ESTF2021 Virtual Series

Distributed Aperture Radar Tomographic Sensors to map Changing Surface Topography and Vegetation Structure

Marco Lavalle

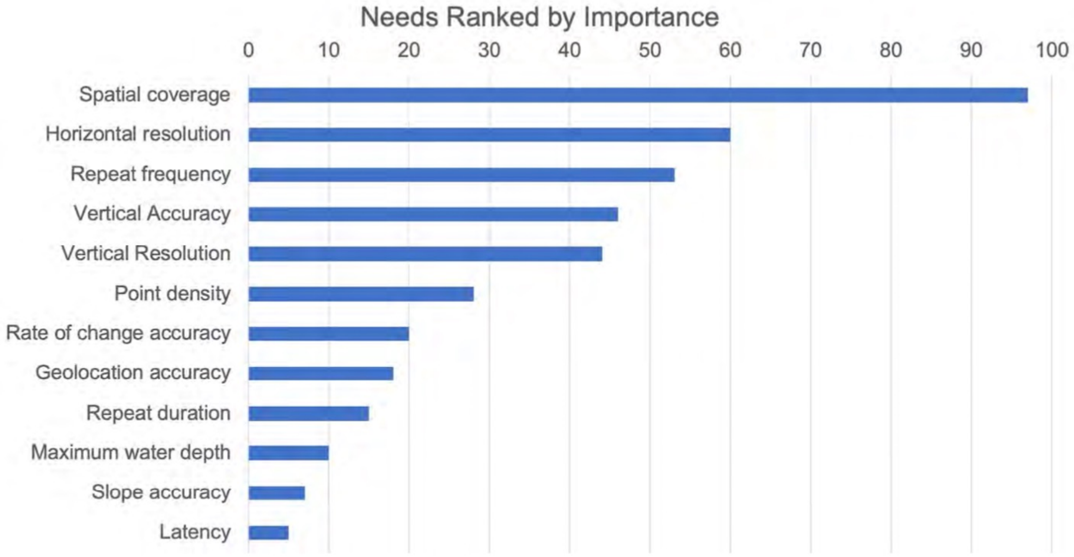
B. Hawkins, R. Beauchamp, M. Haynes, D. Clark, R. Ahmed, S. Prager, I. Seker, E. Loria. N. Chahat, P. Focardi, D. Hawkins, M. Anderson, K. Masuka, V. Capuano, J. Ragan, J. D. Walker, S.-J. Chung

Jet Propulsion Laboratory, California Institute of Technology

Science needs

- Global, fine-scale observations of surface topography and vegetation structure (STV) are critical to address key science and applications questions in Solid Earth[SE], Ecosystems[V], Cryosphere[C], Hydrology[H], and Coastal Processes[CP] disciplines
- 2017-2027 Decadal Survey recommended surface topography and vegetation as a Target Observable
- Surface Topography and Vegetation (STV) Study Team formed by NASA HQ in 2020 identified STV products needs and science/technology gaps

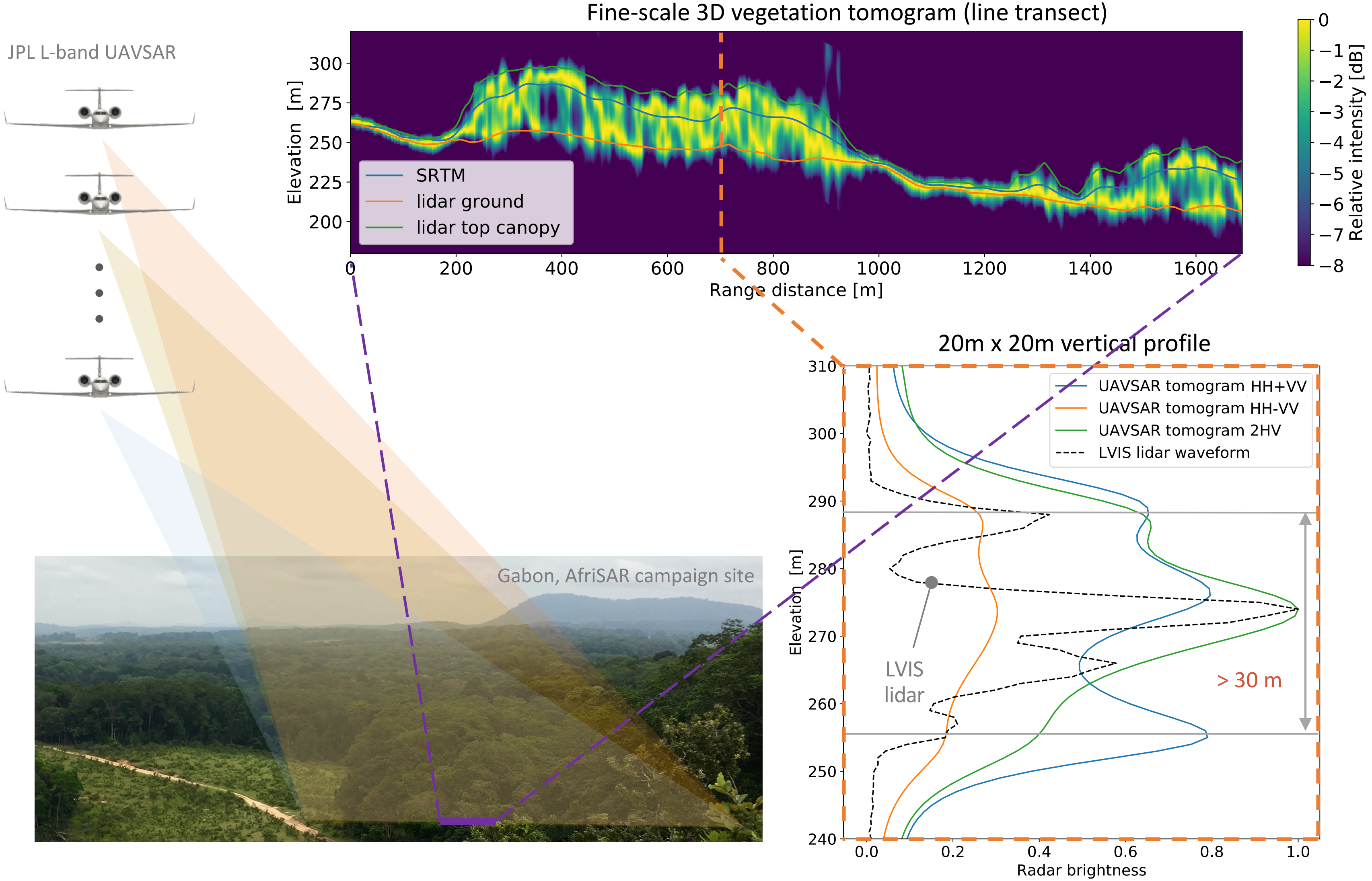
Parameter		Aspirational			Threshold		
		Median Need (rounded)	Most Stringent Need	Most Stringent Discipline	Median Need (rounded)	Most Stringent Need	Most Stringent Discipline
Coverage Area of Interest	%	90	95	C, H	55	90	C
Latency	Days	5	0.5	SE	60	1	SE
Duration	Years	9	10	SE, C, A	3	3	SE, V, C, CP
Repeat Frequency	Months	0.1	0.03	SE, A	3	0.2	SE
Horizontal Resolution	m	1	1	SE, C, H, A	20	3	SE
Vertical Accuracy	m	0.2	0.0	SE, C, H	0.5	0.1	C
Vegetation Vertical Resolution	m	1	0.5	H, A	2	0.2	CP
Bathymetry Max Depth	m	25	30	C, CP	10	10	SE, C, CP
Geolocation Accuracy	m	1	1.0	SE, V, H, A	5	3	SE, V
Rate of Change Accuracy	cm/yr	5	1	SE, C, A	35	1	SE



Charts from STV study white paper: *science.nasa.gov/earth-science/decadal-stv*

How do we measure STV globally, frequently, and at fine scale?

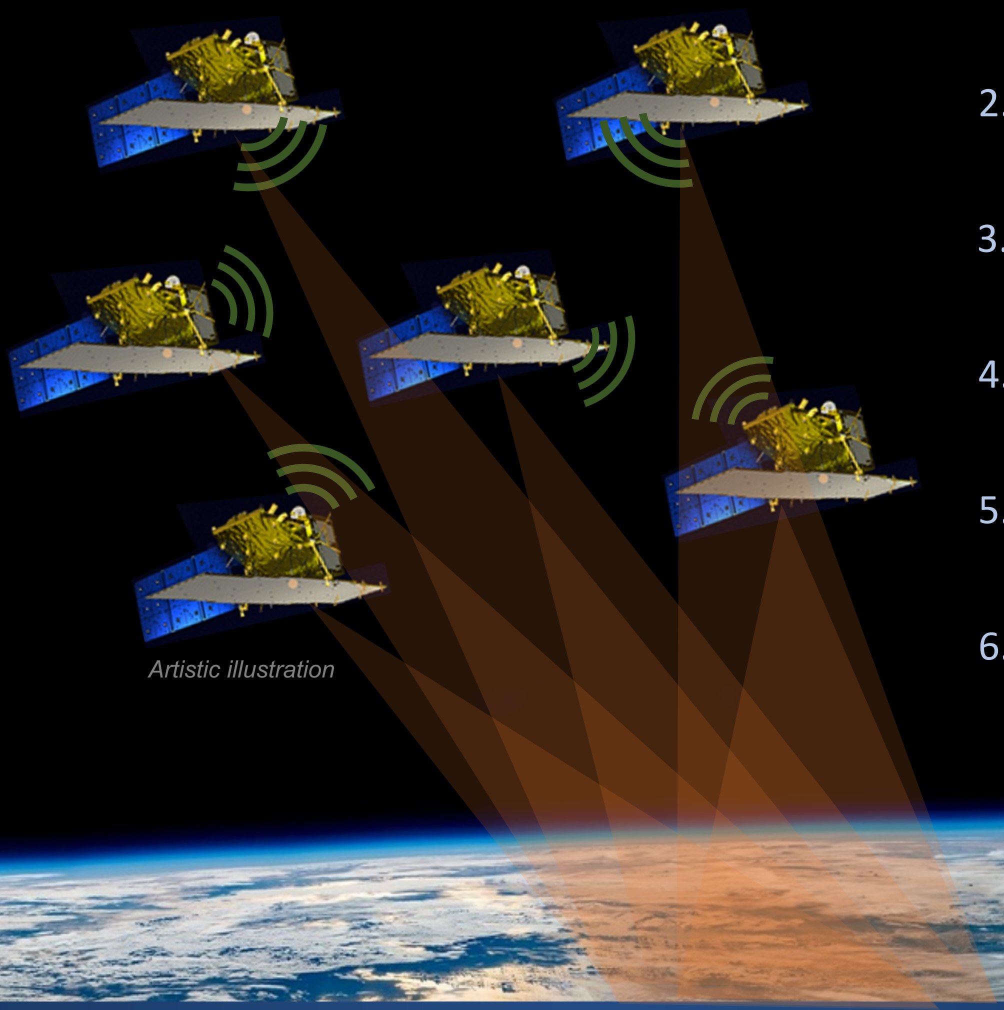
- TomoSAR = tomography synthetic aperture radar, including *multi-baseline* polarimetric InSAR
- TomoSAR signals received at different platform locations carry spatial harmonics proportional to height of the scatterers
- TomoSAR signal phase history coupled with canopy penetration enable recover topography and 3D vegetation structure
- Joint NASA-ESA 2016 AfriSAR Campaign collected *repeated* airborne TomoSAR tracks
  - Shiroma and Lavalle (2020)
  - Fatoyinbo et al. (2021) – *in review*



Shiroma G. H. X. and M. Lavalle, "Digital Terrain, Surface, and Canopy Height Models From InSAR Backscatter-Height Histograms," in *IEEE TGRS*, vol. 58, no. 6, June 2020

marco.lavalle@jpl.nasa.gov

Technology gaps for spaceborne SAR tomography



Artistic illustration

1. Formation geometry and radar operation
   Single/repeat-pass and receive/transmit combinations
2. Relative positioning
   Wavelength/20, explore GPS-only and intersatellite range
3. Mutual signal synchronization
   Nanoseconds-level phase sync for signal coherency
4. Light-weight antenna and compact radar
   L or S-band, deployable patch array, membrane antennas
5. End-to-end system design and performance
   Trade study tool with inputs from STV study team's SATM
6. Multi-static tomographic SAR processor
   Static and dynamic experiments using COTS hardware and Caltech drones. It could be on-board

2020-2022
DARTS IIP
working on solutions with documented performance for TomoSAR-STV mission concept

marco.lavalle@jpl.nasa.gov

Approach and timeline of DARTS IIP

Software component

- End-to-end trade study tool
- Integration of algorithms for synchronization, positioning, orbits, multi-static SAR modes, etc.
- Performance metrics informed by STV needs
- Explore complex trade space
- Julia language

Hardware component

- SDRadar implemented in RFSoC
- Implementation of radar functionalities, synchronization and positioning algorithms, GPS, etc.
- Multi-static radar demonstration via bench tests and UAS experiments
- Antenna prototype fabrication and test

Development and maturation of individual technologies

Integration in Trade Study Tool

Implementation in RFSoC hardware

Mission concept formulation and demonstration

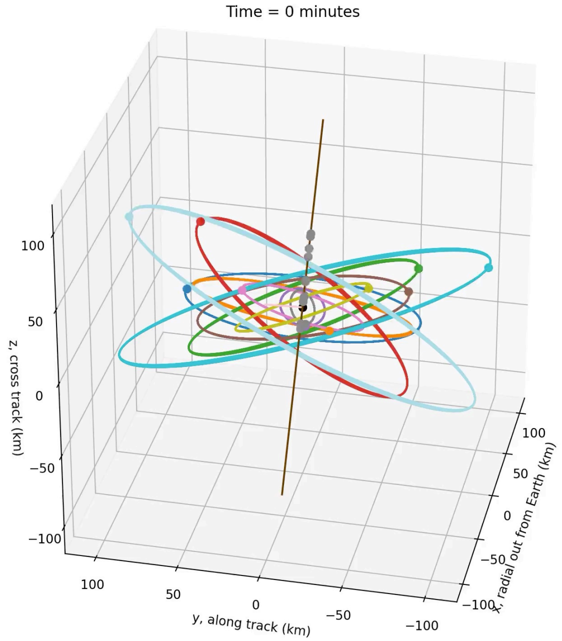
4/2020 YEAR 1 – TRL 2/3

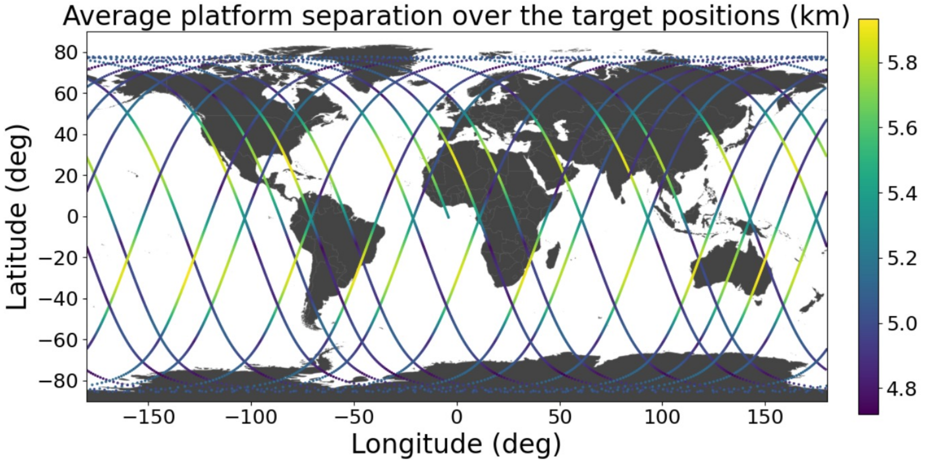
4/2021 YEAR 2 – TRL 3/4

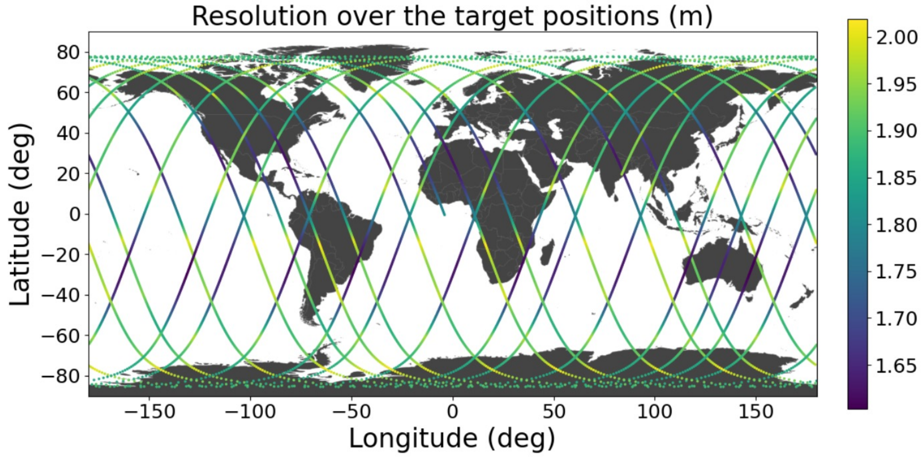
4/2022 YEAR 2 – TRL 5/6

Orbits of distributed formation

- Orbits design based on J2-invariant Passive Relative Orbits in the Local Vertical Local Horizontal (LVLH) frame
  - Central s/c is the chief, outer s/c are the deputies with motion relative to the chief's perspective
  - Minimize drift and fuel costs under J2 disturbance
  - Passively stay within vicinity of chief even after hundreds or orbits
- Design orbits wrt first-order STV science metrics (e.g., vertical resolution) using variable number of platforms and geometries
  - Genetic algorithm used to search the configuration space of possible initial formations. This is integrated over 12 days, and best formations are kept and mutated
  - Current tests with 4, 6, 10, and 12 platforms



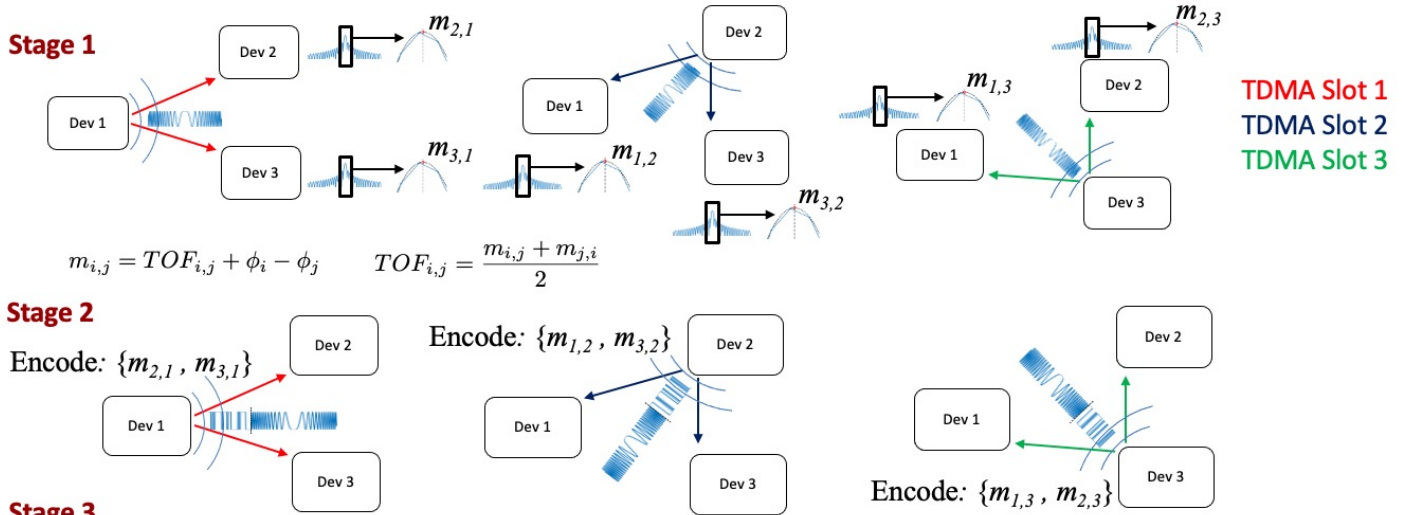




J. Ragan, R. Ahmed, K. Matsuka, I. Seker, J. Walker, S.-J. Chung, and M. Lavalle, "Optimizing formation flying orbit design," in Advances in the Astronautical Science, 2021

Mutual phase synchronization

- Synchronization algorithm based on inter-satellite links with GPS-only option and oscillators models (USO, USRP)
- Models and algorithms integrated in DARTS trade study with realistic orbits, radar multi-static operation, positioning algorithm, antenna pattern, etc. to evaluate requirement on phase synchronization for STV
- Algorithm being implemented in RFSoC for hardware experiment to validate model and algorithm

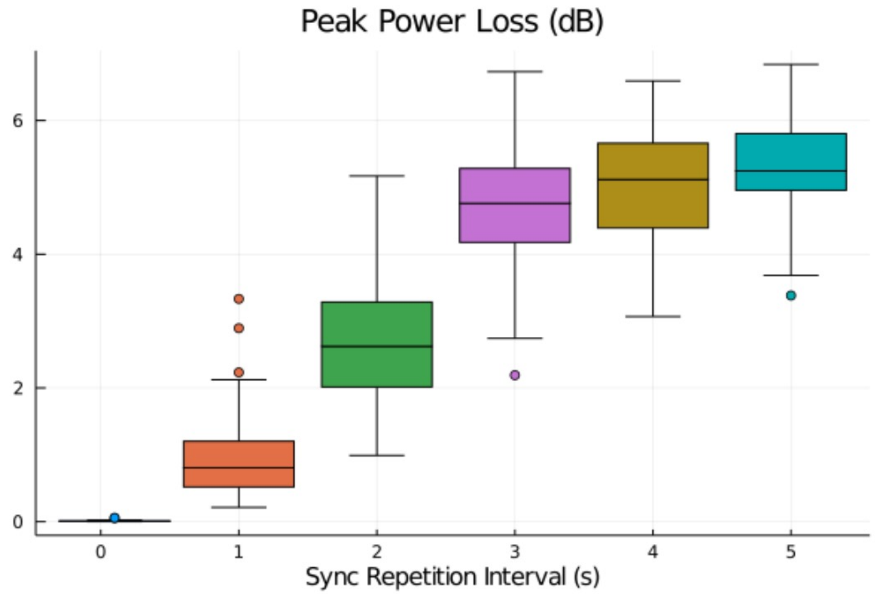


Stage 3

Result is shared clock/phase offset information

$$\begin{bmatrix} 0 & TOF_{1\to2} & TOF_{1\to3} \\ TOF_{2\to1} & 0 & TOF_{2\to3} \\ TOF_{3\to1} & TOF_{3\to2} & 0 \end{bmatrix} \qquad \begin{aligned} \Phi_{i,j} &= m_{i,j} - TOF_{i,j} \\ &= \phi_i - \phi_j \end{aligned} \qquad \gamma_{err:i,j} = 2\pi f_c TOF_{i,j} - \angle d_{i,j}(\tilde{t}_{pk:i,j})$$

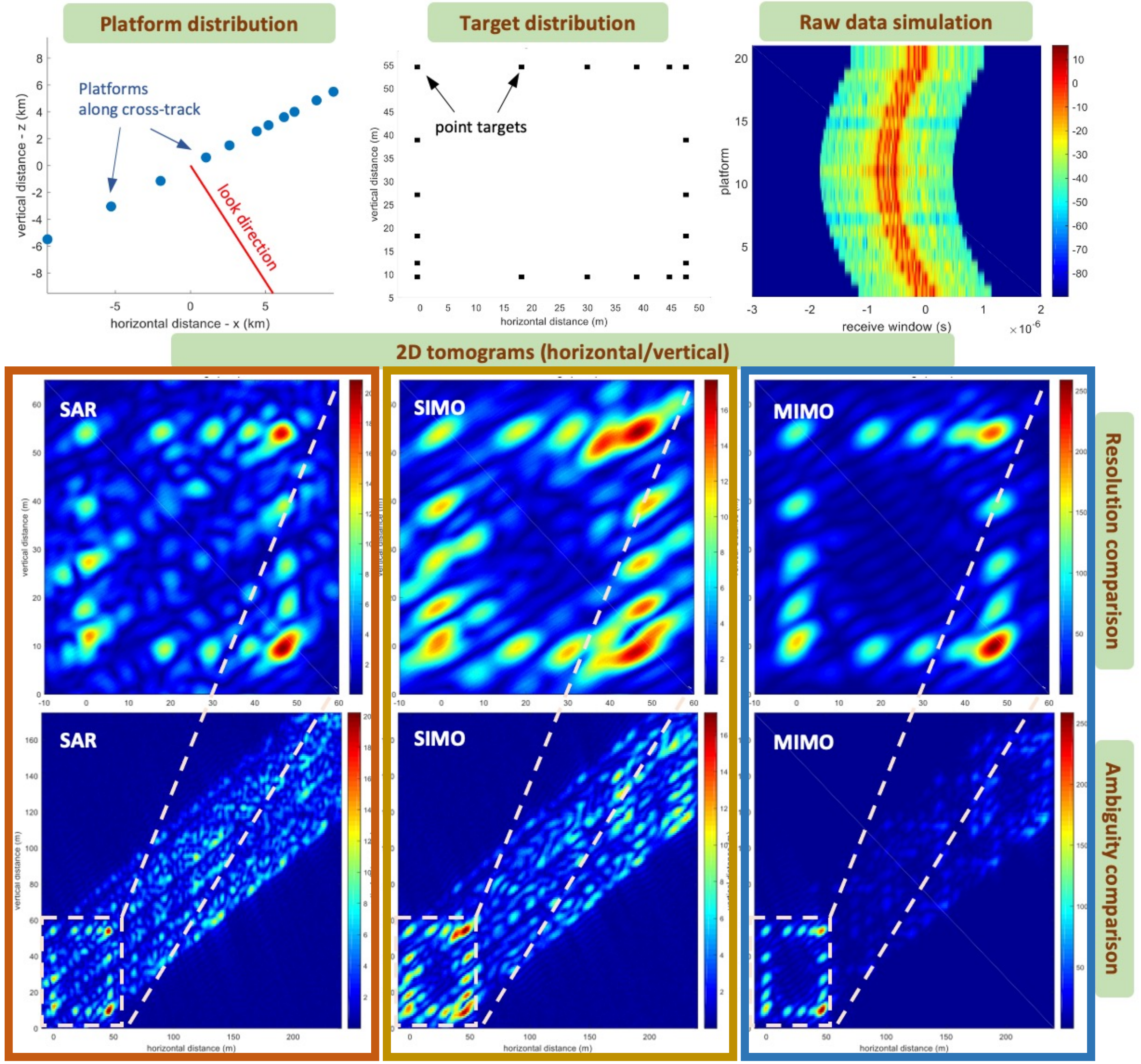
Example of trade study showing the effect of the oscillator frequency offset and sync repetition interval without GPS-DO



S. Prager, M. S. Haynes, and M. Moghaddam, “Wireless Sub-nanosecond RF Synchronization for Distributed Ultrawideband Software-Defined Radar Networks,” *IEEE TMTT,* 2020.

Receive and transmit strategies in a SAR formation

- **SAR: Same platform transmits and receives**
  - Pros: resolution, low data size then MIMO, no sync needed
  - Cons: ambiguity, low SNR, high side-lobes, all Tx/Rx platforms
- **SIMO: One platform transmits and all receive**
  - Pros: ambiguity, data size, only 1 Tx
  - Cons: resolution, depends on Tx location, low SNR, high-side lobes
- **MIMO: All platform transmit and all receive**
  - Pros: overall SNR, resolution, ambiguity, side-lobes
  - Cons: all Tx/Rx, sync, scheduler, data size
- **Hybrid:**
  - Partial MIMO
  - Mix of single- and repeat-pass baselines

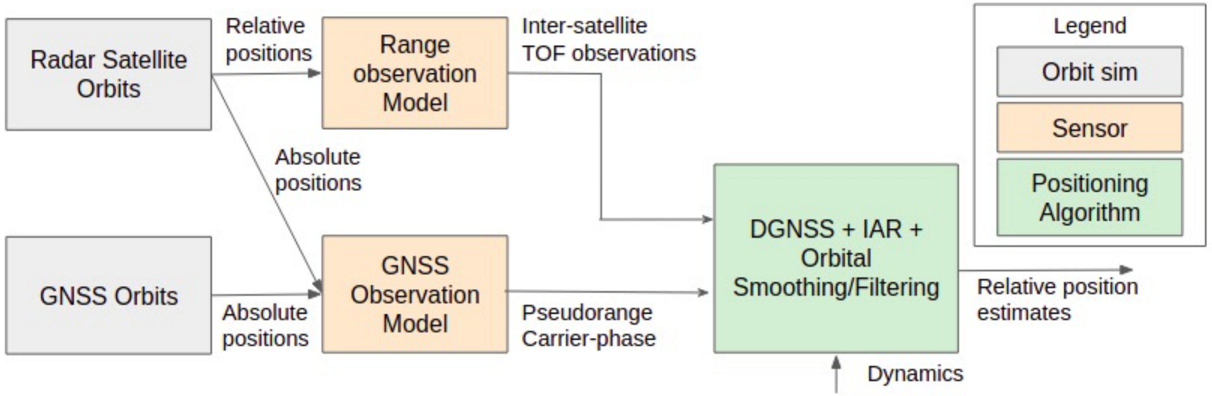


Seker I., and Lavalle M. “Tomographic Performance of Multi-Static Radar Formations: Theory and Simulations.” *Remote Sensing,* 13, no. 4: 737, 2021.

marco.lavalle@jpl.nasa.gov

Spacecraft position determination in DARTS formations

Positioning simulation and estimation



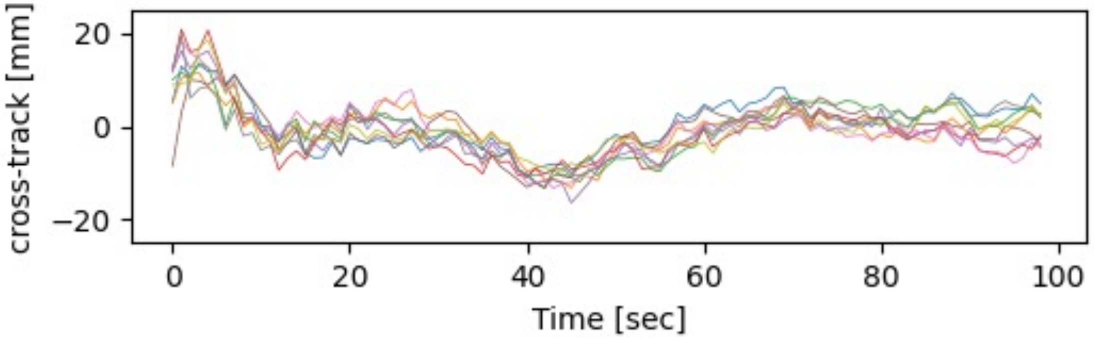
Observations

- GNSS pseudorange, double-differenced carrier-phase, high-precision inter-satellite TOF. Use observations for all N>3 satellites
- Inter-satellite range for high LOS accuracy, DGNSS for persistent 3D relative position estimation

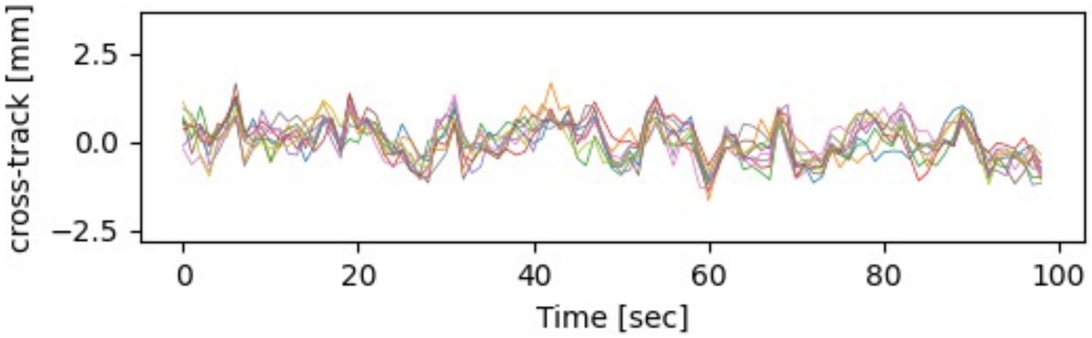
Positioning Algorithm Approaches

- We developed mm-level precision relative positioning algorithm that uses double-differenced GNSS+range, solves IAR, and dynamics fusion for spacecraft swarm.
- Positioning analysis considers both post-process (primary) and real-time (secondary)

Relative estimates of 10 deputies (range-only)



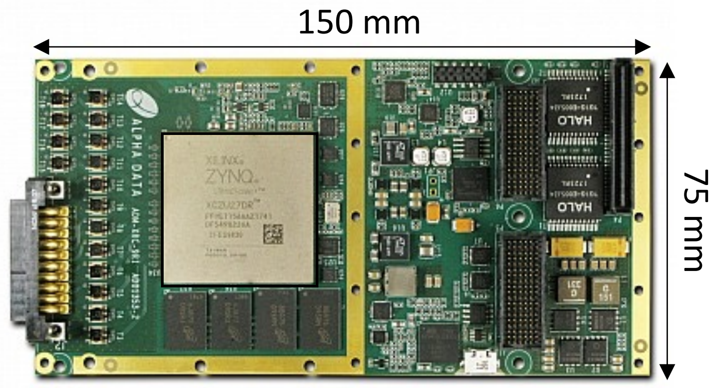
Relative estimates of 10 deputies (range-DGNSS, tight fusion)



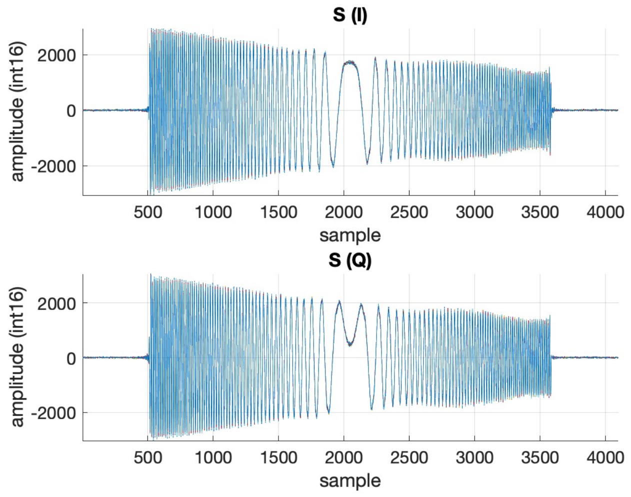
marco.lavalle@jpl.nasa.gov

DARTS RFSoC: Next Generation Software Defined Radar

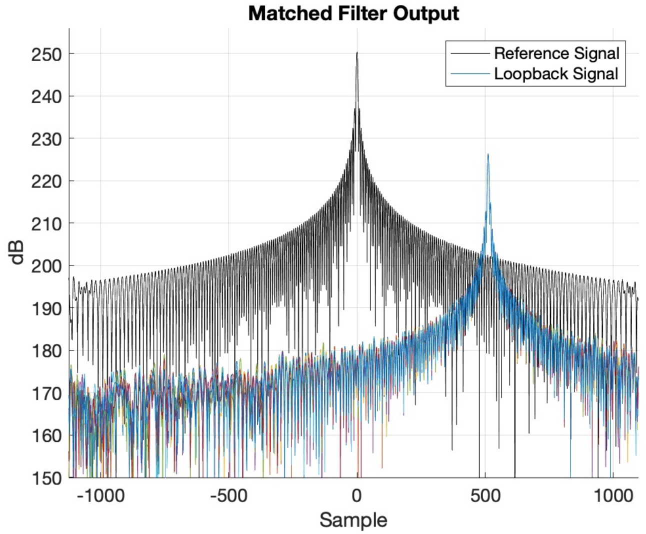
- Software defined radio/radar (SDR/SDRadar) with arbitrary waveform generator (AWG) and wireless synchronization that run on RF System on Chip (RFSoC) developed by DARTS
- Xilinx RFSoC platforms combine high RF performance and extremely low SWaP (ARM processor, Ultrascale+ FPGA, ADCs, DACs)
    - Ideal development test bed for multistatic/MIMO radar algorithms
    - Rapid hardware prototyping and development due to high level of integration
    - Low SWaP make it ideal for ground validation of distributed radar systems
    - RF and digital performance can be dynamically configured to match target flight hardware for space-borne missions



Alpha-Data ADM-XRC-9R1 RFSoC board



Baseband Received Chirp Signals



MF output with reference signal autocorrelation

- Loopback test successful:
    - DAC/ADC external cable loopback with 10 dB attenuator
    - SDRadar AWG loaded with chirp waveform sample file
    - 500 MHz bandwidth waveform upsampled to 4 GSPS and mixed to 1 GHz center frequency
    - Digitally down-mixed to complex baseband and low pass filtered
    - 16 Pulses transmitted at PRI 100 usec
    - Pulses are time-aligned and phase coherent

marco.lavalle@jpl.nasa.gov

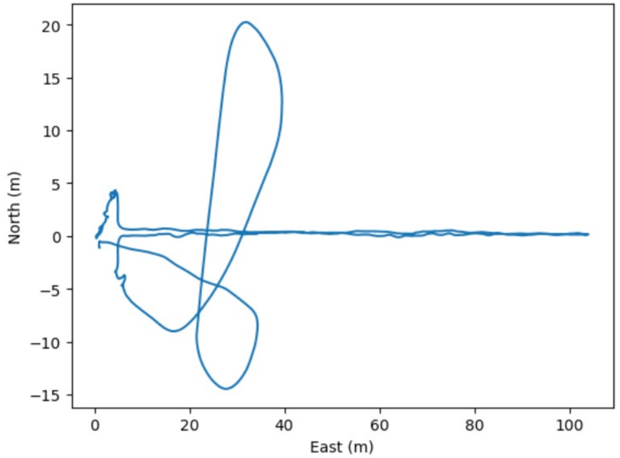
UAS multi-static SAR field experiments

Repeat-pass tomographic flights over corner reflectors using L-band Ettus USRP 312 85 MHz on Caltech campus on Monday May 3 2021

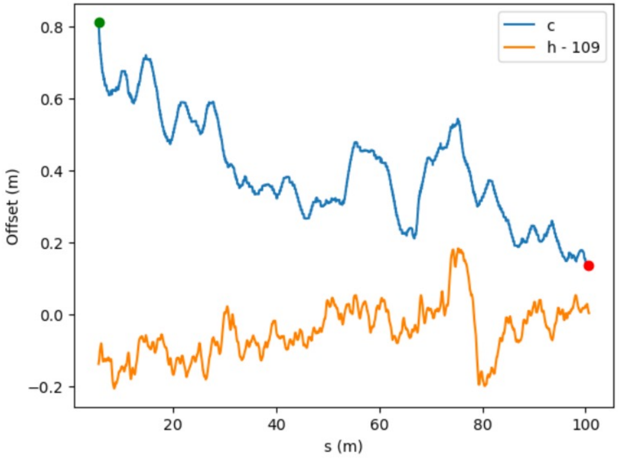
marco.lavalle@jpl.nasa.gov

UAS multi-static SAR field experiments

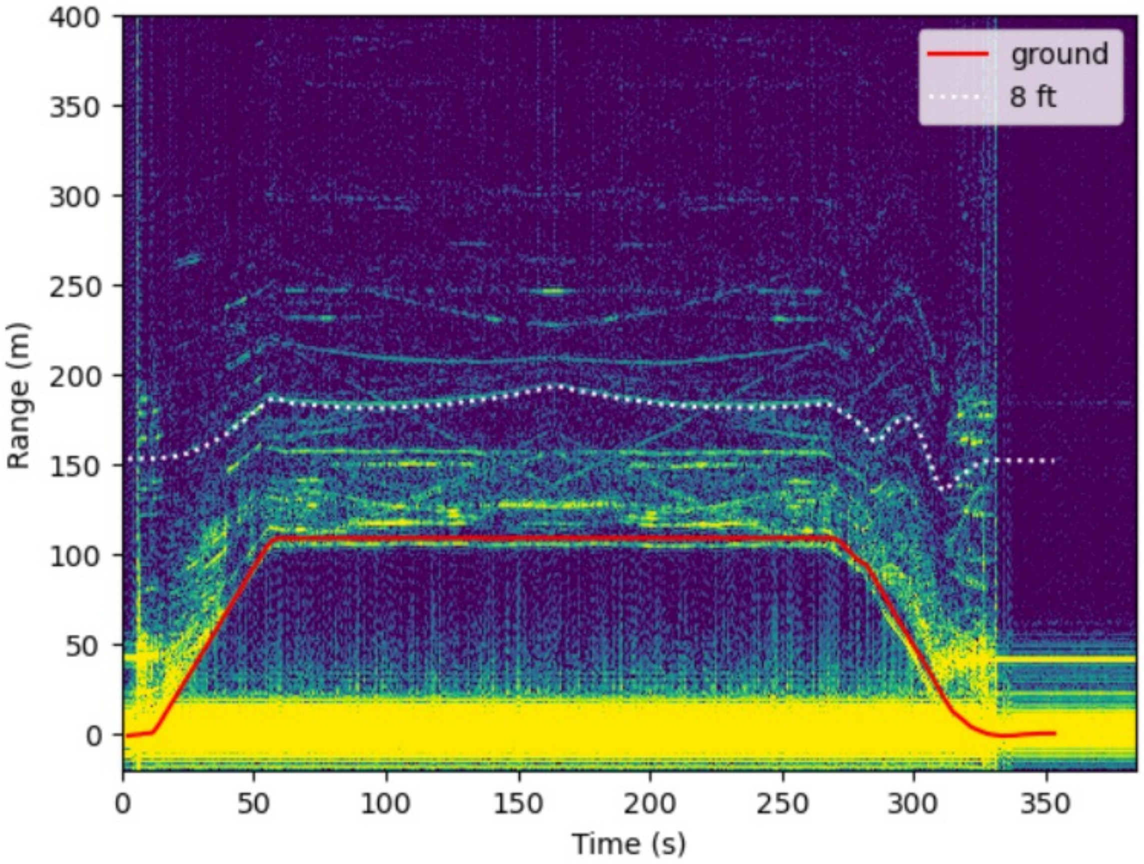
Full UAV trajectory (North/East)



Single track UAV trajectory (SCH)



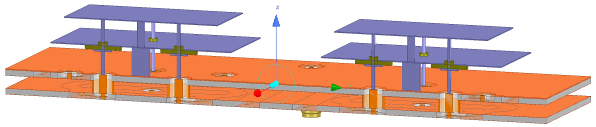
Preliminary range-compressed L-band SAR image obtained 24h after the UAS experiment on Monday May 3, 2021



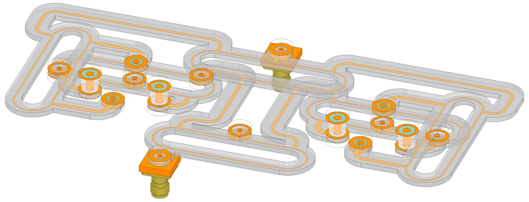
Deployable antenna for DARTS

- Preliminary antenna design guided by NISAR concept but more lightweight solutions are under evaluation
- Smaller sub-assembly (one patch pair) with dual feed point / patch / polarization and wider sub-assembly separation
- Striplines, rat races, vias, terminations, connectors and power dividers were redesigned for wider bandwidth
- Sub-assembly: Stacked patch configuration, TNC connectors for power handling, 150 mm x 300 mm x 43 mm
- Single panel: Array made with 18 sub-assemblies, panel size: 90 cm x 90 cm, Cx-Coupling < -38 dB and Cx-Pol < -60 dB

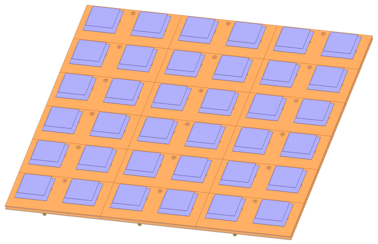
Cross section of sub-assembly



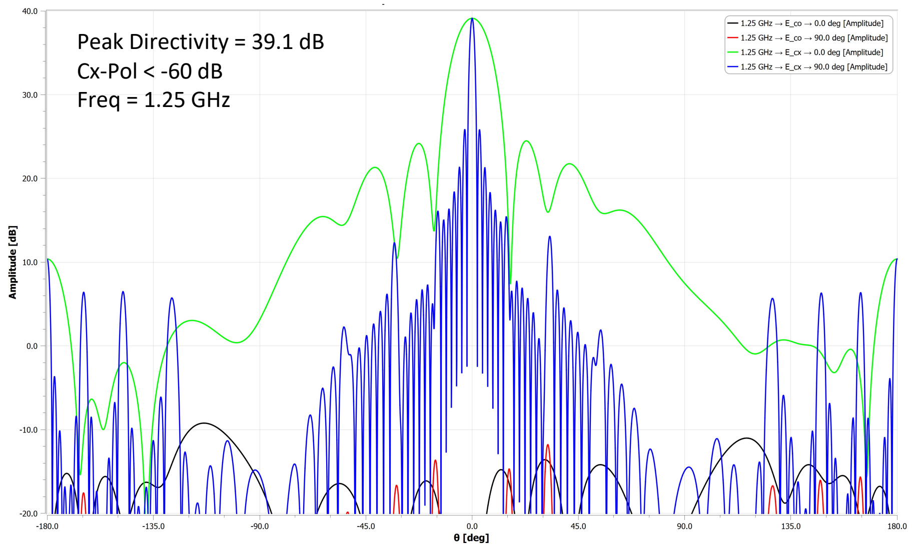
Dual layer feeding network



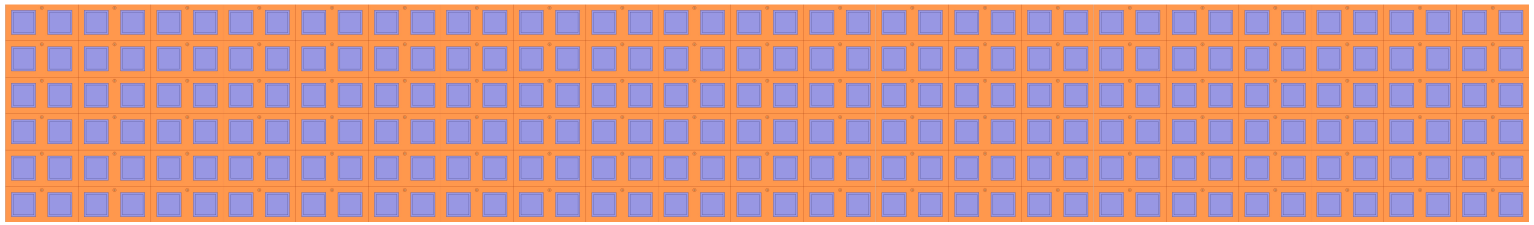
Single panel 0.9 m x 0.9 m



H-pol antenna pattern



Array size: 0.9 m x 6.3 m | Peak Directivity > 39 dB | Cx-Pol < -60 dB



marco.lavalle@jpl.nasa.gov

DARTS and STV: Take-away messages

1. DARTS (PI: Marco Lavalle) is a 3-year IIP project started in April 2020 to mature and demonstrate technologies that enable global vegetation structure and surface topography measurements using TomoSAR from space
2. DARTS concept consists of a distributed formation of SmallSat SARs with several trade-offs informed by SATM developed as part of the NASA STV Study in 2020-2021
3. Preliminary results show that a formation of >6-12 spacecraft can satisfy STV resolution and ambiguity needs at L-band. Higher-frequency (eg. S-band) may offer same performance with miniaturized radar electronics
4. Technologies are at TRL 3-4, e.g. synchronization and positioning algorithms developed and demonstrated with mm-level and sub-nanoseconds accuracy in simulations and preliminary hardware experiments
5. Major next steps are the integration of the various technologies within simulation environment and test with SDRadar RFSoC and UAS hardware
6. More results at our invited session at IGARSS 2021 "*Technology and science advances of SmallSat distributed SAR systems*" (12-16 July 2021)