Multi-Application Smallsat Tri-band Radar - MASTR

Mauricio Sanchez Barbetty[1]
Gregory Sadowy[1]
Simone Tanelli[1]
Dalia MacWatters[1]
Kyle Stewart[1]
David Miller[2]
Chris Hermanson[2]
Ken Vanhille[2]
PJ Novak[2]
Benjamin Cannon[2]
Deepa Rajamani[2]
Jim Looney[2]
Tonda MacLeod[2]

1 Jet Propulsion Laboratory, California Institute of Technology.
2 Nuvotronics Inc.

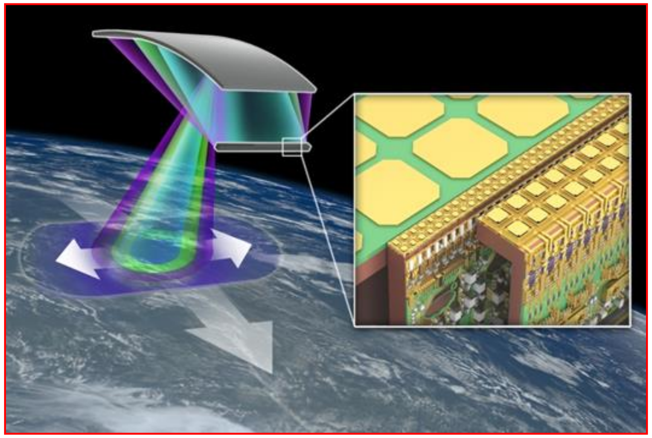
Why MASTR?

Clouds and Precipitation

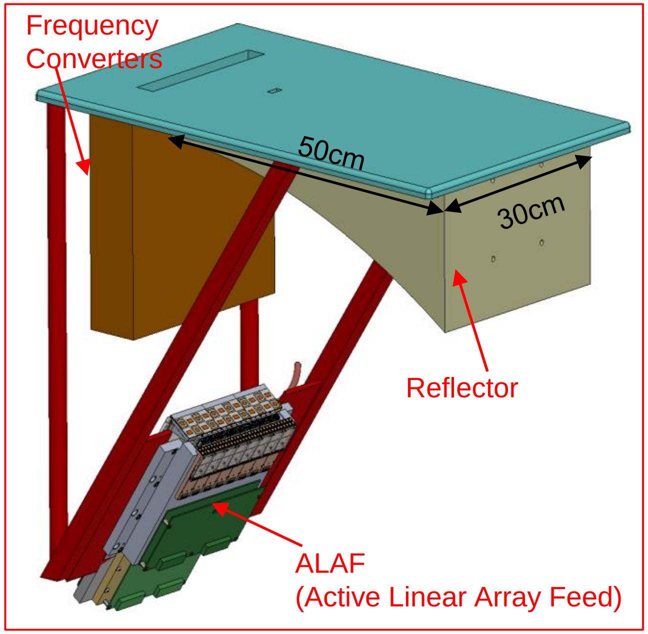
- Addressed separately by active instruments so far (i.e., TRMM, GPM & RainCube at Ku and Ka band, vs CloudSat and EarthCARE at W-band).
- Three-frequency single aperture radar enables holistic view of the cloud-precipitation process
  - e.g., J. Leinonen, et al. 2014, ACE decadal survey mission concept (Ka- / W-band), Cloud and Precipitation Processes Mission (CaPPM) concept. (Ku-, Ka-, W-band) responses to Decadal Survey 2017.
- Technology maturity over the last decade enables scanning at W-band as well as tri-band integration

Altimetry and Scatterometry

- Once an RF front end for a Ku/Ka-/W- real aperture scanning radar is available, making it suitable for other applications is possible.
  - For altimetry it is "only" a matter of opening up the bandwidth ;
  - For scatterometry more significant changes are necessary, but still possible (i.e., changing viewing geometry and tightening calibration requirements)



Space MASTR Concept
Courtesy of Nuvotronics Inc.



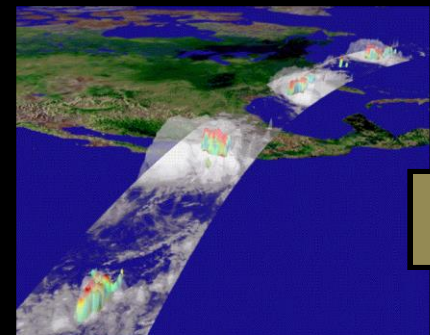
AirMASTR – Preliminary Instrument Model

MASTR is tri-band (Ku-, Ka-, W-band) **scalable** phased array radar. Designed to work as a Cloud and Precipitation Radar, an Altimeter, or a Scatterometer (in a Spinning platform). A modular, scalable architecture enables technology maturation via an airborne demonstration AirMASTR. A compact profile allows multiple implementations depending of mission requirements, power, and budget available (ranging from SmallSats to large platforms).

Spaceborne "Tropospheric Radar" landscape (2017)

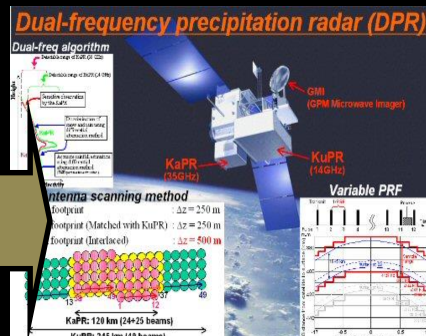
The 5 missions with Spaceborne C&P Radars

TRMM/PR – NICT/JAXA
Ku, Scanning , Tropical Rain



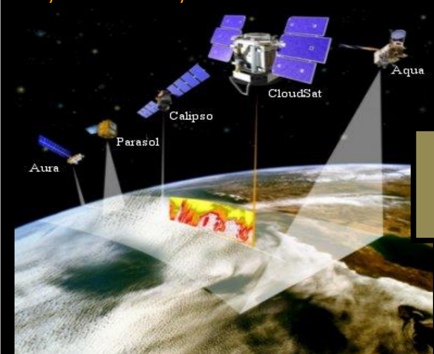
1997-2015

GPM/DPR – NICT/JAXA
Ku/Ka, Scanning, Precipitation



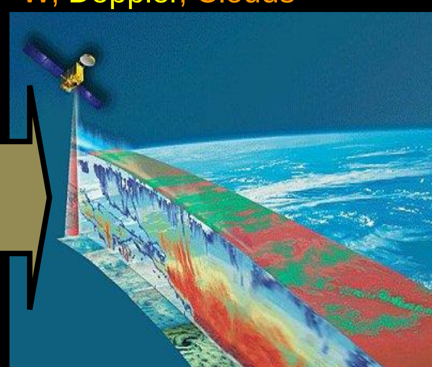
2014-Today

CloudSat/CPR
JPL/NASA/CSA
W, -30dBZ , Clouds



2006 -Today

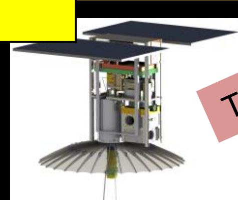
EarthCARE/CPR
NICT/JAXA
W, Doppler, Clouds



NET 2019

Next up: Launch NET Mar 2018

RainCube
JPL/NASA InVEST Tech Demo
Ka, Precipitation, 6U CubeSat



NET 2018

Temporal

Some concepts under development or proposed by the international community

PHDsat (2002)
Ka/Ku, Scanning Doppler

SnowSat / PPM
W/Ka, Doppler

Temporal

NIS (2004)
W/Ka, Scanning,
Doppler, GEO

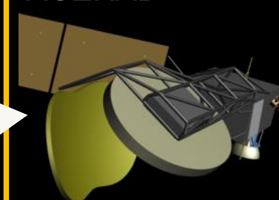
StormSat on ISS (2016)
Ka/, DPCA Doppler

Dynamics

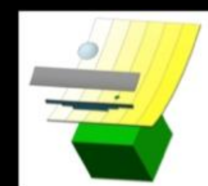
ES DS 2007:
ACE Mission Concept Radar
Ka/W, Doppler, Scanning (Ka)

Wide Swath Winds
W Conical Scanning

ACERAD



ReflectArray ACE radar



Water Vapor in Cloud

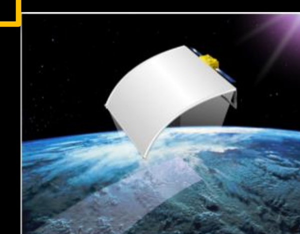
VIPR
183 GHz line
Water Vapor

StereoRadar
Dual Beam

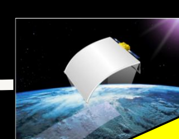
Precip Mapping

Scanning W on ISS
W Scanning
Wide Swath
Ka/Ku Scanning

ED DS 2017:
CaPPM 3CPR
Ku/Ka/W, all Doppler,
all Scanning



IIP 2016: MASTR
Ku/Ka/W, Scanning,
SmallSat



New Entry

ES DS 2017:
Radar Constellation
Core S/C: Ku/Ka/W,
Trains: RainCube

Recent GPM/ACE joint Experiments

The **ACE Science Working Group** and **GPM ground validation program** have successfully completed two joint projects where **multi frequency cloud-precipitation radar** data were acquired:

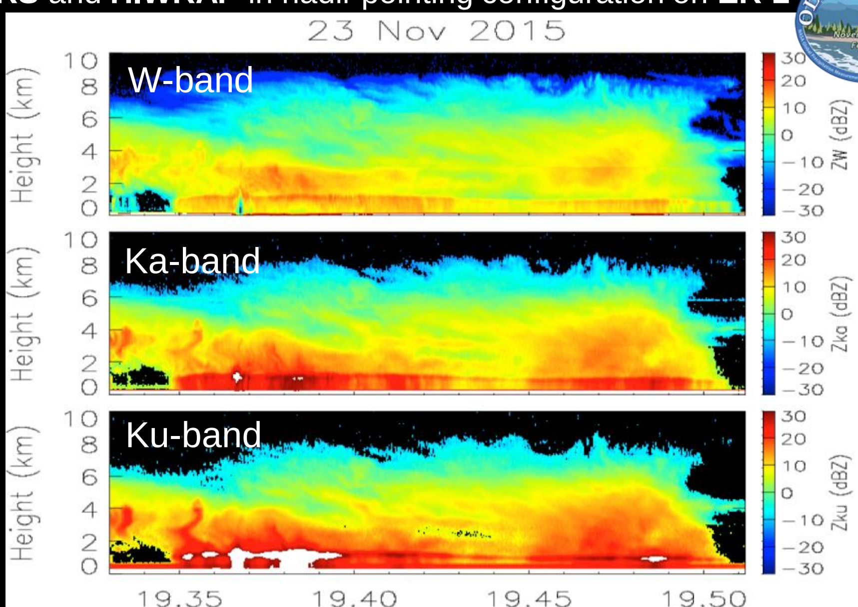
- **IPHEX/RADEX'14**, N. Carolina, May/Jun 2014
- **OLYMPEX/RADEX'15**, Washington, Nov/Dec 2015.

W. Petersen, M. Schwaller, J. Mace, R. Marchand. A. Barros, R. Houze, L. McMurdie and many others.

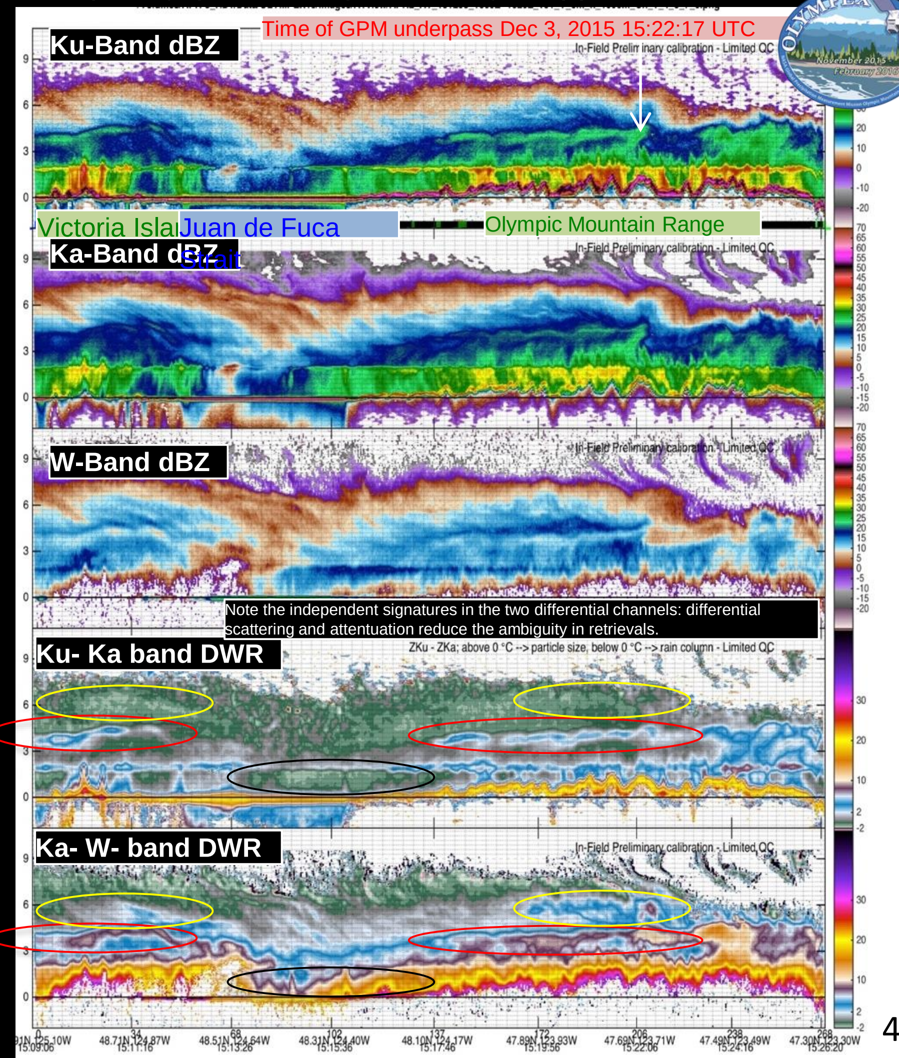
- GPM exploits the multi frequency radar data to better constrain the validation of GPM retrievals.
- ACE seeks to demonstrate and refine the definition of the radar for the ACE mission.

The radar measurements acquired from both the DC-8 and the ER-2 are proxies to the ACE/CCP radar observables. Ground based radar measurements provided complementary view.

CRS and **HIWRAP** in nadir pointing configuration on **ER-2**

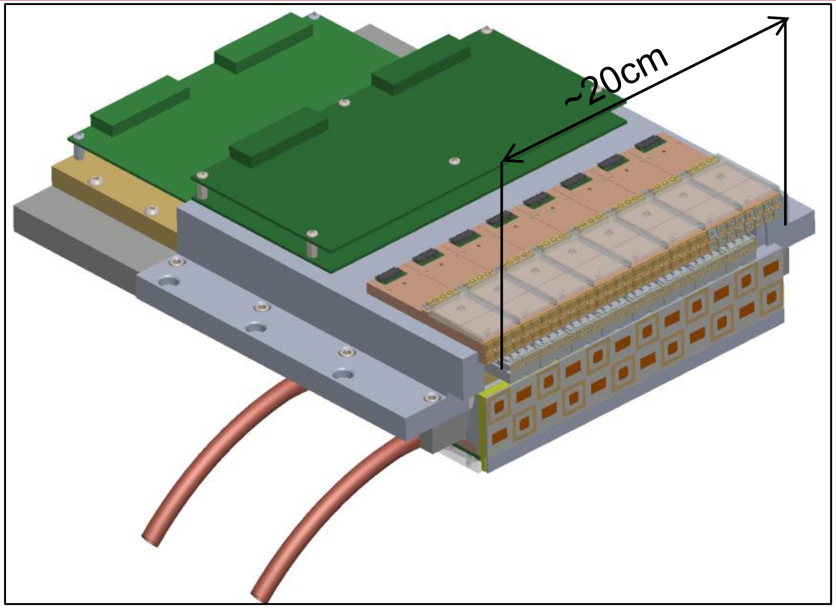


APR-3 on DC-8 (ESTO/AITT Program) is the first 3-frequency (Ku, Ka, W), scanning, Doppler, airborne radar

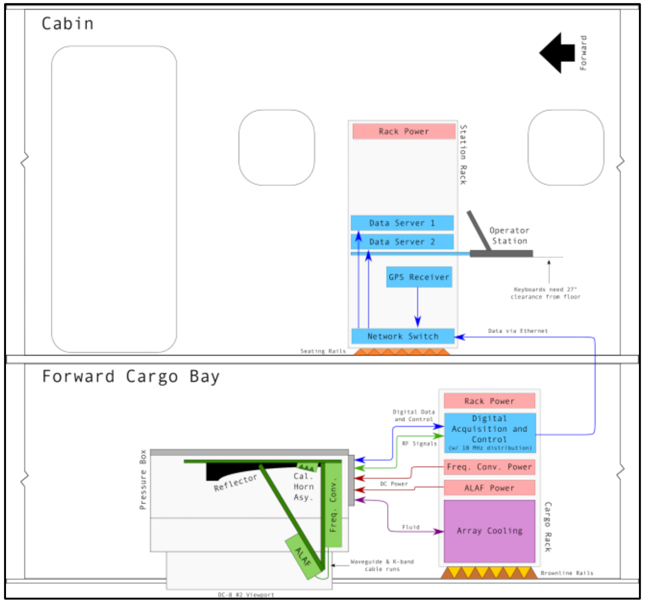


AirMASTR Instrument overview

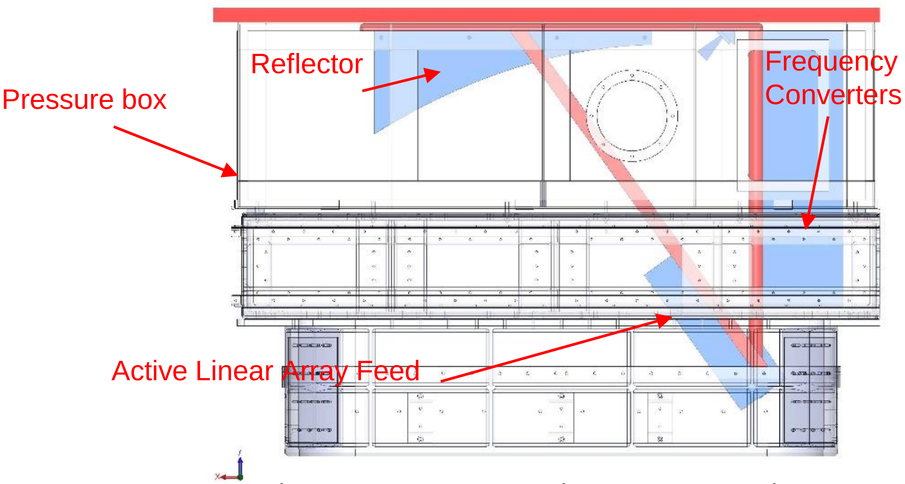
- Airborne demonstration of MASTR using fewer tiles. TX power per element and tile design are essentially the same as MASTR.
- AirMASTR will be capable of Ku/Ka/W-band cross-track scanning, Doppler, and polarimetry.
- Reflector size 30cmx50cm.
- Transmit RF peak power
  - W-band: 64W
  - Ka-band: 160W
  - Ku-band: 240W
- Direct frequency conversion and baseband digital electronics based on RainCube.



Tri-band Active Linear Array Feed (ALAF)
Courtesy of Nuvotronics Inc.



AirMASTR layout in DC8 aircraft

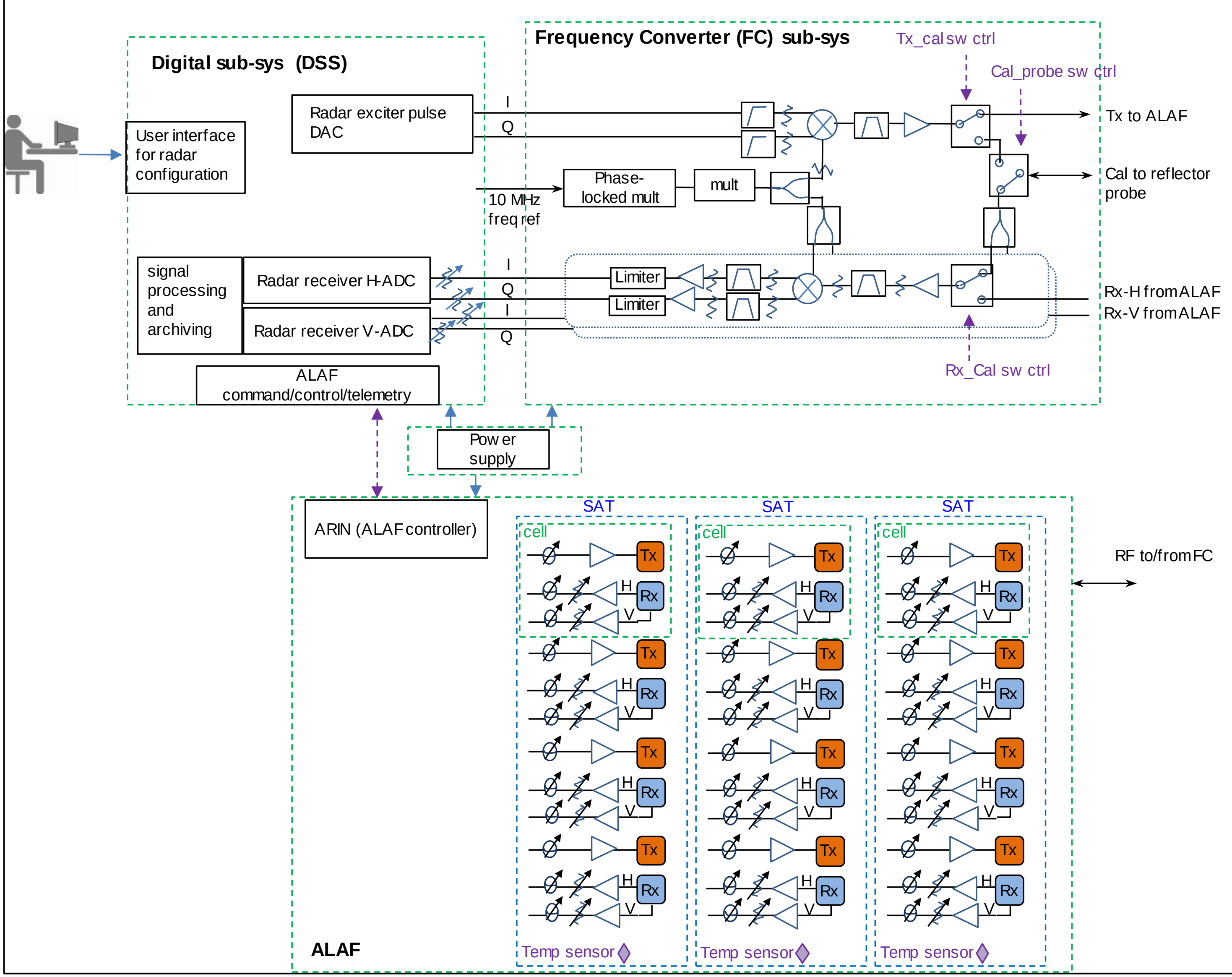


AirMASTR components in DC8 pressure box

AirMASTR Architecture

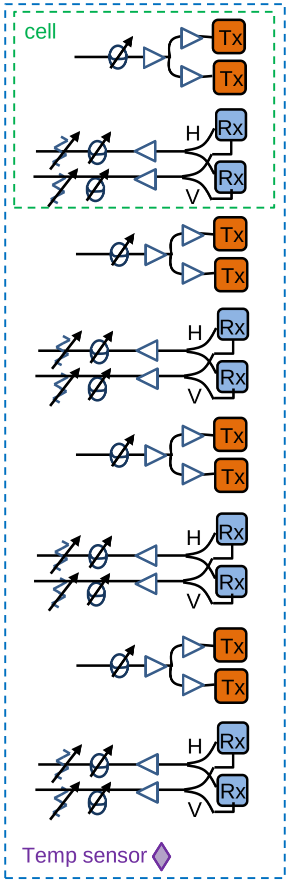
- Baseband IQ
- Single stage up/down conversion, inherited from Raincube.
- Active Linear Array Feeds in close proximity at the focal plane of a parabolic reflector provide cross track scanning.
- System capable to high bandwidth (<300MHz) for Altimetry.
- Each band is independent, allowing implementations with subset of the band (e.g. Only Ku and W).
- Analog beamforming solution.

AirMASTR interfaces block diagram (common to the 3 bands, shown for Ku)

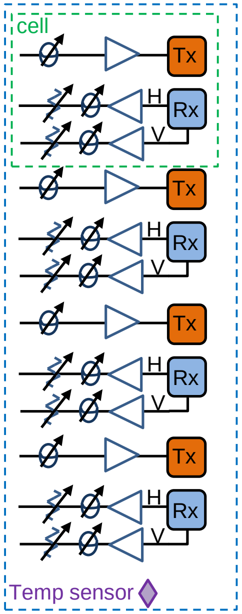


AirMASTR antenna SAT/cell topology

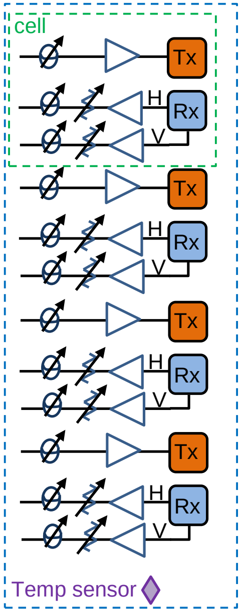
W-SAT (8 SAT's, 32 cells total)



Ka-SAT (8 SAT's, 32 cells total)

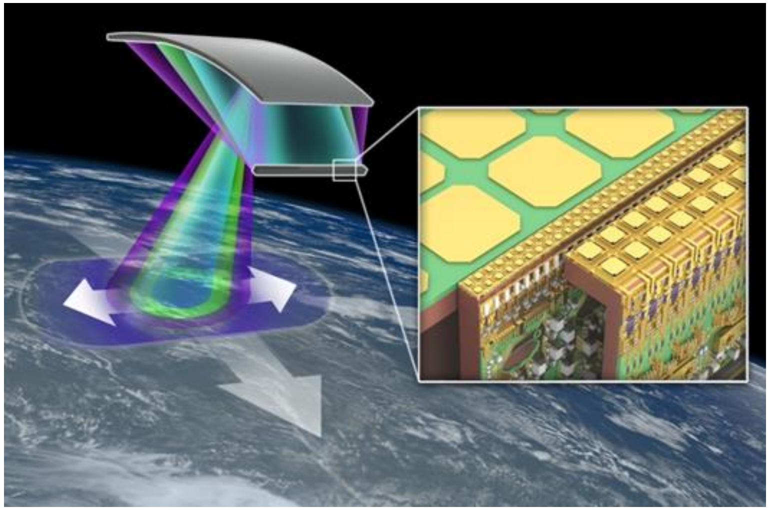


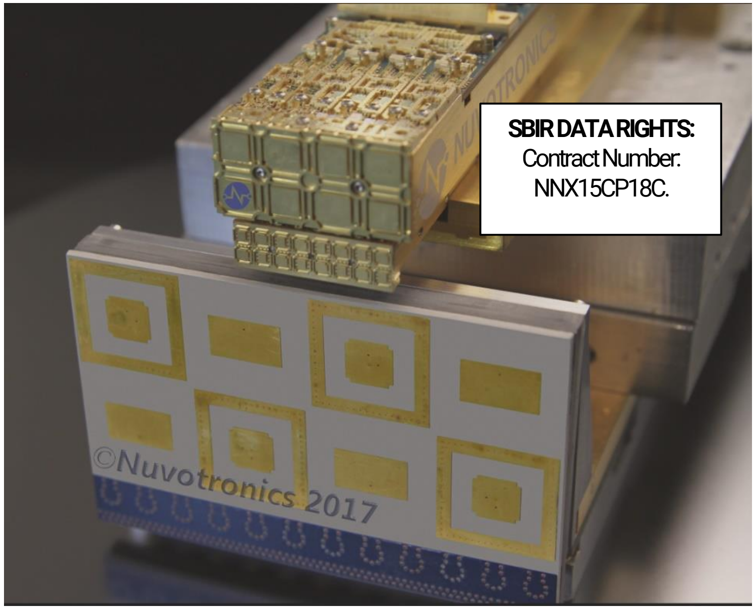
Ku-SAT (3 SAT's, 12 cells total)



Nuvotronics' MASTR Involvement

- Multi-band cloud and precipitation radar identified in latest decadal survey as a high-priority earth-science observation
- Nuvotronics has supported JPL over several years to develop demonstration hardware for front-end radar modules in support of possible JPL instrument architectures





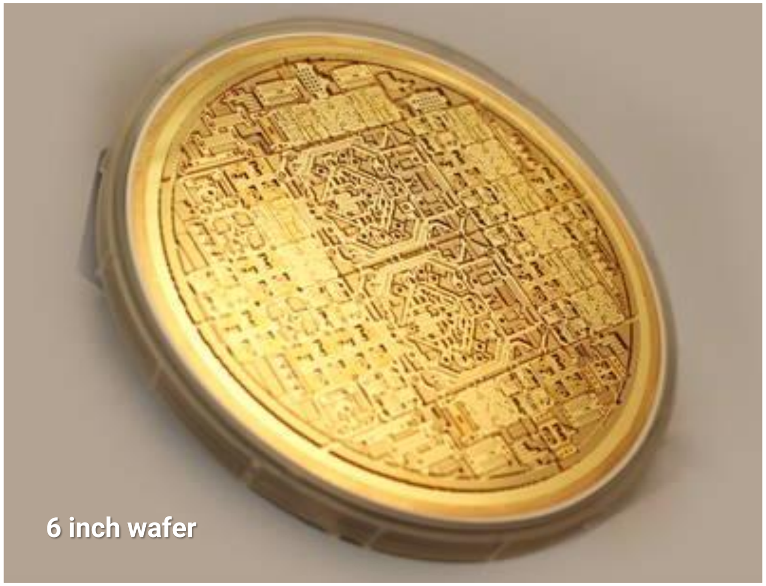
- Nuvotronics' MASTR-specific involvement includes:
  - W-band T/R modules delivered under JPL-led 3CPR IIP project (2013 IIP award) and SBIR Phase II Enhanced project
  - Ku-band T/R modules under development with current MASTR effort
  - Ka-band T/R modules under development with current MASTR effort
  - High-level, front-end integration study

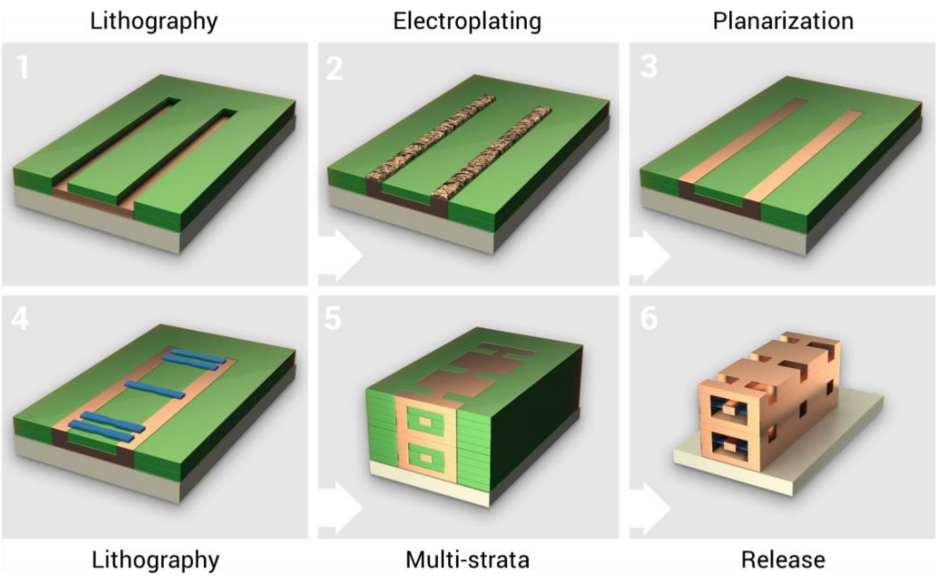
Nuvotronics, Inc. Overview

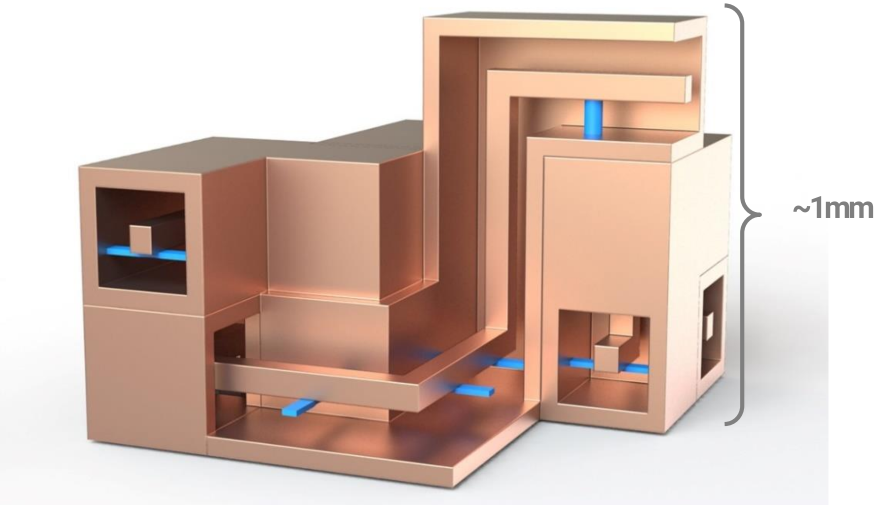
- Focused on delivering microwave and mm-wave products for government applications
  - Shipping products to government and commercial customers
  - Fabrication process also capable of microfluidic devices, thermal management and mechanical devices
- Privately-held small business
- Design, Fabrication / Manufacturing and Test capabilities
- R&D, including SBIR work remains a portion of our business
- AS9100 Certified

The PolyStrata® Fabrication Process

- Compact & precise 3D air-dielectric coaxial circuits
- Wafer-level batch processing
- Low cost and optimum part to part repeatability
- Micron-scale tolerances in all three axes
- Low RF loss and high isolation from DC to > 100 GHz

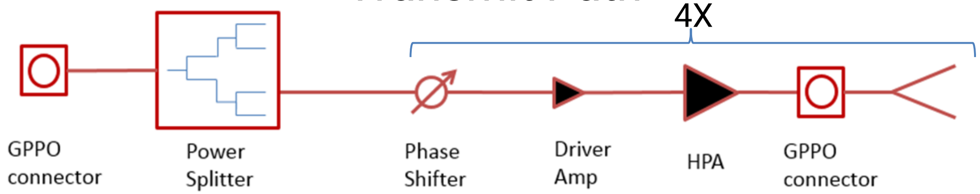




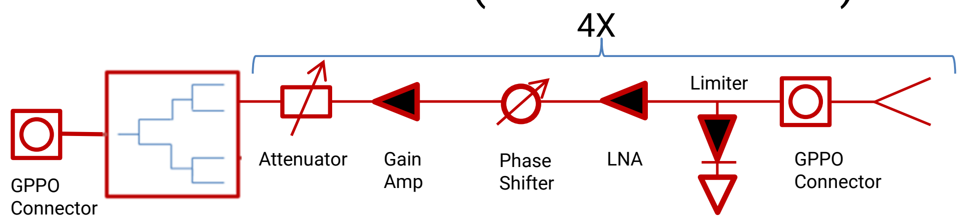


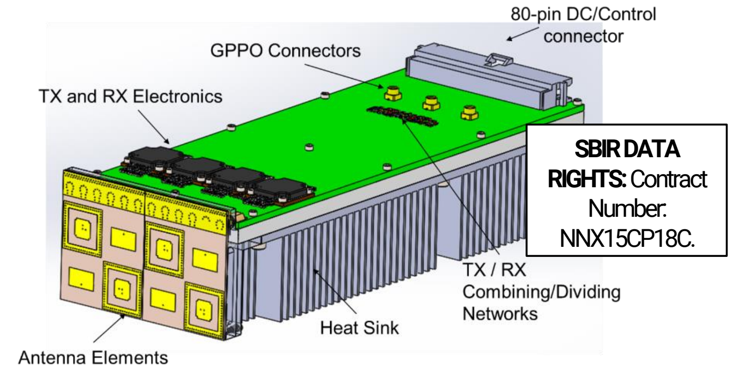
Ku-band Scanning Array Tile (SAT) Front-End Module

Transmit Path



Receive Path (X 2 Polarizations)

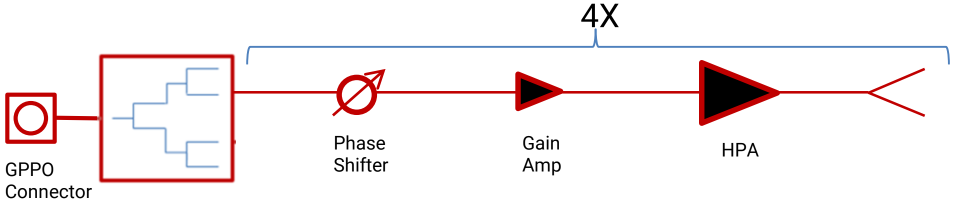




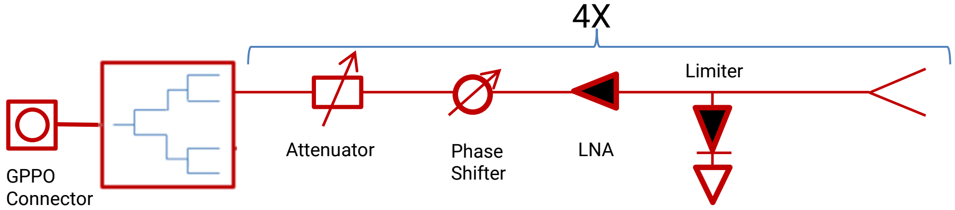
Description	Value	Unit	Spec Type	Details
Frequency	13.6	GHz	typical	
Tx elements	4		nominal	
Rx elements	4		nominal	
Tx power	+43	dBm	typical	Peak per element
Tx duty cycle	10	%	maximum	pulsed drain current
Tx polarization	1	horizontal	nominal	
Rx polarization	2	horizontal; vertical	nominal	simultaneous operation
Rx noise figure	4.5	dB	maximum	each channel
Size	64 x 44 x 175	mm	maximum	W x H x L

Ka-band Scanning Array Tile (SAT) Front-End Module

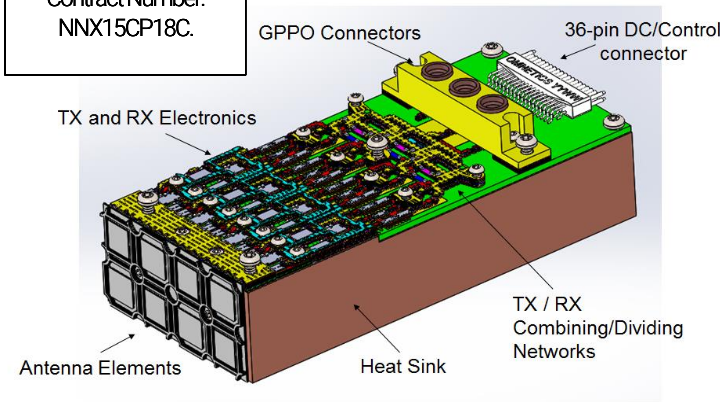
Transmit Path



Receive Path (X 2 Polarizations)



SBIR DATA RIGHTS:
Contract Number:
NNX15CP18C.



Description	Value	Unit	Spec Type	Details
Frequency	35.75	GHz	typical	
Tx elements	4		nominal	
Rx elements	4		nominal	
Tx power	+36.7	dBm	typical	peak per element
Tx duty cycle	10	%	maximum	pulsed drain current
Tx polarization	1	horizontal	nominal	
Rx polarization	2	horizontal; vertical	nominal	simultaneous operation
Rx noise figure	4	dB	maximum	each channel
Size	23.6 x 16 x 54	mm	maximum	W x H x L

Design Improvements Compared to SBIR Assemblies

- Ku Critical Design Objectives
  - Manage Stack Up Tolerances
  - Ease of Assembly
  - Minimize Signal Interference
  - Follow updated PCB design guidelines
  - Optimize Noise Figure performance
  - Follow methodical change control practices

- Design Modifications to Ku SAT include
  1. Design for Assembly Improvements
  2. Design for Diagnostics & Repair
  3. Noise Figure improvements

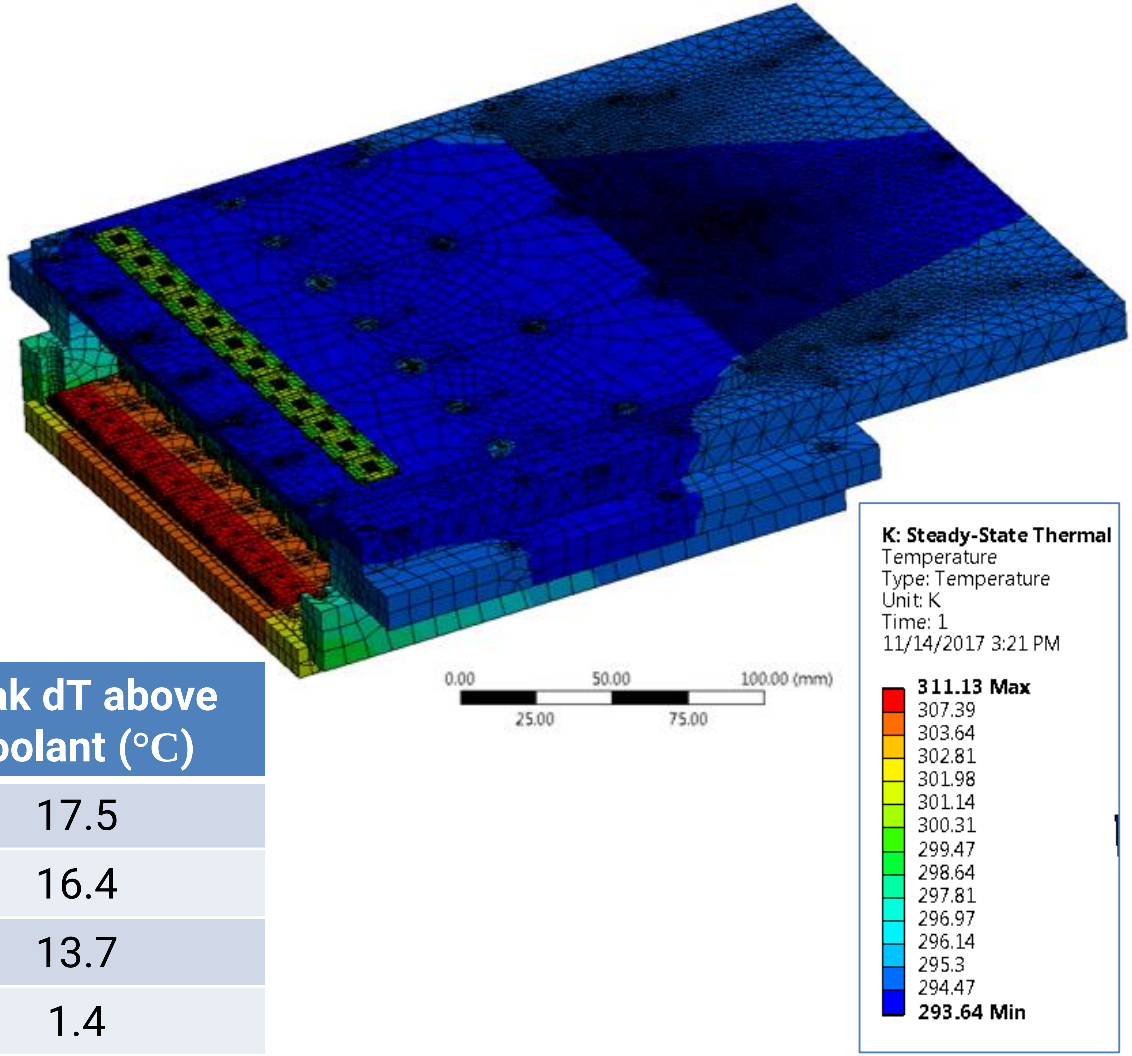
- Ka Critical Design Objectives
  - Efficient & low cost wire bonding operation
  - High yield for wire bonds
  - Easily of Assembly
  - Design for Analysis/Repair
  - Minimize the cost of testing
  - Avoid signal interference
  - Improve Noise Figure performance
  - Robust DC Connections - PS to board
  - Enable electronic testing of Ka Module

- Design Modifications to KA SAT include
  1. Design for Assembly Improvements
  2. Design for Test, Diagnostics & Repair
  3. Noise Figure improvements

Initial Ku-band and Ka-band front-end modules were built on a previous SBIR contract. Lessons learned have been incorporated in these MASTR designs.

Estimated ALAF Temperature Map

- Temperature rise estimates based on thermal load estimates determined by IC efficiency, location and operation modes.
- Isothermal boundary condition in coolant tube = 293.6K
- Peak temperature rise of all metal structures is 17.5°C



Component	Peak dT above Coolant (°C)
Ku SAT	17.5
W SAT	16.4
Ka SAT	13.7
Cold Plate	1.4
Waveguide Combiner	3.9

AirMASTR Development Status

- Instrument architecture completed and subsystems requirements documents generated.
- Scanning Array Tiles
  - W-band delivered.
  - Design revision completed for Ku-band and Ka-band.
  - Currently manufacturing polystrata pieces.
- Active Linear Array Feeds
  - Ku/Ka Band: Timing, control, RF Performance, Power, and Mechanical requirements all defined. Subcontract in work.
  - W-band: Under development by 3CPR-IIP, P.I. G. Sadowy
- Digital subsystem:
  - Designed under subcontract with Remote Sensing Solutions. Delivery on fall 2018.
- Frequency converters:
  - Requirements document released. Currently competing subcontract.
- I&T and Instrument accommodation
  - Working with DC8 team on requirements and resources.
- Planning first flight for November 2019.

THE END

Thank you for your attention

Questions?

Acknowledgement: This research was carried out in part at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

Thanks to NASA ESTO IIP and ACT programs, NASA SBIR and JPL R&TD and CIF programs for supporting this work and work that lead to the current status of this project.

Thanks to Nuvotronics for developing the W-band, Ka-band, and Ku-band modules that have made MASTR possible, and for its developing innovative microwave and mm-wave technologies.

Thanks to Remote Sensing Solutions for the development of the digital subsystem.

BACKUP SLIDES TO FOLLOW

MASTR vs the Decadal Survey

Targeted Observable	Science/Applications Summary	Candidate Measurement Approach	Designated	Explorer	Incubation
Aerosols	**Aerosol properties, aerosol vertical profiles, and cloud properties** to understand their effects on climate and air quality	Backscatter lidar and multi-channel/multi-angle/polarization imaging radiometer flown together on the same platform	X		
Clouds, Convection, and Precipitation	**Coupled cloud-precipitation state and dynamics** for monitoring global hydrological cycle and understanding contributing processes including cloud feedback	Radar(s), with multi-frequency passive microwave and sub-mm radiometer	X		
Mass Change	**Large-scale Earth dynamics** measured by the changing mass distribution within and between the Earth's atmosphere, oceans, ground water, and ice sheets	Spacecraft ranging measurement of gravity anomaly	X		
Surface Biology and Geology	**Earth surface geology and biology,** ground/water temperature, snow reflectivity, active geologic processes, vegetation traits and algal biomass	Hyperspectral imagery in the visible and shortwave infrared, multi- or hyperspectral imagery in the thermal IR	X		
Surface Deformation and Change	**Earth surface dynamics** from earthquakes and landslides to ice sheets and permafrost	Interferometric Synthetic Aperture Radar (InSAR) with ionospheric correction	X		
Greenhouse Gases	**CO_2 and methane fluxes and trends,** global and regional with quantification of point sources and identification of sources and sinks	Multispectral short wave IR and thermal IR sounders; or lidar**		X	
Ice Elevation	**Global ice characterization** including elevation change of land ice to assess sea level contributions and freeboard height of sea ice to assess sea ice/ocean/atmosphere interaction	Lidar**		X	
Ocean Surface Winds and Currents	**Coincident high-accuracy currents and vector winds** to assess air-sea momentum exchange and to infer upwelling, upper ocean mixing, and sea-ice drift	Doppler scatterometer		X	
Ozone and Trace Gases	**Vertical profiles of ozone and trace gases** (including water vapor, CO, NO_2, methane, and N_2O) globally and with high spatial resolution	UV/Vis/IR microwave limb/nadir sounding and UV/Vis/IR solar/stellar occultation		X	
Snow Depth and Snow Water Equivalent	**Snow depth and snow water equivalent** including high spatial resolution in mountain areas	Radar (Ka/Ku band) altimeter; or lidar**		X	
Terrestrial Ecosystem Structure	**3D structure of terrestrial ecosystem** including forest canopy and above ground biomass and changes in above ground carbon	Lidar**		X	

IDEAL
(Baseline for W-4a)

Direct CONTRIBUTION

Indirect CONTRIBUTION

	stock from processes such as deforestation and forest degradation				
Atmospheric Winds	**3D winds in troposphere/PBL** for transport of pollutants/carbon/aerosol and water vapor, wind energy, cloud dynamics and convection, and large-scale circulation	Active sensing (lidar, radar, scatterometer); passive imagery or radiometry-based atmos. motion vectors (AMVs) tracking; or lidar**		X	X
Planetary Boundary Layer	**Diurnal 3D PBL thermodynamic properties and 2D PBL structure** to understand the impact of PBL processes on weather and AQ through high vertical and temporal profiling of PBL temperature, moisture and heights	Microwave, hyperspectral IR sounder(s) (e.g., in geo or small sat constellation), GPS radio occultation for diurnal PBL temperature and humidity and heights; water vapor profiling DIAL lidar; and lidar** for PBL height			X
Surface Topography and Vegetation	**High-resolution global topography** including bare surface land topography ice topography, vegetation structure, and shallow water bathymetry	Radar; or lidar**			X

** Could potentially be addressed by a multi-function lidar designed to address two or more of the Targeted Observables

Other ESAS 2017 Targeted Observables, not Allocated to a Flight Program Element

Aquatic Biogeochemistry	**Radiance Intercalibration**
Magnetic Field Changes	**Sea Surface Salinity**
Ocean Ecosystem Structure	**Soil Moisture**

Credit: ESAS 2017

MASTR vs the Decadal Survey : the W-4a Objective

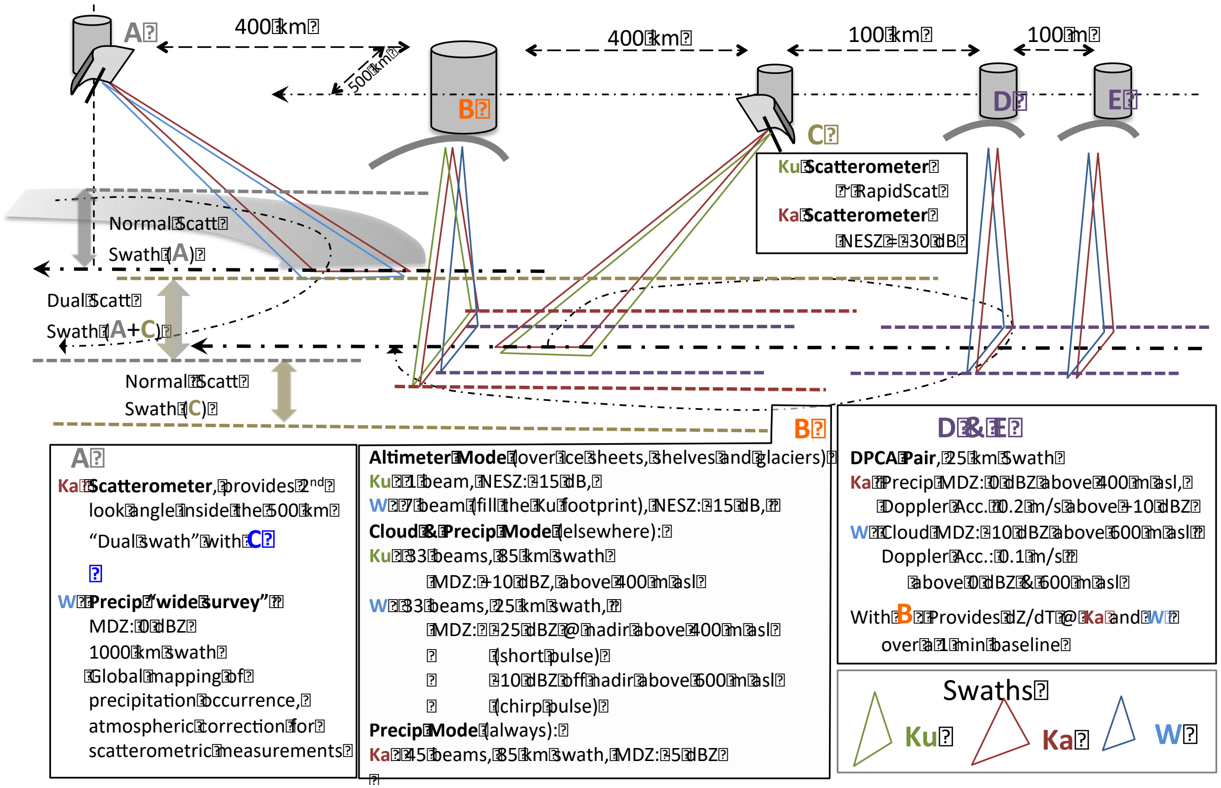
Objective W-4a: Measure the vertical motion within deep convection to within 1 m/s and heavy precipitation rates to within 1 mm/hour to improve model representation of extreme precipitation and to determine convective transport and redistribution of mass, moisture, momentum, and chemical species.

"An example baseline radar system would include a three-frequency system centered upon scanning Ku, Ka and W-band (e.g. 13, 35 and 94 GHz) radars,
with Doppler capability at all frequencies.
Addressing this objective requires measurement of particle vertical velocities ideally with ~20 cm/sec accuracy or better in cloud and stratiform precipitation,
and at least 50 cm/s accuracy inside deep convection.
Radar reflectivity of ice particles should be measured with a sensitivity of approximately -30 dBZ in cloud and -10 dBZ in precipitation.
The mean particle diameter estimated from multi-frequency reflectivity observations can be used to estimate the terminal fall speed and density and habit.
Measurements should be acquired at a vertical resolution of at least 250 m to resolve the vertical structure in the storm, and a horizontal resolution of 1 km in cloud and light precipitation. A horizontal resolution of 2 km is preferred to resolve convection. All measurements are to be acquired over a swath of a few tens of km to sufficiently cover the convective-scale storm system."

Credit : ESAS 2017

	Baseline Example	MASTR	Minimum Configuration @ 400 km
Frequency	Ku, Ka and W	✓	
All scanning		✓	
All Doppler		✓	
	20 cm/s in stratiform	✓	3 m single or 1 m DPCA (@ nadir)
	50 cm/s in convection	✓	3 m single or 1 m DPCA (@ nadir)
Sensitivity			
	-10 dBZ in precip	✓	2 m (@ nadir) or 3 m (@ swath)
	-30 dBZ in cloud	✓	2 m (@ nadir) or 3 m (@ swath)
Vertical Resolution	250 m	✓	
Horizontal Res.			
	1 km in cloud	✓	1.5 m
	2 km in convection	✓	2 m
Swath	A few tens of Km	✓	

Relevance and Vision



[…] we focused on an architecture that emphasized *time-sharing* and *design-sharing*. It was observed that measurement approaches requiring *simultaneous* acquisition of different sensor data for multiple applications using the same instrument quickly lead to complex designs, with correspondingly large size, weight and power (SWaP), and/or a requirement for technologies that are not yet mature. A different approach is to seek a design that does not acquire all measurements simultaneously but is capable of addressing all objectives sequentially in a *time-sharing approach*. Furthermore, the recent rapid evolution of SmallSats and low-cost access to space can be best exploited by architectures that utilize multiple instrument configurations each comprised of the same modular hardware. Here, a specific configuration is chosen to optimize the sensor for different objectives while using the same electronics designs, termed a *design-sharing approach*. ***MASTR adopts both time-sharing and design-sharing to provide the flexibility of tailoring the instrument design to a range of science applications while minimizing instrument electronics NRE, spacecraft and launch costs.***

MASTR as "Team Player"

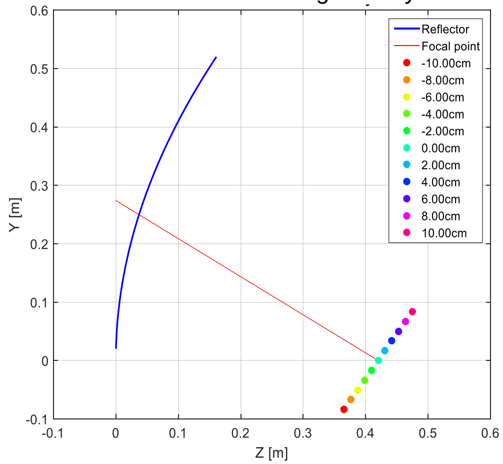
MASTR architecture is very well suited to leverage on POR or contributions from other agencies/nations because it is <u>really</u> modular and scalable.

DISCLAIMER: All of the examples below are only examples to convey the flexibility – they are not point designs or options already agreed upon by anyone, some, in fact don't even make sense from a timeline point of view.

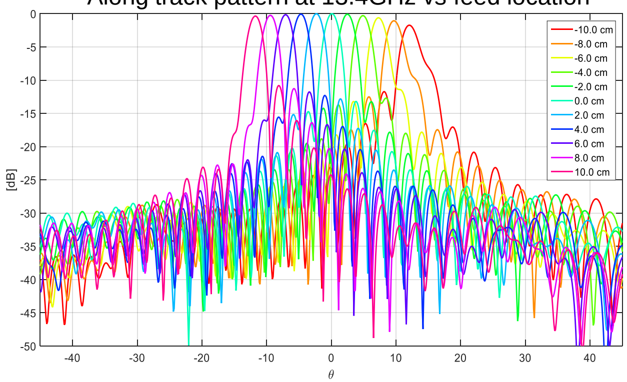
1. **Fly in formation with GPM/DPR to complement it as "light precipitation detector"?**
   1. **→ 1m MASTR with only Ka and W band implemented on a small sat (ESPA class)**
2. **Fly in formation with EarthCARE CPR to observe moderate precipitation and Doppler in Convection when in the Tropics and ice/snow extent and height/depth when in polar regions?**
   1. **→ 2m MASTR with only Ku and W implemented on a CloudSat-class bus (i.e., BCP 2000)**
      Switch between Precipitation Mode and Cryo-Altimetry Mode at seasonally prescribed latitudes.
3. **Fly in the context of an Asian constellation of Ku-band Small-Sat radars (being considered by JAXA) to observe the vertical fluxes in tropical convection?**
   1. **→ a low inclination train with three 1m MASTR (ESPA class) with only Ka and W, two of them in DPCA autonomous formation flying and one trailing them by 90 seconds to observe the change in storm structure at the convective time scale.**
      Note: the pair of MASTR DPCA could be replaced by a pair of RainCube DPCA for cost savings, accepting some loss in capability (i.e., no scanning).
4. **Fly in formation with the Aerosol TO Lidar to achieve only the Aerosol-Cloud components ?**
   1. **→ MASTR 3 m with W-band only, in loose formation similar to CloudSat/CALIPSO: formation flying requirements reduced and radar-lidar product quality improved because of the W-band swath (as opposed to nadir-only), high accuracy Doppler pursued only in the nadir beam, but meets the -30 dBZ sensitivity over a swath of 10-20 km.**
5. **Fly in smart-formation with a wide swath radiometer leading the train and target the MASTR narrow swath (as informed by the radiometer) to focus on weather of interest?**
6. **Fly in formation with a SmallSat SAR for multi-wavelength surface state observations?**
7. **…**

Antenna Reflector Scaling and Feed Displacement

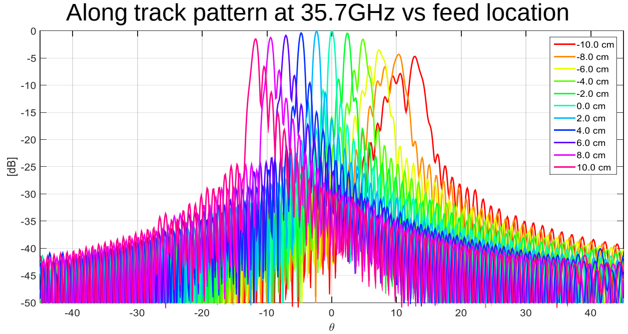
Side view of feed geometry

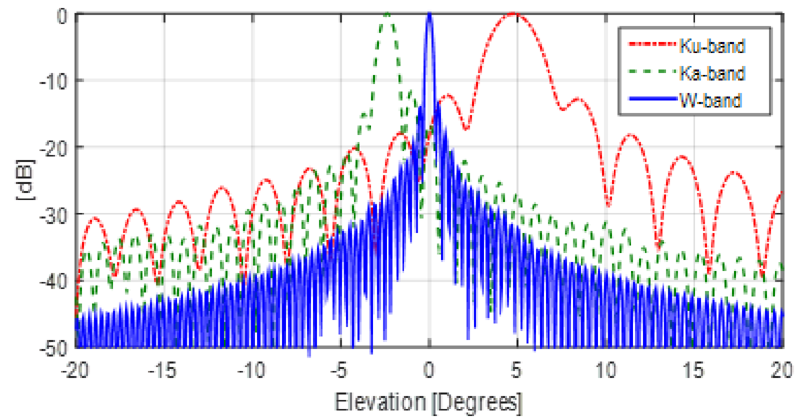


Along track pattern at 13.4GHz vs feed location

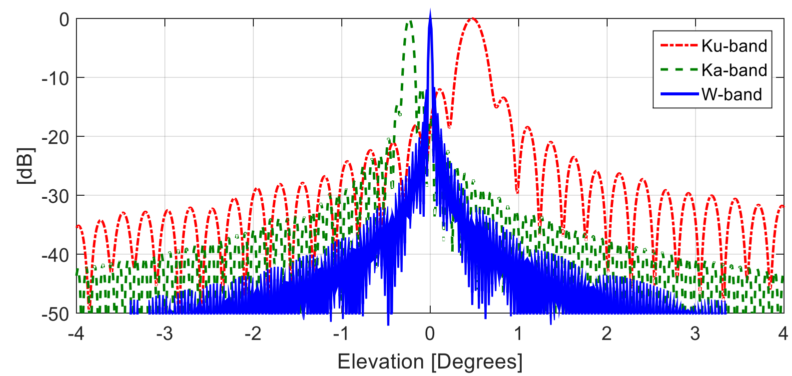


Along track pattern at 35.7GHz vs feed location





Along Track Radiation Pattern of Airborne Concept (50cm)



Along Track Radiation Pattern of Spaceborne Concept (5m)

In both cases the W-band feed is at the focal point of the reflector, the Ka-band displace 2cm in one direction and the Ku-band displaced 4cm in the opposite direction.