A Terrestrial Positioning and Timing System (TPTS)

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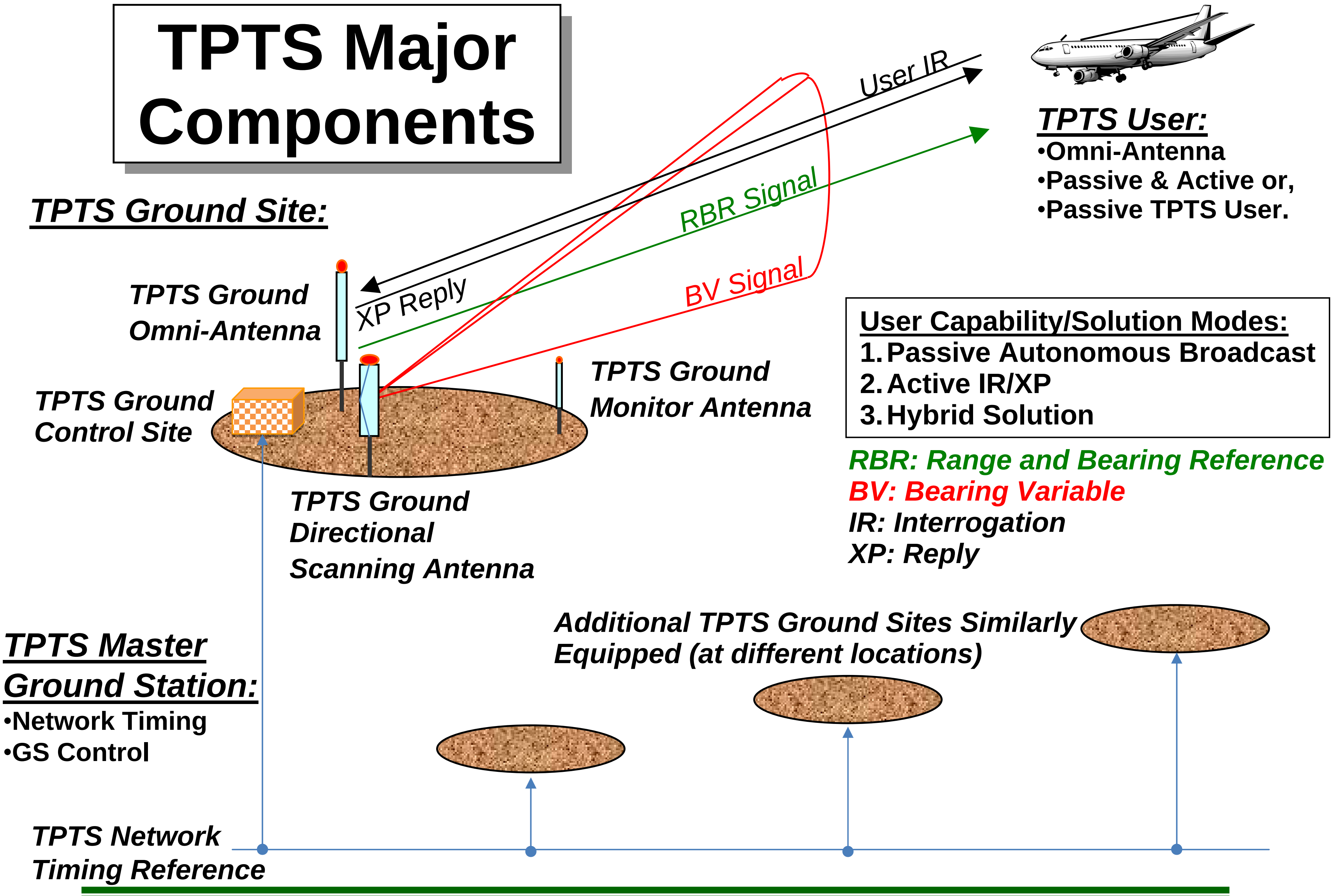
Introduction

- Genesis: Informal discussions with FAA at ION GNSS 2011
- Paper presented at IEEE/ION PLANS last week.
- Draws upon past experience with GPS Pseudolite developments
- Also draws upon heritage of other terrestrial based navigation systems: VOR, TACAN, DME, ATC
- TPTS Utilized CDMA for accuracy determination vice pulse modulation techniques
- TPTS is envisioned to operate within the DME frequency bands, and incorporate new signals to support PNT services within the NAS
- New ground and user equipment are within scope
- Additional research efforts needed to further develop and validate these concepts, parameters, and techniques
- TPTS could provide a robust PNT service in the event of GPS non-availability within the National Airspace System (NAS).

TPTS Major Components



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TPTS Mode and Signal Components (1 of 3)

- **Autonomous Broadcast Mode (single channel) has two signal components:**
  1. **Range and Bearing Reference (RBR) Signal**
     - » **Time of transmission synchronized to TPTS System Time with a North Bearing Reference**
     - » **TPTS Message Types Identifier (MTID) encoded onto the broadcast via the local TPTS Control site (17 MTID) identified**
     - » **CDMA (generated at constant rate), low duty cycle pulsed BPSK signal**
     - » **Carrier frequency generated at an integer multiple of code clock to maintain code-carrier coherency**
     - » **Data-less quadrature channel**
     - » **Transmission via vertically polarized Omni-direction antenna (beacon like)**
     - » **Projected peak transmission power levels of 29dBm (0.8W) to support 30nmi; 46dBm (36W) for 200nmi.**

TPTS Mode and Signal Components (2 of 3)

- **Autonomous Broadcast Mode (single channel) has two signal components:**
  2. Bearing Variable (BV) Signal
  - » **Time of transmission synchronized to TPTS System Time with a North Bearing Reference**
  - » **Low rate modulation on BV reference oscillator**
    - **Low frequency modulation rate equal to antenna scan rate**
    - **Very low frequency deviation equal to the desired maximum code and carrier deviation, (e.g., 5Hz on code and 500Hz on carrier)**
  - » **CDMA pulsed signal (generated at varying rate), medium duty cycle pulsed BPSK signal (with slightly varying code and carrier rates)**
  - » **Carrier frequency generated at an integer multiple of code clock**
  - » **No data on BV signal**
  - » **Transmission via directionally scanning antenna in azimuth (i.e., fan beam)**

TPTS Mode and Signal Components (3 of 3)

- **Active Interrogation/Reply (IR/XP)**
  - » **IR from airborne user**
    - **IR format similar to RBR format**
      - » **IR in "selective" or "all-call" format**
      - » **Different PRN code from Autonomous RBR signal**
      - » **Different frequency channel than Autonomous RBR signal**
    - **Utilize existing DME omni-directional antenna on the aircraft**
  - » **IR decoded by TPTS Ground site via omni-directional antenna and validated**
    - **XP on different frequencies (i.e., ±63MHz) with**
    - **Different PRN code (different from IR and Autonomous RBR Signal).**
    - **XP addressed specifically for IR**

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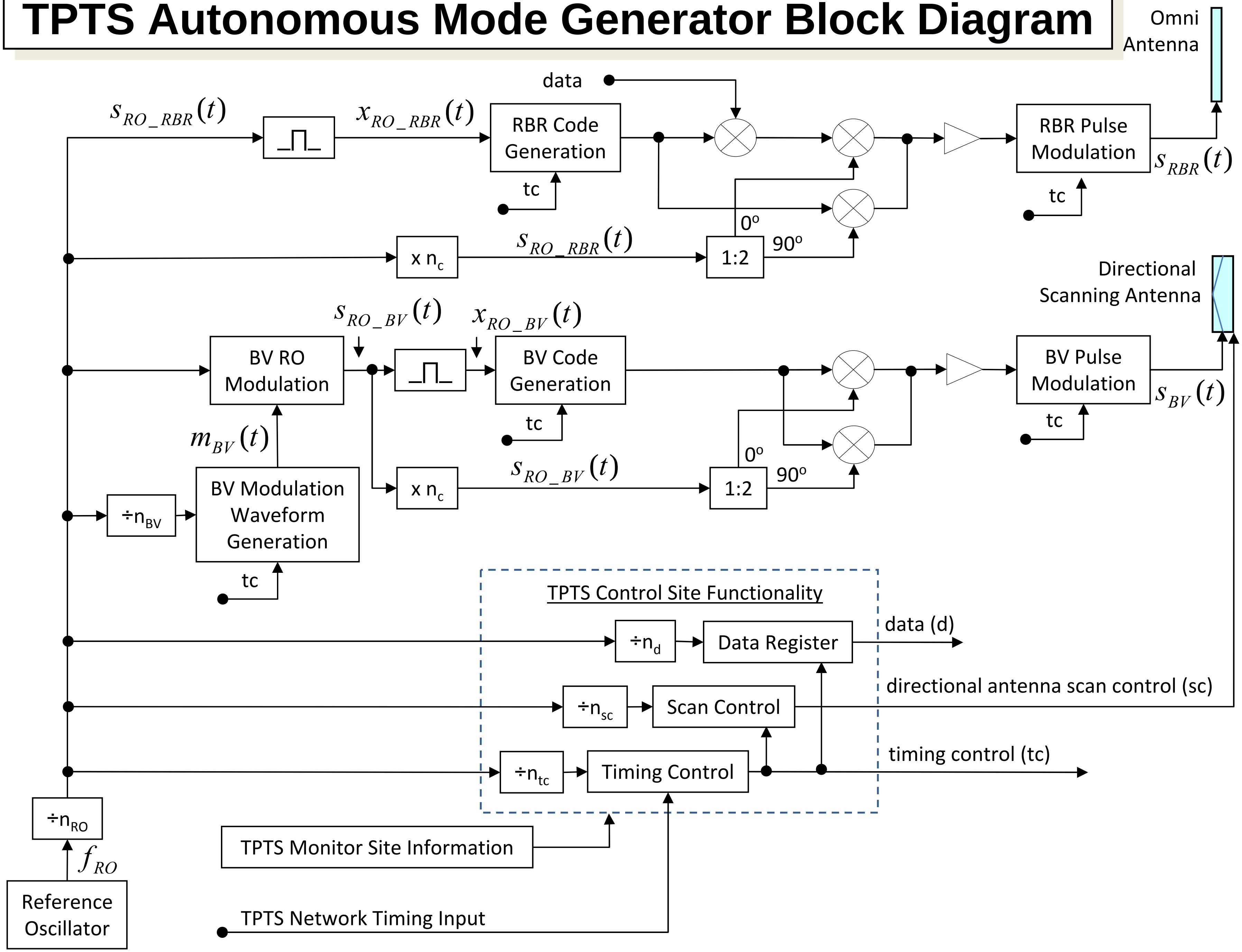
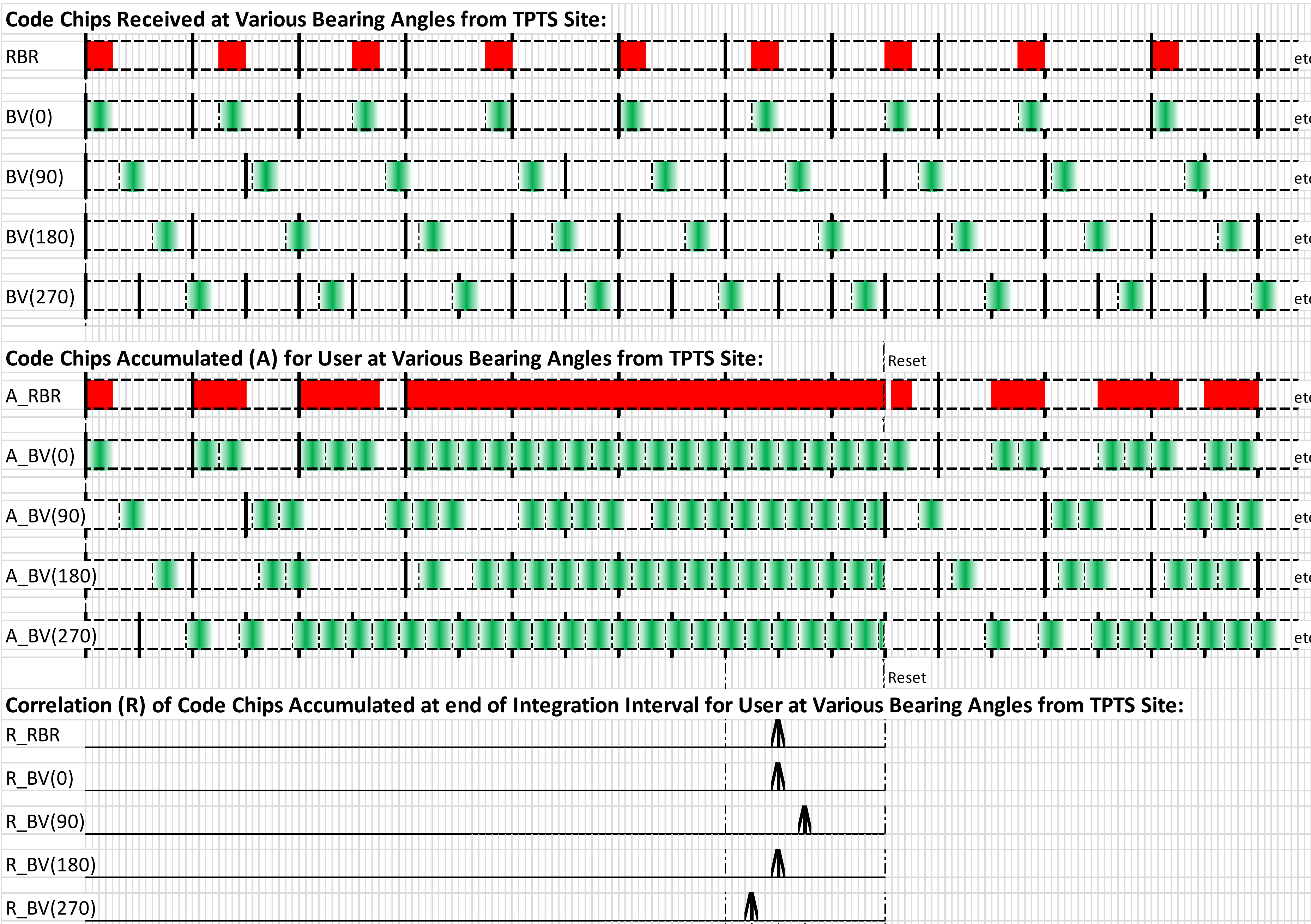
TPTS Autonomous Mode Generator Block Diagram



TPTS RBR and BV Chips Received for Various User Bearing Angles from a TPTS Site



Additional TPTS System Characteristics

- Spreading codes and rates: L5 may be best choice
- Pulsing on various signal components:
  - » RBR Signal component: low duty cycle~5%
  - » BV Signal component: medium duty cycle~25%; with antenna~5%
  - » IR and XP Signal components: low duty cycle~5%
- Self-blanking:
  - » With knowledge/estimate of system variables: All desired chips to pass, ground out “off times”.
- Frequency deviation (Δf) selected based on max rate variation on BV code and carrier components
- Frequency deviation (f_m) selected based primarily on BV scanning antenna rate.
- RBR channel used for pseudorange/range determination
- RBR and BV channel used for bearing determination
- Preliminary position error budget vs Mode: ~35-80m

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TPTS Parameter Selection Path

- Additional study needed to define the exact carrier frequencies, code type, code rates, and bandwidth for the Autonomous RBR, BV, and active IR/XP Modes
- Compatibility with the existing DME systems as well as a DME to TPTS transition plan.
  - » Backward and electromagnetic compatibility to be ensured for legacy DME users
- Spreading codes and rates: m-sequence, L5 codes, L1C (L5 spreading codes believe to be best suited)
- Example parameters:
  - » f_c=1,000 MHz, f_{RO}=10.0 MHz,
  - » R_{RO_RBR}=1.0 Mcps for RBR Signal
  - » Let: Δf=Max Code Rate Variation=10 Hz:
    - Max BV code rate deviation would be 10Hz (like code Doppler)
    - Max BV carrier rate deviation would be 1,000 Hz (like carrier Doppler)
  - » FM rate: f_m= Antenna Scan Rate, between 400 and 1000 Hz.

TPTS Configuration vs. Capabilities

TPTS CAPABILITIES					
	TPTS Ground Site				TPTS User Side
Row	N	RBR	BV	ACTIVE	User Solution Capability
1	1	1	0	0	1 PR (i.e., with receiver clock bias)
2	1	1	1	0	1 PR, 1 Bearing
3	1	1	0	1	1 Range, Time
4	**1**	**1**	**1**	**1**	**1 PR 1 Bearing, Time -> PVT**
5	2	1	0	0	2 PRs
6	**2**	**1**	**1**	**0**	**2 PRs, 2 Bearings -> PVT**
7	2	1	0	1	2 Ranges, Time -> PVT
8	2	1	1	1	2 Ranges, 2 Bearings, Time -> PVT
9	**3**	**1**	**0**	**0**	**3 PRs ->PVT**
10	3	1	1	0	3 PRS, 3 Bearings -> PVT
11	3	1	0	1	3 Ranges, Time -> PVT
12	3	1	1	1	3 Ranges, 3 Bearings, Time -> PVT

Conclusions

- **TPTS presented for an L-band based system to be integrated/compatible with the DME system.**
- **TPTS varying configurations provide varying capabilities for ground and air segments.**
- **Three main operational modes were presented:**
  - **1) Autonomous Broadcast Mode (RBR and BV signals),**
  - **2) Active Interrogation/Response (IR/XP) Mode, and**
  - **3) Hybrid solution Mode**
- **An operational TPTS, to provide PVT Solutions:**
  - » **One TPTS Site for an Active TPTS User:**
  - » **Two TPTS sites for a passive TPTS User:**
  - » **Three TPTS sites for a passive TPTS User with only the RBR info.**
- **Additional research efforts needed to further development**
- **TPTS could provide a robust PNT service in the event of GPS non-availability within the NAS.**

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Questions?

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Additional Slides

Parameters for a TPTS Autonomous Link

Parameter		Value		Description
f	=	1215 MHz		frequency (highest possible frequency selected here)
S_{min}	=	-125 dBm		Minimum avg power received at aviation user for min S/N (w/ no pulsing)
G_t	=	9 dBil		Gain of DME transmission antenna on ground (in LOS)
G_r	=	-2 dBil		Gain of DME reception antenna on aircraft (in LOS)
L_r	=	3 dB		Loss of reception cable & antenna SWR mis-match
L_t	=	3 dB		Loss of transmission cable & antenna SWR mis-match
L_p	=	2 dB		Loss due to polarization mis-match
L_{int}	=	3 dB		Loss due to interference
L_{atm}	=	2 dB		Loss due to atmospheric absorption
L_M	=	6 dB		Link Margin (treat as a loss)
dc	=	10 dB		Loss due to pulse at duty cycle of 5%, i.e., 10log(1/dc); log is base 10
$P_t(30)$	=	29 dBm		Power, peak transmitted at ground site (pulsed at dc), for 30nmi (i.e., ~0.8 W)
$P_t(200)$	=	46 dBm		Power, peak transmitted at ground site (pulsed at dc), for 200nmi [(i.e., ~36 W)

TPTS Message Type Identifiers (MTID)

- **Basis is GPS CNAV message structure for TPTS CNAV (TNAV)**
  - » Preamble
  - » PRN
  - » MTID
  - » WN
  - » TOW
  - » Alert Flag
  - » Data Field
  - » CRC
- **Synchronous with TPTS System Time**

MTID	Message Description
0	Test Message (Default)
1	Platform Identification Information (e.g, ATC Code)
2	BV Signal Information (PRN, etc.)
3	Pseudorange Correction for RBR signal component
4	Pseudorange Correction for BV signal component
5	Carrier Phase Corrections for RBR signal component
6	Carrier Phase Corrections for BV signal component
7	Transmitter Clock Corrections
8	TPTS, GPS to UTC time information
9	Additional Bearing Variable Corrections
10	Transmitter Station Coordinate Information
11	Transmitter Station Configuration Information
12	Power Messaging Information (levels received and sent)
13	TPTS Almanac data for other TPTS stations
14	RBR to BV Inter-channel Group Delays
15	IR-to-XP Group Delays
16	Atmospheric Information
17	Integrity Information
18	Text message

TPTS RBR Signal Analytical Expressions

Code Clock:

$$x_{RO\_RBR}(t) = \mathrm{sgn}\left[A_{RO\_RBR}\cos(\omega_{RO\_RBR}t)\right] \qquad (2)$$

where:

A_{RO_RBR} = Amplitude of the RO_RBR, [V]

ω_{RO_RBR} = frequency of RO_RBR clock, [rad/s].

Local Oscillator:

$$s_{LO\_RBR}(t) = 2A_{LO\_RBR}\cos(\omega_{c\_RBR}t) \qquad (3)$$

where:

$2A_{LO\_RBR}$ = Amplitude of the LO RBR signal, [V]

ω_{LO_RBR} = frequency of the LO signal, [rad/s]

$f_{LO\_RBR} = n_c f_{RO\_RBR}$, [Hz].

RBR Signal:

$$s_{RBR}(t) = d(t)x_{SC\_RBR}(t)p_{RBR}(t)A_{c\_RBR}\cos(\omega_{c\_RBR}t) \qquad (4)$$

where:

$d(t)$ = TPTS data, [V]

$x_{SC}(t)$ = RBRspreading code, [V]

$p_{RBR}(t)$ = RBR pulsing sequence, [V]

A_{c_RBR} = Amplitude of the RBR signal, [V]

ω_{c_RBR} = frequency of the RBR signal, [rad/s].

TPTS BV Signal Analytical Expressions

Message:

$$m_{BV}(t) = A_m \cos(\omega_m t) \qquad (5)$$

where:

A_m = Amplitude of the "message", [V]

ω_m = frequency of "message", [rad/s].

BV Reference Oscillator:

$$s_{RO\_BV}(t) = A_{RO\_BV} \cos\left(\omega_{RO} t + \beta_f \sin(\omega_m t)\right) \qquad (6)$$

where:

A_{RO_BV} = Amplitude of the RO BV signal, [V]

$\beta_f = \frac{\Delta f}{f_m}$ = modulation index for the RO BV signal

$\Delta f = A_m k_f$ = frequency deviation of the RO BV signal (i.e, one way from center), [Hz]

k_f = sensitivity of the frequency modulator, [Hz/V]

ω_{RO} = frequency of the RO signal, [rad/s].

BV Code Clock:

$$x_{RO\_BV}(t) = \text{sgn}\left[s_{RO\_BV}(t)\right] \qquad (7)$$

Local Oscillator:

$$s_{LO\_BV}(t) = 2A_{LO\_BV} \cos\left(\omega_{LO\_BV}(t)t\right) \qquad (9)$$

where:

$2A_{LO\_BV}$ = Amplitude of the LO BV signal, [V]

$\omega_{LO\_BV}(t) = 2\pi f_{LO\_BV}(t)$ = frequency of the LO signal, from (8), [rad/s].

$$f_{LO\_BV}(t) = n_c f_{RO\_BV(}(t) = \frac{n_c}{2\pi}\left[\frac{d\phi_{RO\_BV}(t)}{dt}\right] \qquad (8)$$

where:

$\phi_{RO\_BV}(t)$ = phase of RO BV signal in (6).

BV Signal:

$$s_{BV}(t) = x_{SC\_BV}(t)\, p_{BV}(t)\, A_{c\_BV} \cos\left(\omega_{c\_BV}(t)t\right) \qquad (10)$$

where:

$x_{SC\_BV}(t)$ = BV spreading code, [V]

$p_{BV}(t)$ = BV pulsing sequence, [V]

A_{c_BV} = Amplitude of the RBR signal, [V].

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Estimated TPTS 2D Position Error Budget for Mobile Aviation User

(After Differential Error Mitigation Techniques with TPTS Monitor Site, TPTS Data Broadcast, and Vertical Estimator)

	Error, [m], (1 σ)								
TPTS Solutions Using TPTS Signal Components:	1 TPTS GS (RBR+BV+I/R)			2 TPTS GS (RBR+BV)			3 TPTS GS (RBR)		
Error Source	Bias	Rand	Total	Bias	Rand	Total	Bias	Rand	Total
Transmitter Survey Errors	0.5	0.2	0.5	0.5	0.2	0.5	0.2	0.1	0.2
Network Time/Transmitter Clock Error	10.0	0.5	10.0	10.0	0.5	10.0	10.0	0.5	10.0
Clock Modulation Error	20.0	1.0	20.0	15.0	1.0	15.0	0.0	0.0	0.0
Ionosphere Delay Error	1.0	0.1	1.0	1.0	0.1	1.0	1.0	0.1	1.0
Troposphere Delay Error	5.0	0.5	5.0	2.5	0.5	2.5	2.5	0.5	2.5
Multipath Error (high quality receiver)	10.0	1.0	10.0	5.0	1.0	5.1	5.0	1.0	5.1
Power Bias Error	10.0	1.0	10.0	5.0	1.0	5.1	5.0	1.0	5.1
Receiver Measurement Noise	0.2	1.6	1.6	0.1	0.8	0.8	0.1	0.8	0.8
User Equivalent Error (UEE), rms	15.0	2.0	15.2	11.5	1.5	11.6	11.5	1.5	11.6
Horizontal DOP (different for each method)			5.0			4.0			3.0
Horizontal Position Error (UEE*HDOP)			75.9			46.4			34.8

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