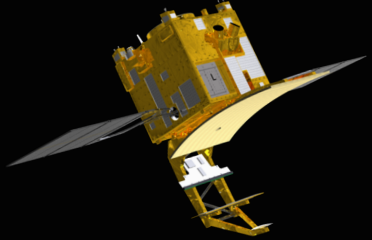


Wide-swath Shared-aperture Cloud Radar (WiSCR)

Earth Science Technology Forum

June 25, 2015

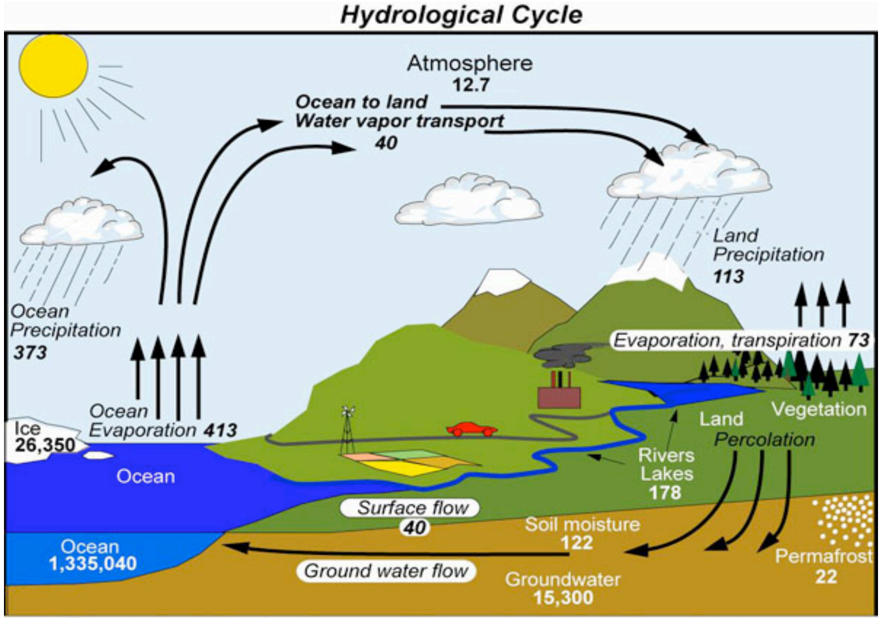
GSFC: Lihua Li, Paul Racette, Gerry Heymsfield , Matthew McLinden,
Vijay Venkatesh, Michael Coon, Martin Perrine
NGES: Richard Park, Michael Cooley, Pete Stenger ,Thomas Spence,
Tom Retelny

Outline - WiSCR Objectives

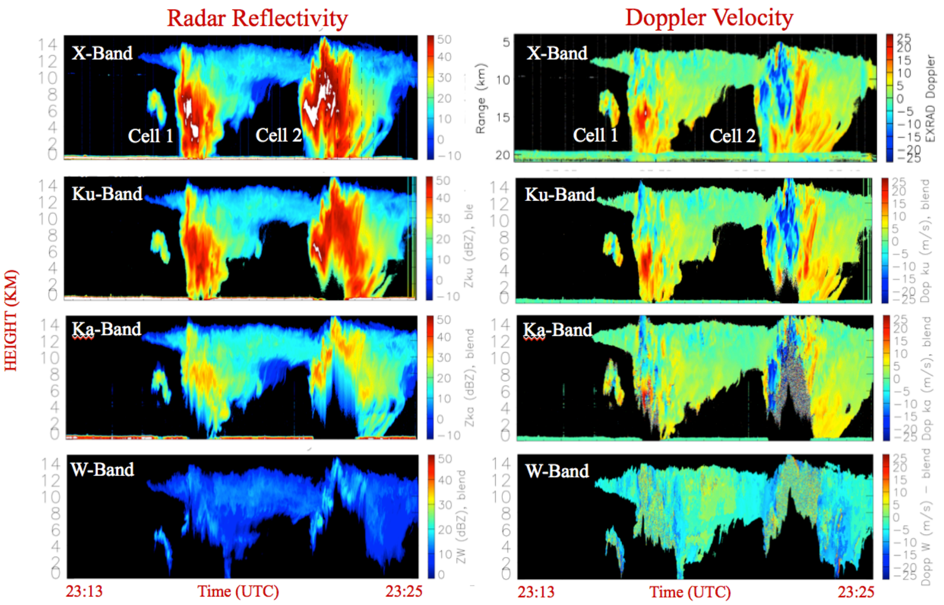
- Science Motivations
  - Science background
  - ACE / CaPPM radar concept
- Tri-band Antenna Architecture Study
  - Design trades
  - Performance parameters
- Ka-band AESA T/R Module Development
  - Module design
  - MMIC development
- Advanced Doppler Radar Technologies
  - Frequency diversity pulse pair Doppler technique
  - Multi-channel waveform generation and frequency conversion modules with shared circuit to reduce SWaP
- Summary and Path Forward

Science Motivations

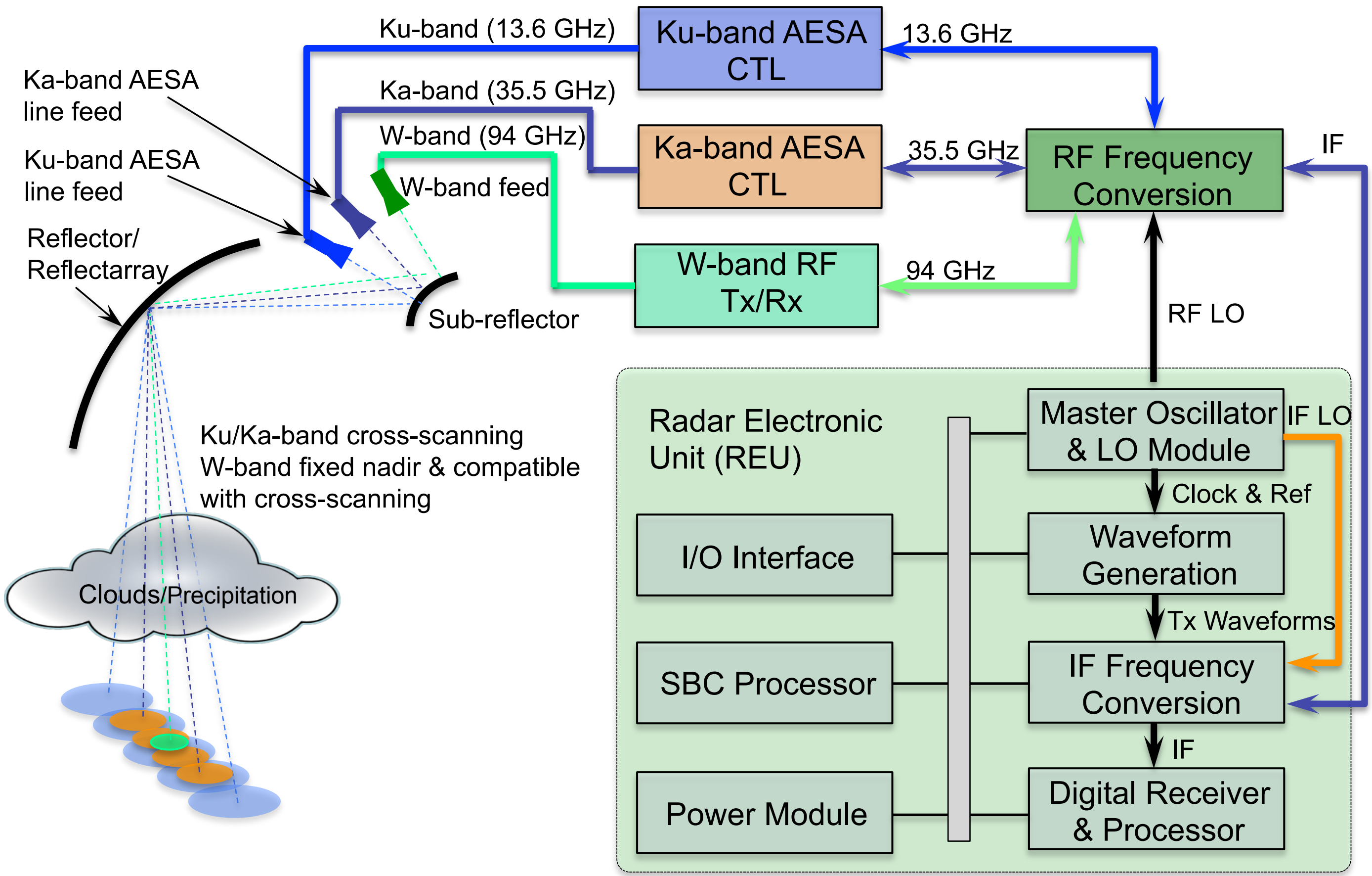
- Clouds and precipitation are among the greatest sources of uncertainty in climate change prediction. Global-scale measurements are critically needed.
- Multi-frequency radar with Doppler and imaging capability is crucial for improved understanding of the characteristics of clouds, precipitation, and their interaction.
- Decadal Survey (DS) Aerosol Cloud Ecosystem (ACE) calls for a dual frequency (Ka/W-band) radar while the more recent Cloud and Precipitation Process Mission (CaPPM) concept requires a tri-frequency imaging Doppler radar.



Units: Thousand cubic km for storage, and *thousand cubic km/yr* for exchanges



Dual- or Tri-band Radar Concept for ACE and CaPPM



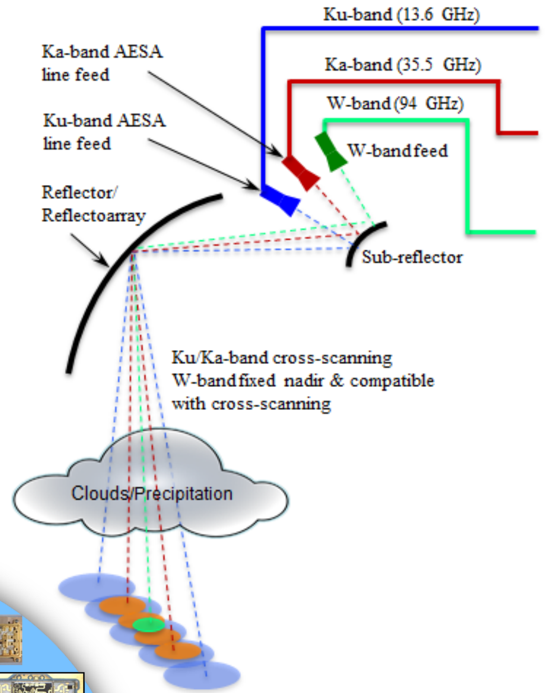
- IIP 2010 Achievements
  - Demonstrated an efficient dual-frequency (Ka/W), shared aperture antenna architecture
    - › Reflector/reflectarray technologies
    - › Sub-scale antenna
  - Developed Scalable Antenna Designs (7-17 sqm)
    - › Dual-band (Ka/W) antenna
    - › Ka-band AESA feed
    - › Ka-band T/R module
- ACE Technology Maturation Study (2013)
  - Performed TRL assessment for Ka/W-band radar
  - Identified key areas to be advanced
  - Defined a pathway to space

Science Objectives Are Closely Tied to the Antenna Design and Associated Trades

Various antenna parameters must be balanced to meet mission objectives…

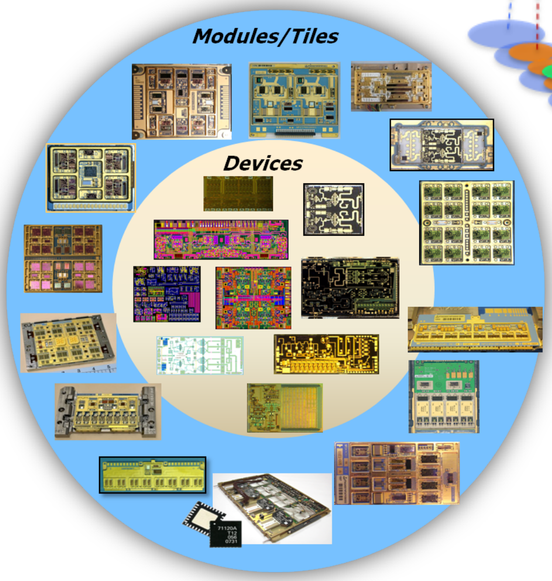
Radar Parameter	Antenna Parameter/Feature
Spatial Resolution	Aperture Size
Vertical Resolution	Tx Pulse Width
Field of View	Beam Steering
Polarimetry	Dual-Polarization
Sensitivity	Size, Radiated Power, Efficiency, Noise Figure
Data Diversity	Multi-Band Antenna

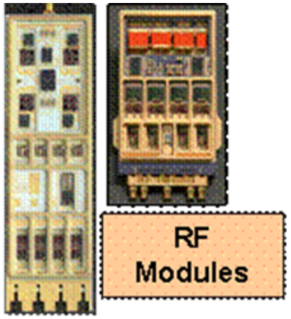
One of the explored architectures…



AESA and T/R Module Experience, Technology Base & TRL

- X/Ku-band AESA & T/R module technology is high TRL
  - *NGES has extensive experience*
- Ka-band AESA & T/R module technology rapidly maturing
  - *Funded under ACE IIPs and demonstrated for various other programs/applications*
- W-band AESA technology emerging
  - *Funded under ACE IIPs and via other sources (e.g. DARPA)*
- GaN MMIC technology proliferating very fast at X, Ku, Ka, & W-bands





Key Parameters from the Tri-Band Antenna Study Design Budget [Assuming a 7 sqm main reflector]

	Ku	Ka	W Fixed Beam*	W AESA	Notes
Sensitivity (dBZ @ Nadir)	0.0	-12.9	-34.4	-31.4**	For Ku & Ka it assumes system dwells equally across swath. See below for W band **
Transmit Power (kW)	2.4	2.6	1.6	1.9	At antenna feed. 3-tier AESA Tx pwr
Antenna Gain (dBi)	49.8	58.3	67.7	66.7	Assumes 3 x 2.33 m antenna
Cross Track Resolution (km)	5.1	2.1	0.6	0.5	
Along Track Resolution (km)	3.4	1.4	0.7	0.8	
Cross Track Swath (± deg)	10.0+	8.5	N/A	2.0	
Noise Figure (dB)	3.3	4.6	5.7	7.0	
Number of Integrated Pulses	151	29	725	642**	Constant CT Scan Rate
Duty (%)	1.56	1.56	1.56	1.56	
Pulse Width (us)	1.67	1.67	1.67	1.67	250 m resolution
Number of T/R Modules	128	288	N/A	384	4 channel Ka & Ku module 8 channel W module

*Estimates assume the 7m^2 antenna architecture & CouldSat-style beam waveguide hardware

+ Greater swaths (e.g., +/- 17 deg) are supported with a minor adjustment in the assumed Ku band grid.

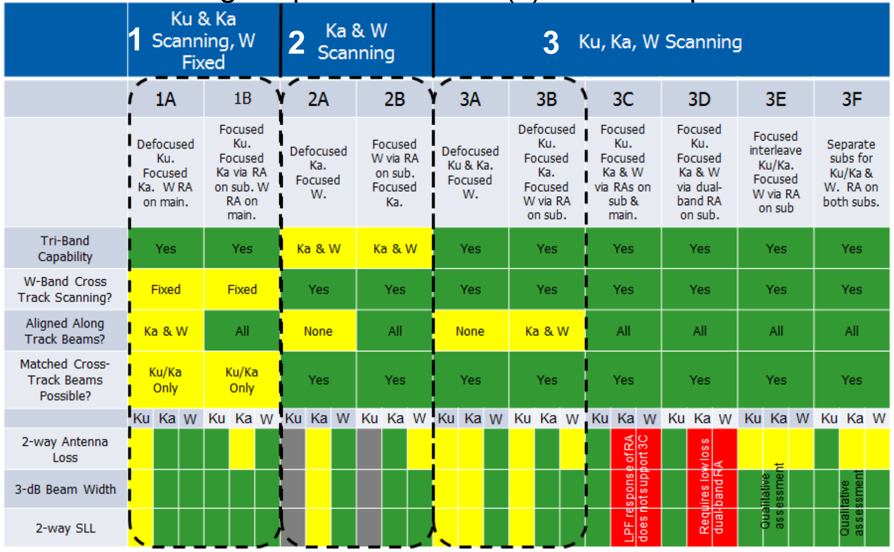
**AESA architecture permits flexible dwell times; dwelling longer in regions of interest is possible. This trade is most pronounced at W-band, where the beam width is most narrow. For reference, the sensitivity shown assumes dwelling on nadir only. A peak transmit power of 2W/site is assumed.

Antenna Architectures Were Derived Based on Detailed Radar System Budgets

Tri-Band Antenna Trade Study Assessment/ Conclusions

Rich Trade Space

Enables tailoring for particular band(s) and/or requirements



	1 Ku & Ka Scanning, W Fixed		2 Ka & W Scanning		3 Ku, Ka, W Scanning					
	1A	1B	2A	2B	3A	3B	3C	3D	3E	3F
	Defocused Ku. Focused Ka. W RA on main.	Focused Ku. Focused Ka via RA on sub. W RA on main.	Defocused Ka. Focused W.	Focused W via RA on sub. Focused Ka.	Defocused Ku & Ka. Focused W.	Defocused Ku. Focused Ka. Focused W via RA on sub.	Focused Ku. Focused Ka & W via RAs on sub & main.	Focused Ku. Focused Ka & W via dual-band RA on sub.	Focused interleave Ku/Ka. Focused W via RA on sub	Separate subs for Ku/Ka & W. RA on both subs.
Tri-Band Capability	🟩 Yes	🟩 Yes	🟨 Ka & W	🟨 Ka & W	🟩 Yes	🟩 Yes	🟩 Yes	🟩 Yes	🟩 Yes	🟩 Yes
W-Band Cross Track Scanning?	🟨 Fixed	🟨 Fixed	🟩 Yes	🟩 Yes	🟩 Yes	🟩 Yes	🟩 Yes	🟩 Yes	🟩 Yes	🟩 Yes
Aligned Along Track Beams?	🟨 Ka & W	🟩 All	🟨 None	🟩 All	🟨 None	🟨 Ka & W	🟩 All	🟩 All	🟩 All	🟩 All
Matched Cross-Track Beams Possible?	🟨 Ku/Ka Only	🟨 Ku/Ka Only	🟩 Yes	🟩 Yes	🟩 Yes	🟩 Yes	🟩 Yes	🟩 Yes	🟩 Yes	🟩 Yes

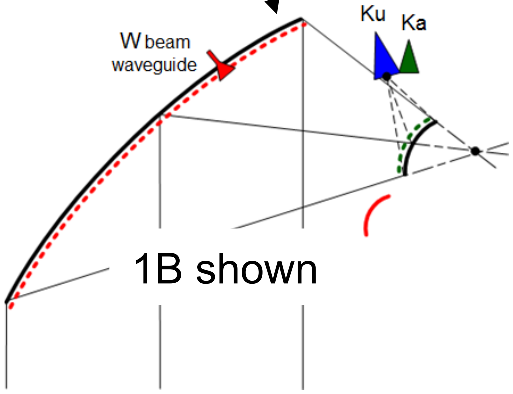
	1A			1B			2A			2B		
	Ku	Ka	W	Ku	Ka	W	Ku	Ka	W	Ku	Ka	W
2-way Antenna Loss	🟨	🟩	🟩	🟩	🟨	🟩	⬛	🟨	🟩	⬛	🟩	🟨
3-dB Beam Width	🟨	🟩	🟩	🟩	🟩	🟩	⬛	🟨	🟩	⬛	🟩	🟩
2-way SLL	🟨	🟩	🟩	🟩	🟩	🟩	⬛	🟨	🟩	⬛	🟩	🟩

	3A			3B			3C			3D			3E			3F		
	Ku	Ka	W	Ku	Ka	W	Ku	Ka	W	Ku	Ka	W	Ku	Ka	W	Ku	Ka	W
2-way Antenna Loss	🟨	🟨	🟩	🟨	🟩	🟨	🟩	🟥 LPF response of RA does not support 3C	🟥	🟩	🟥 Requires low loss dual-band RA	🟥	🟨	🟨 Qualitative assessment	🟨	🟩	🟨 Qualitative assessment	🟨
3-dB Beam Width	🟨	🟨	🟩	🟨	🟩	🟩	🟩	🟥	🟥	🟩	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩
2-way SLL	🟨	🟨	🟩	🟨	🟩	🟩	🟩	🟥	🟥	🟩	🟥	🟥	🟩	🟩	🟩	🟩	🟩	🟩

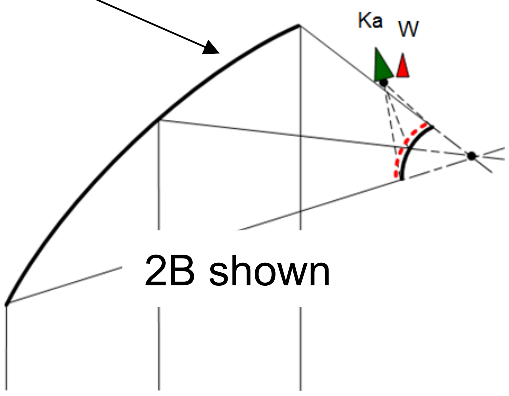
RA = reflectarray

Trade Study Summary

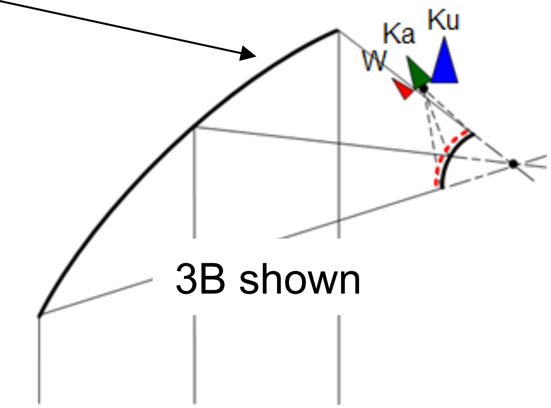
- Identified, assessed 10 candidate architectures (3 classes)
- Down selected primary candidates from each class
- Leveraged IIP 2010 design tools and technologies
  - Reflectarray and reflector design/analysis tools
  - Low loss reflectarray element (including FSS properties)
  - Ka-band AESA and T/R module design
- Evaluated & traded various AESA and T/R module design approaches (Ku, Ka and W-band)
- Explored usage of reflectarrays for tri-band architectures
  - Potential benefits in mitigating defocusing scan losses (Ka/W-band)



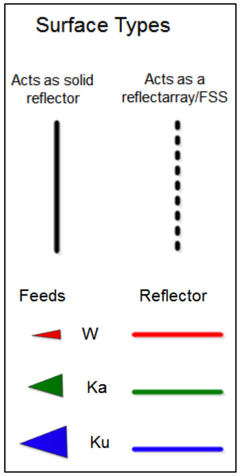
1B shown



2B shown

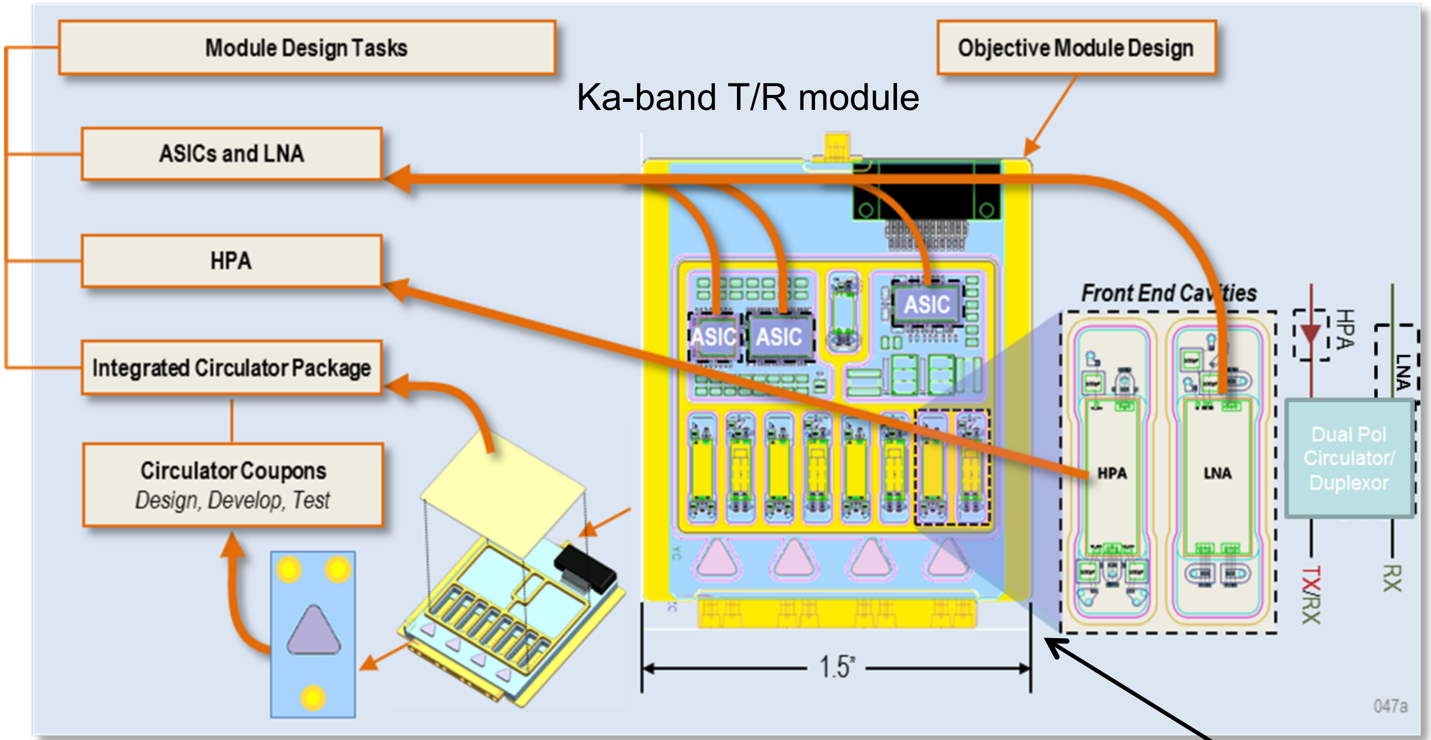


3B shown



Objective Ka-Band T/R Module Design
Development Path Overview

Integrated circulator, MMIC and ASIC development currently under development…



Module Design Tasks

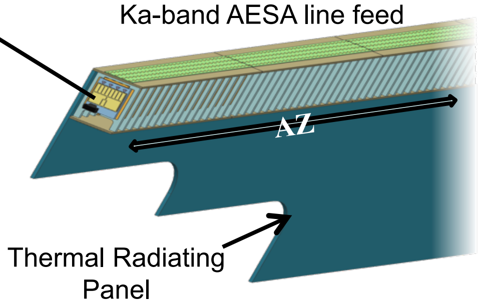
ASICs and LNA

HPA

Integrated Circulator Package

Circulator Coupons
Design, Develop, Test

Objective Module Design



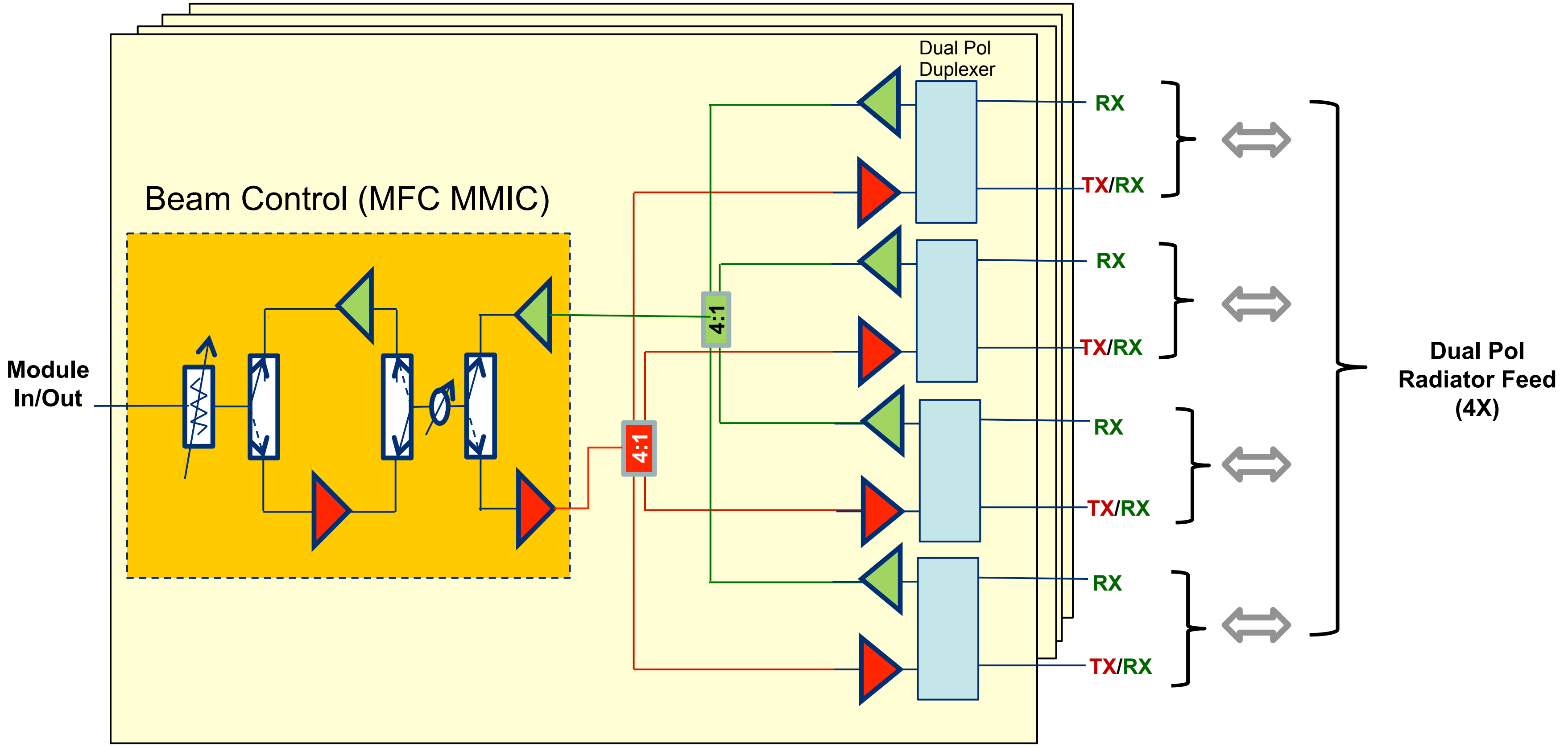
- Held PDR, CDR, FDR for LNA and Key MFC MMIC Circuits
- 3 Design Options For Circulator
- ASIC Requirements for control and telemetry concept

T/R Module RF Architecture

Supports Efficient T/R Functionality and Polarization Diversity

🟥 = *Transmit Path*
🟩 = *Receive Path*

~ 300 modules, each with 4 TR channels, form phase array line feed to reflector

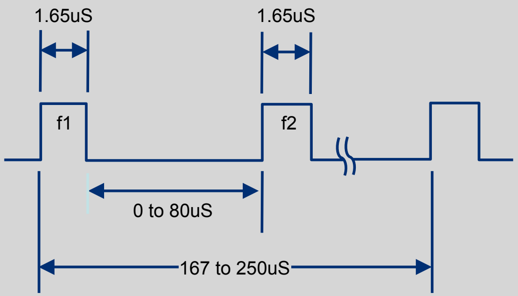


- *Module front end architecture down-selected from 10 options*
- *Selected option provides best balance between system sensitivity, module cost and weight*

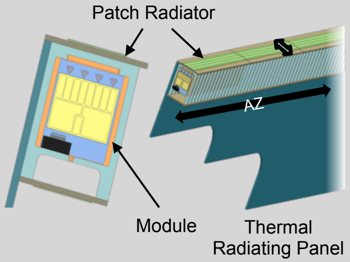
Ka-Band AESA and T/R Module Overview

System Performance Context: 4 Main Modes of Operation

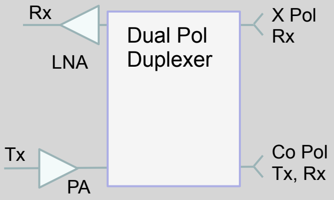
1 Module 1D Scanning Radar Pulsed Modes



- Switch Independently Between Rx Co-pol and X-pol
- Duty Cycle held at 1.56%

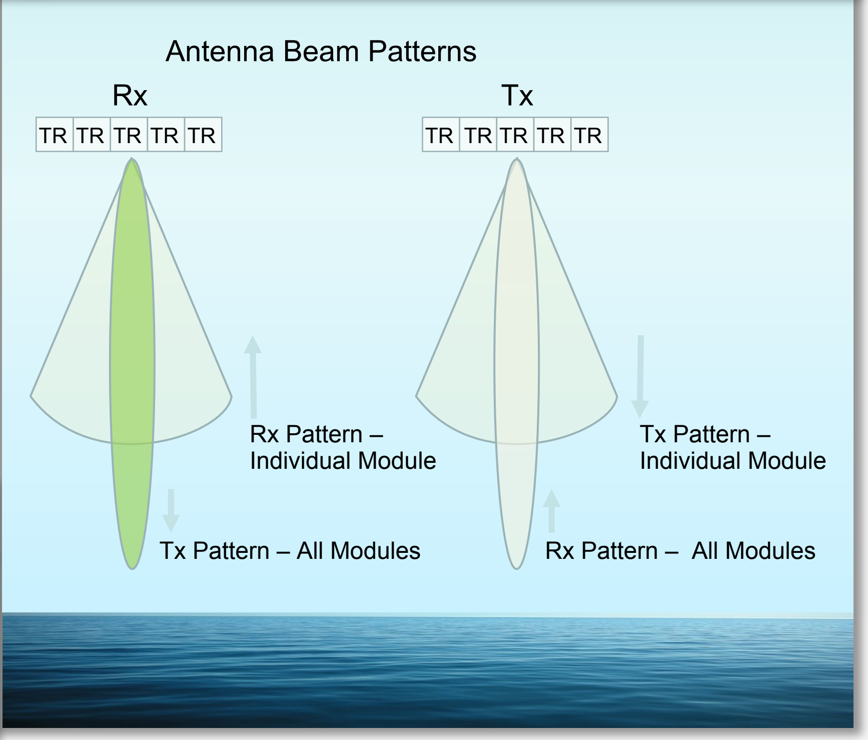


TR Module Front End



4 TR Head Count Mode (Health Check)

Antenna Beam Patterns



Other health check modes under consideration:

2 Telemetry – Metadata Modes

- Temperature , Current, Voltage
  - Trading whether at individual module or subarray level
- Phase and Amplitude Control Read-back
  - Serial phase shift and attenuator commands are read back to beam steering control unit

3 Power Up/Down Modes

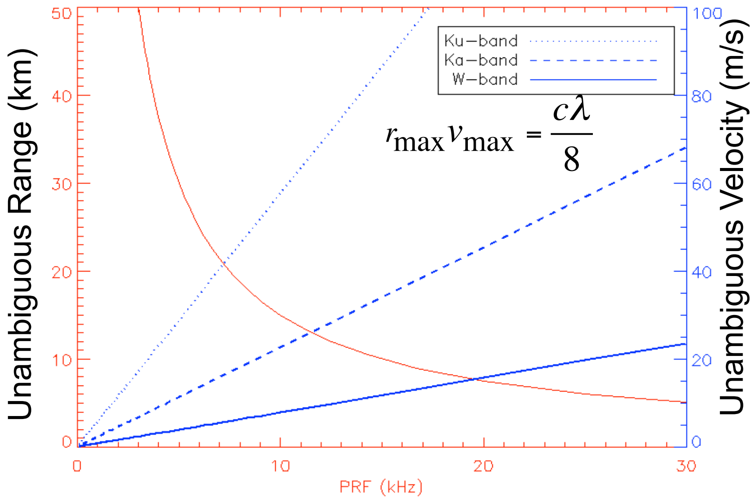
- Standby
  - TR Module powered up without TR pulsing
- All OFF Power Down
  - “zero” DC current draw

TR Module (optional) Head Count Mode

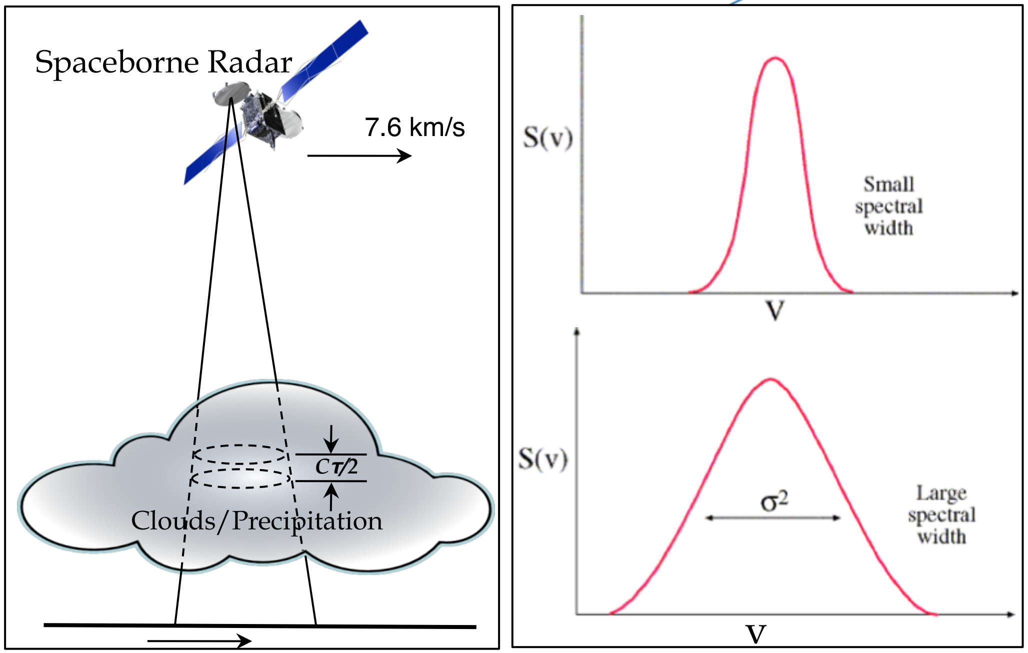
- Mutual Coupling Across Module Radiators
- Receive Noise Power Check at IF Receiver

Frequency Diversity Pulse Pair for Space-borne Doppler Measurement – Motivation

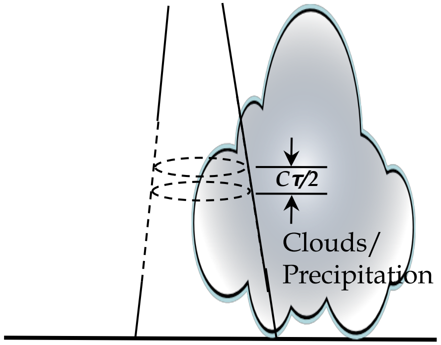
- Velocity folding and Doppler spectrum broaden due to spacecraft ground speed (7.6 km/s).
- Larger resolution volume could result in non-uniform filled beam and multi-scattering biases.
- Required $\sigma/2V_{max} < 0.3$ for good Doppler measurements ($v_{\max} = \frac{\lambda \bullet PRF}{4}$)
- Approaches:
  - large antenna: reduce σ
  - higher PRF, stagger PRF: increase V_{max}



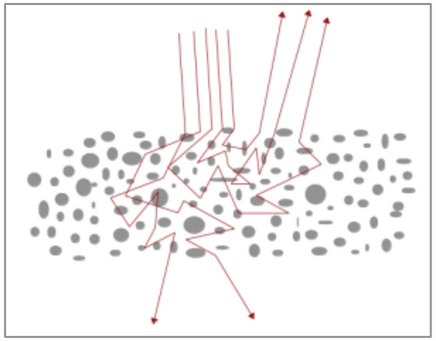
Unambiguous range & Doppler velocity versus PRF



Doppler spectrum broaden

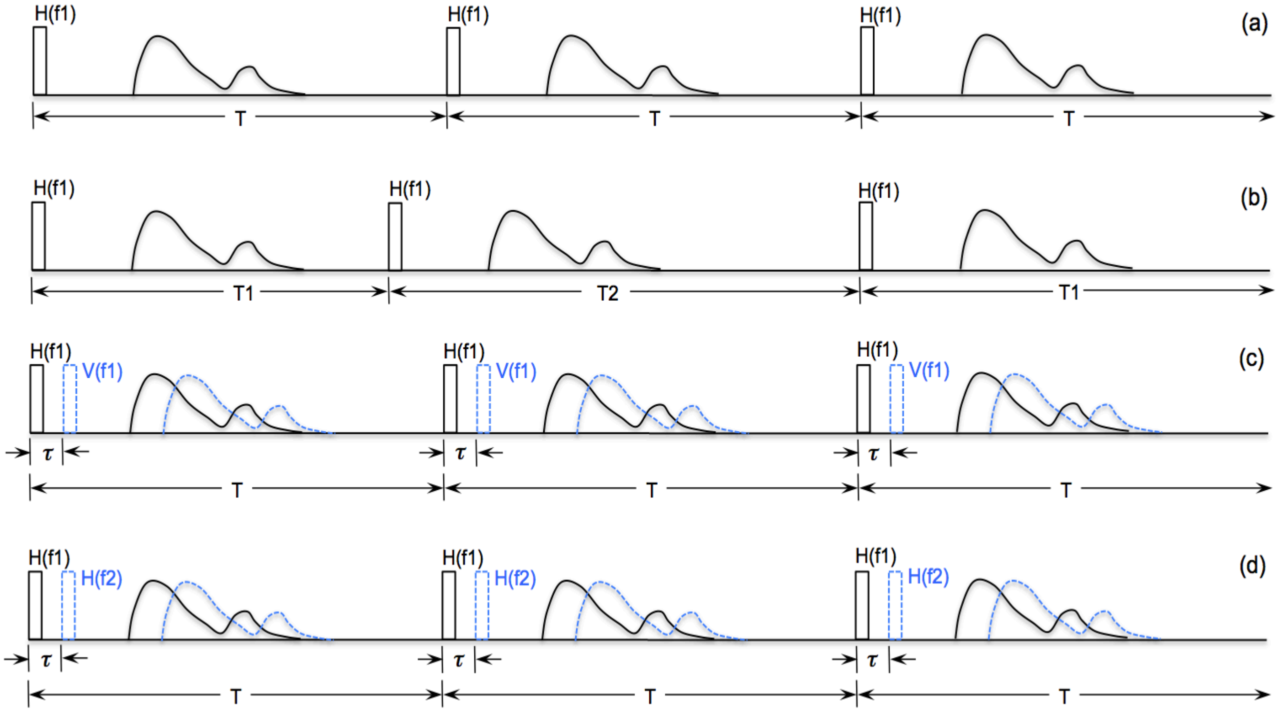


Non-uniform beam filling



Multi-scattering

Techniques to Mitigate Range-Doppler Velocity Ambiguity



Traditional Pulse-pair
(PP)

Stagger PRF Pulse-pair
(SRPP)

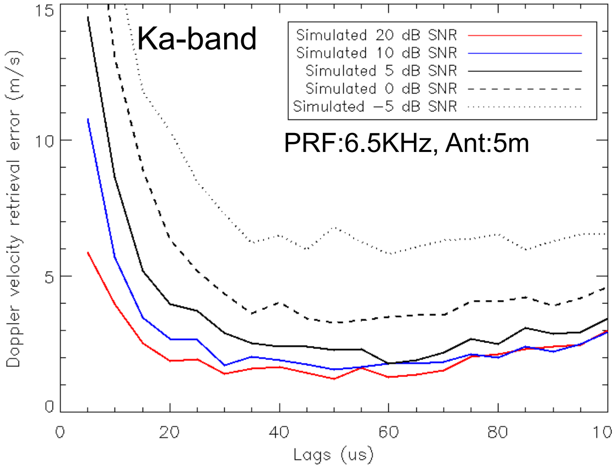
Polarization Diverse Pulse-Pair
(PDPP)

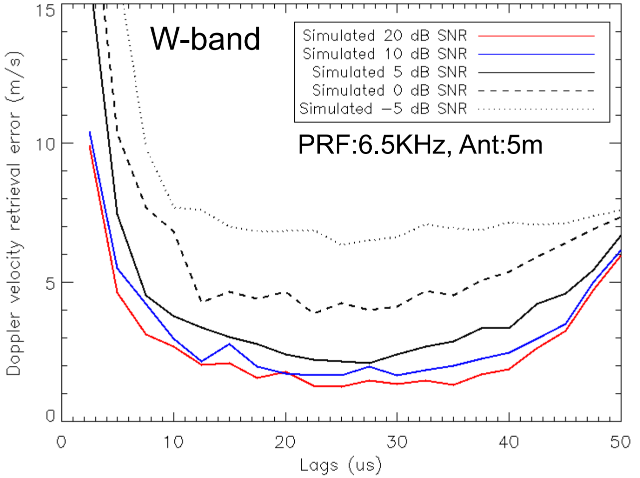
Frequency Diverse Pulse-Pair
(FDPP)

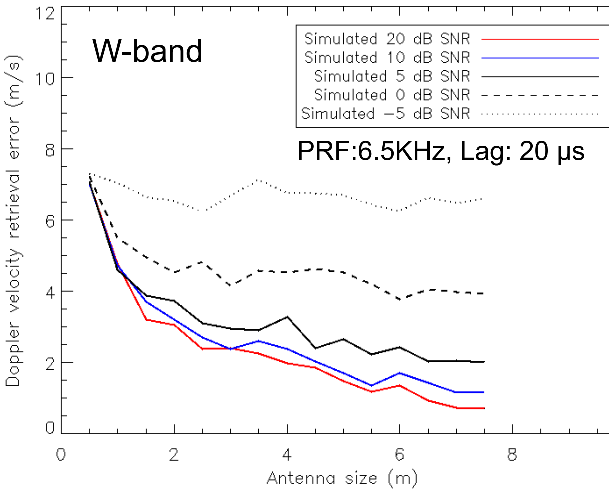
	Pulse Pair	Dual-PRT Pulse Pair	Polarization Diversity Pulse Pair	Frequency Diversity Pulse Pair
Pros	- Simple processing	- Mitigate velocity ambiguity	- Mitigate range/velocity ambiguity - High immunity to SNR	- Mitigate range/velocity ambiguity - Simple radar hardware
Cons	- Decorrellation due to spacecraft motion	- Decorrellation due to spacecraft motion	- Dual-pol Tx/Rx hardware - Poor channel isolation	- Performance at low SNR

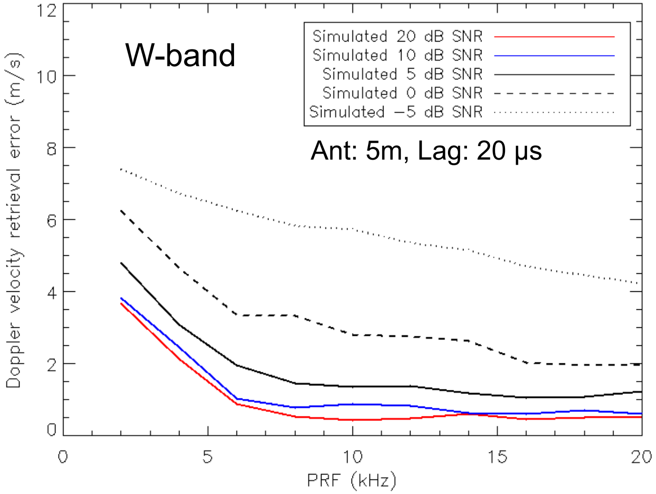
Simulated Doppler Velocity Accuracy Versus Lag Time, Antenna Size and PRF

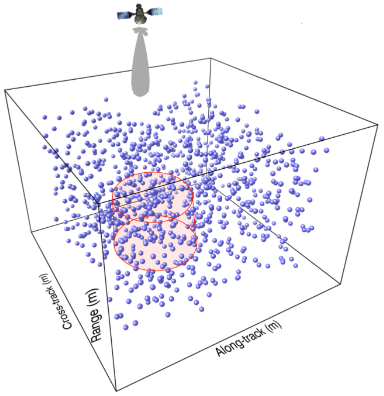
- Monte-Carlo based simulation
- Assuming scatter particle size distribution and use radar parameters to calculate backscattering power and phase
- Calculate Doppler velocity accuracy versus pulse pair lag time, antenna size, PRF, along track integration time et al.
- Preliminary results show potential to achieve ~1 m/s Doppler accuracy for Ka and W-band respectively for high SNR targets.
- More details are under study for low SNR cases.
- Roof-top test and airborne demonstration are planed.











Multi-Channel Tx Waveform Generation and Frequency Conversion Modules

Motivations:

- ACE/CaPPM radar requires multi-channel waveform generator and frequency conversion
- Use shared hardware to reduce SWaP
- Risk reduction for space

Objectives:

- Develop FPGA firmware based on a commercial module
- Support versatile waveform for pulse or pulse compression mode operation
- Develop compact, low power prototype frequency conversion module to reduce risk for space

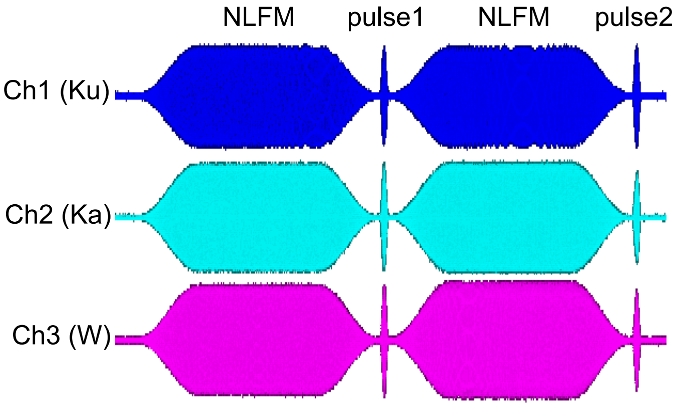
Key challenging:

- Support up to 4 pulses and chirps per PRF cycle per channel
- Use minimum bandwidth for multi pulses
- Amplitude modulation for better channel isolation in spectrum
- Minimize SNR loss due to amplitude modulation

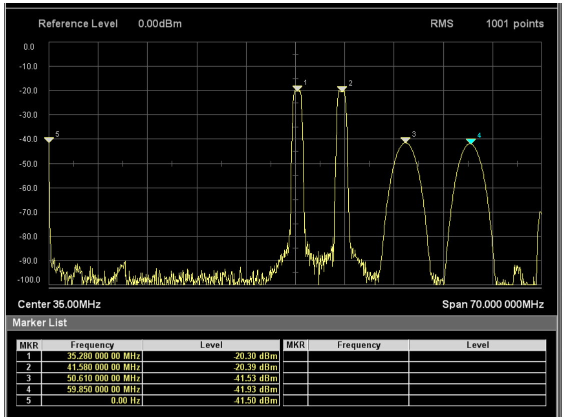
Status:

  - Channel frequency mapping, firmware development
  - Module design, simulation and part selection

Time Domain Waveforms



Frequency Domain Spectrum

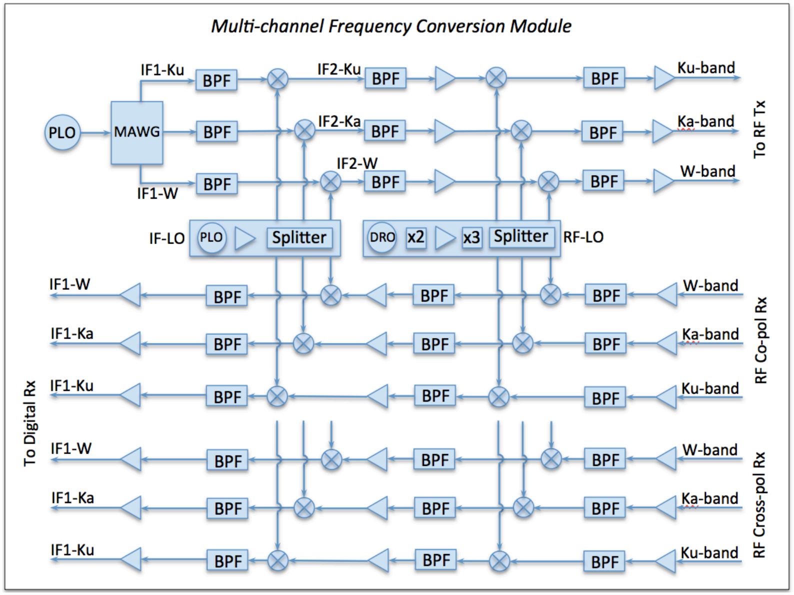


Reference Level 0.00dBm RMS 1001 points

Center 35.00MHz Span 70.000 000MHz

Marker List

MKR	Frequency	Level	MKR	Frequency	Level
1	35.280 000 00 MHz	-20.30 dBm			
2	41.580 000 00 MHz	-20.39 dBm			
3	50.610 000 00 MHz	-41.53 dBm			
4	59.850 000 00 MHz	-41.93 dBm			
5	0.00 Hz	-41.50 dBm			


Multi-channel Frequency Conversion Module

Summary and Path Forward

- Tri-band, shared-aperture antenna study
  - Evaluated 3 classes and 10 candidate architectures
  - Down selected to primary candidates supporting final mission requirements
  - Addresses various band combinations with options for W-band fixed beam and scanning
  - Includes application of proven reflectarray technologies
- Ka-band AESA T/R module development
  - Module RF and mechanical design
  - MMIC and circulator development approaching fab
  - GaN HPA MMIC design verification test underway
- FDPP Doppler measurement technique development
  - Performance simulation
  - Roof-top test is under way
  - Airborne demonstration planned during the GPM ground validation campaign - Olympex flights (Nov-Dec, 2015)
- Multi-channel waveform generation and frequency conversion
  - Developed multi-channel waveform generation firmware
  - Carried out frequency conversion module design and simulation
  - Frequency conversion module layout underway

Spaceborne Atmospheric Radar
Past, Current and Future

	TRMM	CloudSat	EarthCare	GPM		ACE (GSFC/NGES)		CaPPM (GSFC/NGES)		
Frequency (GHz)	13.8	94	94	13.6	35.6	35	94	13.6	35	94
Primary Target	Rain	Clouds	Clouds	Rain/Snow		Clouds		Clouds & precipitation		
Measurements	Reflectivity	Reflectivity	Reflectivity, Doppler	Reflectivity		Reflectivity, Doppler		Reflectivity, Doppler, & Polarimetric (option)		
Retrieval Products	Rain rate	IWC, LWC	IWC,LWC	Rain rate, particle size		IWC, LWC, particle size		IWC,LWC, particle size, rain rate, weather system dynamics		
Orbit Altitude (km)	402	720	400	407		420		420		
Transmitter	SSPA Array	EIK	EIK	SSPA Array	SSPA Array	AESA	EIK	AESA	AESA	EIK or AESA
Tx Peak Power (W)	500	1820	1800	1012	146	2000	1600	2000	2000	1600
Antenna Size (m)	2.1	1.85	2.5	2.1	0.8	2.3x3.0 to 3.0x5.0		2.3x3.0 to 3.0x5.0		
Vertical Res. (m)	250	500	500	250	250/500	250	250	250		
Horizontal Res. (km)	5.2	1.4	0.8	5.2	5.2	2.0x1.5	0.75x1.0	5.0x4.0	2.0x1.5	0.75x1.0
Cross Track Swath (km)	245	Nadir	Nadir	245	120	120	Nadir	245	120	TBD
Nadir Sensitivity (dBZ)	18	-28	-35	17	12	-14.0	-34.0	1.0	-14.0	-34
Swath Sensitivity (dBZ)	18	N/A	N/A	17	12	-11.0	N/A	4.0	-11.0	TBD
Doppler Capability	No	No	Yes	No	No	Yes	Yes	Yes	Yes	Yes
Polarimetric Capability	No	No	No	No	No	LDR	Optional	LDR	LDR	LDR