S-Band Smallsat InSAR Constellation for Surface Deformation Science

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S-Band Smallsat SAR Concept

Science Justification

- Repeat-pass InSAR, is used by Earth scientists to study surface deformation in geophysically active areas
- Examples include deformation along earthquake faults, in volcanic regions, subsurface aquifers, and the major ice sheets.
- Long-standing science community goal to field a constellation of InSAR satellites, producing deformation maps at **up to daily intervals**, with **full vector displacements** and submillimeter per year accuracies.
- The joint NASA/ISRO SAR mission,known as NISAR, currently planned for launch in 2021, is a significant step on the road to this future capability, with global access on a **12-day revisit** interval.

Value Proposition

- A Synthetic Aperture Radar Smallsat that fits within an ESPA-ring form factor:
  - 1.0x0.7x0.6 m volume
  - < 180 kg mass

  could be executed for < $100M*
- Bulk production should lower that unit cost to allow a low-cost constellation
- ESPA rings allows launch of 6 Smallsats at a cost of ~$10M each
- ROM cost for a constellation of 12 ≅ 1 to 1.5 X full NISAR mission
- Use case:
  - Systematic surface deformation mapping at 1-2 day intervals, with multiple look directions (to map vector deformation)

*The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

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Mission Design - Orbit

- Orbit has to provide global access, at lowest possible altitude for radar operation, with acceptable drag levels to reduce orbit maintenance operations.
- Orbit selection - preferred orbit for constellation is sun-synchronous, circular and near-polar at an altitude of ~600 km.
- A constellation of 12 satellites, spaced at one-day intervals, in a 12-day exact repeat orbit, would provide the required temporal revisit frequency.

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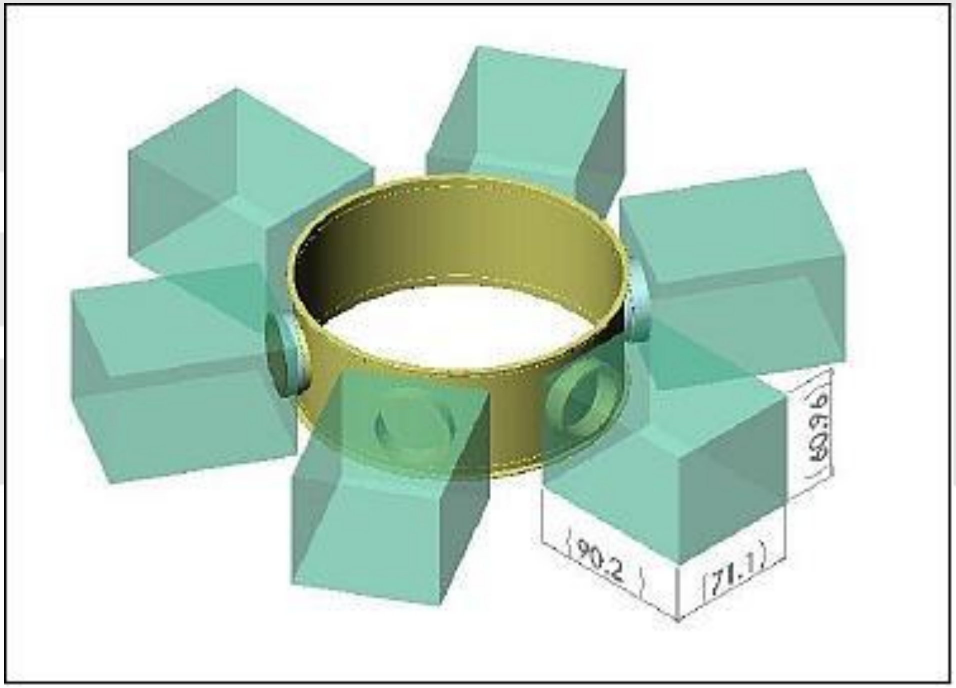
Mission Design – Launch Strategy I

- An ESPA-ring class spacecraft, with dimensions 1.0x0.7x0.6 m, and mass < 180 kg, allows one to take advantage of low-cost secondary launch opportunities on ESPA ring slots
- An ESPA-ring enables up to six elements of the InSAR constellation to be launched at a time



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Mission Design – Launch Strategy II

- After launch, individual elements of the constellation would have to be phased into their required orbits, using a propulsion system, also needed for orbit maintenance

- ESPA-ring spacecraft are also compatible with the Venture-class, low-cost small launch vehicles that NASA is currently sponsoring

- Flexibility in launch options also makes for easy replenishment of the constellation as it ages and elements are retired.

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Wavelength Selection

- Of the frequencies available for Earth observation using radar, we select S-Band for the following reasons:
  - Longer decorrelation times than for shorter wavelengths
  - Less severe ionospheric effects than at L-Band
  - S-Band SAR antennas are generally smaller than L-Band antennas

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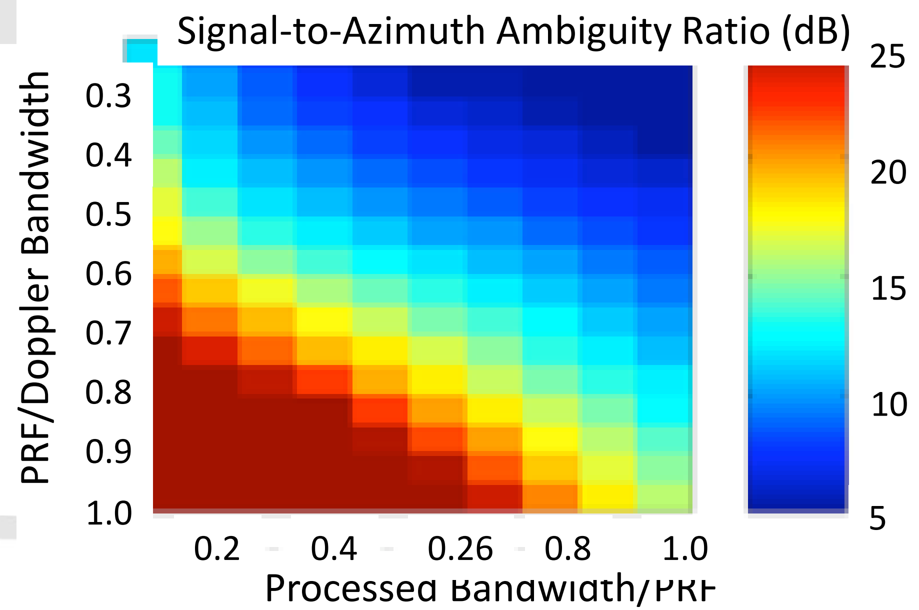
Design Methodology*

- Lowest possible orbit altitude to reduce power needs
- Antenna height sized to illuminate the desired swath of 80 km
- Smallest possible antenna length in azimuth - 5m
  - Set PRF = 0.85 B_D
  - PBW = 0.5 PRF
  - Penalty in achievable Az. Res.

    $> \rho_{min}/(0.85*0.5)$

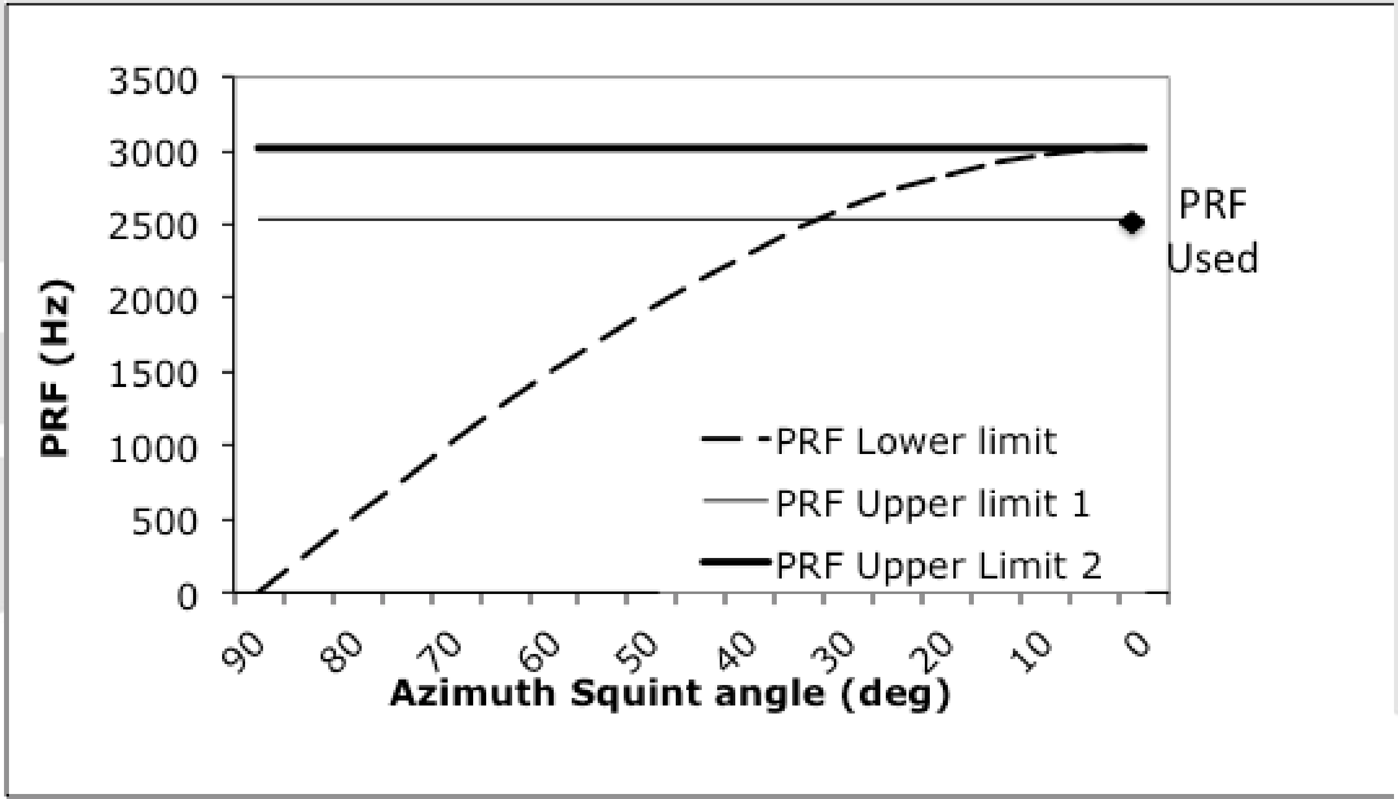
    $= 2.35*\rho_{min}$
  - But lower PRF allows full swath coverage to be achieved



*On the Use of Small Antennas for SAR and SAR Scatterometer Systems
A. Freeman and C. Chen (unpublished)

Setting the PRF

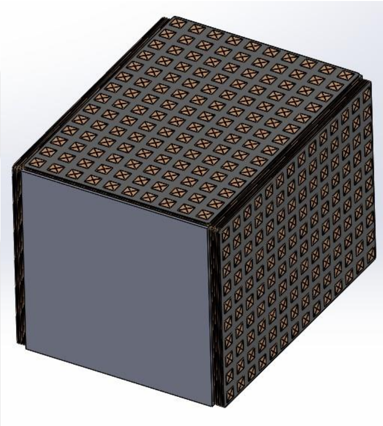
- In conventional SAR design,
  - PRF has to be > B_D (Lower limit)
  - Avoid range ambiguities in the illuminated swath (Upper limit 2)
  - Can't transmit while receiving (Upper limit 1)
- With a SAR antenna that's too short, can set PRF < B_D, but now we can't use the full Doppler bandwidth to get the theoretical limit azimuth resolution (L/2)
- More margin in PRF selection for non-zero squint angles, but swath width is reduced

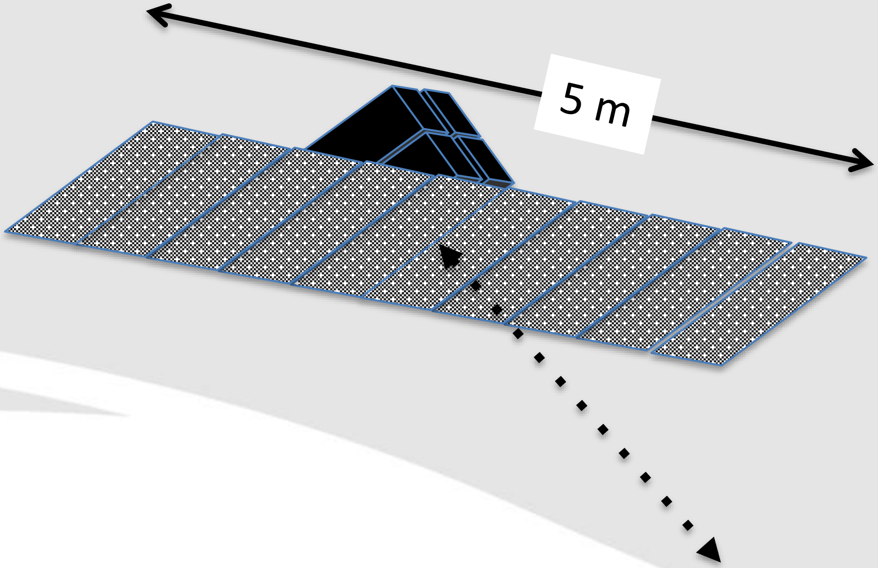


S-Band SAR Concept

Orbit altitude	600 km
Center frequency	3.2 GHz
Incidence angle	25 - 35 deg
Tx Power	1000 W
DC power	340 W
On-orbit average DC Power	102 W
Radar Electronics Mass	25 kg
Pulse length	50 μs
Antenna size (L X W)	5.0 X 1.0 m
F/D ratio	0.5
Bandwidth	25 MHz
Data rate (3:1 presum, 8:4 BFPQ)	65 Mbps
On-time per orbit	20-30 mins
Downlink rate	300 Mbps
Noise-equivalent σ^o	-21 dB
Spatial res./ [# looks]	10 m/ [1]
Swath width	80 km

- Stowed Configuration:
  - ESPA-ring Compatible Spacecraft
  - 1.0x0.7x0.6 m volume
- Deployed Configuration
- Solar array + μstrip patch antenna





SNR Calculation

Parameter	*dB value*
Peak Transmit Power, P_t	30
Antenna Gain Squared, G_A^2	77.1
Wavelength Cubed, λ^3	-30.8
Speed of light, c	84.8
Pulse length, τ_p	-43
Insertion Loss (2-way)	-8.3
Sigma0	-21
$(4\pi)^3$	33
Range cubed (R^3)	175.5
Boltzmann's constant, k	74
Bandwidth, B	74
Noise Figure	2.5
$2\sin\theta_L$	0.6
SNR	0

Noise-Equivalent Sigma0

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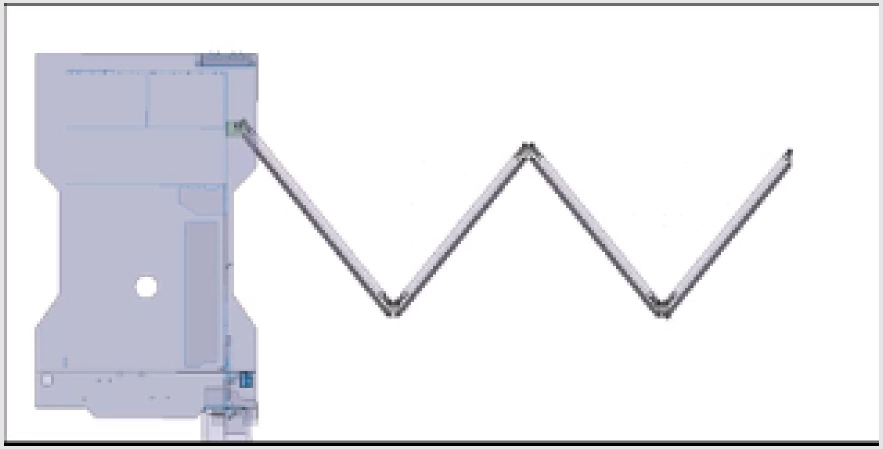
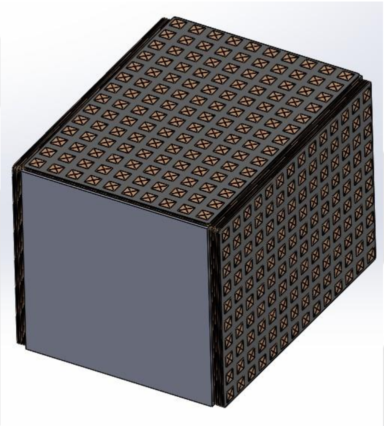
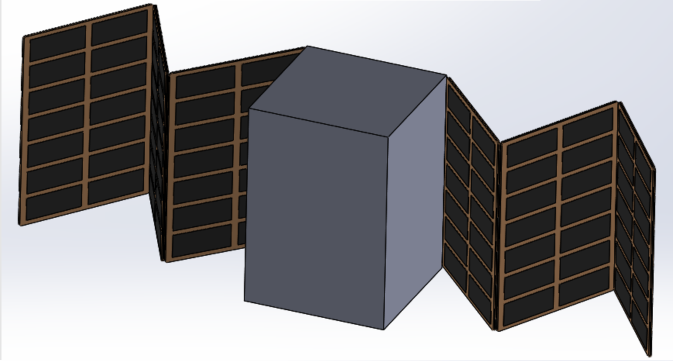
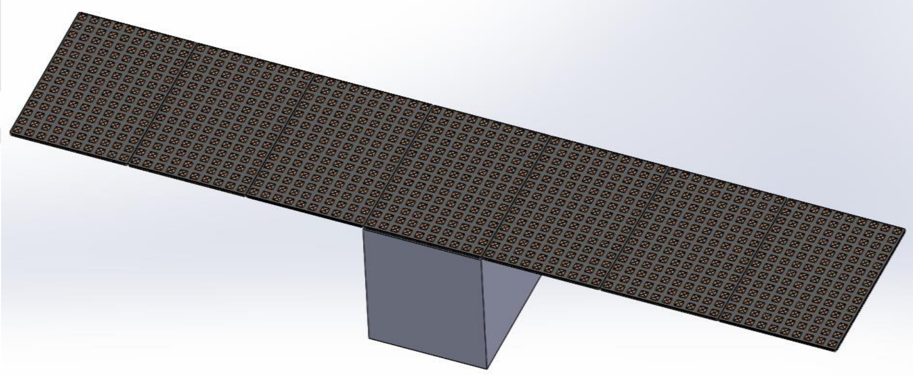
Deployment Mechanism



Example: Oxford Space Systems



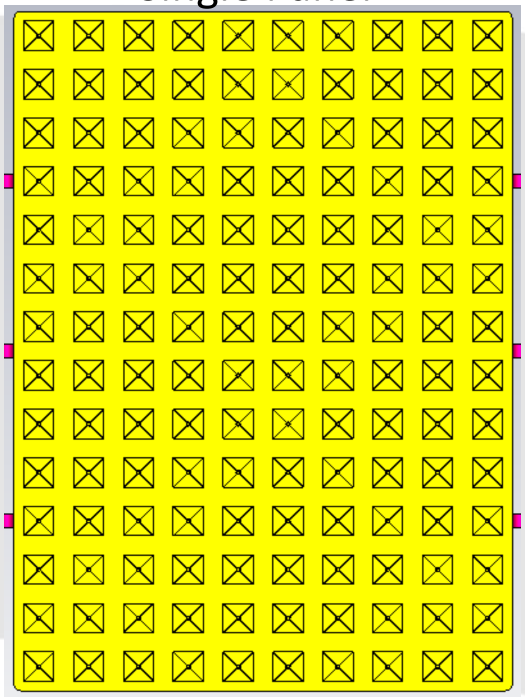




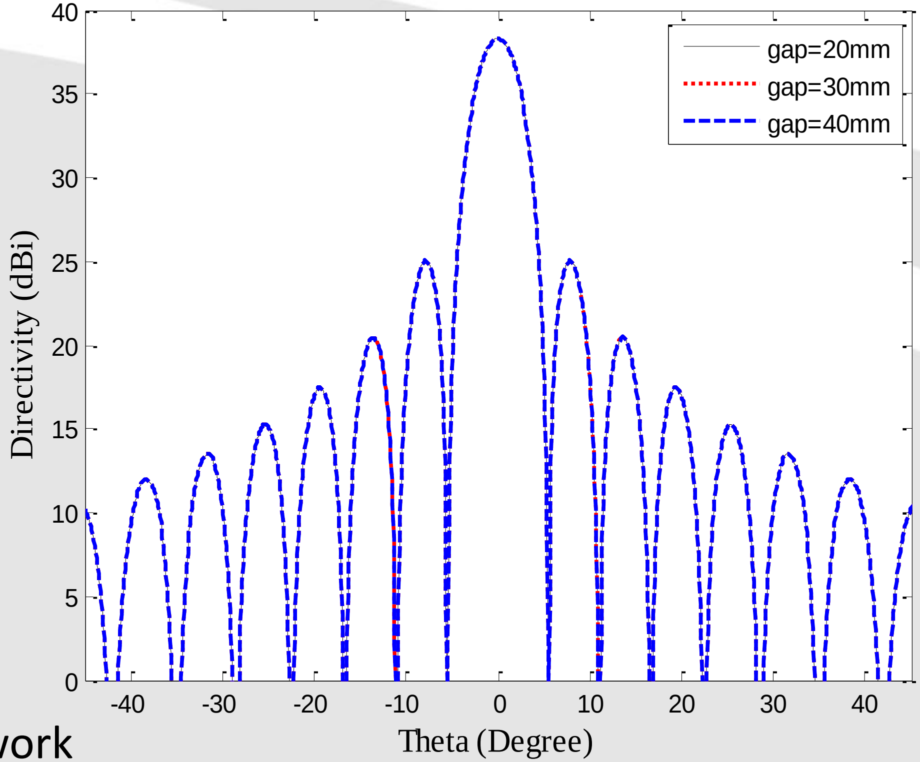
- Antenna panels deploy in 2 simple wings to form a 5 X 1 meter microstrip patch antenna

Microstrip Patch Array

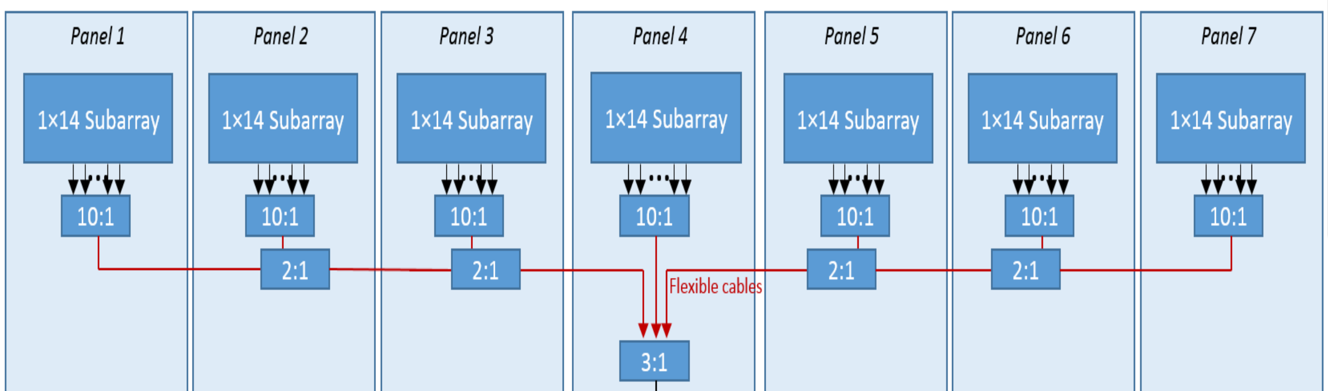
Single Panel



Beam Pattern



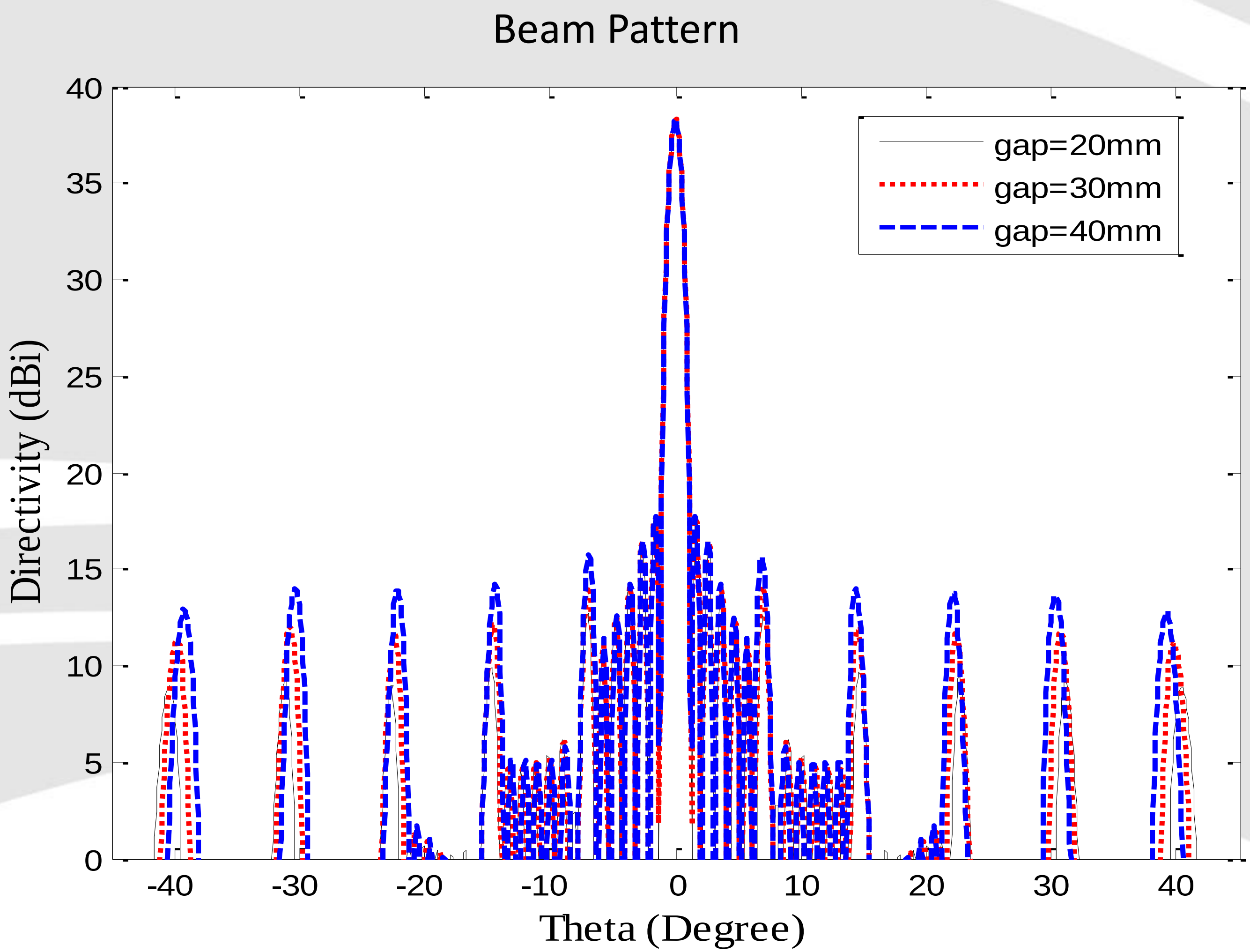
Feed Network



Insertion loss is 4.15 dB

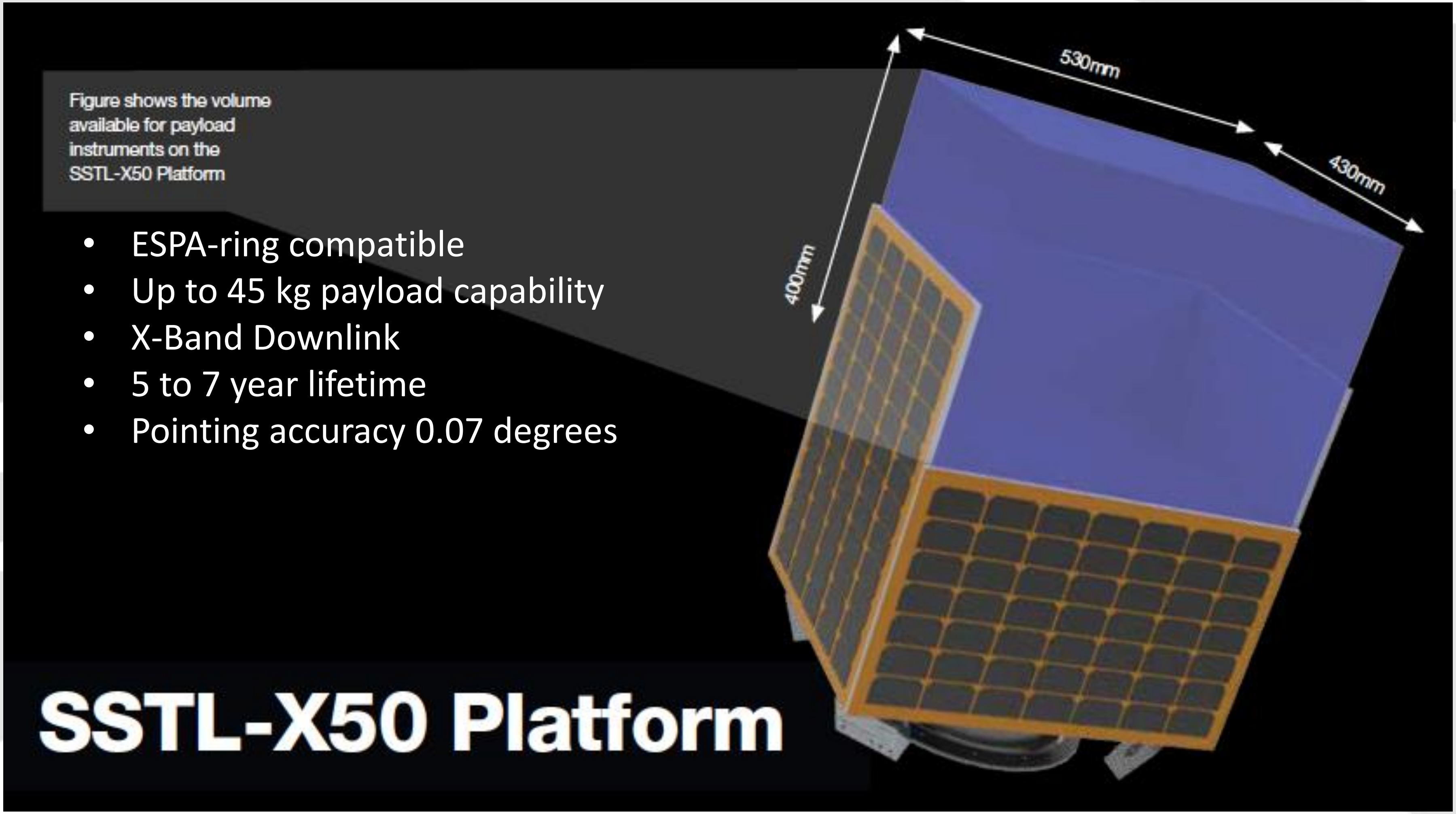
Microstrip Patch Array

- Factoring in the effect of gaps between panels on antenna performance



Spacecraft Example

- Several spacecraft manufacturers based in the US offer suitably inexpensive, ESPA-ring class spacecraft



- ESPA-ring compatible
- Up to 45 kg payload capability
- X-Band Downlink
- 5 to 7 year lifetime
- Pointing accuracy 0.07 degrees

S-Band Smallsat SAR Concept

Concept of Operations

- Each Smallsat SAR has sufficient power to operate for up to 30 mins/orbit, with an 80 km wide swath
- Data is downlinked thru 1 or 2 high latitude ground stations (store and forward)
- Downlink opportunities/data volumes restrict operations to ~ 20 mins per Smallsat
- With 12 Smallsat SARs in separate orbits, could image anywhere on Earth once per day
- 12 Smallsat SARs can be launched on two ESPA rings
- Need cold gas propulsion system for orbit distribution/orbit maintenance

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Repeat-Pass Performance

- Overall performance of the S-Band SAR constellation as an InSAR system for surface deformation depends on the ability of each S/C to maintain a precise and repeatable orbit track.
- Requirement for NISAR is to fly the same orbit ‘tube’ for repeat-pass observations, with a maximum allowable separation of 500m in the across-track direction
- The areal cross section of the satellites in the Smallsat S-Band constellation are ~ 0.7 m^2, and the nominal orbit altitude is 600 km

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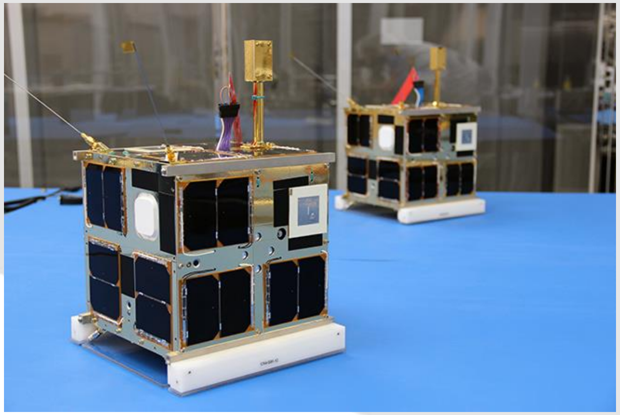
State-of-the-art for Formation Flying

- DLR's Tandem-X mission team achieved precision flying within a 250 m tube from orbit pass to orbit pass, controlling each satellite's across-track position to within 5m, and along-track to with 50m, at an altitude of 515 km
- Both Tandem-X satellites use cold gas propulsion for orbit maintenance, and their cross-section in the ram direction is 3.1 m^2

- In 2014, the University of Toronto's 6 kg CanX-4 and CanX-5 nanosats were used to demonstrate autonomous formation flying with sub-m precision and cm-level relative position knowledge, at an altitude of 660 km and at multiple satellite separation distances, from 50 m to 1000 m
- CanX-4 and -5 both use cold-gas propulsion systems to maintain orbit and have an areal cross-section of 0.04 m^2



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Conclusions

- A constellation of 12 S-Band Smallsat InSARs appears feasible
- A rough estimate of the cost of such a system would put it at 1 to 1.5 times the cost of a full, single-S/C NISAR mission
- The constellation should satisfy the science requirement for deformation maps at **up to daily intervals and** sub-mm/yr. accuracies
- And it would have the flexibility to demonstrate full vector displacements measurements