Jet Propulsion Laboratory
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A GNSS-Reflectometry Instrument for Wetland Extent and Dynamics

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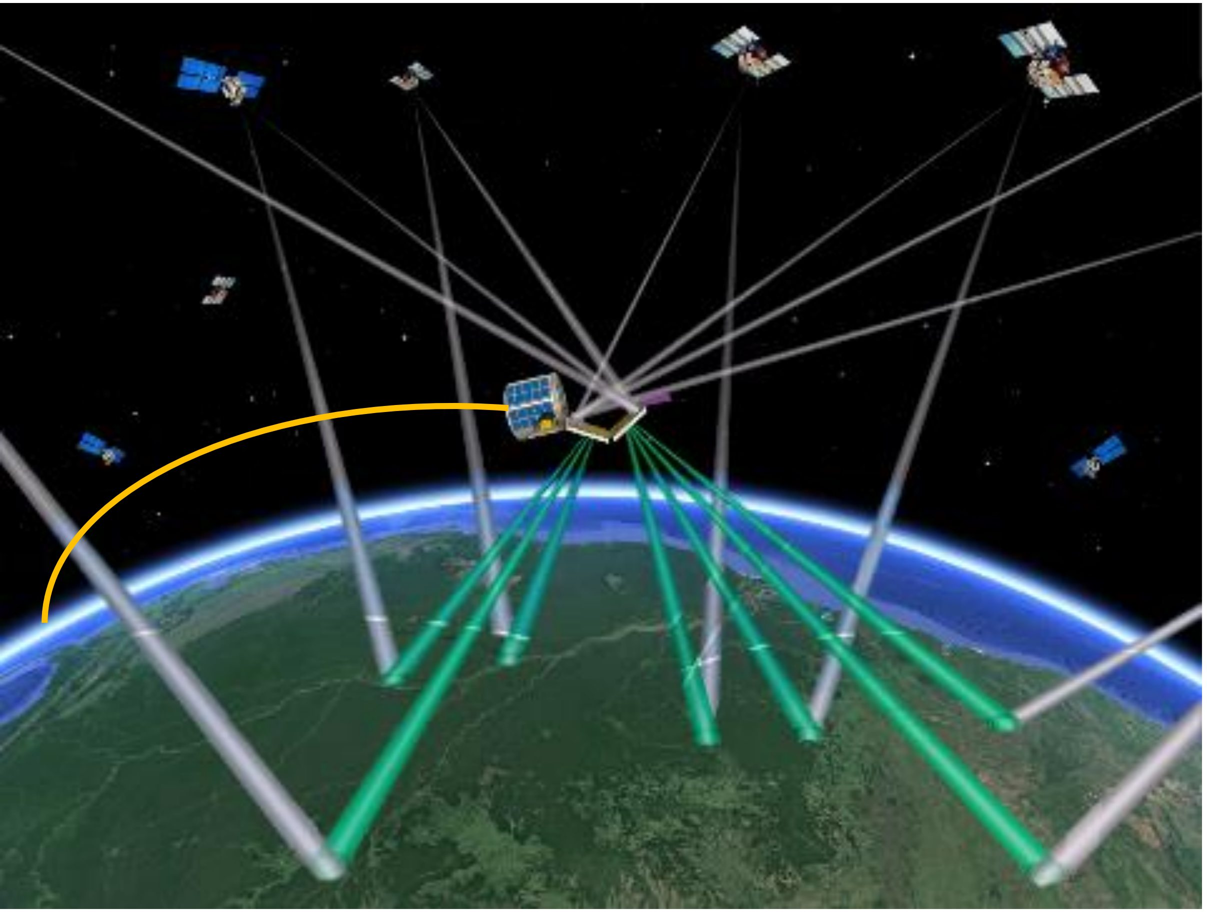
Outline

- Measurement concept
- Science motivation and requirements
- Instrument design
  - Front end: Low-power RF ASIC
  - Real-time navigation/timing: Real-Time Gipsy X (RTGx)
  - Processing surface-reflected signals: Delay Doppler Map
  - Noise calibration system
- Current status
- Summary

GENESIS
GNSS-Reflections Multistatic Radar for Wetland Dynamics



Instrument collects reflected GNSS signals (green) for remote sensing the Earth's surface, direct signals (upper white) for POD, and rising/setting signals (orange) for radio occultations

Concept:
Genesis collects Earth-reflected GNSS signals for remote sensing

Primary Science:
Wetland inundation/extent

Additional Science:
Soil moisture, sea-ice extent, ocean surface winds (CyGNSS)

Additional Capabilities:
Radio-Occultations: Atmospheric temperature and humidity, Precise Orbit Determination (POD)

Small size/cost/power:
Deploy 6-8 in single launch for dense surface coverage

GENESIS

Concept Advantages:

- Multiple, simultaneous bistatic measurements
- No transmitter - lower cost
- Low power (RF ASIC developed under ACT)
- Constellations feasible (eg CyGNSS) - High spatial/temporal coverage
- Forward scattering, L-Band - Improved penetration through vegetation
- Increasing number of GNSS/SBAS transmitters - Currently ~100 transmitters
- Long-term GNSS stability (SI traceability)

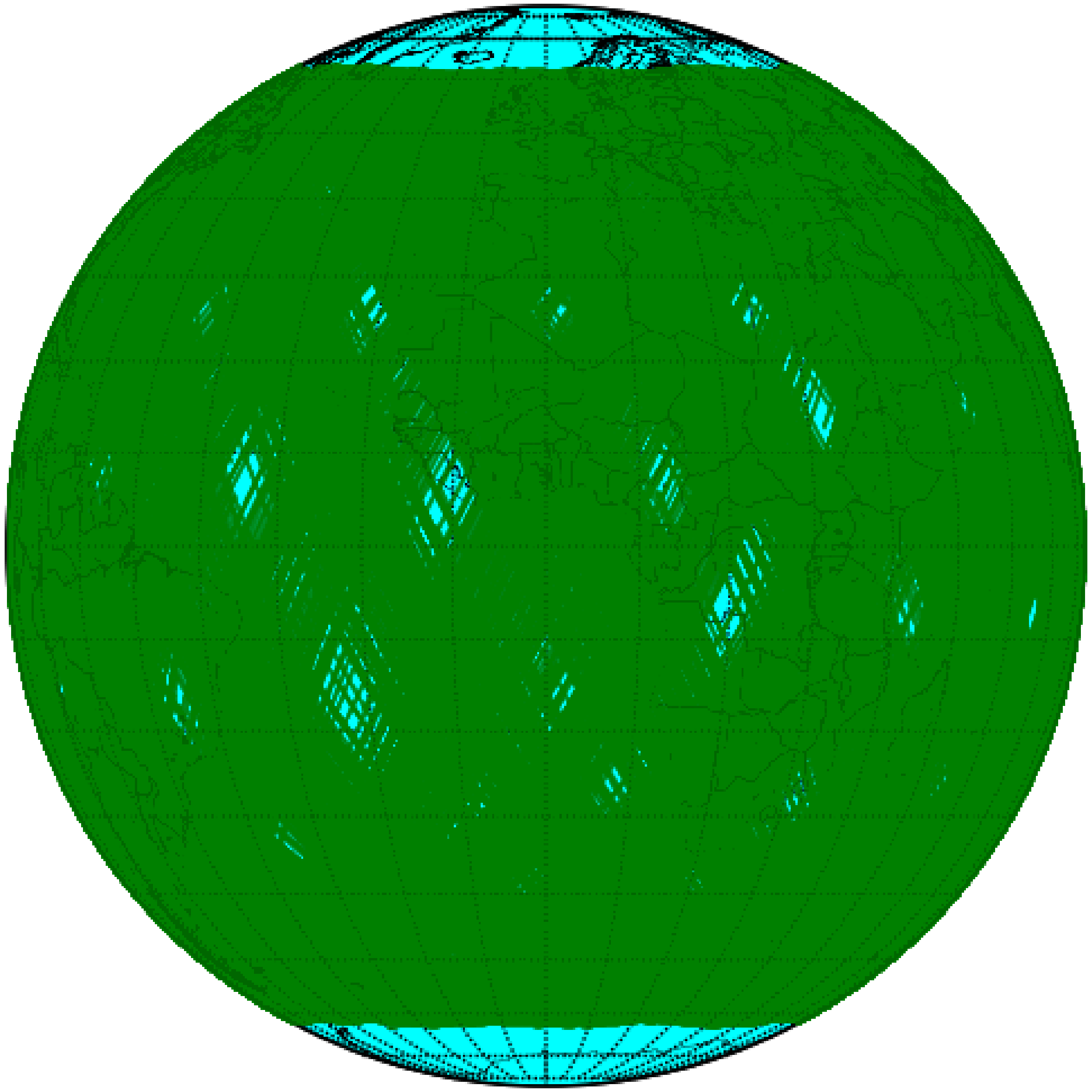
Decadal Survey Priorities Addressed:

- “Understanding the sources and sinks of carbon dioxide and methane, and how they may change in the future.”
- “Quantifying trends in water storage…”

Decadal Survey Goals Addressed:

- Cost Effectiveness
- Science Continuity

Spatial Coverage – Concept Mission



24 hour coverage simulation:

- 8 satellites
- 60^o inclination orbit
- GNSS + SBAS

Science

Primary Science: Wetland Inundation and Dynamics

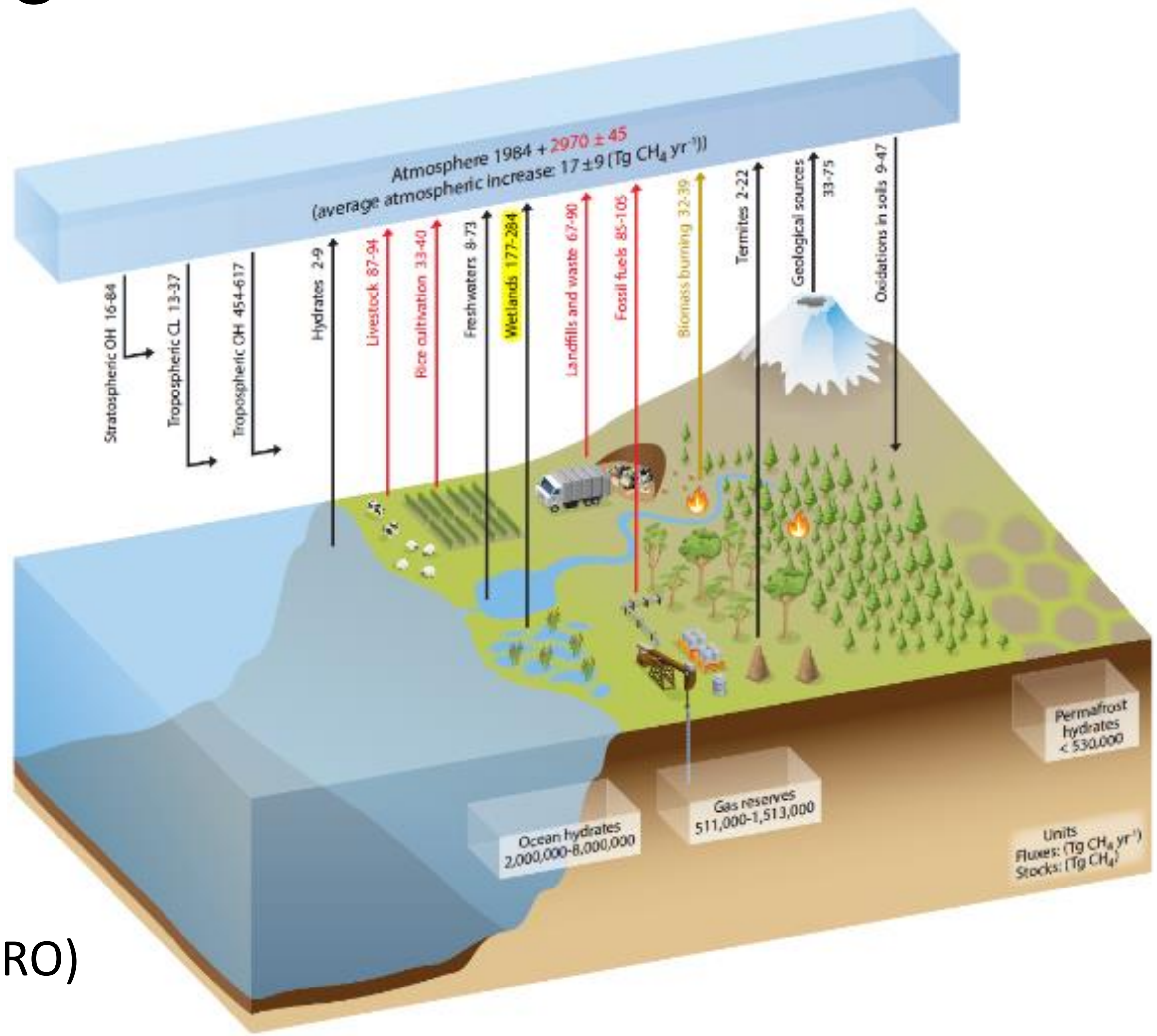
- Wetlands largest contributor to atmospheric methane
  - Largest contribution uncertainty
- Connections to carbon and water cycles
- Dynamics studies possible with high sampling rates

Secondary Science:

- Soil Moisture
- Freeze/Thaw Cycle
- Sea-ice extent (polar orbit)
- Ocean surface winds (CyGNSS)

Other Capabilities:

- Simultaneous Radio Occultation measurements (GNSS-RO)
  - Atmospheric temperature and humidity
- Precise Orbit Determination (POD)



Atmospheric Methane
From IPCC AR5 Report

Science Requirements

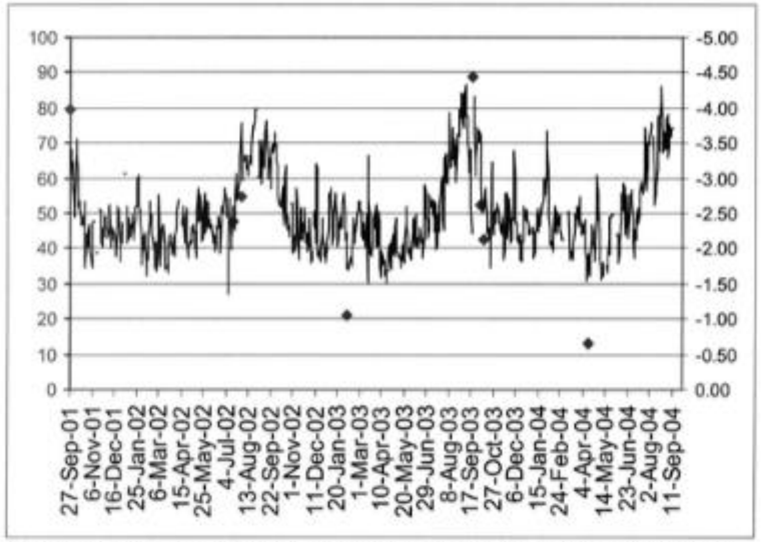


Fig. 3. Time series of QuikSCAT/SeaWinds polarization ratio measurements in dB over Gaging Reach 22, Gandak River, India (blue line, 3-day forward running means), compared with MODIS reach water surface area measurements in square kilometers (red dots). Timing and extent of the monsoon-related seasonal discharge changes can be precisely determined with this sensor.

Wetland/Hydrology Science Requirements

Hydrologic cycle:

- Dynamics: runoff operates on ~4 week time scales

  Brakenridge, G. R., S. V. Nghiem, E. Anderson, and S. Chien (2005), Space-based measurement of river runoff, Eos Trans. AGU,86(19), 185–188, doi:10.1029/2005EO190001

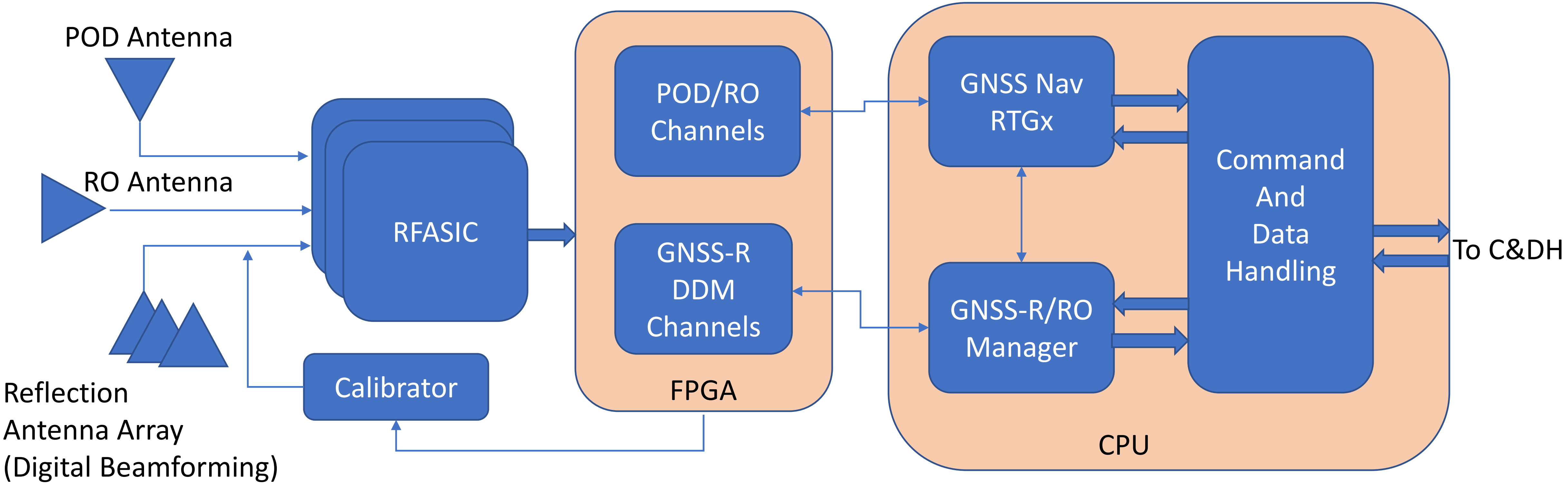
- Catchment area / Wetland inundation extent: 1-2 km spatial resolution

  Nghiem, S. V., C. Zuffada, R. Shah, C. Chew, S. T. Lowe, A. J. Mannucci, E. Cardellach, G. R. Brakenridge, G. Geller, and A. Rosenqvist (2017), “Wetland monitoring with Global Navigation Satellite System reflectometry”, Earth and Space Science, 4, 16–39, doi:10.1002/2016EA000194.

⟹ **Require global (+/- 60^o latitude) inundation maps every 10 days**

- Process all GNSS + SBAS signals
- 5 Hz observations
- Spatial resolution:
  - 1.5 km X 1.5 km cells ⟹ ~4 receivers
  - 1.0 km X 1.0 km cells ⟹ ~8 receivers

Genesis Block Diagram

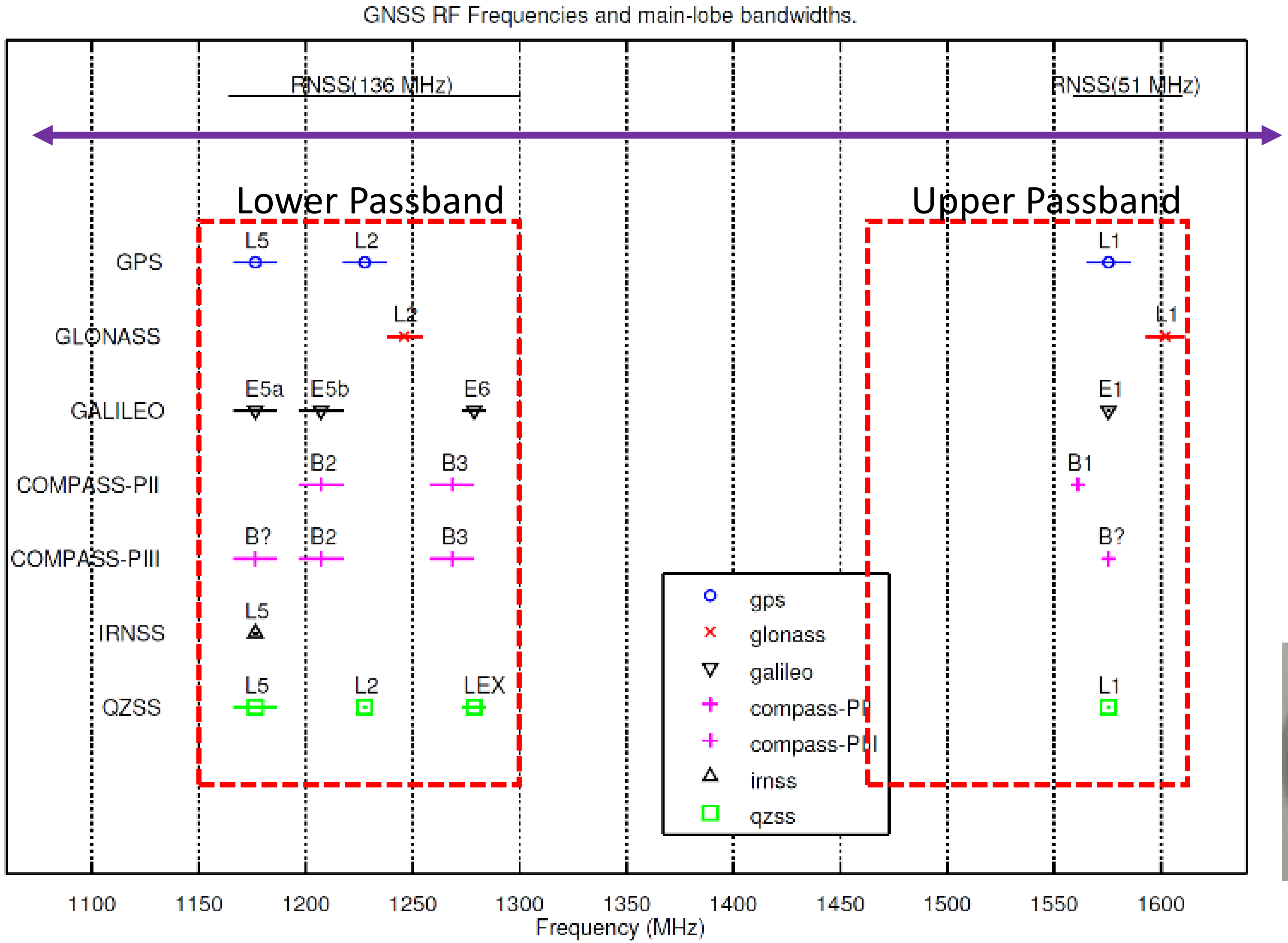


Instrument Specifications

	This Instrument	CYGNSS
Surface Spatial Resolution	**1 km (wetlands) 7 km (oceans)**	25 km (oceans)
Polarization	**H+V (Dual Pol)**	LCP
Number of simultaneous reflections observed	**32**	4
Power	**15 W**	12 W
GNSS Signals	**GPS L1/L2/L5, GLONASS L1/L2, Beidou B1/B2, Galileo E1/E5a/E5b, IRNSS L5, QZSS L1/L2/L5**	GPS L1
Radiation	**100 kRad**	5 kRad
Channel Spectral Width	**40 MHz per channel**	4 MHz per channel
Radio Occultation Support	**Yes**	No
Antenna Inputs	**Reflections: 12 POD: 1 RO : 2**	Reflections: 2 POD: 1 RO: 0
Beamforming Support	**Yes**	No
Science Data Rate	**1000 Hz to 1 Hz**	1 Hz

RF-ASIC

Digitized Frequencies



Developed under ACT

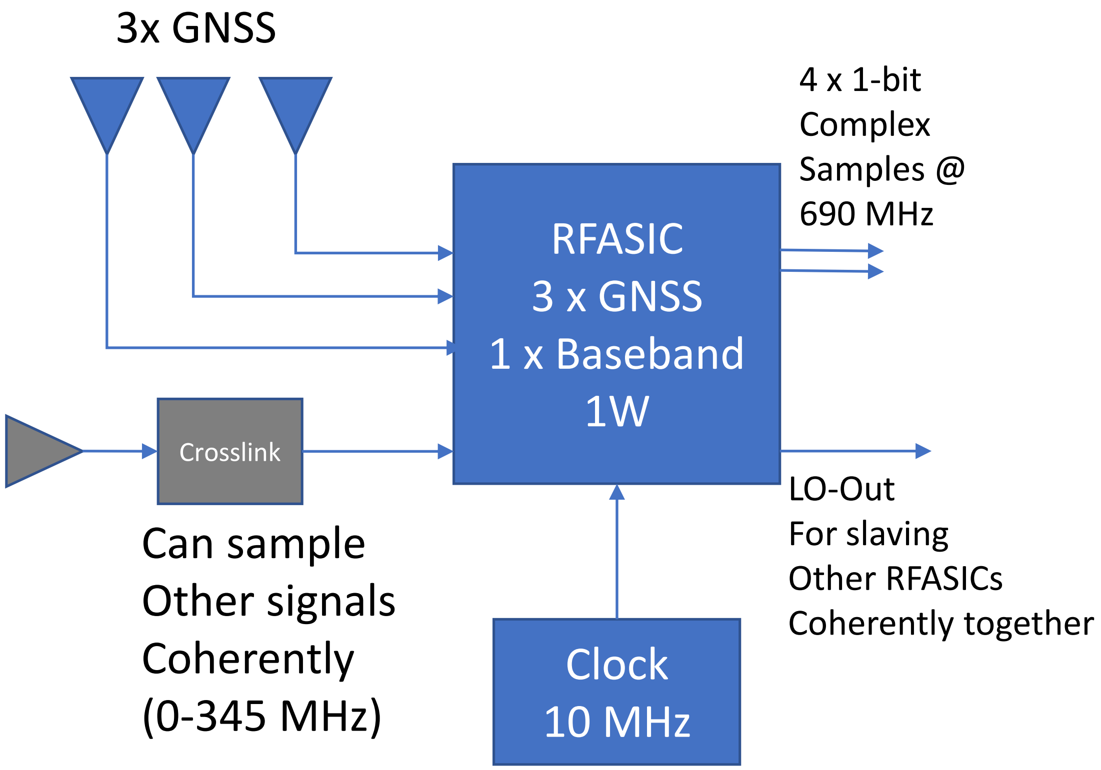
Digitizes all L-band GNSS signals

- GPS L1/L2/L5
- GLONASS L1/L2
- GALILEO E1/E5a/E5b/E6
- Beidou B1/B2/B3
- IRNSS L5
- QZSS L1/L2/L5 LEX
- WAAS, EGNOS, MSAS, GAGAN, SDCM

3 antenna input RFASIC

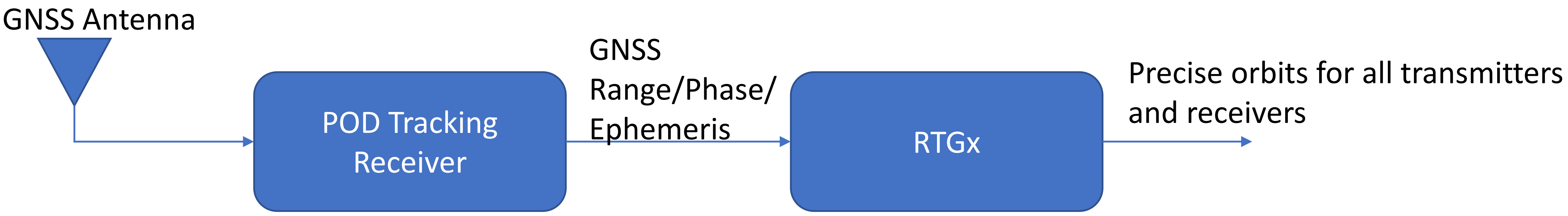
RF-ASIC

3 Antenna inputs: All-GNSS



- **Radiation hardened** GNSS RF ASIC (RF-to-bits)
- 4 inputs per chip
  - **3x L-Band** (1150-1610 MHz)
  - 1x Baseband (0-350 MHz)
- 1 W per RFASIC (total power)
- Runs off standard **10 MHz reference oscillator**
- **Can slave N of these chips together** for 3*N phased array applications. Slaves run at 0.75W per 3 antennas.
- Each chip **replaces about 24 MAX2112s** and does this for 1/10th of the power.

Real-Time Gipsy X (RTGx) Navigation Software



- A state-of-the-art GNSS navigation software package from JPL
- Real-time precise orbit determination (POD)
- For GNSS-R: Provides real-time estimates of current (and future) receiver/transmitter locations.
- Decimeter-level real-time on-board positioning

Reflections Processing: Delay Doppler Map

- Delay doppler map (DDM): matrix of received signal power vs. doppler and delay
- Primary observable for GNSS scatterometry
- Accumulation of incoming signal with signal model for various values of doppler and PRN code delay

$$\text{DDM} = \int s(t)e^{j2\pi t(f_C+f_D)}c(t+\tau)dt,\ \forall f_D,\tau$$

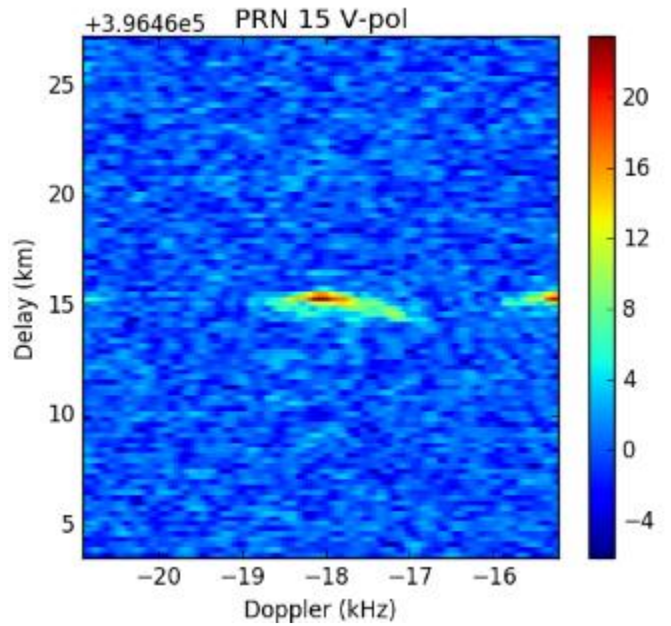
$s(t)$: *incoming signal*

$c(t)$: *PRN code sequence*

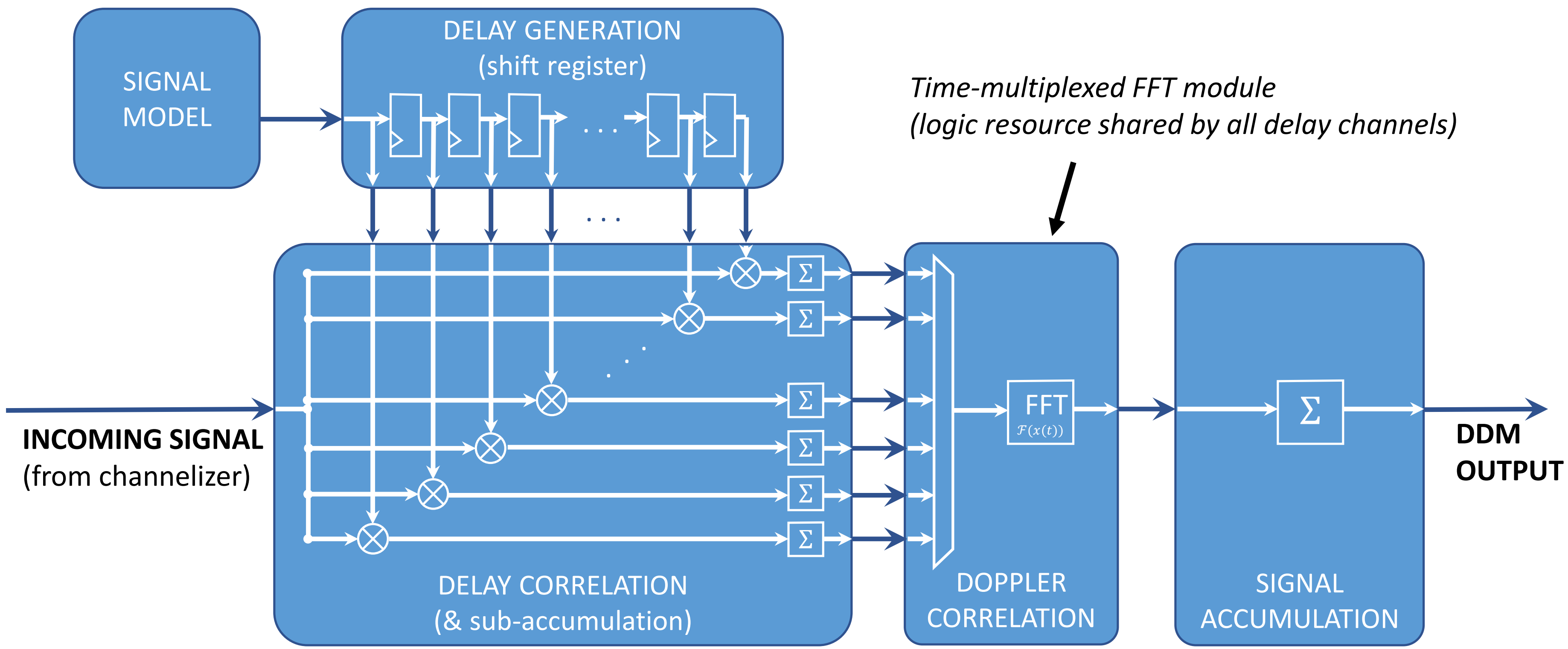
f_C : *signal carrier frequency*

f_D : *doppler frequency (local signal model)*

τ : *code delay (local signal model)*



DDM Algorithm



DDM Implementation Status

- **DDM Algorithm Fully implemented in Verilog Hardware Description Language**
  - Fully parameterized design, optimized for FPGA footprint (minimal resources)
  - Includes AXI-Stream interfaces for simple, reliable transfer of DDM data to processor memory
  - Currently running on receiver prototype

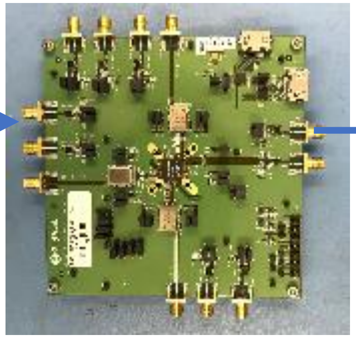
- **Full support for all GNSS constellations & bandwidths**
  - GPS, Galileo, GLONASS, Beidou, QZSS, IRNSS, etc.
  - User-selectable bandwidth:
    - 1MHz/10MHz signals, etc.
    - Delay resolution

- **Validation in progress**
  - Comprehensive verification via simulation and hardware testing

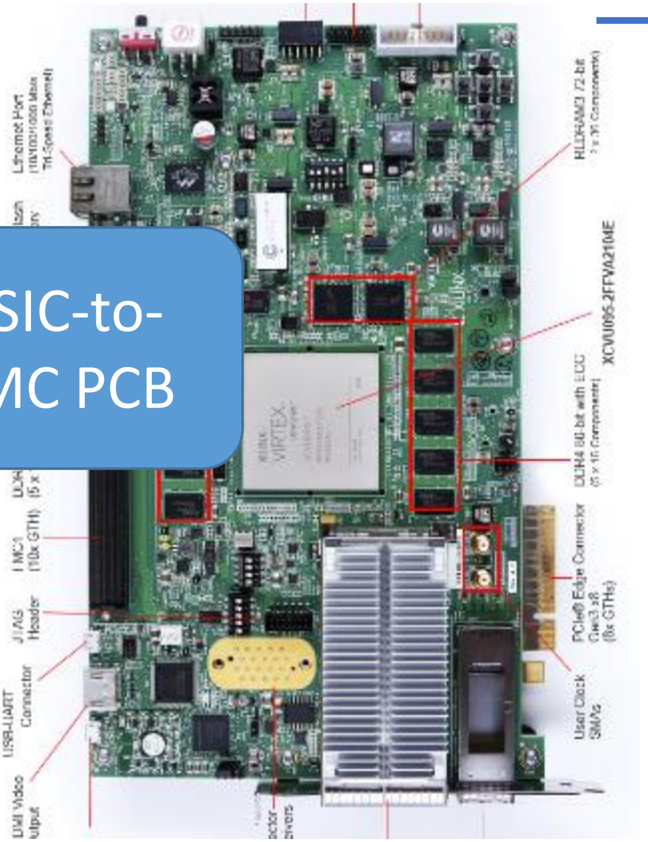
Hardware Demonstration (Feb 2018)

Sig Gen PRN1

RFASIC Dev Board



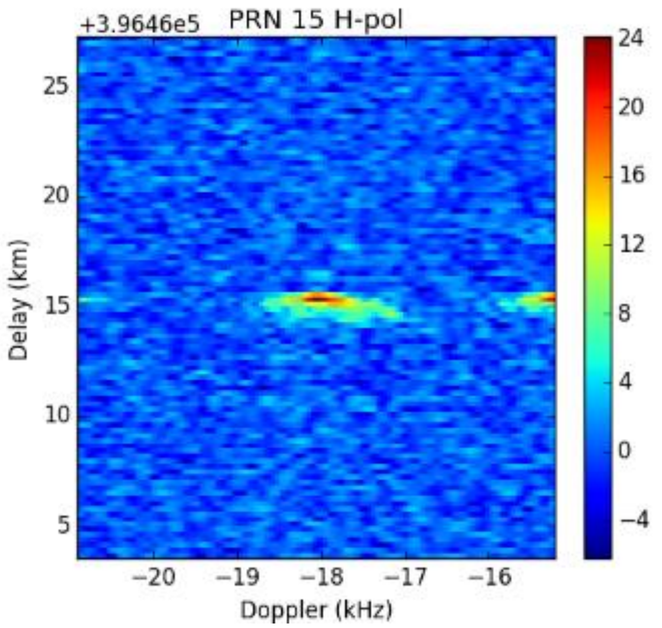
ASIC-to-FMC PCB



FPGA Board

PC For Display

Generate Real-Time DDM



FPGA Comparison

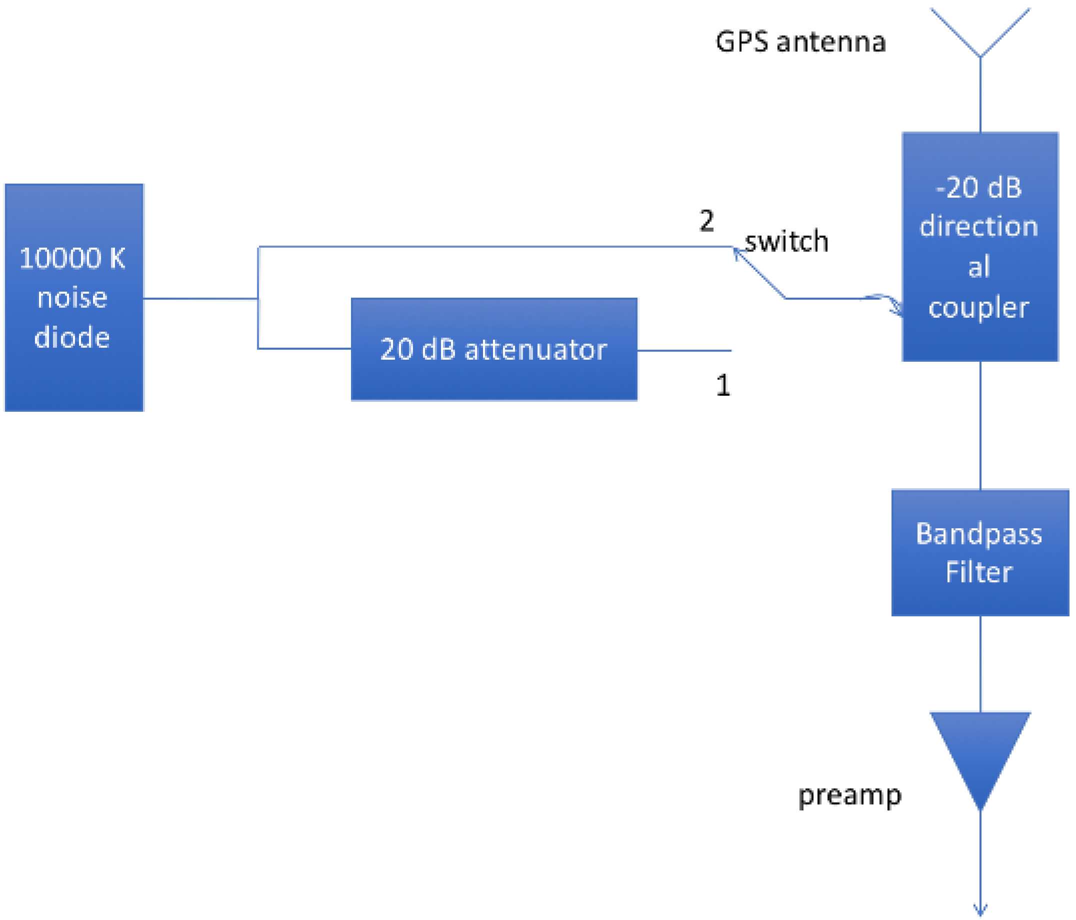
Device	Max DDM Channels	Dynamic Power (per channel)	Static Power (per device)
Ultrascale Kintex 60 (XCKU060)	**23**	**133mW**	**596mW**
Ultrascale Virtex 95 (XCVU095)	38	149mW	915mW
Zynq 7100	22	175mW	220mW
Zynq 7030	6	174mW	124mW

Signal Power Calibration

- Receiver measures Signal-to-Noise ratio
- Need to calibrate
  - Antenna gain vs angle (Measured on satellite to include multipath)
  - Uncalibrated portion of receiver circuit loss
  - System noise (monitored while tracking)
- JPL patented a precise noise calibration technique sponsored by the USAF GPS OCX system (US Patent 20140065994)

Noise Calibration Technique

Antenna gain (dB)	0.25	0.059 (linear)
Cable losses (dB)	0.25	0.059 (linear)
Noise Calibration (dB)	0.20	0.047 (linear)
RSS (dB)	0.40	0.096 (linear)



US Patent 20140065994

Year 1 (Feb 2017 – Feb 2018) Milestone Status

Milestone	Status
Instrument requirements definition	Complete
Processor and Operating System (OS) trade study	Complete
Integration of RF ASIC (ACT2013) into existing GNSS testbed	Complete
GNSS software development to support reflections (GPS)	DDM complete
RF ASIC Fabrication run to support instrument: Note: 12 ASICS now in hand	Deferred to Year 2
Prototype unit using COTS development boards, RF ASIC	Complete

Year 2 (Feb 2018 - Feb 2019) Milestones

- Schematic Design of RF and Digital Processing Board
- Chassis Design and Fabrication (or leverage COTS boards)
- Implementation of Reflection Schedule Software
  - Functionality completed in year 1 – need to integrate into operations
- GNSS software to support reflections (Glonass, Beidou, etc)
- Port RTGx to selected operating system
  - This work has started in year 1. Evaluating scope to port to RTEMs
- Layout and Fabrication of EM boards
- Evaluate ASIC update plans

Summary

- We're building most capable GNSS reflectometry instrument for space applications
  - Number of simultaneous DDMs
  - Number/type of GNSS signals processed

- Unique features:
  - Low-power RF ASIC: enables antenna arraying
  - RTGx for Position Navigation and Timing (PNT)
  - Always-on noise calibration system

- On schedule:
  - 3 months into 2^{nd} year of 3-year program

Backup

GNSS+SBAS Signals

		Public			Encrypted		
		Band	Name	Code	Band	Name	Code
GNSS	GPS (31)	L1	C/A	BPSK(1)	L1	P/Y	BPSK(10)
		L2	L2C	BPSK(1)		M1	BOC(10,5)
		L5	L5I	BPSK(10)	L2	P/Y	BPSK(10)
			L5Q	BPSK(10)		M2	BOC(10,5)
	Glonass (24)	G1	C/A	BPSK(0.5)			
			P	BPSK(5)			
		G2	C/A	BPSK(0.5)			
			P	BPSK(5)			
	Galileo (15/30)	L1	E1b/c	Note A	L1	E1a	BOC(15,2.5)
		E5	E5a (L5)	BPSK(10)	E6	E6b	BPSK(5)
			E5b (B2)	BPSK(10)		E6c	BPSK(5)
	Beidou (21/?)	B1	E2-I	BPSK(2)	B1	E2-Q	BPSK(2)
		B3	E6-I	BPSK(10)	B3	E6-Q	BPSK(10)
		B2	E5b-I	QPSK(2)	B2	E5b-Q	QPSK(10)
Regional	IRNSS (6/7)	L5	Std	BPSK(1)	L5	Restr-I	BOC(5,2)
	India					Restr-Q	BOC(5,2)
	QZSS (3)	L1	C/A	BPSK(1)			
	Japan		C	BOC(1,1)			
			SAIF	BPSK(1)			
		L2	L2C	BPSK(1)			
		L5	L5I	BPSK(10)			
			L5Q	BPSK(10)			
SBAS	WASS (3/4)	L1	C/A	BPSK(1)	L1	P/Y	BPSK(10)
	USA				L2	P/Y	BPSK(10)
	EGNOS (2/3)	L1	C/A	BPSK(1)			
	EU	E5	E5a (L5)	BPSK(10)			
			E5b	BPSK(10)			
	MSAS (2)	L1	C/A	BPSK(1)			
	Japan						
	GAGAN (3)	L1	C/A	BPSK(1)			
	India	L5	C/A	BPSK(1)			
	SDCM (3)	L1	C/A	BPSK(1)			
	Russia						

Public	BPSK Slow
Encrypted	BPSK Fast
	QPSK Slow
	QPSK Fast
	BOC Slow
	BOC Fast

Note A

BOC(1,1)+BOC(6,1)

Onboard Navigation / Precise Orbit Determination

- GPS, Glonass, Galileo, Beidou

Science Signals

- GPS, Glonass, Galileo, Beidou
- QZSS, IRNSS
- WAAS, EGNOS, MSAS, GAGAN, SDCM

4 Global GNSS Constellations:

GPS, Glonass, Galileo, Beidou

2 Regional Systems:

IRNSS, QZSS

Several Satellite-Based Augmentation System (SBAS) Transmitters:

WAAS, EGNOS, MSAS, GAGAN, SDCM

DDM Implementation Approach

- **Computational requirements of GNSS-R receiver are driven by DDM generation**
  - Number of operations proportional to f_{BB} * N_{dopp} * N_{delay} (f_{BB} = baseband freq.)
    - For Navigation/RO tracking, N_{dopp} = 1, N_{delay} = 3-5
    - Typical GNSS-R DDM might use N_{dopp} = 32, N_{delay} = 128 (~1000x ops, relative to Navigation/RO)
  - Efficiency of DDM algorithm drives capability of receiver (e.g. number of channels)

- **For Genesis IIP, using hybrid time domain + frequency domain approach**
  - Optimal for FPGA targets
  - Delay correlation in time domain
  - Doppler correlation in frequency domain
  - Max frequency of FPGA >> f_{BB}, use time multiplexing of logic resources to increase capacity (number of channels per FPGA)