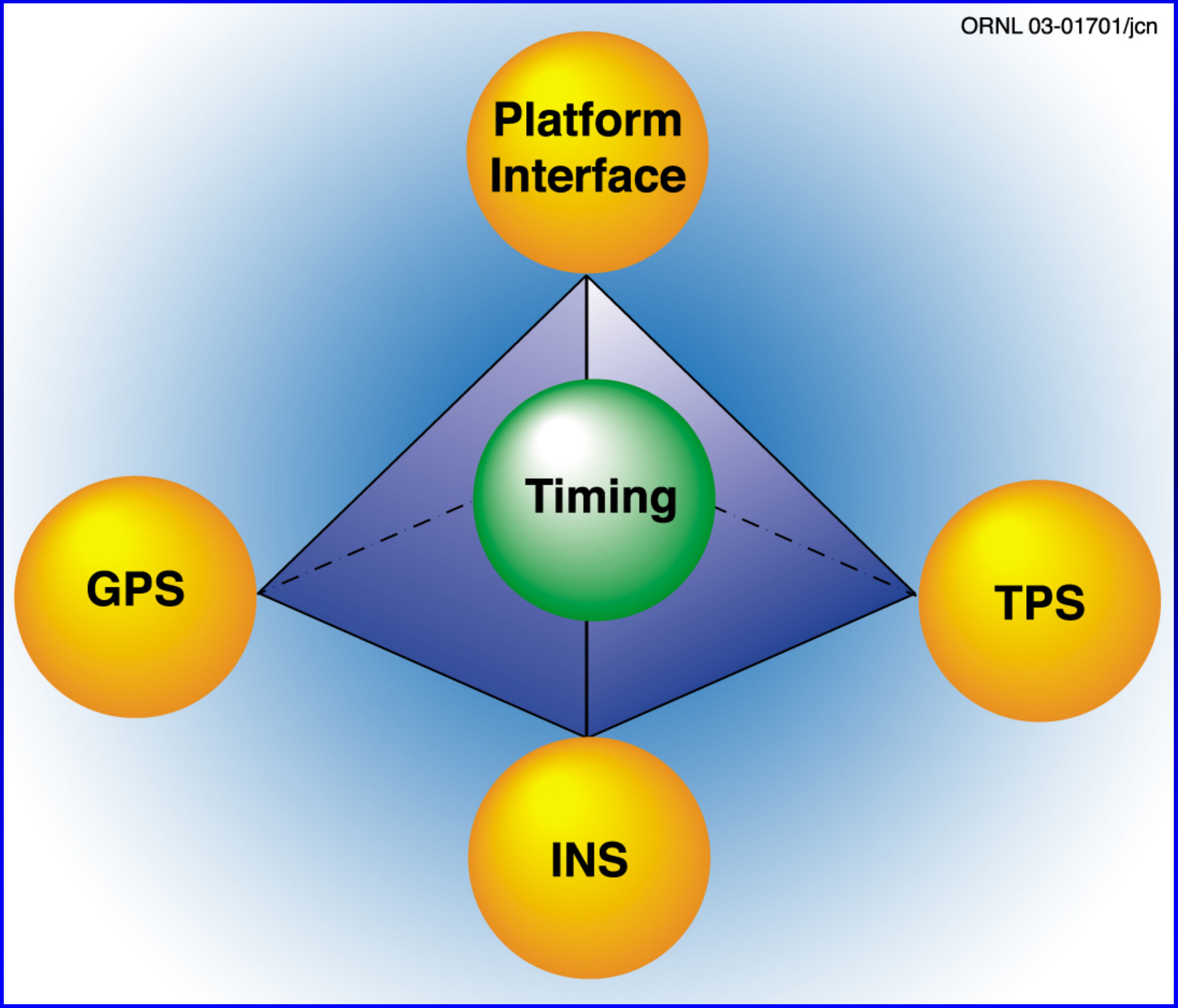
(Triply-Redundant Integrated Navigation & Asset Visibility System)

***"A three-fold cord is not quickly broken"* - Eccl. 4:12**

Presentation Outline

- Technology Background
- TRI-NAV™ Overview
- Timing Technology
- TPS & LORAN
  - Overview
  - Architecture
  - Applications
- Conclusions

TRI•NAV™ System Concept



TRI·NAV™ Features

- **Fault-tolerant, triparte system combines advanced, low-power INS (Sensor + custom ORNL electronics) with advanced timing, mil-quality GPS, and an agile, robust "theater" RF location scheme.**
- **We are proposing for the "theater" radiolocation (TPS) a new, robust, spread-spectrum system in the same LF range of the highly reliable and commercially proven LORAN-C. Alternative TPS versions would be implemented in the HF-SHF range.**
- **The new system is frequency-agile (including a special hopping protocol) and would be very difficult to jam effectively (PG > 30 dB).**
- **These "local" RF-type signals would be highly effective in foliage, rough terrain and in urban, built-up areas and would complement (and thus back up) GPS satellites.**
- **These new signals would also permit precise time, wide-area tactical operational information and DGPS data distribution.**

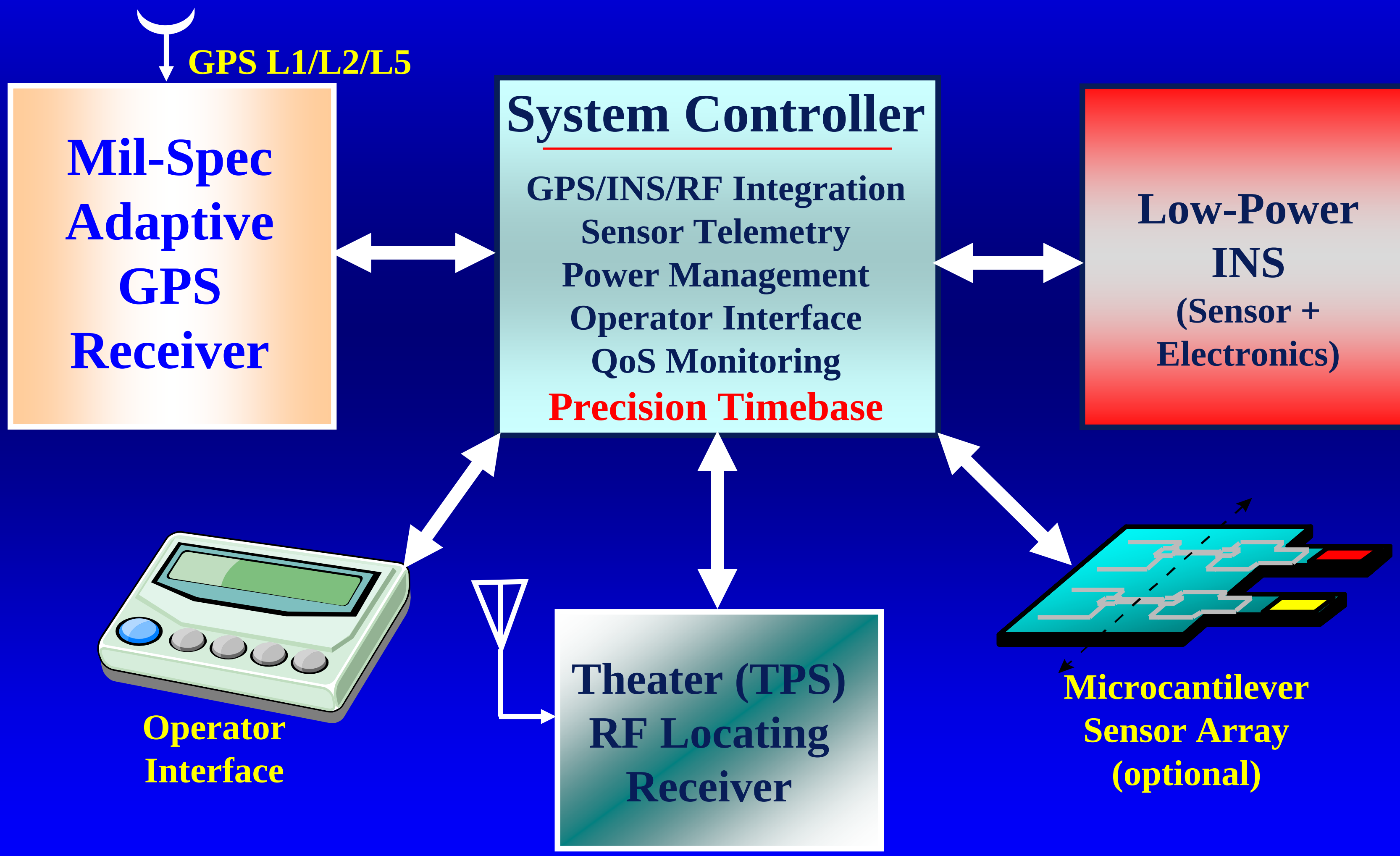
TRINAV will provide accurate, reliable PNT in GPS-denied environments

- Frequency-agile system can operate in diverse environments (large vs. small areas, urban/rough terrain, allocations, etc.).
- GPS and TPS components cross-check each other and continually cross-calibrate the INS unit.
- TPS will provide TTFFs of < 15 seconds (cold start).
- Very low power consumption; TPS/GPS interactions help save power; INS also detects unit motion for sleep mode.
- TPS provides anti-spoofing check for GPS and is totally immune to GPS-spectrum jamming.
- Enhanced real-time PNT solution with reduced latency.
- Back-up high-accuracy time distribution via TPS.
- Better coverage than GPS alone (availability >99.5%).

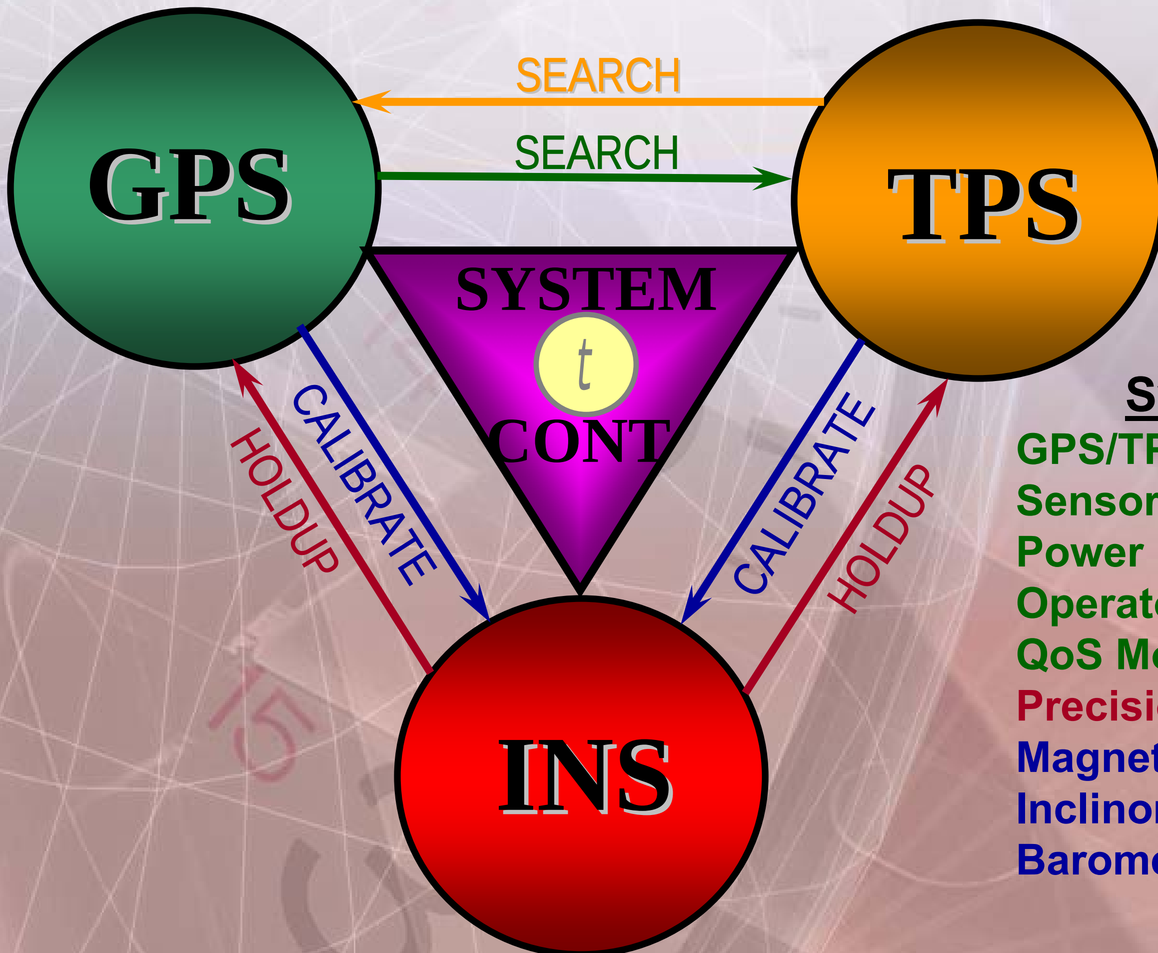
TRINAV Advantages (cont.)

- Permits incorporation of much lower-power, lower-cost (drifty) INS units.
- Highly upgradable SDR-based architecture and low-power ASIC/ FPGA implementation.
- System timing accuracies into sub-10 ns range.
- Longer wavelengths good for fast movers.
- TPS can assist in rapid GPS integer-cycle ambiguity resolution. TPS itself has no inherent ambiguities!
- System fix and time accuracy is dynamically assessed vs. GPS and optimized.
- Hardware consists of minimal RF section plus SDR defined FPGA-based signal processing.
- Advanced TRINAV system timing is being designed with Allan Space Time Solutions.

TRI•NAV™ System Block Diagram



7- D TRI·NAV™ System



System Module:
- GPS/TPS/INS Integration
- Sensor Telemetry
- Power Management
- Operator Interface
- QoS Monitoring
- Precision Clock (EQUATE)
- Magnetic Compass
- Inclinometer
- Barometer

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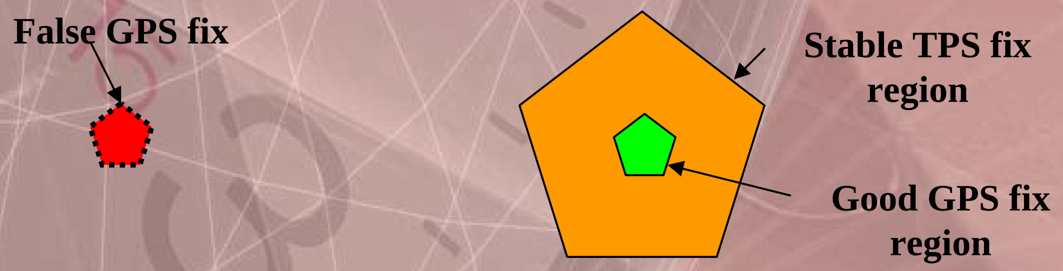
TRI·NAV™ Operation

- GPS is normally the principal positioning source.
- If GPS is unavailable, TPS is used instead (almost as accurate).
- If both RF signals are blocked, the INS unit continues to provide location.
- The system also contains an ultra-accurate, low-power clock (EQUATE).
- All TRINAV components cross-check and cross-calibrate each other.
- The result: TRINAV is an extremely reliable system!

GPS/TPS Cross-Checking



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INS Devices for TRI·NAV™

- **Selectable, based on performance needs.**
- **Existing mil-type nav-grade units (<0.1°/hr), e.g., RLG or FOG types, are quite expensive & power-hungry.**
- **COTS MEMS automotive gyros (e.g., ADI) have high drift rates (35-70°/hr) but are low cost (< $20) and low power (10s of mW).**
- **Three new developing INS technologies are promising:**
  - **Electromagnetic "6-D" Sensor.**
  - **Next-generation MEMS gyro from PSU-ARL [sensor] and ORNL [ASIC electronics] (~ 0.01°/hr).**
  - **EQUATE clock/accelerometer: disruptive technology.**
- **TRI·NAV™ can accommodate a wide range of INS performance levels while maintaining effective integration with the GPS and TPS/LORAN RF radiolocation schemes.**

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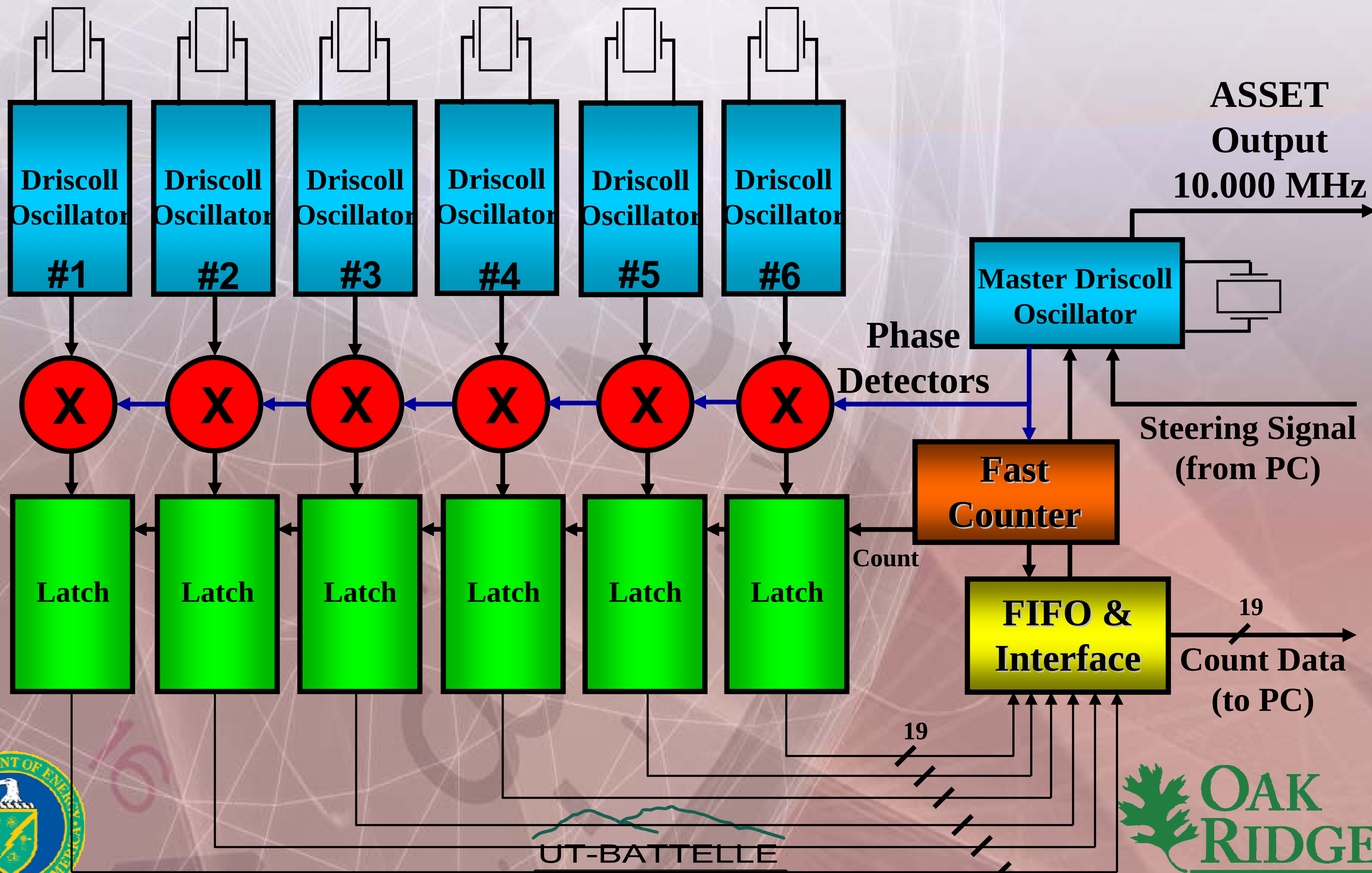
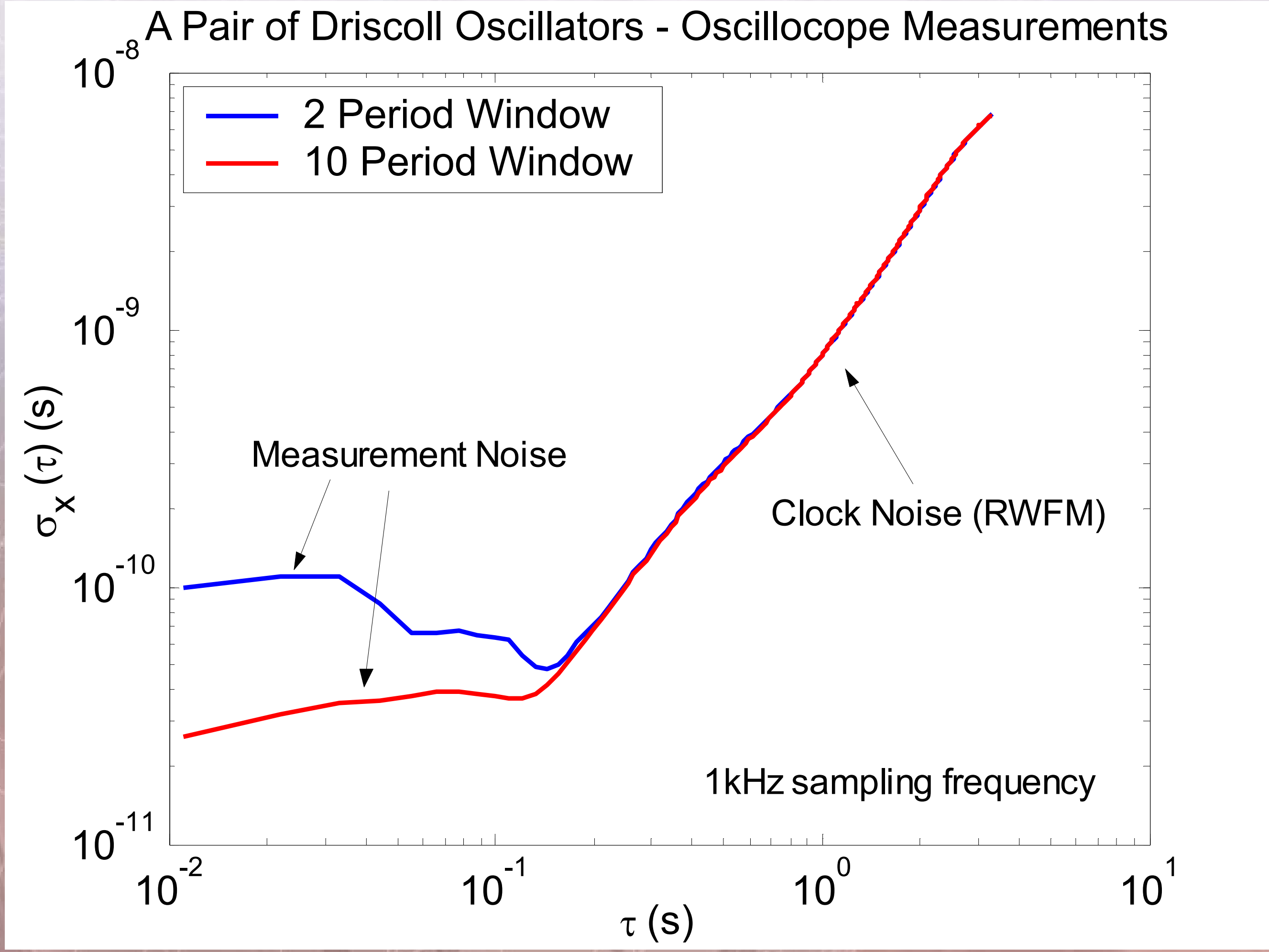
EQUATE 7-Oscillator Array Prototype

Block Diagram

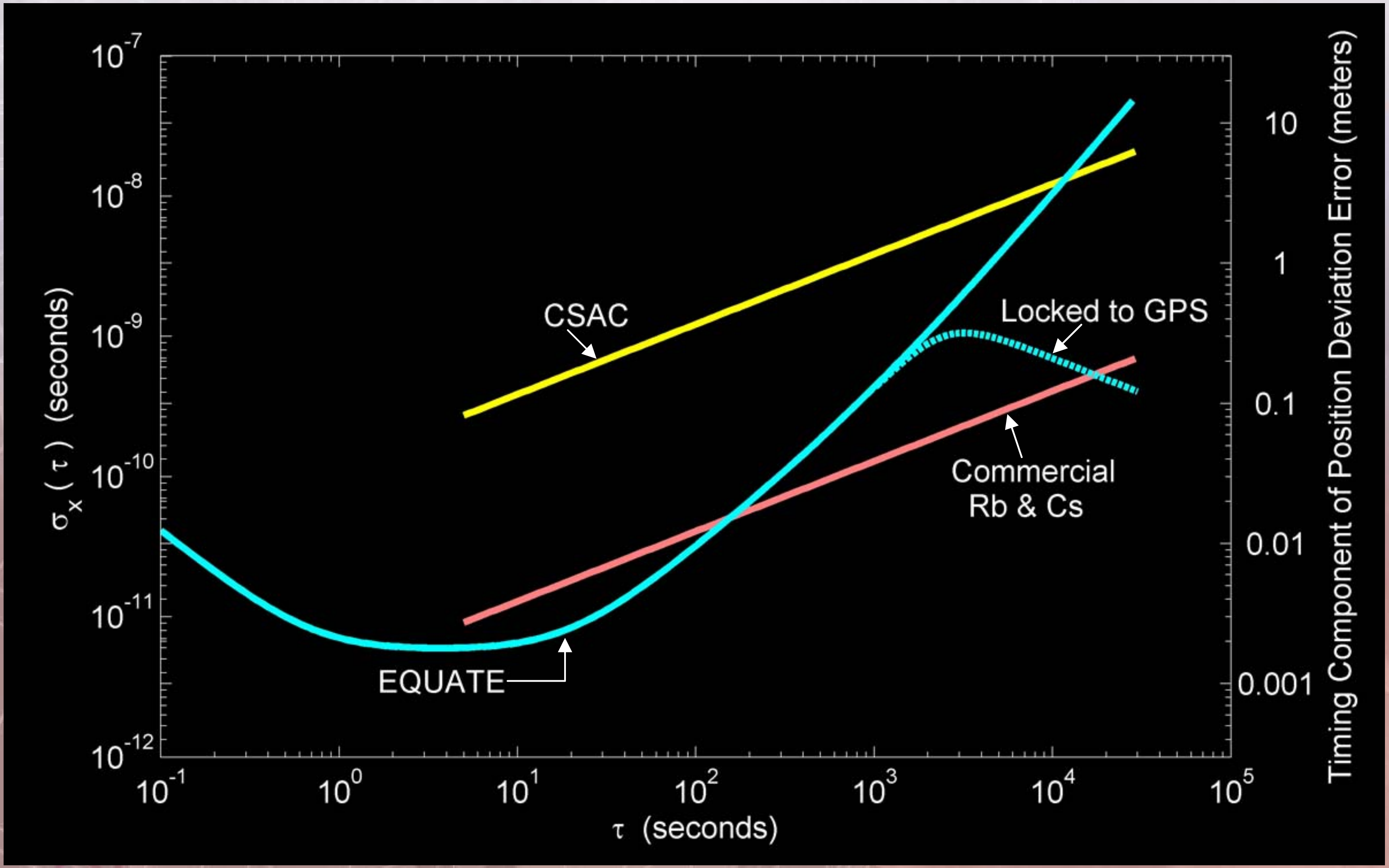


Clock Time-Dispersion Plots



- **Average time dispersion about 0.65 ns/sec.**

Averaged Phase Residuals

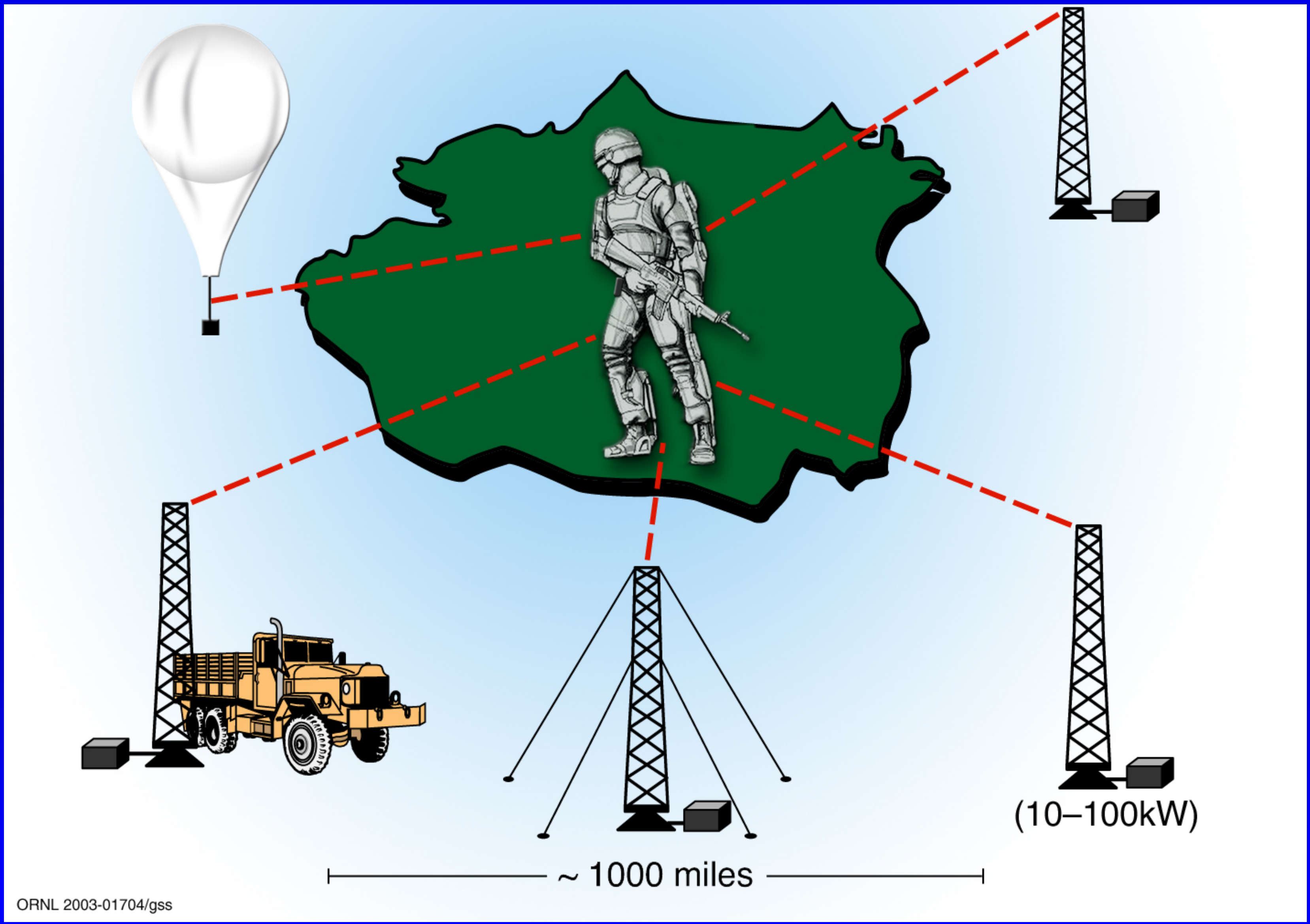


TRI•NAV must operate reliably in all types of terrain

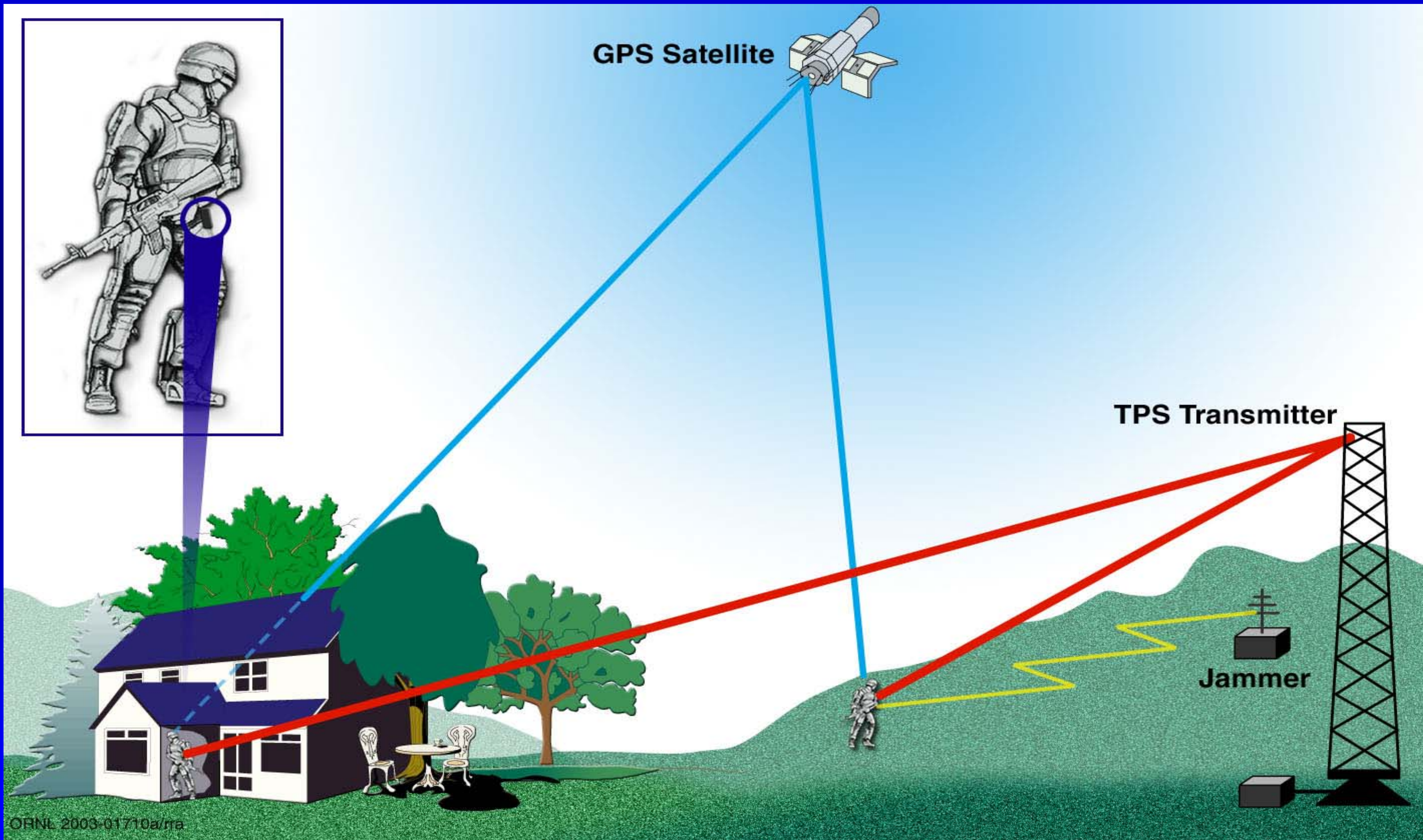
ORNL 2003-01709/gss

Theater Positioning System (TPS)

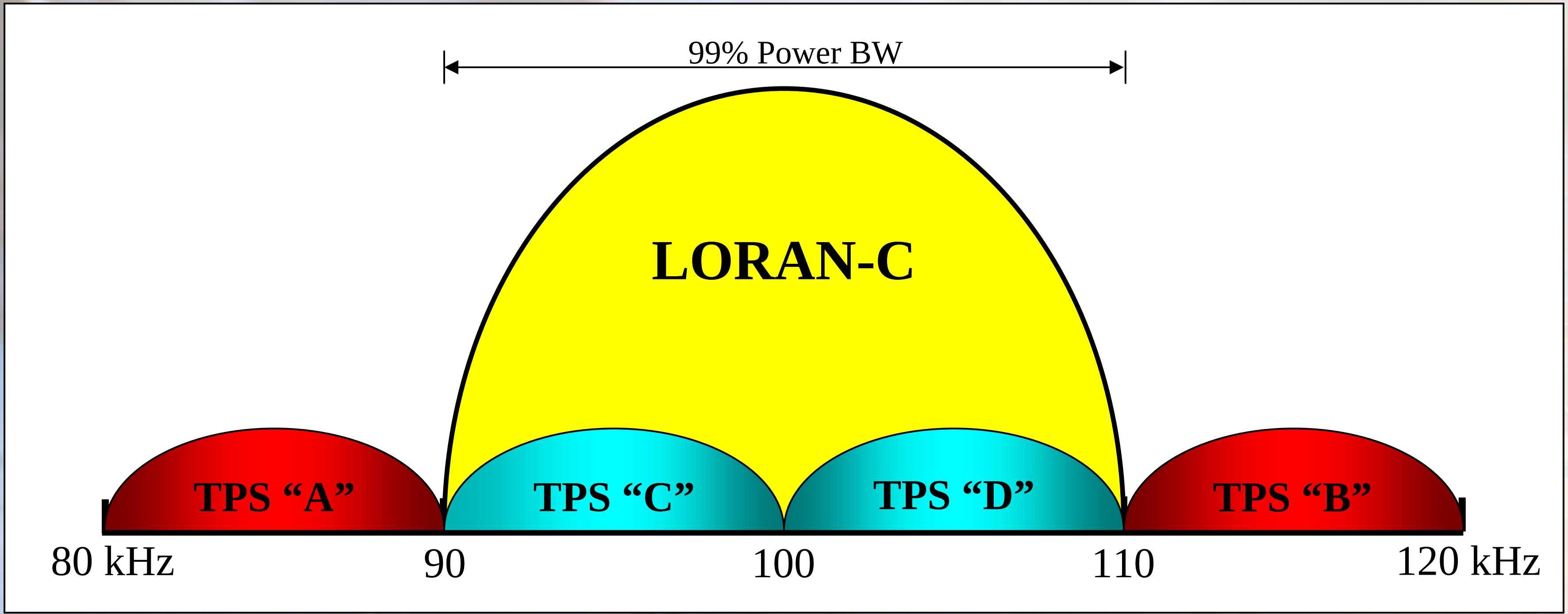
Typical Deployment Scenario



Low-frequency TPS signals will penetrate where GPS won't



TPS/LORAN-C Spectral Tests



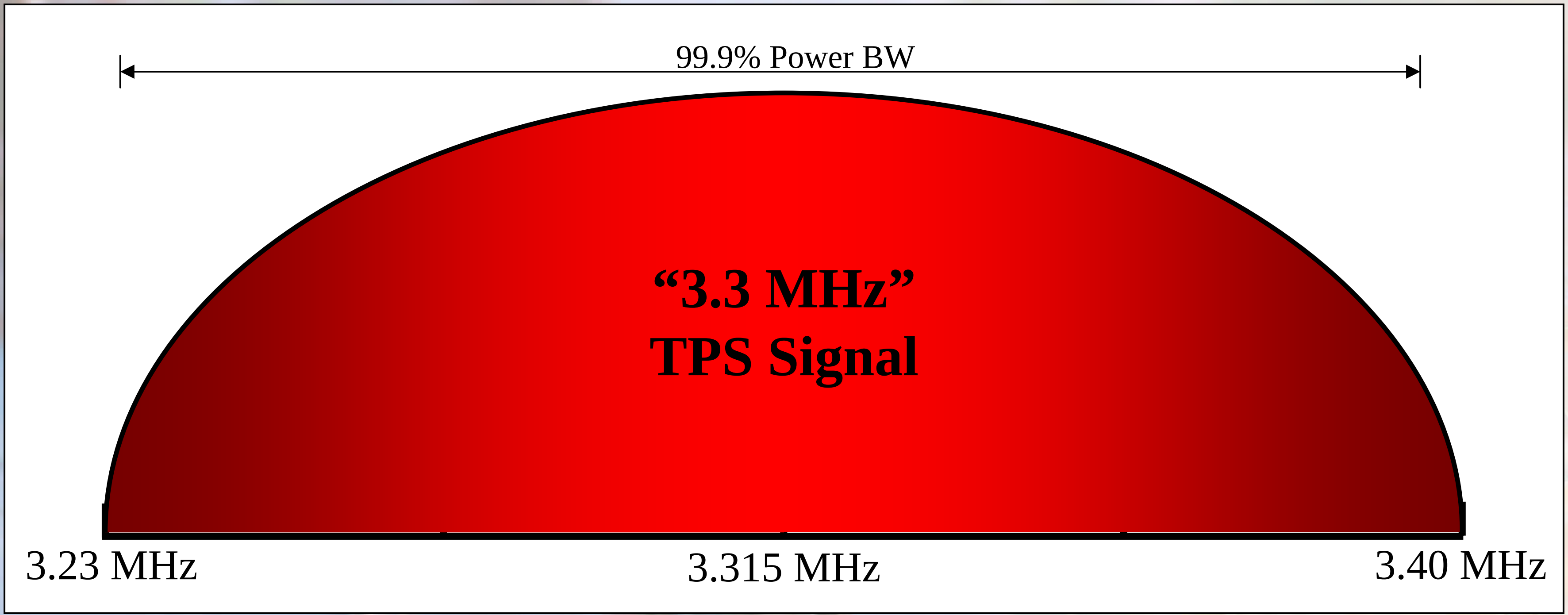
- Standard LORAN-C has >99% of its power from 90-110 kHz.
- TPS A, B are "clear" SS signals centered at 85, 115 kHz.
- TPS C, D are SS signals embedded in LORAN, centered at 95, 105 kHz.

TPS/LORAN Testing Setup

TPS/LORAN Conclusions

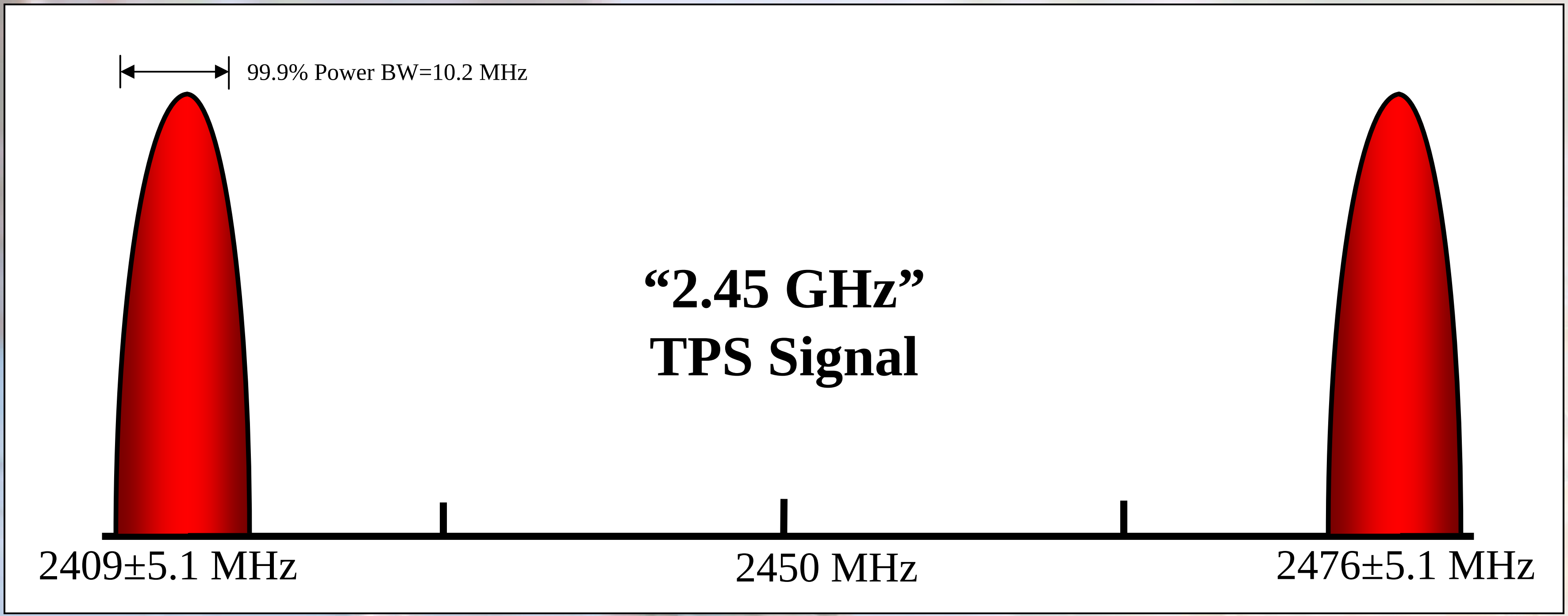
- **TPS signals, being spread-spectrum, can peacefully coexist with standard LORAN-C. <u>This is essential for allocation purposes!</u>**
- **Tests at ORNL have shown that simulated, non-filtered TPS signals A & B produce no interference to LORAN location functions at SIRs of -5 dB or better; filtered work to -18 dB SIR!**
- **A full-band, unshaped (80-120 kHz) TPS signal at -3 dB or lower SIR causes no LORAN errors.**
- **TPS signals can be co-transmitted from LORAN-C sites at quite high powers (up to -6 dB) with no ill effects on LORAN systems.**
- **Filtering of TPS A, B signals (as via SOQPSK modulation) offers even higher levels of interoperability (~ -18 dB) SIR.**
- **TPS C, D signals can be additionally used to improve TPS system performance, reliability, and data rates; SIR ~ -7 dB (for equal ABCD signal levels re LORAN).**

MOUT TPS Signal Spectrum



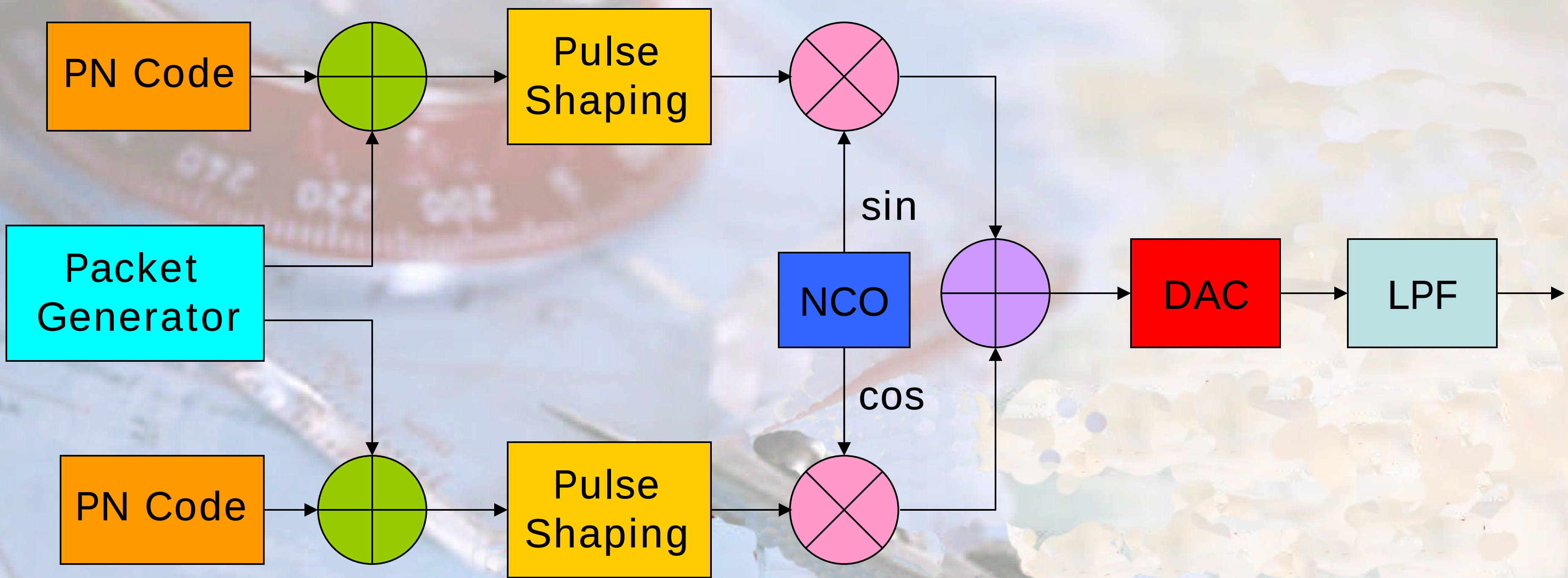
- **New TPS signal occupies radionav band at 3.23-3.40 MHz.**
- **TPS signal is a single carrier at 3.315 MHz with I/Q chipping rates of 85 kHz; tailored for MOUT testing needs.**
- **TPS signal is filtered to avoid out-of-band emissions.**

LOS TPS Signal Spectrum



- **New LOS TPS signal occupies ISM band, 2.40-2.4835 GHz.**
- **TPS signal has dual carriers at ~2409, 2576 MHz with I/Q chipping rates of 5 MHz; tailored for air range testing.**
- **TPS signal is filtered to avoid out-of-band emissions.**

Transmit Channel Architecture

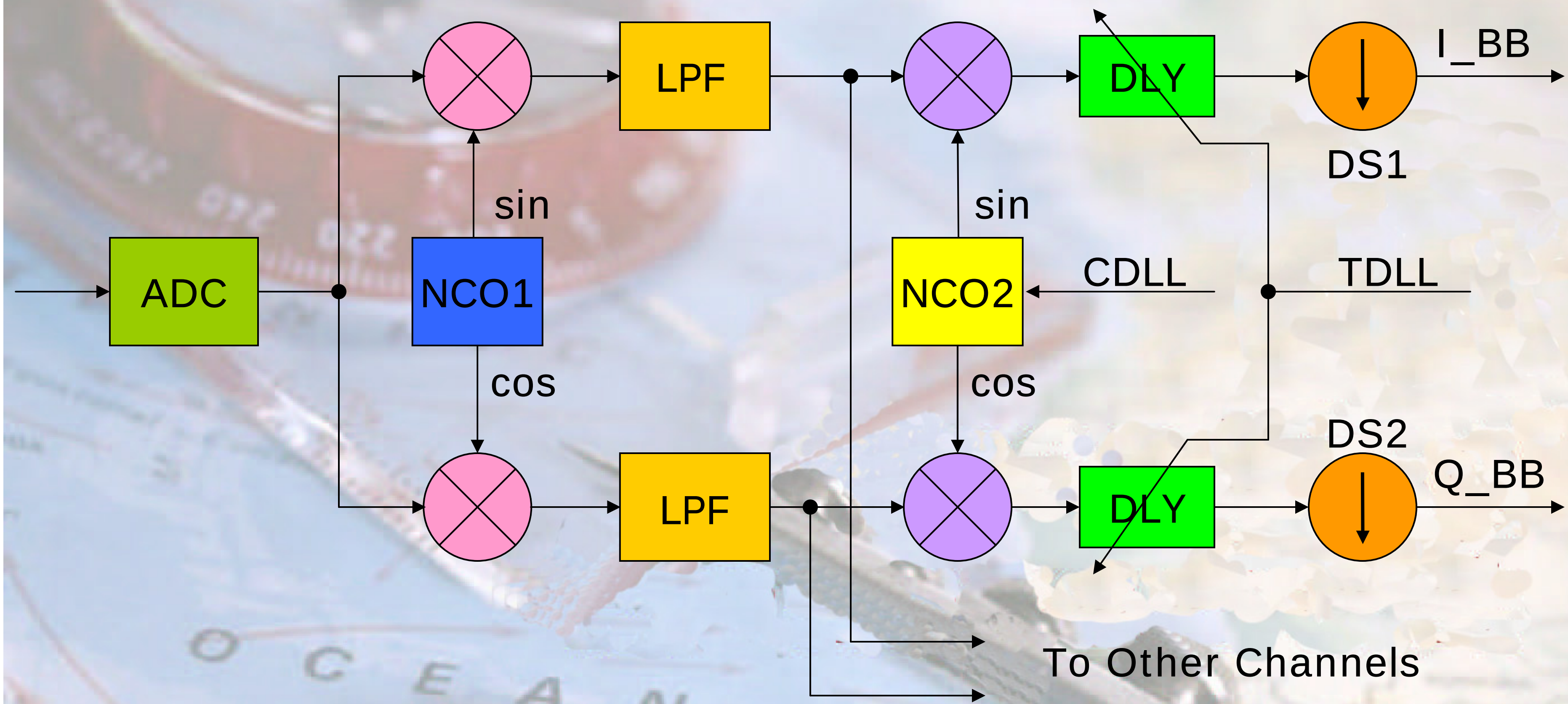


<u>PN Code</u>: 1023 Gold
<u>Symbol Rate</u>: 10/s
<u>BB BW</u>: 5.115 kHz

<u>Packet length</u>: 160 symbols
<u>Preamble</u>: 32 symbols
<u>DDW</u>: 32 MLS aug.
<u>Data Length</u>: 96 symbols

<u>Carrier</u>: 85, 115 kHz
<u>RF BW</u>: 5.115 kHz
<u>Sampling</u>: 26.52 MHz

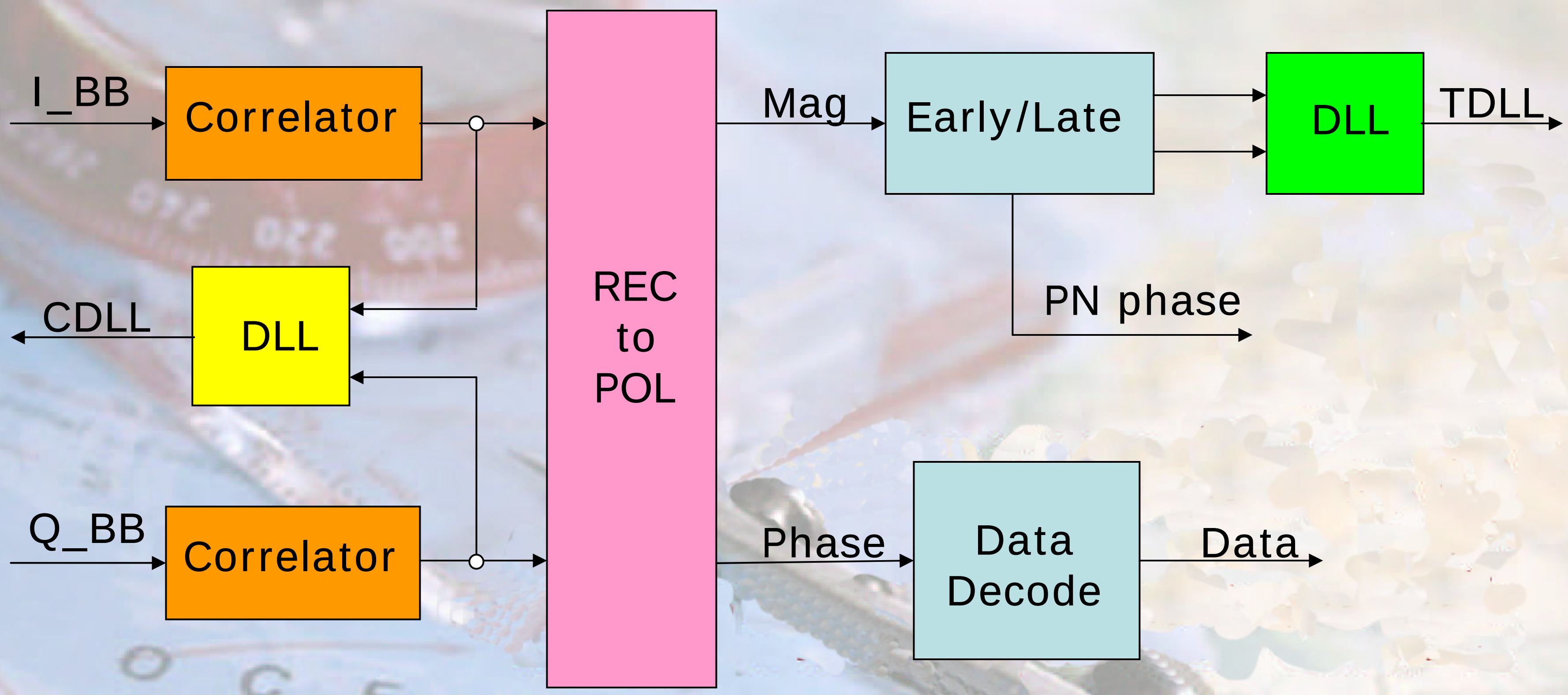
Receiver Architecture



ADC: 14 bits @ 13.26 MHz
NCO1: 85, 115 kHz
NCO2: ~ 0 MHz

DLY step: $T_{ch}/156$
DS1,DS2: 78

Receiver Architecture (cont.)



Correlator: parallel 8-bit@2 samples/chip
RECtoPOL: 14-bit CORDIC
DLL: 2nd order

Output: Data (192 bits)
TDLL Register(7 bits)
CDLL Register(10 bits)
PN Phase(11 bits)

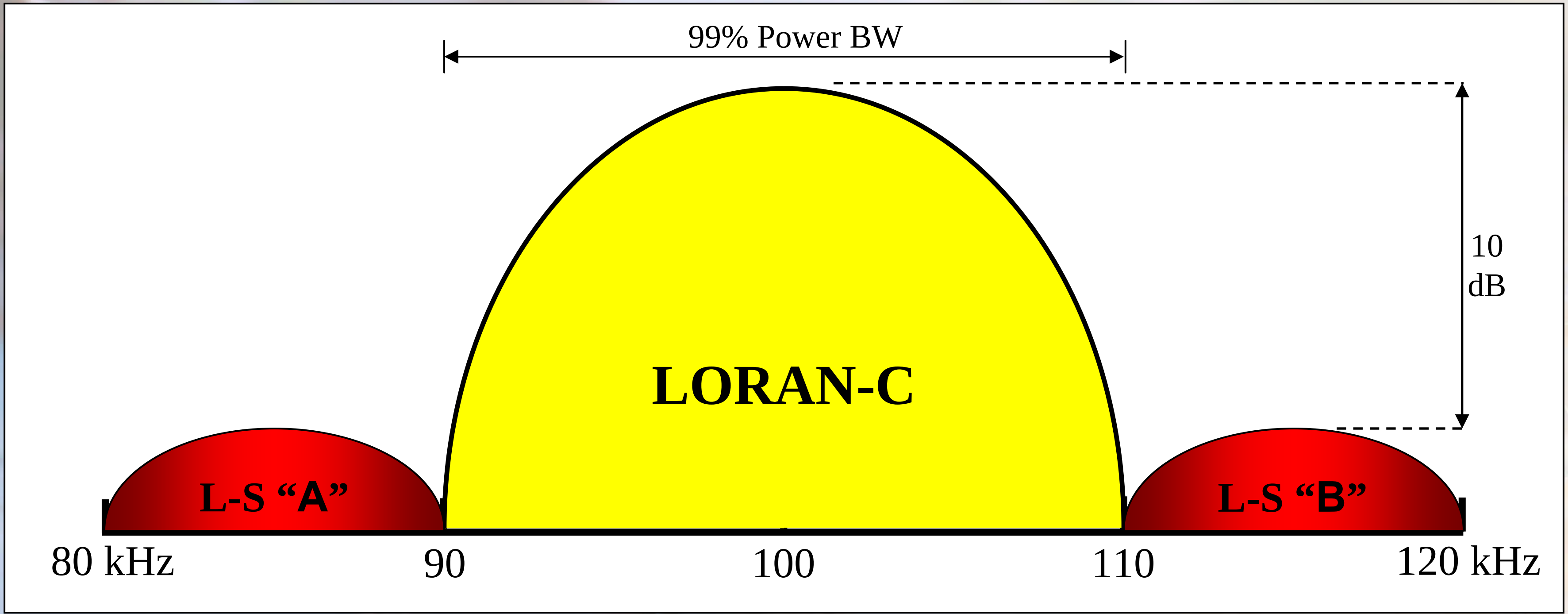
TPS Radiolocation Process

- Like GPS, TPS initially uses DS code phase for coarse ranging.
- Unlike GPS, TPS uses code correlator resolution ($^1/_{17}$, $^1/_{23}$ rather than $^1/_{1540}$) to specify the correct carrier cycle.
- Unlike GPS, TPS uses its extended Costas loop to unambiguously determine the carrier phase to within <0.35° (at 100 kHz, 9.77 ns).
- Essentially no carrier-cycle ambiguity as in GPS.
- Longer code epoch gives ~ 3×10^7 m (18,600 mi.) unambiguous range.

Basic TPS Parameters (~100 kHz)

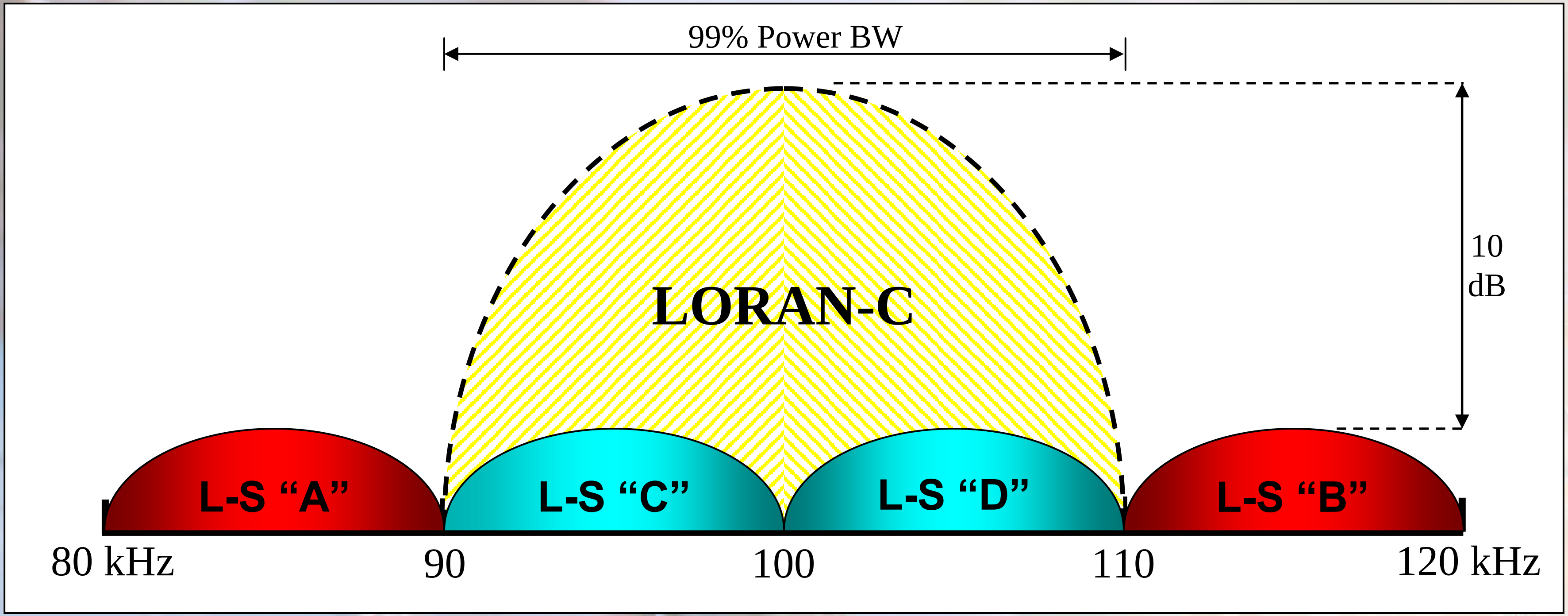
- Carrier frequencies: 85(A), 95(C), 105(D), 115(B) kHz.
- Chipping rate/code: 5.115 kHz, C/A Gold set (I/Q).
- Spreading: DS with FH security component.
- Modulation: Shaped OQPSK, constant envelope.
- Compatibility: Configured to interoperate with standard LORAN-C (-18 dB SIR [AB]; -7 dB [ABCD], lab tests).
- Process gain: 30 dB (1023-length code).
- Power-line noise rejection: 40 dB + 30 dB PG.
- Standalone accuracy (optimized): ~3 m (H), 20-s avg.
- Accuracy in TRINAV™ setup: ~ same as GPS.

LORAN-C/S Spectra, Phase 1



- Standard LORAN-C has >99% of its power from 90-110 kHz.
- L-S "A", "B" are "clear" SS augmentation signals centered at 85 & 115 kHz, at typically 10 dB below the main LORAN-C.
- L-S "A", "B" signals have been verified by measurements to cause no LORAN fix errors up to an SIR of -18 dB!

LORAN-C/S Spectra, Phase 2



- LORAN-S "A" and "B" signals remain as in Phase 1.
- New signals "C" and "D" are added, centered at 95 & 105 kHz, with the same basic format as "A" and "B".
- The LORAN-C signal is discontinued, with a reduction in operating costs and > 20 dB better system performance.

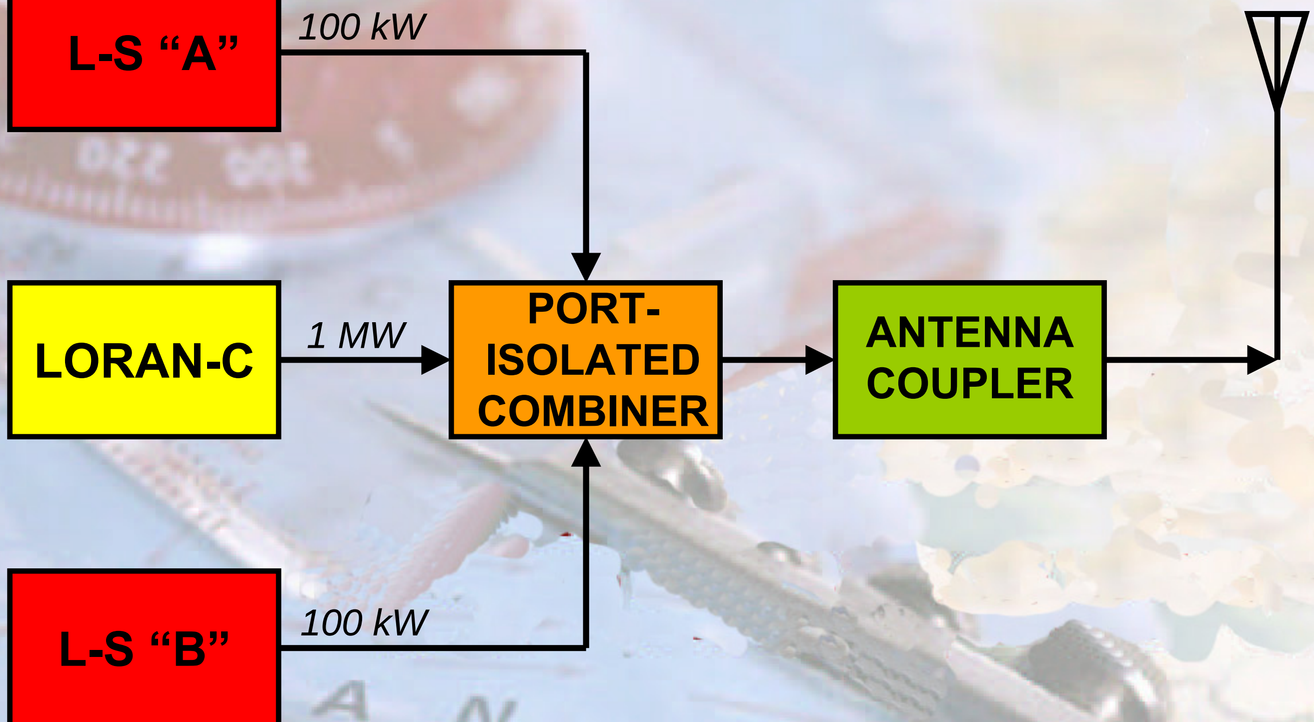
LORAN-S Advantages (Phase 1)

- L-S signals ("A" & "B") are each spread-spectrum for high process gain (30 dB) for excellent narrowband and impulse noise rejection – about 20 dB better than in LORAN-C (–10 dB A/B power).
- Data rate of 5 bits/s (per I/Q phase) permits additional rejection of 50/60-Hz line noise of ~ 40 dB in receiver via integration.
- TTFF of about 15 seconds is much faster than in LORAN-C or GPS.
- Embedded navigation data stream also distributes precise time, wide-area data, weather & emergency alerts, & DGPS/DL-S corrections.
- Basic CDMA approach permits multiple, overlapping service areas for continuous, reliable coverage; raises GPS/TPS availability to >99.5%.
- "A" & "B" signals can be encrypted to prevent unauthorized use.
- Almanac broadcasts provide rapid local propagation corrections.
- L-S can also provide vertical position determinations.

LORAN-S Advantages (Phase 2)

- L-S signals ("A" - "D") are each spread-spectrum for high process gain (30 dB) for excellent narrowband and impulse noise rejection – about 20 dB better than in LORAN-C.
- Data rate of 5 bits/s (per phase) permits additional rejection of 50/60-Hz line noise of ~ 40 dB in receiver via integration.
- TTFF of about 8 seconds is much faster than in LORAN-C or GPS.
- Embedded navigation data stream has double the effective rate of Phase 1; more detailed information available quicker.
- Basic CDMA approach permits multiple, overlapping service areas for continuous, reliable coverage; raises GPS/L-S availability to >99.8%.
- "C" & "D" signals can be encrypted to prevent unauthorized use, or can be altered in emergency situations for rapid data transmission.
- Almanac broadcasts provide rapid local propagation corrections.
- Higher-accuracy vertical position determinations than in Phase 1.

LORAN-S/C TX Implementation

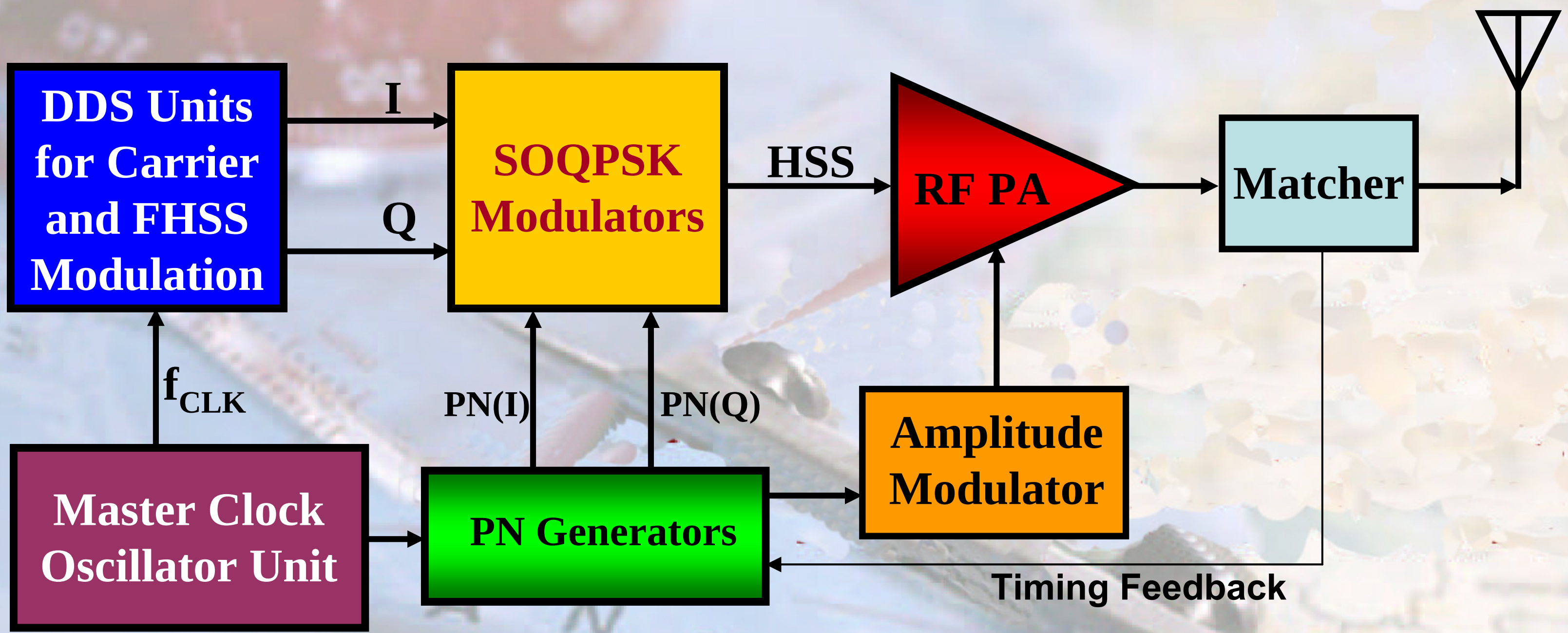


LORAN-S Implementation Summary

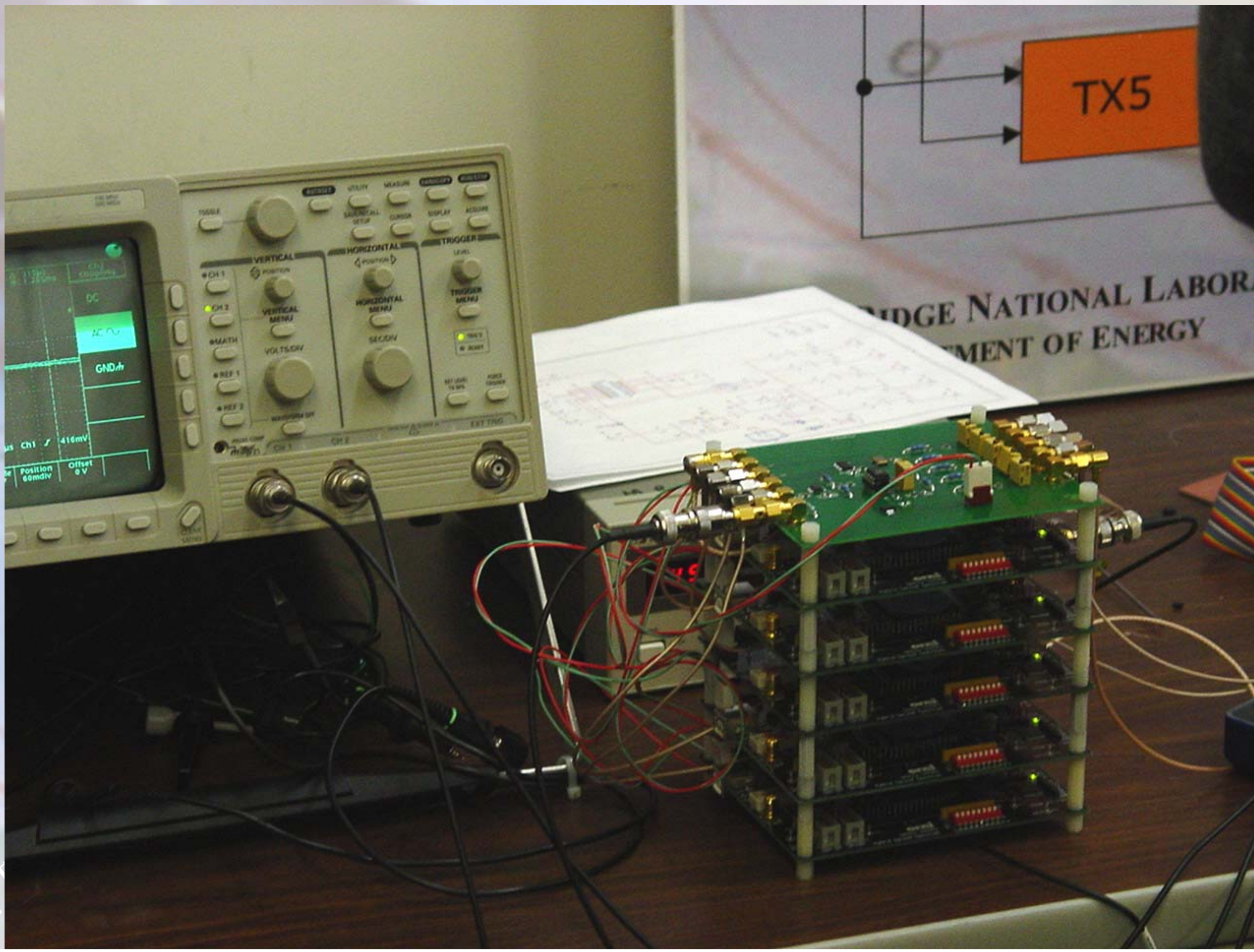
- **LORAN-S would be deployed at existing LORAN-C sites. The two new signals would likely be at a 10-100 kW power level and be coupled into the existing antenna via a port-isolated combiner system. The transmitter and network hardware are of commercially available types.**
- **Operating AC power costs for LORAN-S would range from roughly 25 to 250 kW (about 18% to 185% of a dual rated 1-MW LORAN-C site, depending on the LORAN-S power levels). No additional personnel would be required.**
- **Coverage (noise- and skywave-limited) should be somewhat larger than in LORAN-C and should be much better in electrically noisy urban zones. Time and DGPS data can also be distributed via LORAN-S.**
- **Existing LORAN-C receivers can be straightforwardly redesigned to add LORAN-S service.**

LORAN-S is a strong component in the long-term future of terrestrial PNT sources as a reliable backup to GPS.

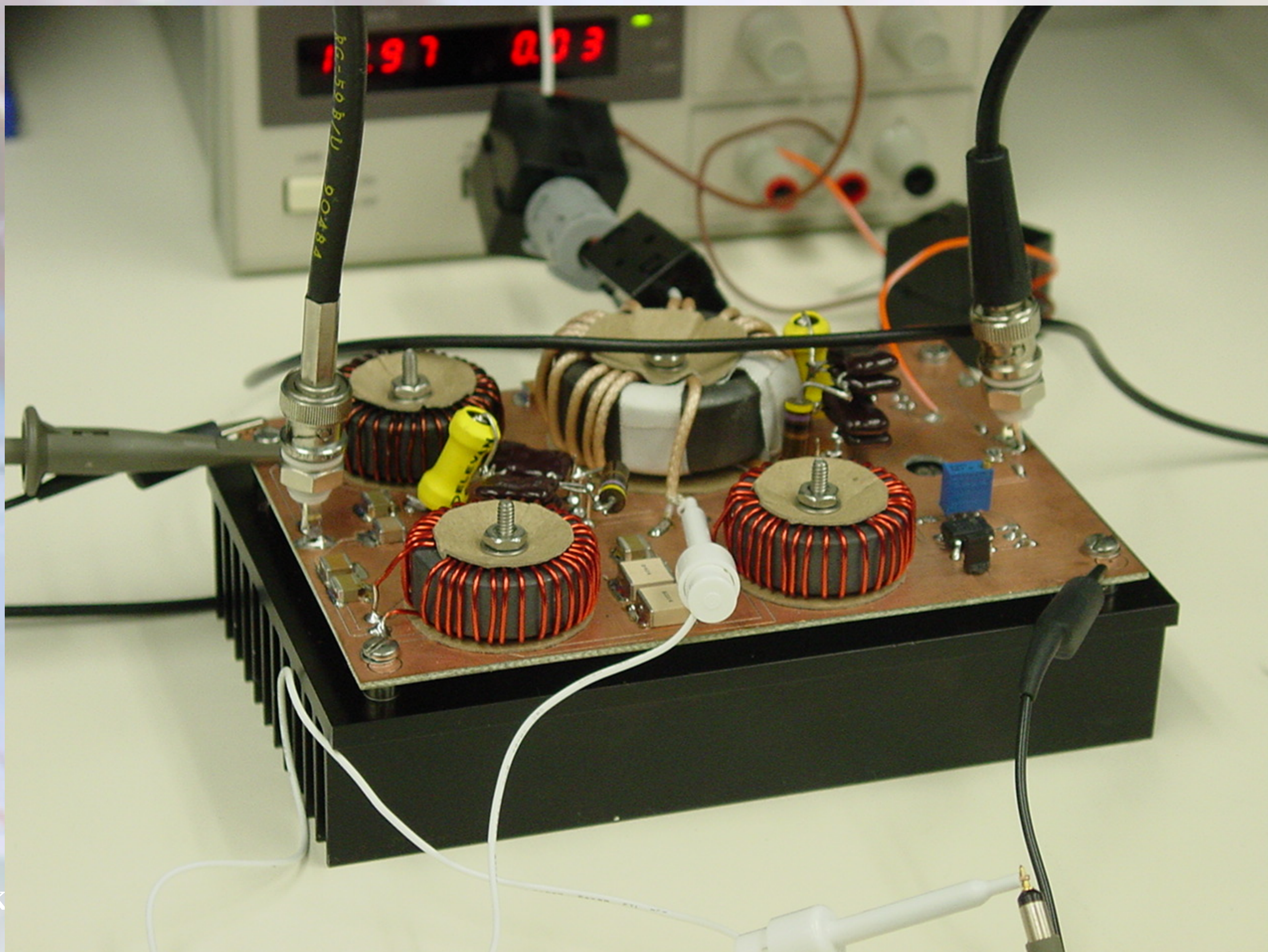
TPS/L-S Transmitter Block Diagram



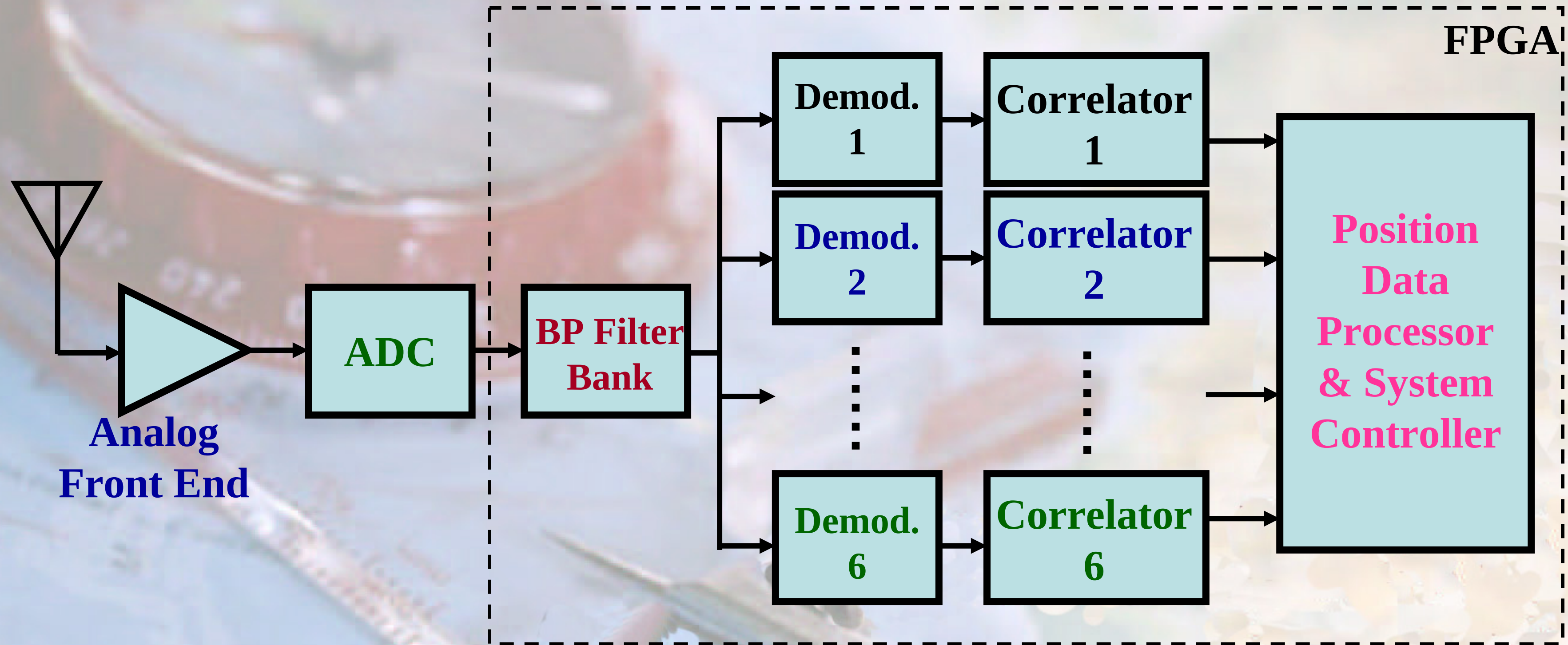
5-Transmitter Test Assembly



TPS 100-kHz RF Power Amp

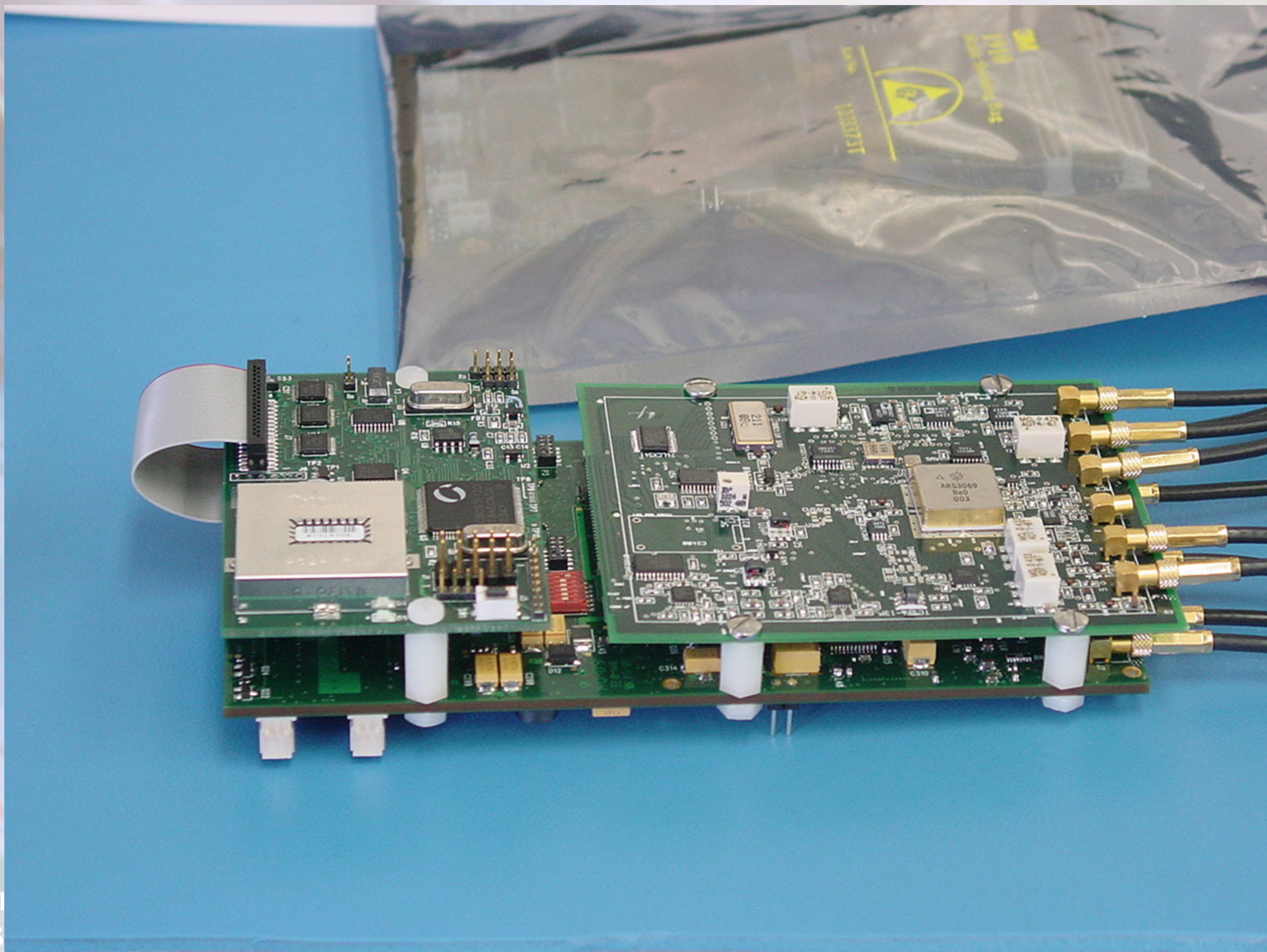


TPS/L-S Receiver Block Diagram

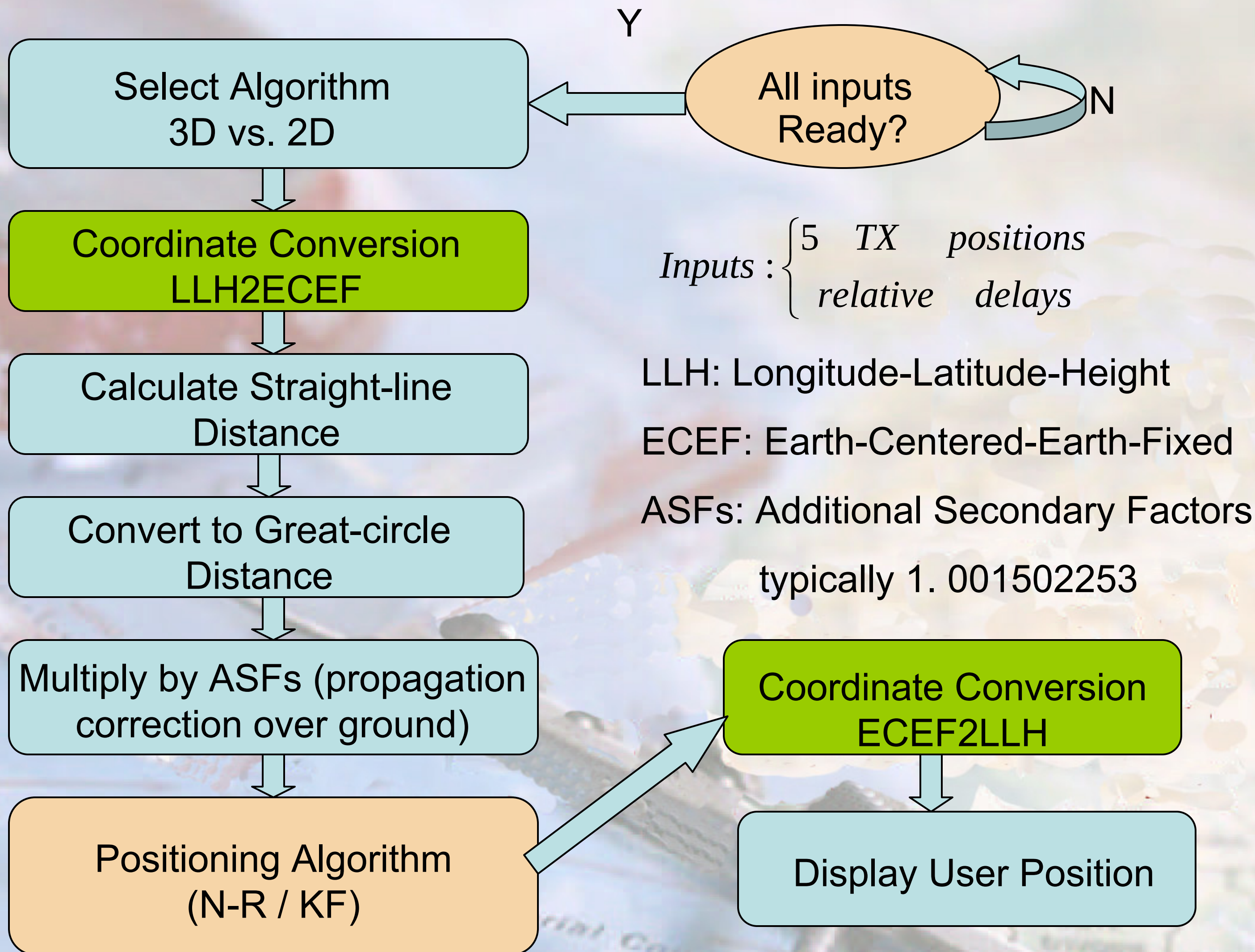


- Low-power digital FPGA-based architecture with µController.
- Multiple (≥6) fast serial correlators/phase detectors for high-resolution TPS/L-S position location.
- Ample RAM for position storage for 96-hr. test duration.
- Operator, GPS data, and INS interfaces can be added.

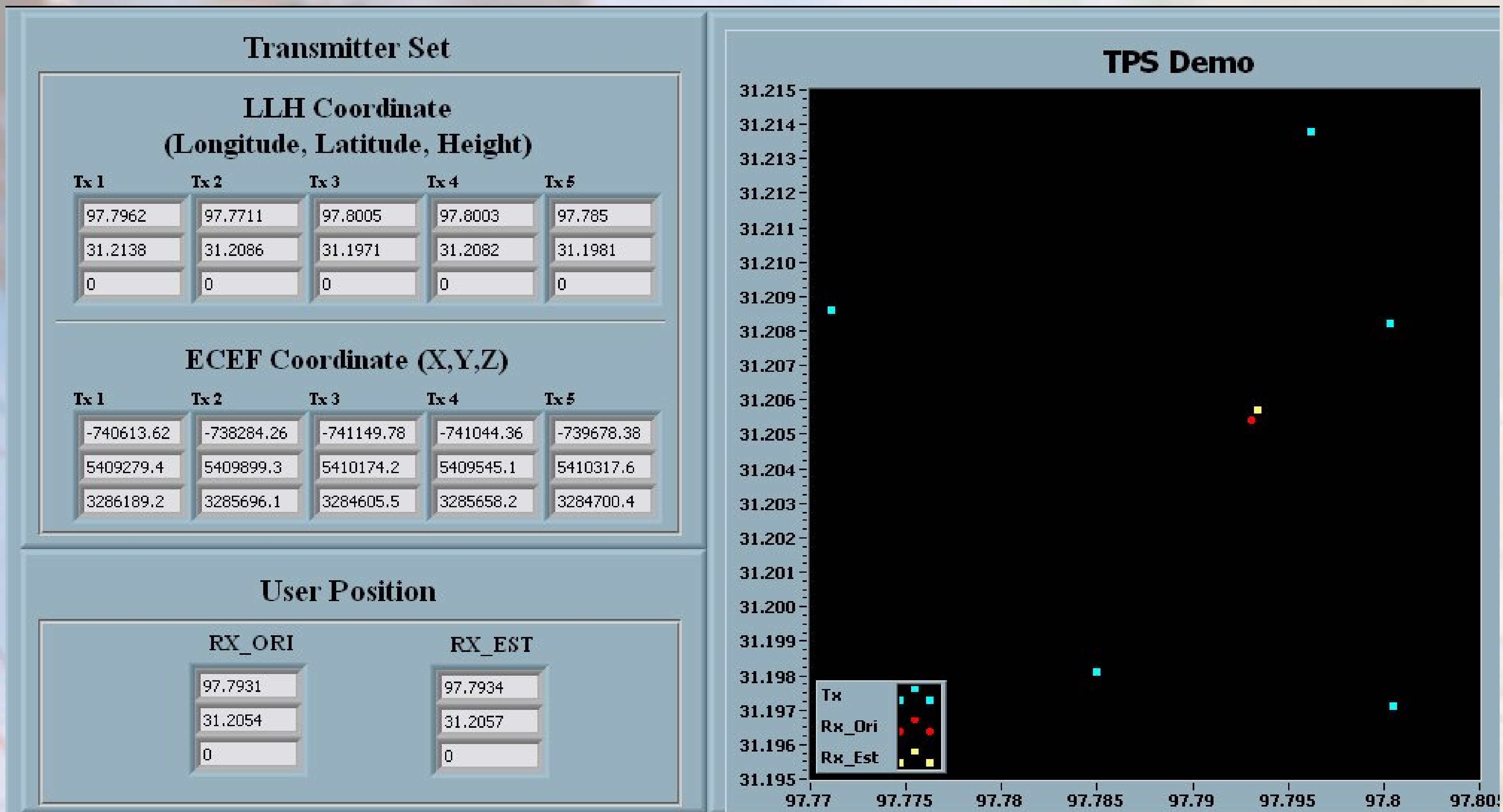
TPS Receiver Prototype Board



Overall Radiolocation Algorithm



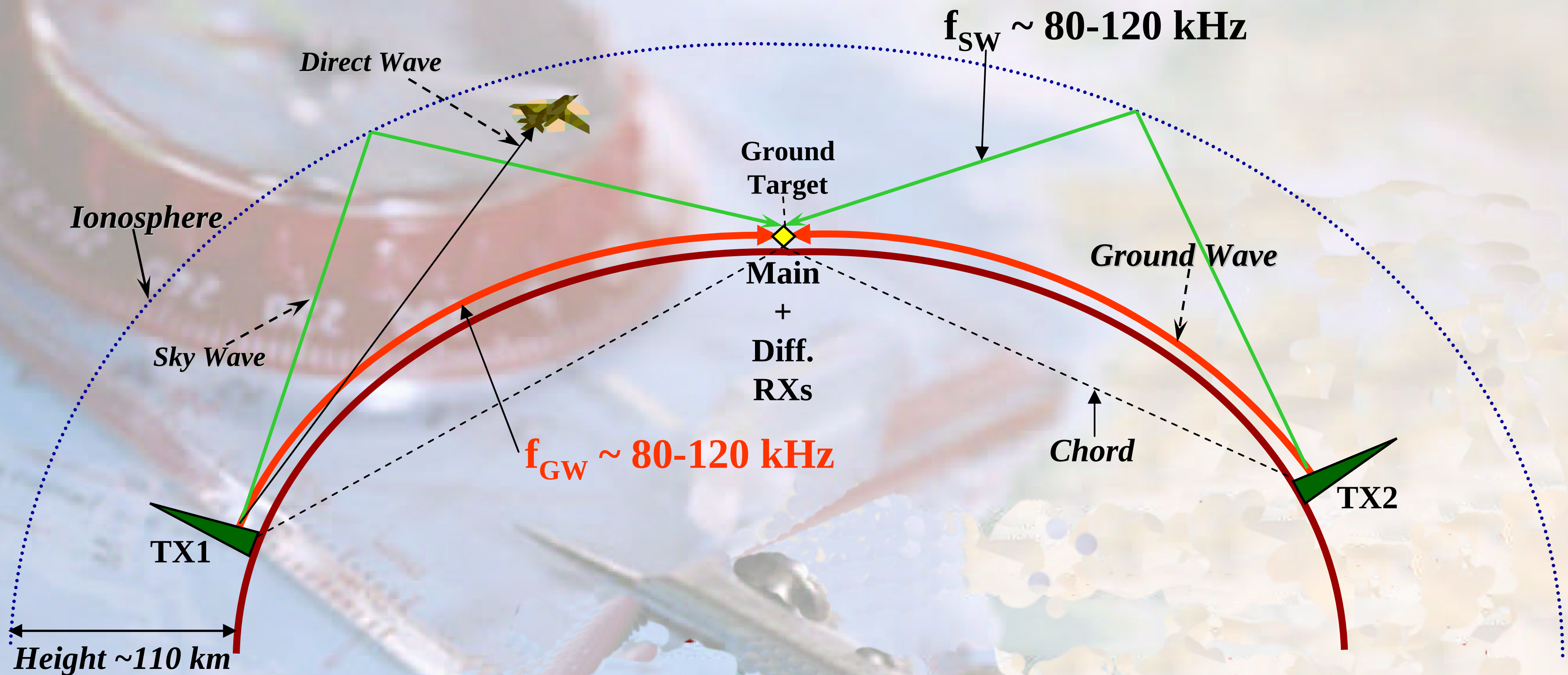
Navigation Software Interface



L-S Navigation Accuracy (100 kHz)

- Basic precision ~0.35° carrier phase (±2.93 m)
- Basic accuracy is limited by:
  - **TX clock dispersion (~*3 ns via ACV-GPS/Rb*).**
  - **TX signal delays (*calibrated and sent*).**
  - **Propagation delay variations (*ASFs from LORAN*).**
  - **RX signal delays (*calibrated and stored*).**
  - **RX clock accuracy (~*5 ns via EQUATE*).**
- Typical optimized L-S system errors < 10 ns.
- Horizontal position uncertainties expected to be < 3 m with reasonable averaging (~ 10-20 sec).

3-D L-S Signal Propagation



- *Basic L-S signals are ground-wave propagated - (main correlators).*
- *Basic L-S range measurements are (X,Y) only (2-D positioning).*
- *3-D L-S receiver processes sky-wave components to get vertical measurements with VDOPs similar to GPS (~3) - (2nd correlators).*

TRINAV™ will provide accurate, reliable PNT in GPS-denied environments

- Frequency-agile system can operate in diverse environments (large vs. small areas, urban/rough terrain, allocations, etc.).
- GPS and TPS components cross-check each other and continually cross-calibrate the INS unit.
- L-S will provide TTFFs of < 15 seconds (cold start).
- Very low power consumption; TPS/GPS interactions help save power; INS also detects unit motion for sleep mode.
- TPS provides anti-spoofing check for GPS and is totally immune to GPS-spectrum jamming.
- Enhanced real-time PNT solution with reduced latency.
- Back-up high-accuracy time distribution via L-S.
- Better coverage than GPS alone (availability >99.5%).

Conclusions

- TRI·NAV/TPS system is ideal for reliable PNT.
  - Highly configurable, easily adaptable to situation changes.
  - System accuracy continuously assessed vs. GPS and optimized during use.
  - INS units (wide quality range) modeled and *in situ* calibrated.
- TPS can be used as a compatible add-on/upgrade for LORAN-C, with excellent RF performance and utility for data distribution (time, DGPS, alerts, etc).
- EQUATE frequency source has been demonstrated.
- SDR-based TPS can easily add LORAN-C reception.