ESTF2015
Earth Science Technology Forum 2015

Three-frequency Cloud and Precipitation Radar (3CPR)

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with contributions from the 3CPR Team:

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Earth Science Technology Forum

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Evolution of an Instrument Concept

1999

Second Generation Precipitation Radar (PR-2)
- Ku/Ka-band Precipitation Radar
- First spaceborne precipitation radar concept using cylindrical parabolic reflector, active linear array feed

2009

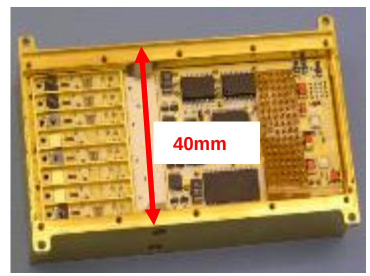
Cloud Cross-track scanning Dual-frequency Doppler radar (C2D2)
- Ka/W-band
- Similar antenna configuration to PR-2
- First concept proposing W-band scanning

2013

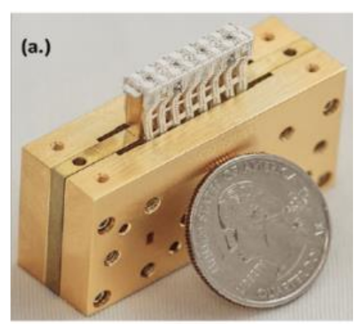
Three-band Cloud and Precipitation Radar (3CPR)
- Ku/Ka/W-band
- Similar antenna configuration PR-2/C2D2
- Combines three active linear array feeds
- Scanning at all three bands
- Capable of simultaneous cloud / precipitation measurements

Deployable Reflector Demo

8 TX / 16 RX Channel Ka-band TR Module



2x8 Element W-band Phased Array



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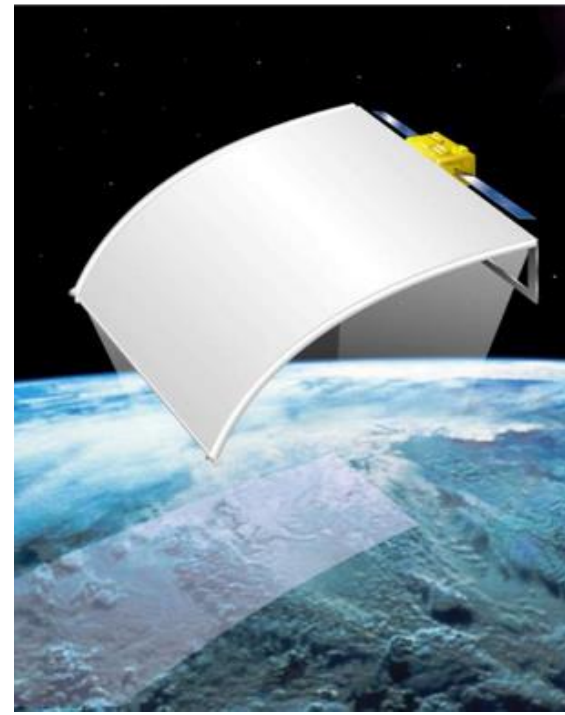
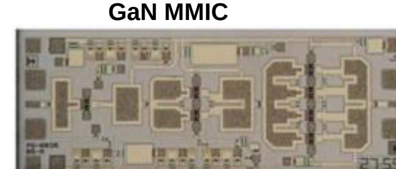
Array-fed Cylindrical Parabolic Reflector common to all three concepts



High-power W-band GaN MMIC

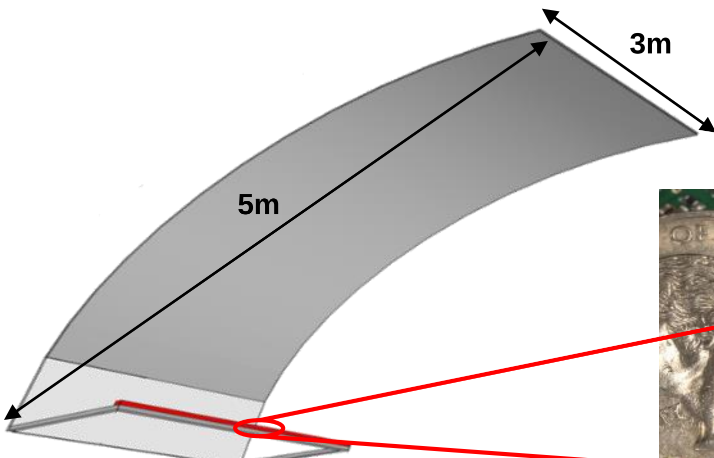


Raytheon

3-band Cloud and Precipitation Radar (3CPR)
ESTO IIP2103

- Cylindrical parabolic antenna provides high gain and cross-track scanning capability at Ku-band (13.4 GHz), Ka-band (35.6 GHz) and W-band (94 GHz)
- No need for heavy, lossy slotted waveguide arrays (as used in GPM)
- Some issues to be addressed including:
  - Reflector illumination over scan
  - Pattern / pointing distortion due to feed point offsets

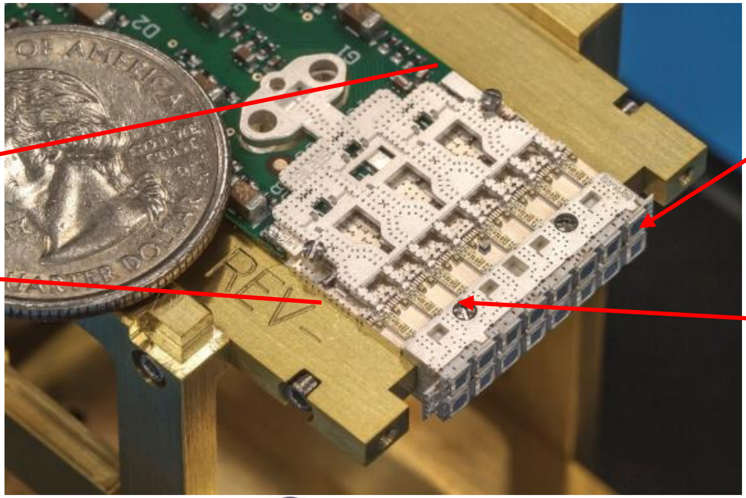
- Feed technology exists for Ku and Ka bands
  - Ka-band TR 8-pack demo at JPL
  - More recent Ka-band developments from GSFC / NGES (*Racette, et al*)
- Focus on new technology required to enable W-band scanning
- IIP2013 task will demonstrate scaled reflector w/ scanning W-band Feed



Cylindrical parabolic reflector with active array linear feeds for Ku/Ka/W band

Only W-band shown

Scanning Array Tile



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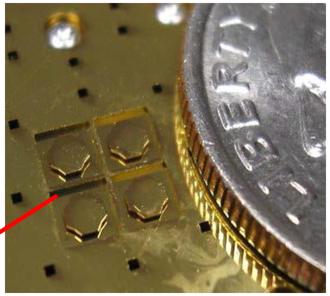
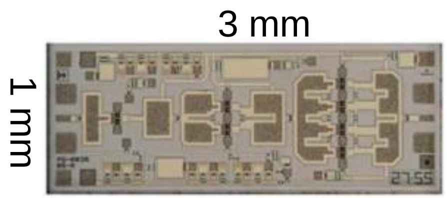




GaN TR MMICs

Raytheon

3CPR System Design

- Supports either:
  - ACE decadal survey mission concept (Ka- / W-band)
  - Cloud and Precipitation Processes Mission (CaPPM) concept. (Ku-, Ka-, W-band)
- ***Most precious resources:***
  - ***Sampling time***
  - ***Transmitted power***
- Pulse-to-pulse beam agility and optimized timing enable optimization of performance WRT certain science requirements
- One point design was chosen for 3CPR system study
  - High-sensitivity nadir measurements
  - Significant swath at all three bands
- Hardware is highly adaptable to changes in measurement priorities or resource limitations.
- Supports adaptive scan strategies and pulsed compression if required by application

3CPR Key Parameters

Parameter	Value (Ku/Ka/W)
Reflector Size	5 m x 3 m
Feed Array Length	2.5 / 2.87 / 2.87 m
Feed elements (each for TX / RX)	160 / 480 / 1152
Transmit Power (peak)	3200 / 1600 / 1267 W
Pulse length	1.5 μs
Scan angle (+/-)	4.5 / 12 / 3.5 degrees

3CPR Predicted Performance

		NADIR			SWATH		
		Ku	Ka	W	Ku	Ka	W
EFOV (along x cross)	km	4 x 4	2 x 1.5	1 x 0.6	4 x 4	2 x 2	1 x 1
Clutter Free MDS	dBZ	-5	-20	-35	+2	-10	-22
Clutter Free hgt	M	300	300	300	500	850	500
Near Surface MDS	dBZ	+12	-5	-20	+12	0	-10
Near Surface hgt	M	250	250	250	400	500	300
Doppler 0 SNR	dBZ	+12	-5	-18	+12	N/A	*-13*
Doppler Prec.	m/s	0.3	0.2	0.1	0.5	N/A	*0.5*
Swath	km				60	195	50
Max Scan Angle	deg				4.5	12	3.5
# Beams		1	1	1	18	96	48
Polarization		FULL	LDR	LDR	FULL	LDR	LDR

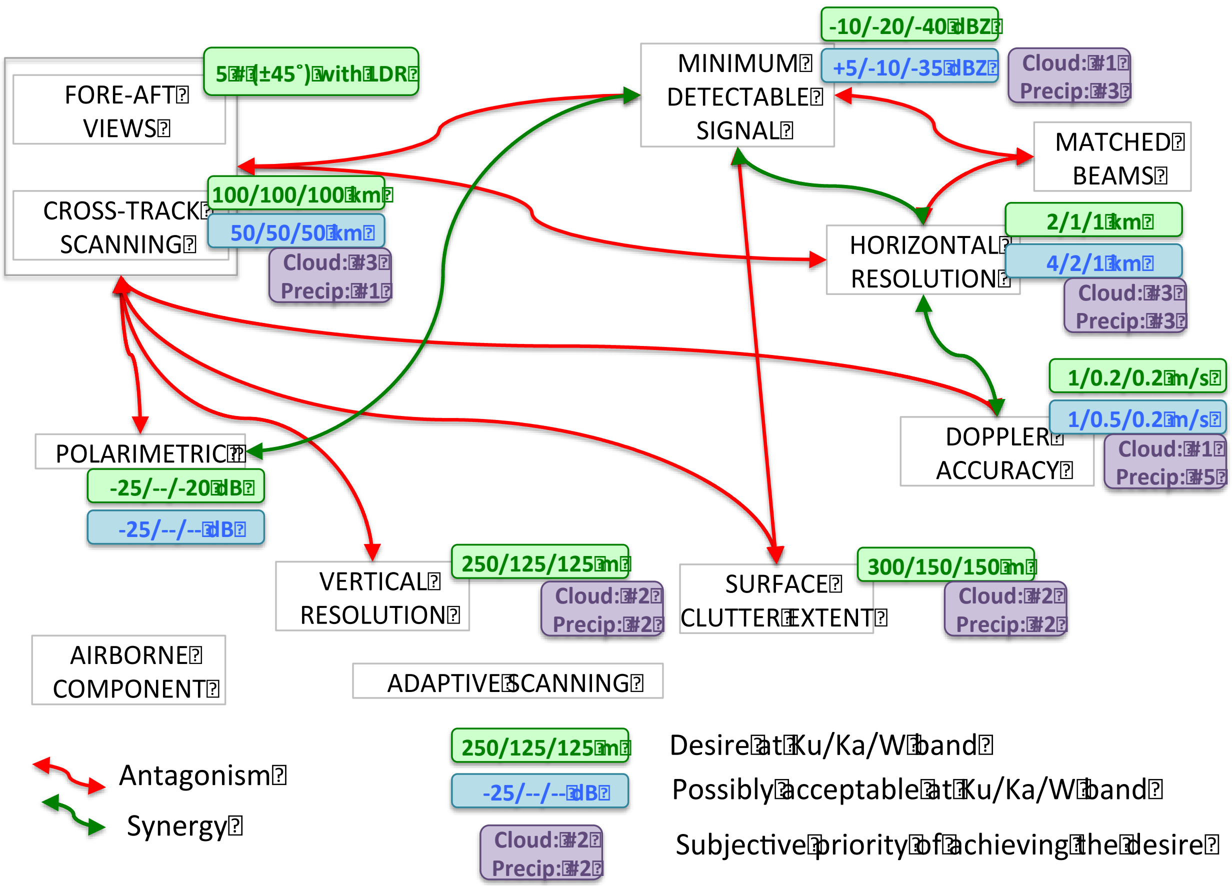
Legend	ACE	Req Met	Goal Met	IWSSM	Req Met	GPCM (Tent.)	Req. Met

Mutating Science Drivers and Trade Space

At this stage of the mission formulation – especially accounting for the ongoing process for the new Decadal Survey – there are **several reasons to explore alternate configurations**. Each of them is **vetted against the technology** being developed to identify what can be accommodated and what can't, and what that implies in regards to cost, risk and performance. Mutation means evolution, and cancer.

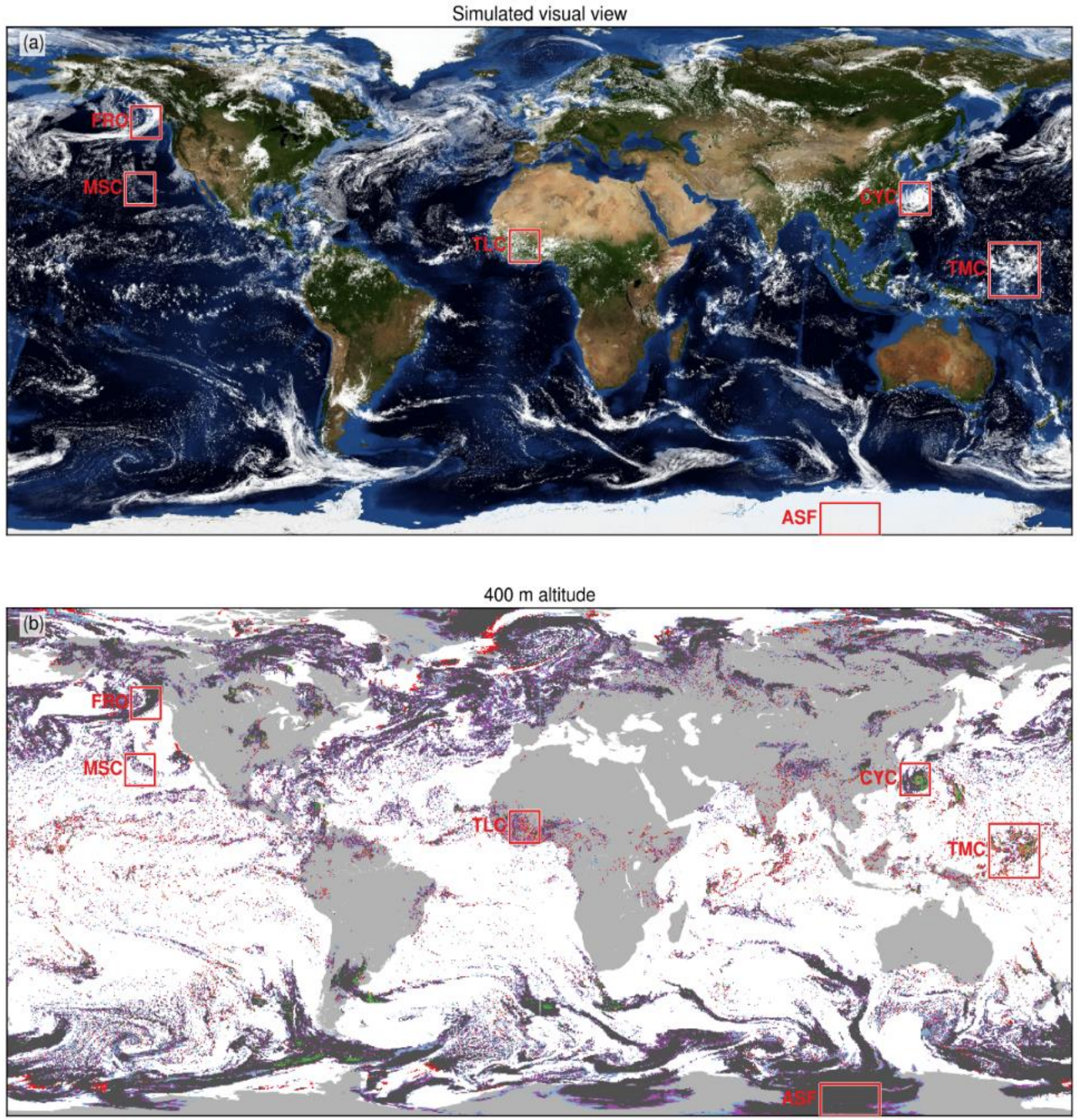
In the following slides we illustrate 3 recent examples of these iterations that directly hinge upon this IIP.

1) The **orbit trade** initiated by ACE SWG
2) The **antenna trades** initiated to explore feasibility and cost reductions.
3) The **sampling strategy trades** initiated by the GPM experience.



Orbit Altitude trades: Impact on science

- A simulation study was performed assuming a radar with 3CPR high level performance (Leinonen et al. 2015, accepted, and Leinonen et al. 2014, AGU FM).
- How much worse would science be if we were to deploy exactly the same radar at 817 instead of 450 km?
- The long answer is in the paper. The short answer is that some of the science of ACE would be almost not affected, but some would be severely impacted.

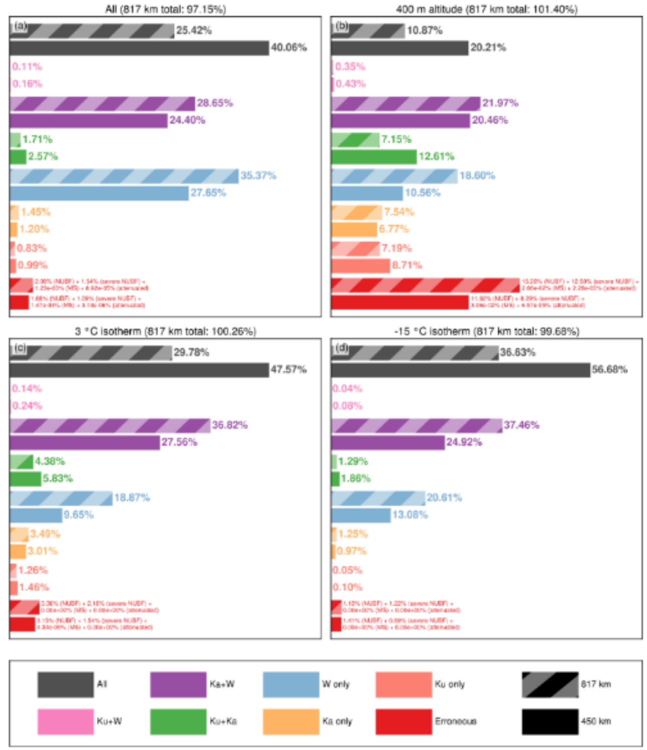


CHANNELS AVAILABLE AT THE NEAR SURFACE RANGE BIN

450 Km Orbit	100%	W only	Ka+W 44%	All	Ku+Ka	Ka only	Ku+W	Ku only	6.9% Erroneous
817 Km Orbit	97%								3.5%

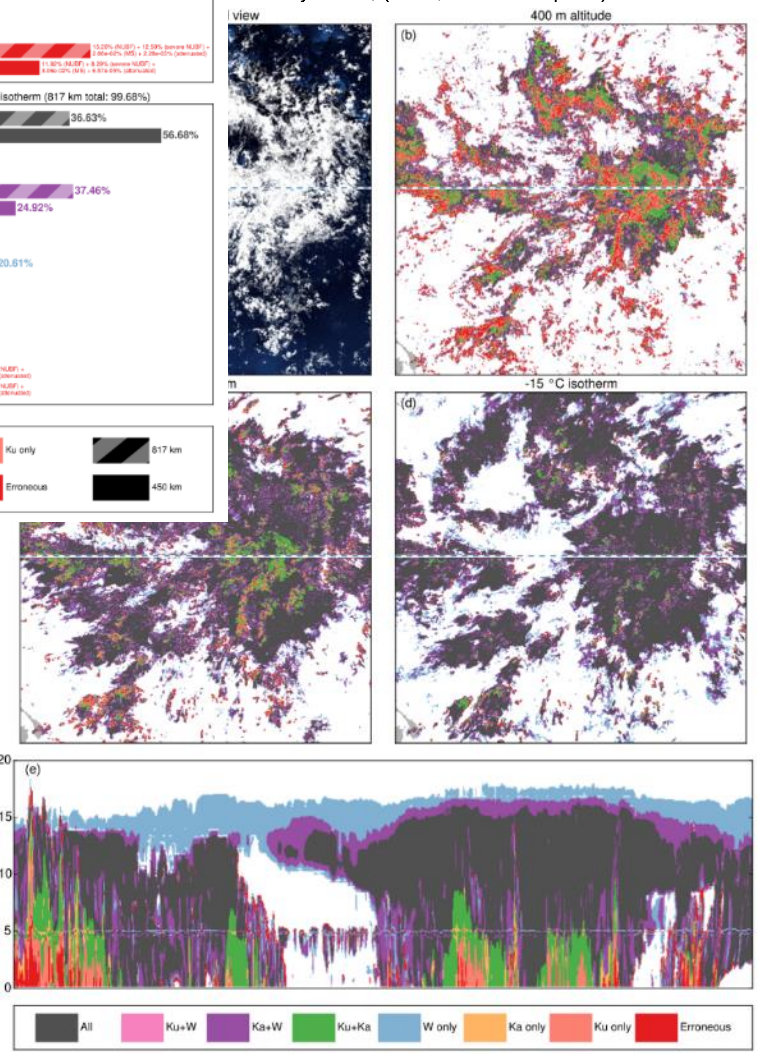
Quality of measurements

- Precision is primarily determined by the number of independent samples:
  - Given a dwell time, the only way to increase the number of independent samples is to increase the bandwidth and/or duty cycle (either frequency diversity, pulse compression, noise codes etc.).
- Accuracy is primarily determined by calibration and second order effects on the measurement:
  - Calibration is unaffected by these trades
  - NUBF and MS are increasingly more important as the footprint increases. Their impact is very dependent on the specific science target of interest.

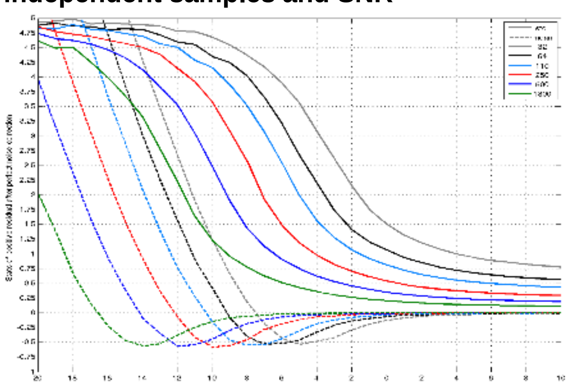


ACCURACY: impact of NUBF and MS on ACE/CaPPM for a Tropical Oceanic Convective System

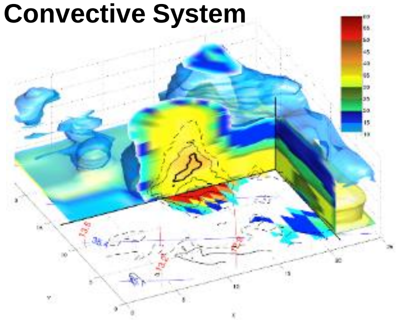
Leinonen, Lebsock,Tanelli, Suzuki, Yashiro, Miyamoto, (2015, cond. accepted)



PRECISION: basic operational dependency on independent samples and SNR



ACCURACY: impact of MS on GPM DPR for a Continental Convective System



Battaglia, Tanelli, Tridon and Mroz (JGR, March 2015)

Orbit Altitude trades

Implications of moving the radar to a 817 km orbit to fly in formation with ESA/EUMETSAT Sentinel-5

1. **Footprint** size grows from 1.5 km (Ka-band) to 2.8 km at nadir → **Non compliant.**
    1. Significant increase of Non-Uniform Beam Filling impact on dual-frequency algorithms and Doppler estimation.
    2. Significant increase of Multiple Scattering in convective clouds
    3. Horizontal resolution at W-band 1 km, worse than EarthCARE (800 m), better than CloudSat (1.4 km).
2. **Sensitivity** worsens by ~4 dB. Some concepts become non-compliant.
3. **Swath** increases by 80%. Improvement.
    1. But Surface Clutter gets worse off nadir
4. **Doppler** accuracy:
    1. Improves in homogeneous clouds
    2. Deteriorates in non-homogeneous clouds

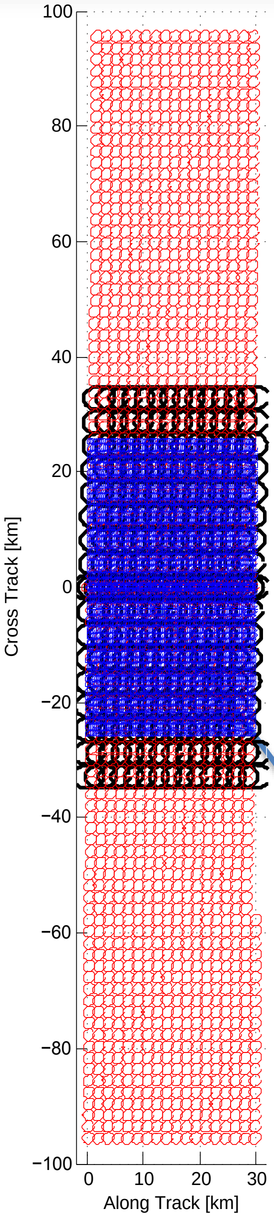
Increase Antenna Size:
Pros: solves all problems.
Cons: Challenging
Significant impact on mission cost: mainly in bus and launcher choices

Increase transmitted energy:
Pros: restores sensitivity
Cons: Impact on mission cost. Does not solve the NUBF & MS problems.

Reduce swath:
Pros: increase integration time, improve sensitivity (a little) and Doppler accuracy (a lot)
Cons: Less swath!

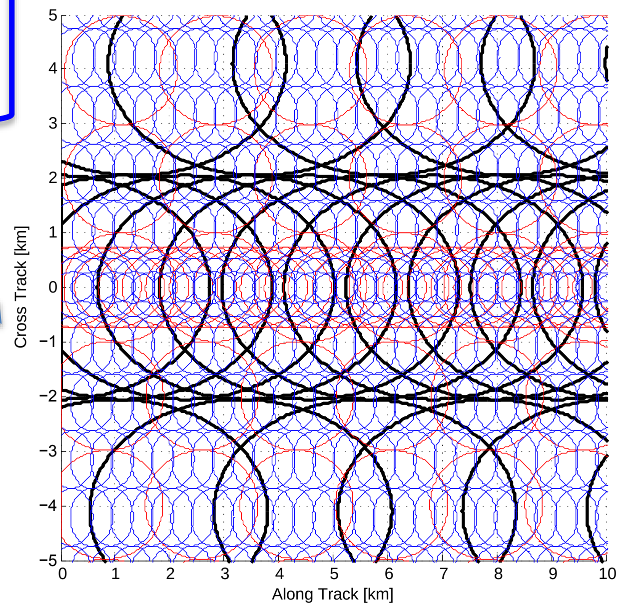
Include radiometric channels in the radar:
Pros: No need to go to 817 for combined. perfectly collocated active/passive as in CloudSat (no parallax, no smearing)
Cons: increases instrument cost. narrower swath

Example Scanning Strategy



Precipitation Mapping Swath (190 km)
Ka-only, 2 Km EFOV, non overlapped
No Doppler, -10 dBZ MDS

Large Scale System Dynamics Swath (65 km)
Ka + Ku
Ku in 4 Km footprints, overlap 2
Doppler 0.5 m/s accuracy
0 dBZ MDS



Small Scale System Dynamics Swath (50 km)
Ka + Ku + W
W in 1 Km footprints, overlap 2
Doppler 0.5 m/s accuracy
-20 dBZ MDS

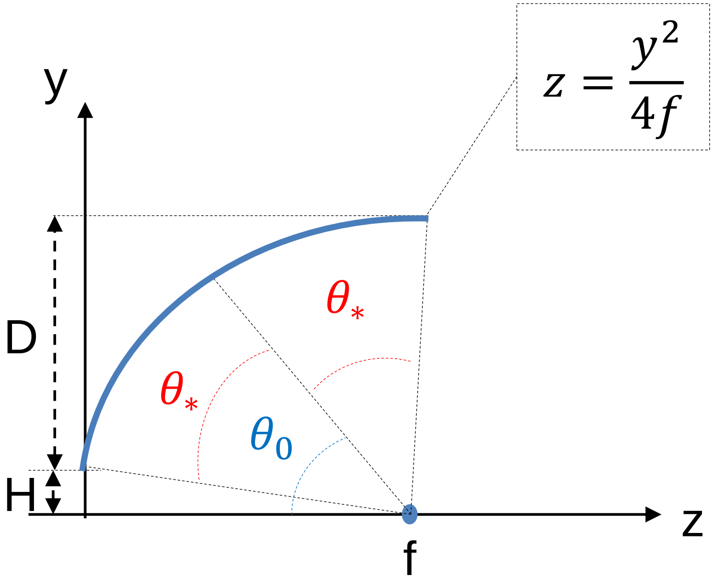
Cloud and Precipitation Process Nadir Curtain
Ka + Ku + W
W: 0.5 Km footprints, overlap 2
Doppler 0.1 m/s accuracy
W -35 dBZ MDS
Ku 0 dBZ MDS, Ka -20 dBZ MDS

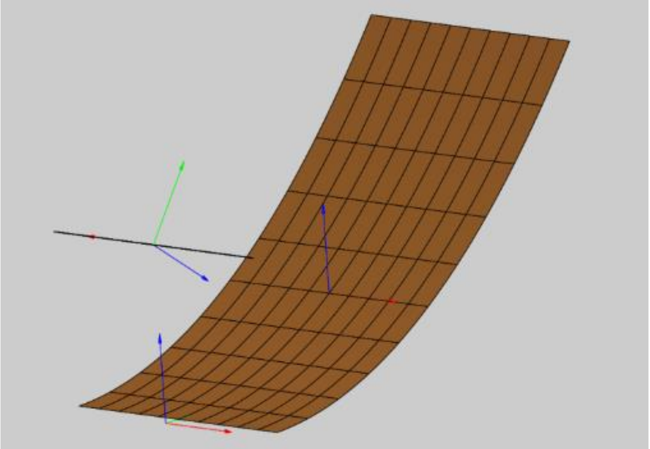
Antenna Size Trades

- Baseline 3x5m:
  - Meets ACE and CaPPM requirements
  - Large, but will still fit in available launch vehicle fairings
  - Manufacturing challenge could drive cost
- Reduced 3m x 3m:
  - Meets most requirements
  - Reduced manufacturing cost / risk
- Small 0.8m x 0.8m:
  - Does not meet ACE or CaPPM requirements
  - Horizontal resolution similar to GPM DPR at Ka-band and similar to CloudSat at W-band (@ 400 km orbit)
  - Performance suitable for tech demo or complimentary sensor flying with other sensors
  - Simple antenna manufacturing
  - Less expensive array
  - Compatible w/ ISS and small sat busses

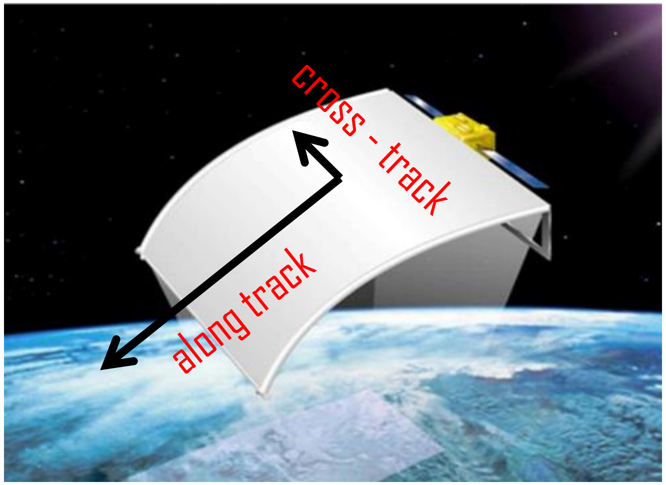
Array-Fed Parabolic Reflector

A singly curved parabolic reflector feed by a 3 linear arrays (one for each frequency). Each one of the Ku/Ka/W feed has electronic scanning on the cross-track direction.



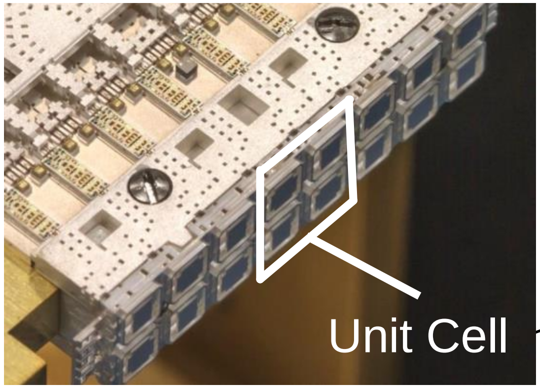


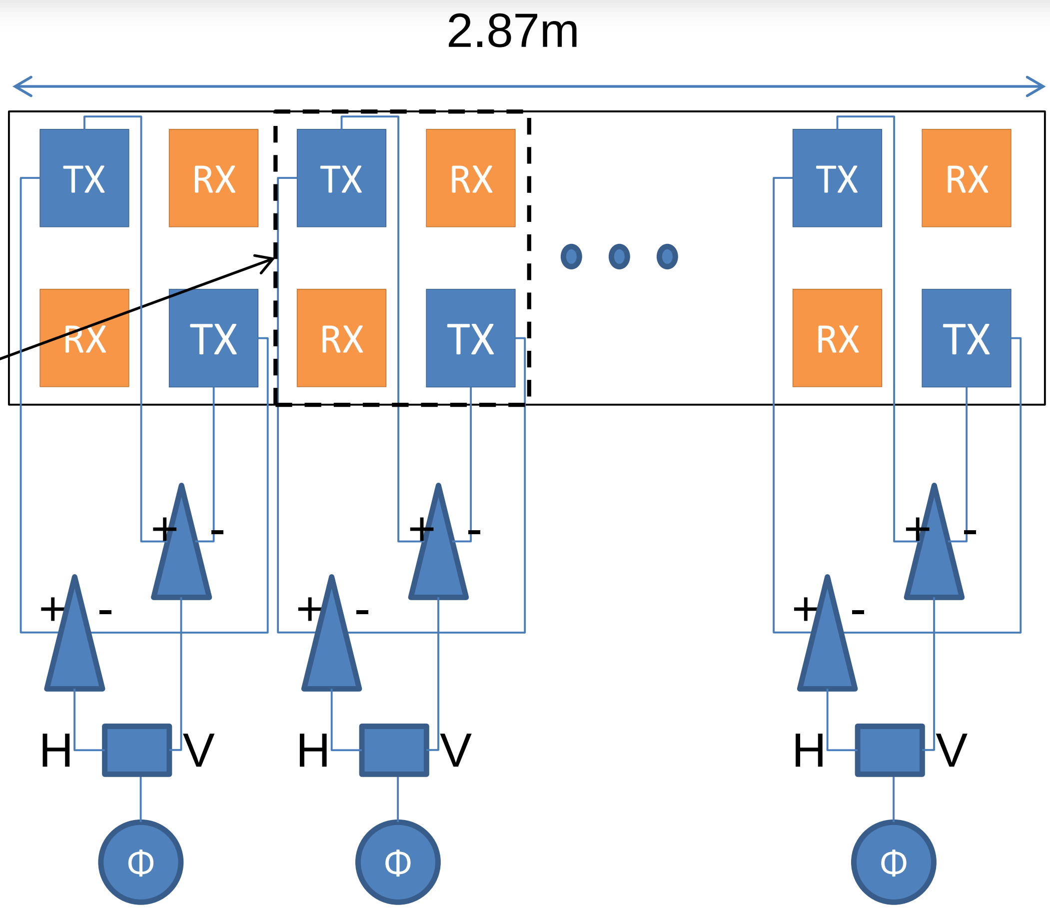
Grasp Model



Instrument Concept

Feed Array Analysis

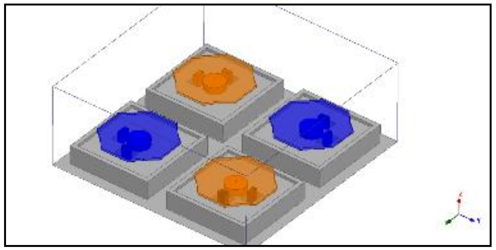




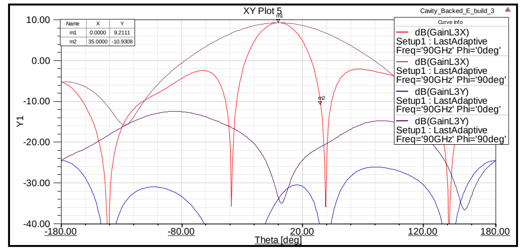
- The element pattern used is the unit cell pattern from the W-band element in the picture above.
- A linear array of unit cells 2.87m long feeds the reflector. The excitation and phase shifting is done per unit cell as shown in the figure to the right.
- The spacing between unit cells is 5mm, making the effective spacing between elements 2.5mm.

Phase shifting per unit cell (only TX shown)

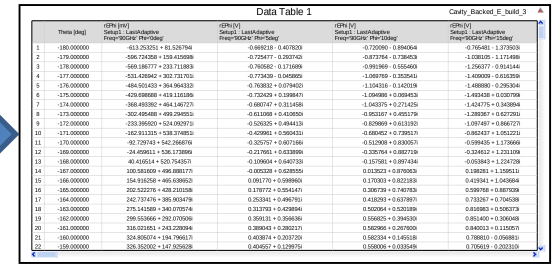
Full wave / Physical Optics Hybrid Modeling Flow



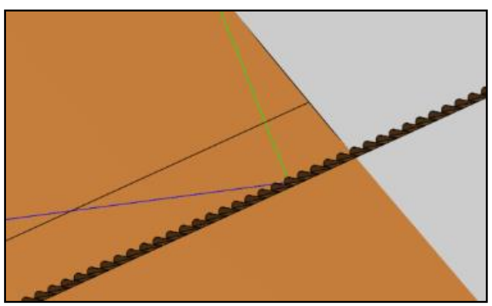
HFSS model of a unit cell



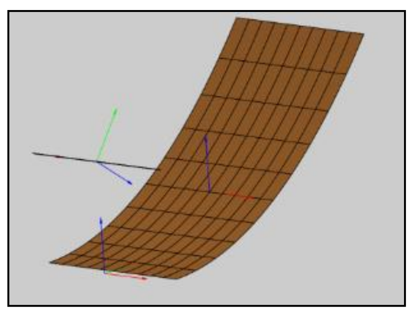
Optimize antenna modeling until radiation pattern meets requirements for feed.



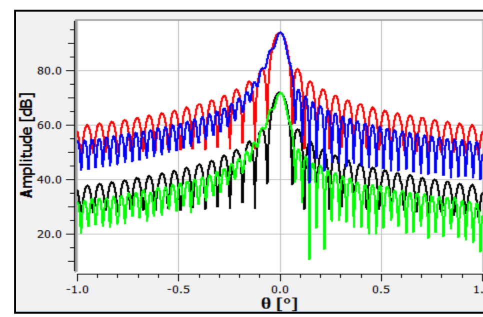
Data export to GRASP



GRASP - Linear array of elements feeding the parabolic reflector.



Using physical optics, calculation of induced current on the reflector surface.

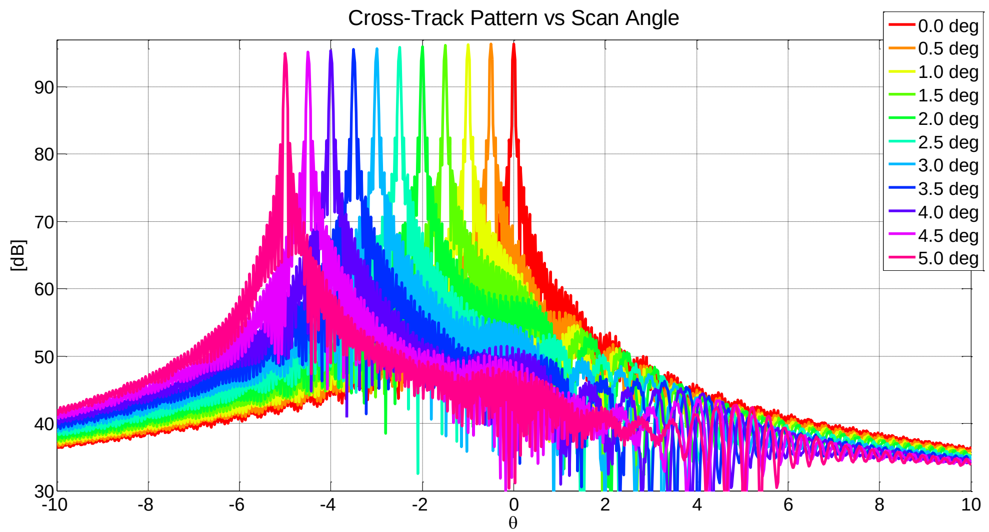


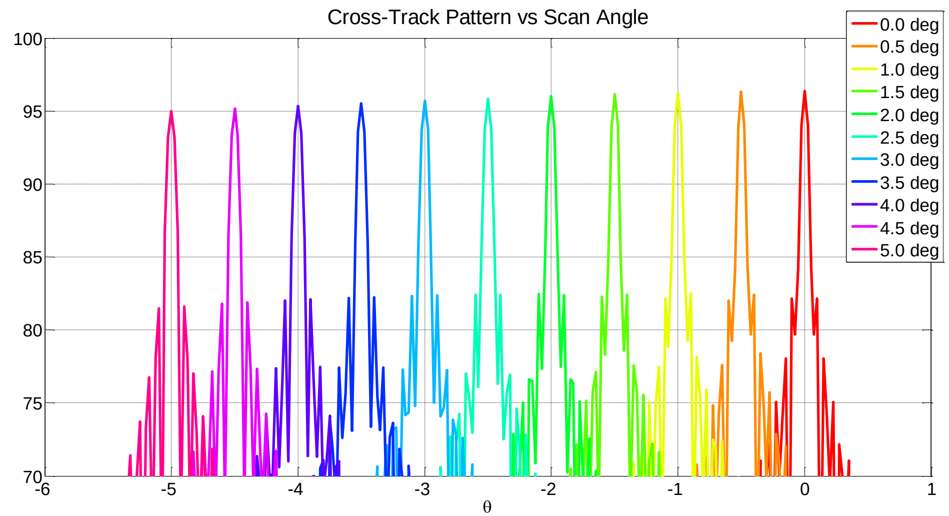
Using the currents from the previous step, then calculate far field radiation pattern

Thanks the combination of full MoM (Method of Moments) simulation techniques and PO (Physical Optics) we can simulate a reflector that is 950λ x 1600 λ in less than 7 minutes. In addition, the process is automated using matlab, so running variations is as simple and running a loop cycle.

Antenna Analysis using Hybrid Modelling

- Trades studies performed:
  - Feed element spacing
  - Phase shifter spacing
  - Phase shifter bits requirement
  - Reflector focal length
    - Drives both length of feed structure and short dimension of feed array
  - Errors due to feed offsets:
    - In a three-band system only one band can be on focal lines
    - Offset lead to beam distortion and along-track squint
      - Distortion shown to be acceptable
      - Effects of along-track squint can be removed by temporal shift of data
- After trades were completed, full simulation of feed+reflector pattern was performed

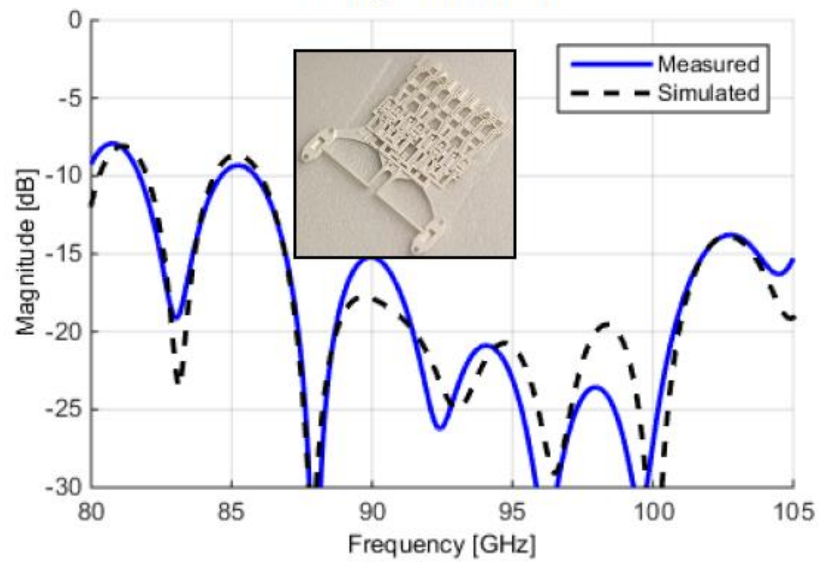




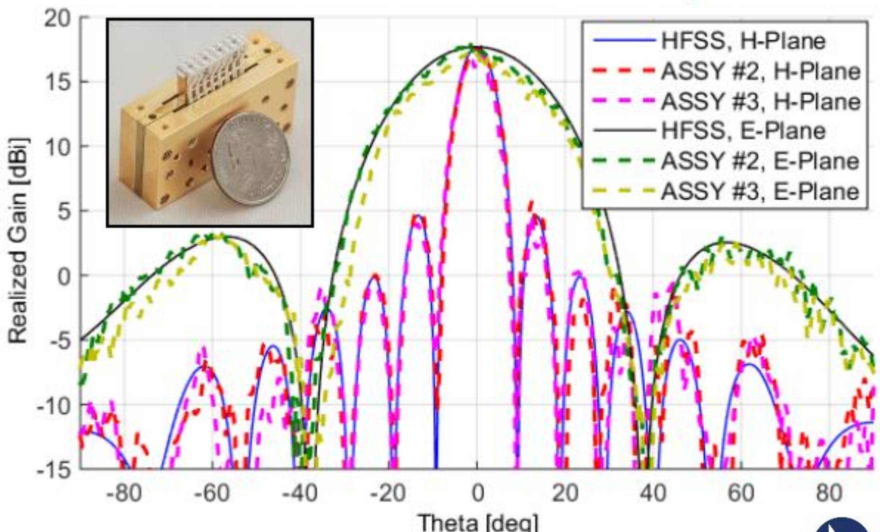
Prototype SAT Component Designs

- PolyStrata W-band designs validated during two previous fabrication cycles during SBIR Phase II
  - Passive array tile module
  - Array tile module with 8x GaN MMICs
- We will leverage previous designs for IIP SAT.
  - Design modifications where necessary.

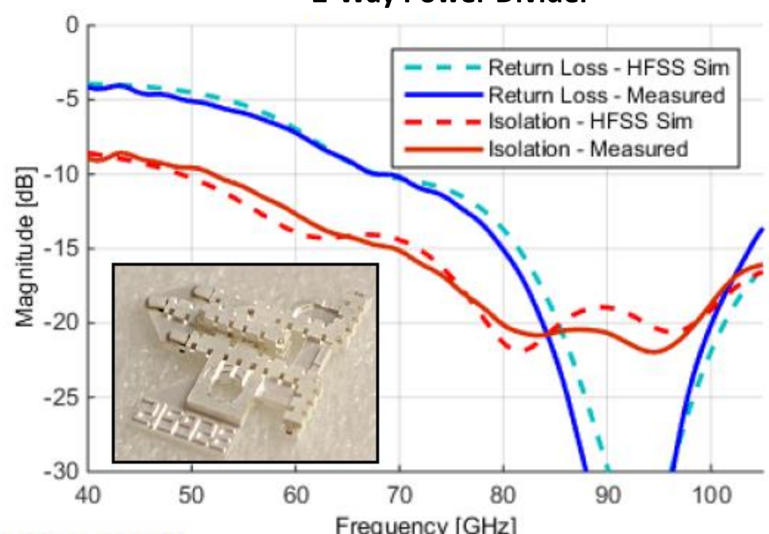
8-way Combiner



Passive 2x8 Antenna Assembly



2-Way Power Divider



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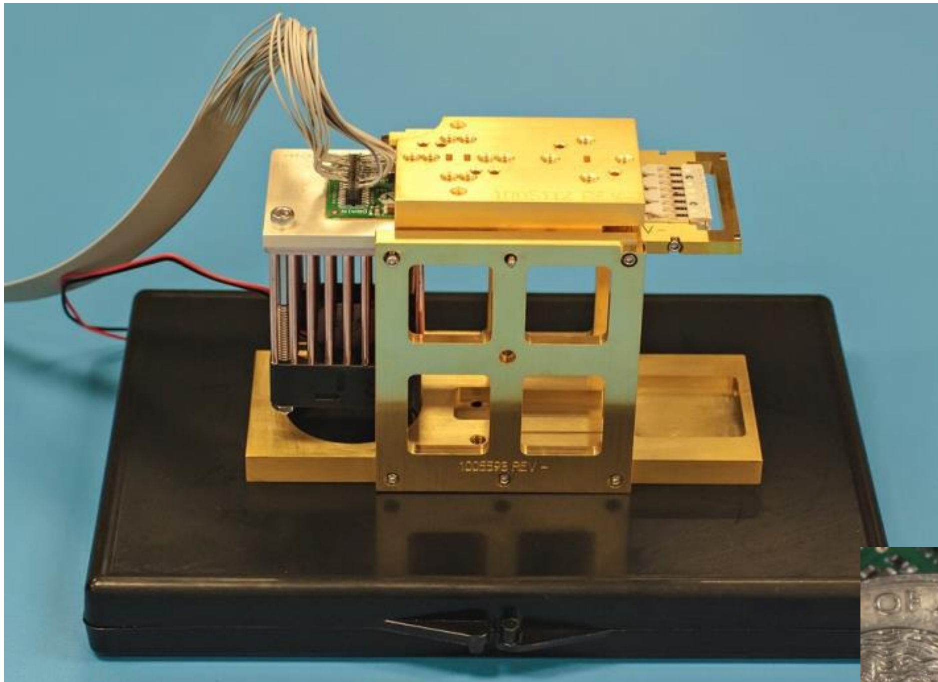
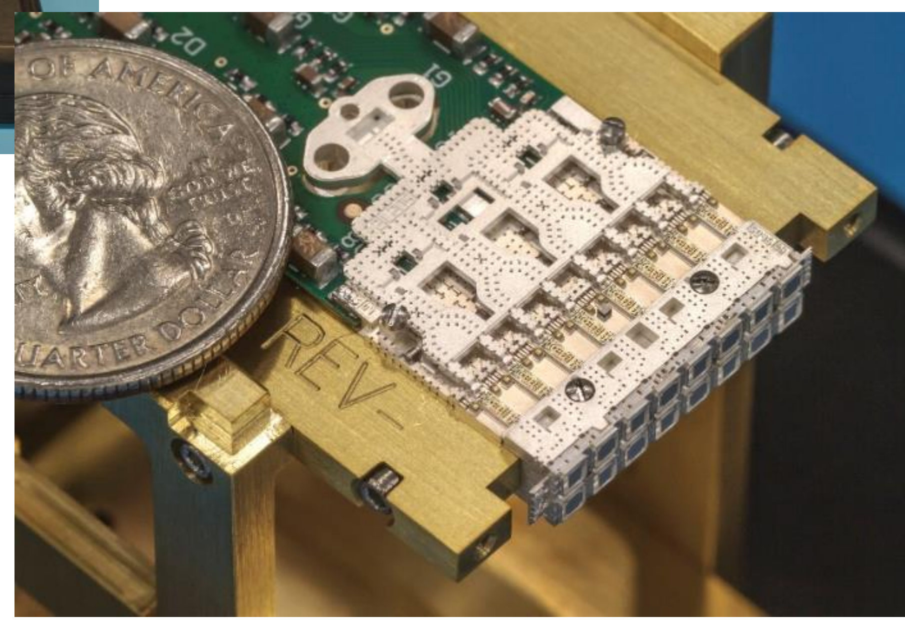
Fixed Beam 8x2 Active Array Demonstration



- Active fixed-beam SAT with
  - 16x 2 radiating elements
  - 8x 1 Watt TX channels
  - 16 RX channels (8 x H,V)
  - 3x 8-way combiners
  - Bias networks



- Used for preliminary demonstration of:
  - RF performance
  - Thermal design
  - Manufacturing approach
  - Assembly approach

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3CPR Development Status

- Initial instrument design trades are complete
  - Trades studies can continue as science requirements change
  - Expected requirements changes do not affect the design of the W-band arrays being developed
- Initial antenna design complete
  - Array parameters are fully defined
  - Parabolic surface defined
  - Feed+array analysis of chosen configuration has been completed
- MMIC fabrication
  - GaN LNA, PA and Driver MMIC fabrication complete (A. Fung ACT)
  - SiGe Phase / Amplitude MMIC fabrication in progress
- SAT development
  - Critical Design Review for Rev 1 completed
  - SAT PolyStrata design complete and ready for fabrication

The End

Thank you for your attention…questions?

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Thanks to NASA ESTO IIP and ACT programs, NASA SBIR and JPL R&TD for supporting this work and the work that lead to it.