National Aeronautics and Space Administration

PHASED ARRAY GNSS ANTENNA FOR THE *FORMOSAT-7/COSMIC-2* RADIO OCCULTATION MISSION

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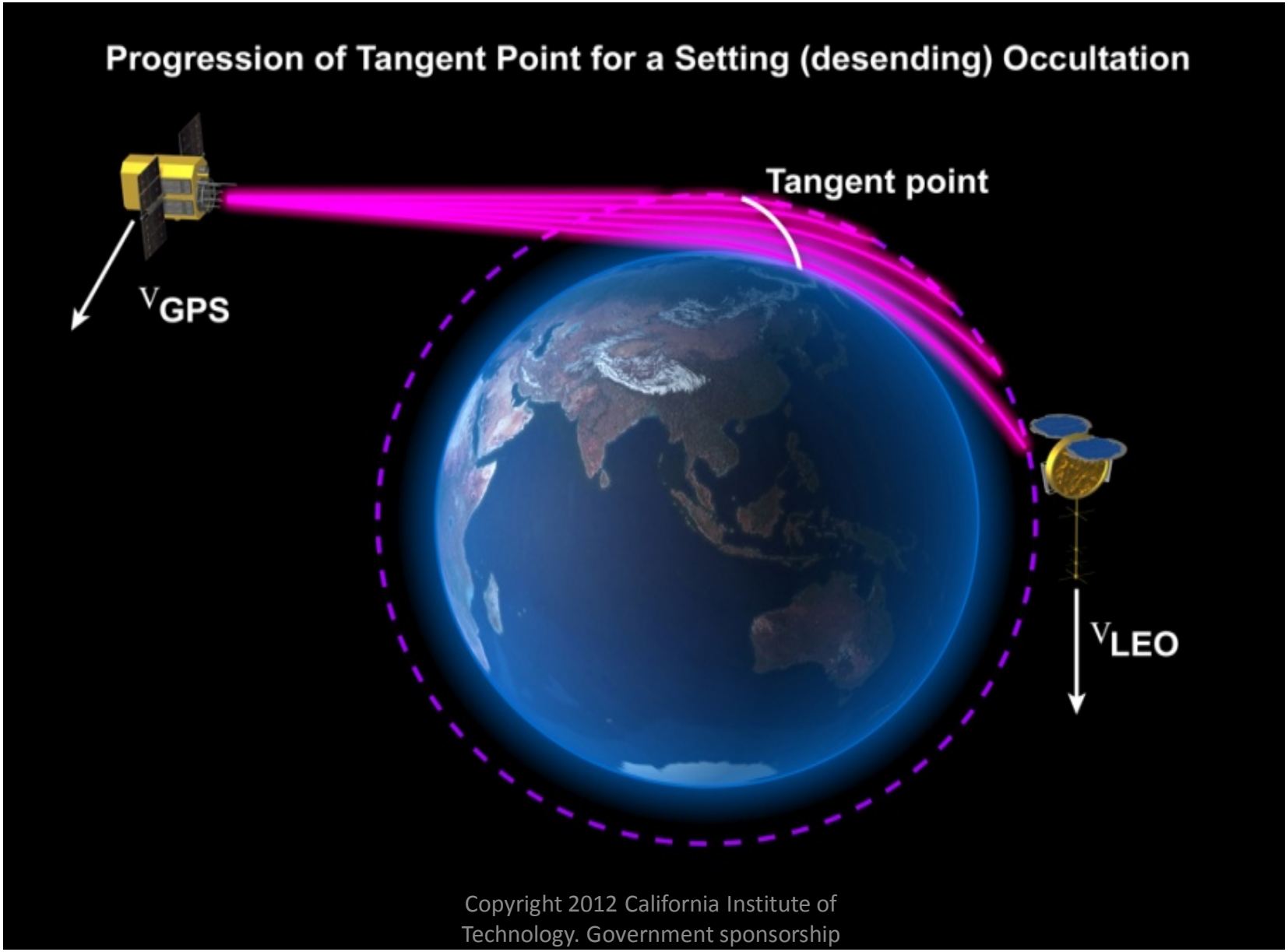
Radio Occultation



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Antenna Requirements

- **Maximum Gain**

- **Field of view**:
  - "Banana-shaped" (along Earth's Limb)
  - -25 ±5 deg Fixed Elevation
  - ±55 degree SCAN ANGLE in Azimuth

- **Spacecraft Constraints**:
  - Must fit inside 60x40x10 cm
  - TRIG has 8 RF inputs, THREE per RO antenna.

- **GNSS** (1.1--1.7 GHz, RCP, etc)

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Figure-of-Merit: ***Aperture Efficiency***

Let's define the following quantities:

- ***Effective Aperture*** = Area over which the antenna extracts power from the incident wave.

  - $A_e = \frac{\Lambda^2}{4*\pi} * Gain$

- ***Physical Aperture*** = Cross-section area perpendicular to direction of incident wave

  - $A_p = 60 * 40 * cos(\theta_{incident})$ [cm^2]

- ***Aperture Efficiency*** = A_e / A_p

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(from Kraus, *Antennas*)

Theoretical Antenna Gain with 100% efficiency Effective aperture: 40 x 60 x COS(-25deg) = $2175cm^2$		
Frequency	**AZ = 0 deg**	**AZ = 55 deg**
L1 (1575 MHz)	**18.8 dBic**	**16.4 dBic**
L2 (1227 MHz)	**16.6 dBic**	**14.2 dBic**
L5 (1176 MHz)	**16.2 dBic**	**13.8 dBic**

For our antenna to have an Effective Aperture as close to this *"Maximum gain"* as possible, we need to have:

1. **Optimum Array Geometry**
2. **High Efficiency Antenna elements**
3. **Low-loss combiner network**

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Array Geometry: ***THREE RF inputs***

- **PROBLEM: How to arrange 60 x 40cm array into 3 subarrays?**

1. We want **fixed, flat, horizontal** beams:

   ⟹ We divide our antenna into THREE VERTICAL sub-arrays

2. Each sub-array will have a collecting area of 60 x 13.3 cm

   Since *elemental apertures* are symmetric, we need:

   ⟹ FOUR ELEMENTS of *about* 14 x 14 cm each

CONCLUSION: IDEAL ELEMENT GAIN: **8.3 dBic** @ L1 (1575 MHz)

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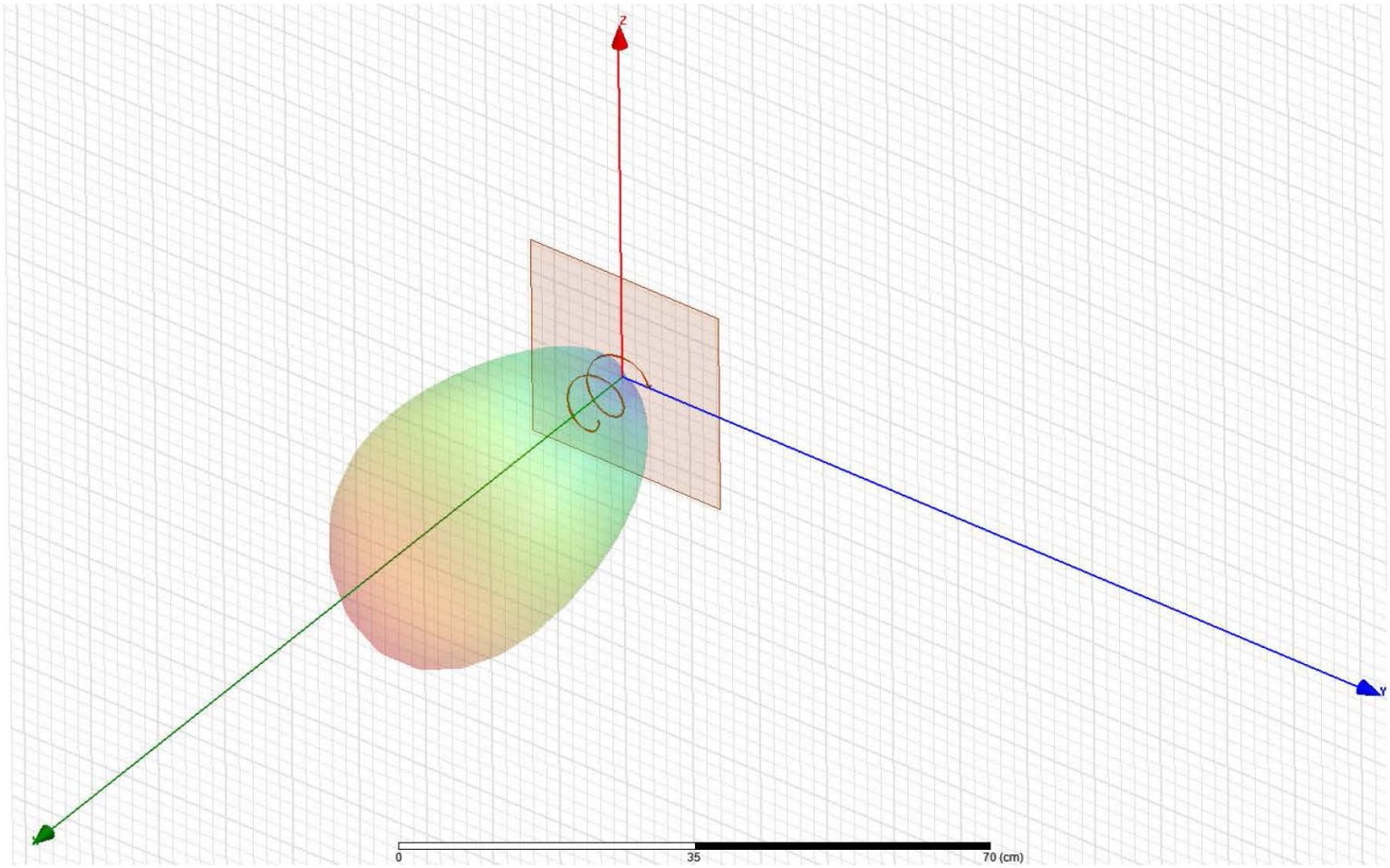
Element Solution: ***2-turn Helix***



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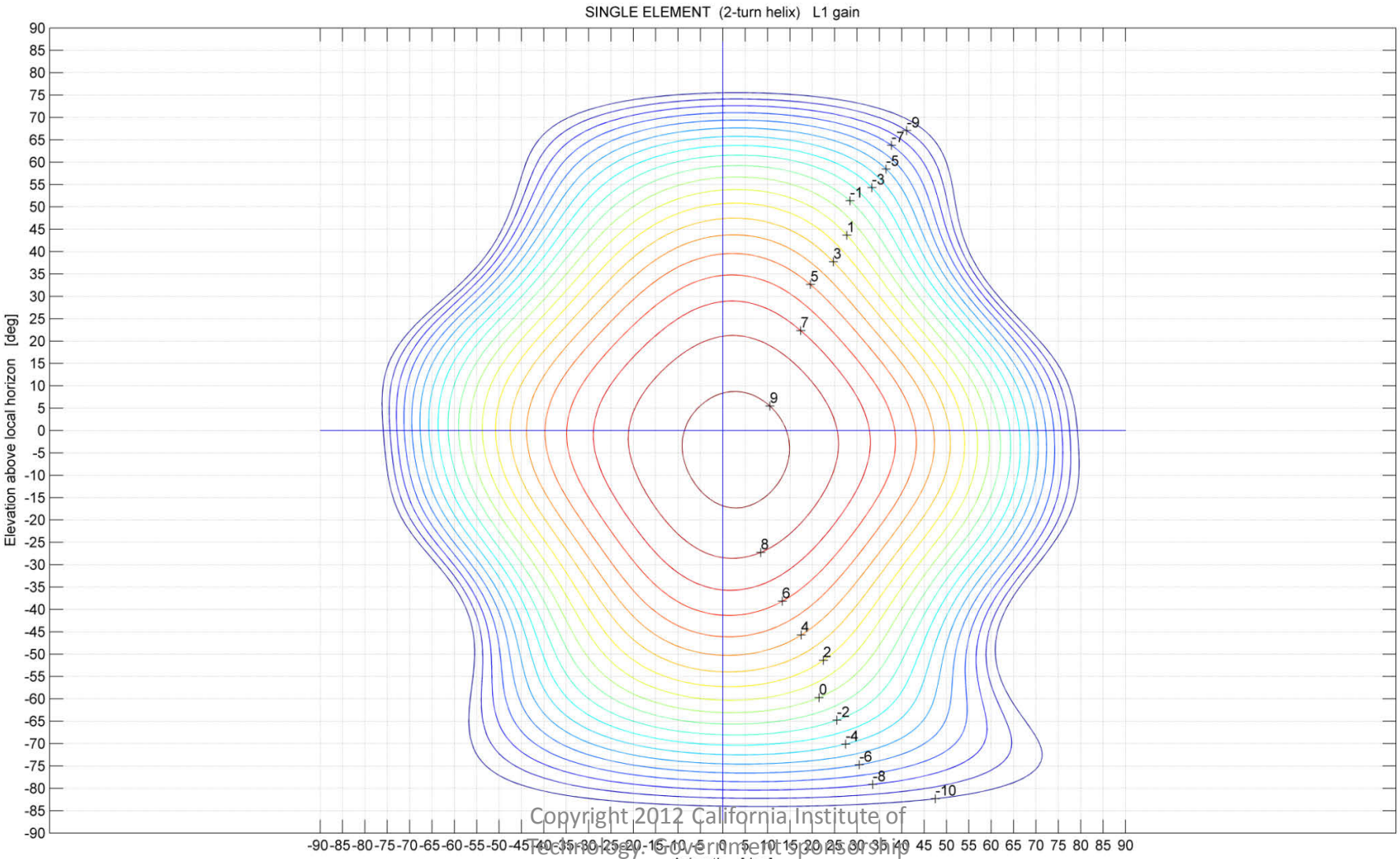
2-turn Helix: L1 Gain



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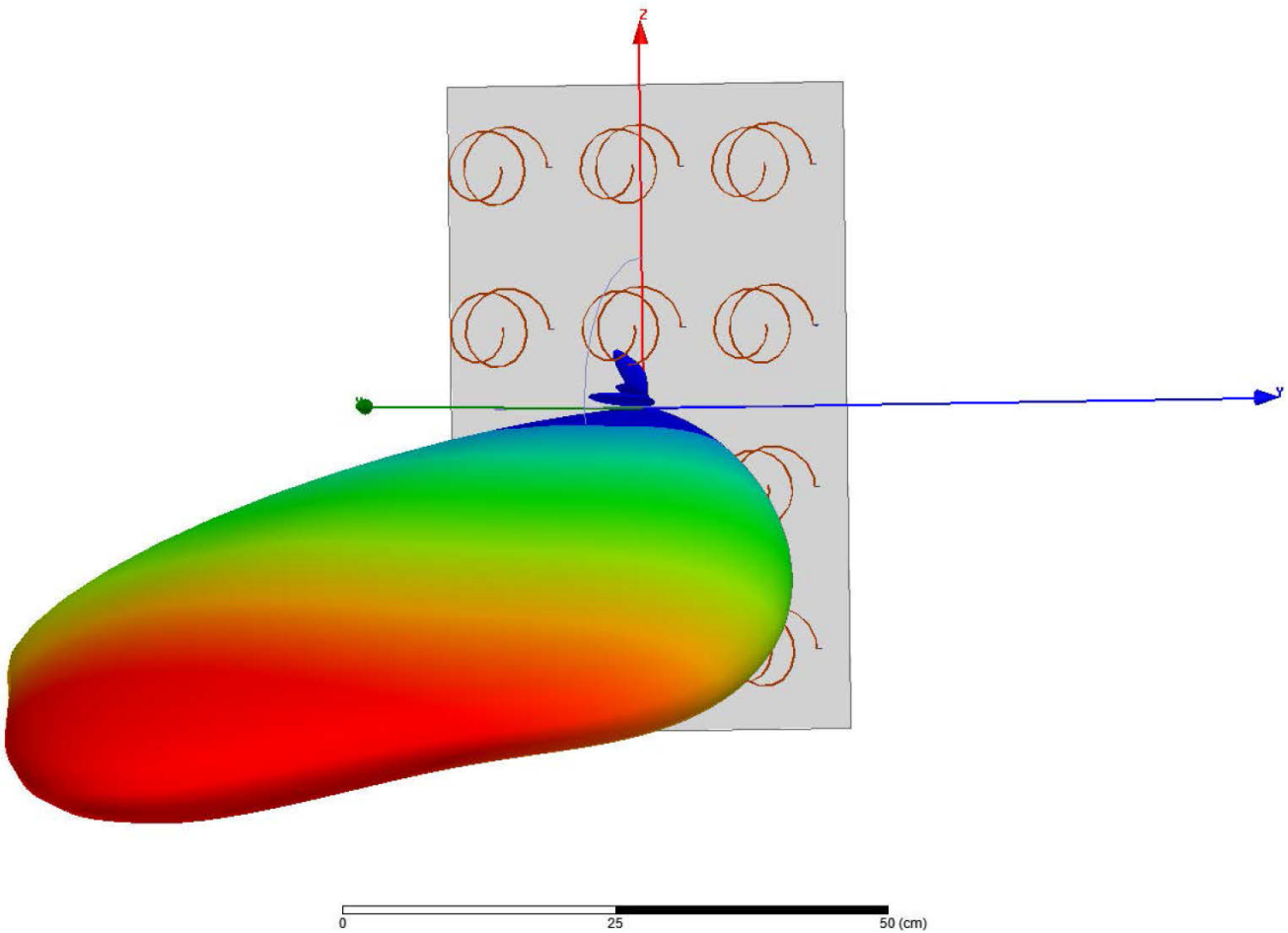
12-element 2-turn Helix ARRAY



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Constraint: Banana-shaped beam

1. **TILTING** THE BACKPLANE by -25deg
   - **PROs: Maximum Gain at 0 deg Az**
   - **CONs: If peak gain is on Earth's limb at 0 deg Az, it is well ABOVE the limb at 55 deg Az.**

2. **PHASING** elements to "STEER the beam" by -25 deg
   - **PROs: Banana-shape: peak gain @ constant -25 deg Elevation.**
   - **CONs: Less gain at peak**

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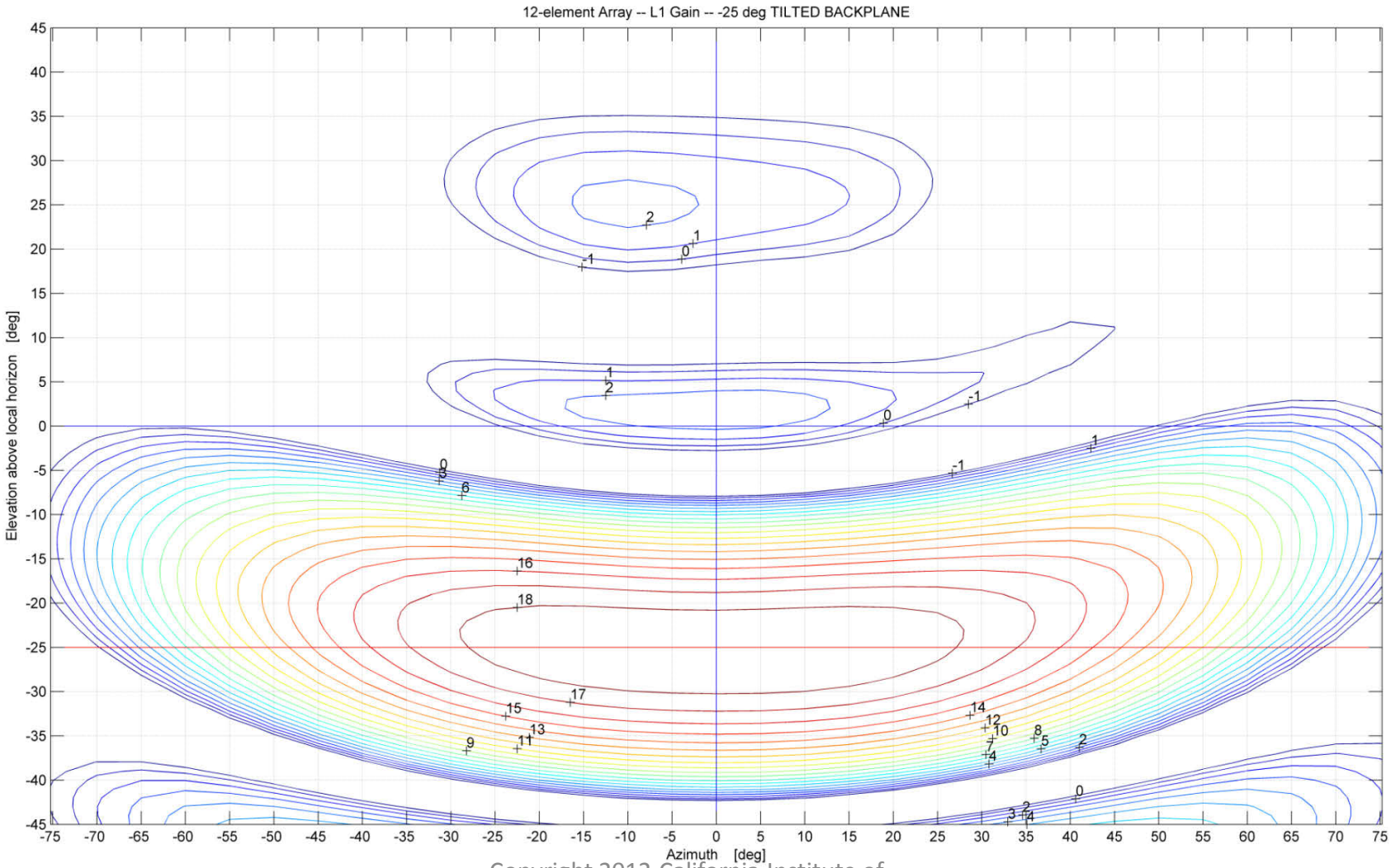
12-element Gain: TILTED



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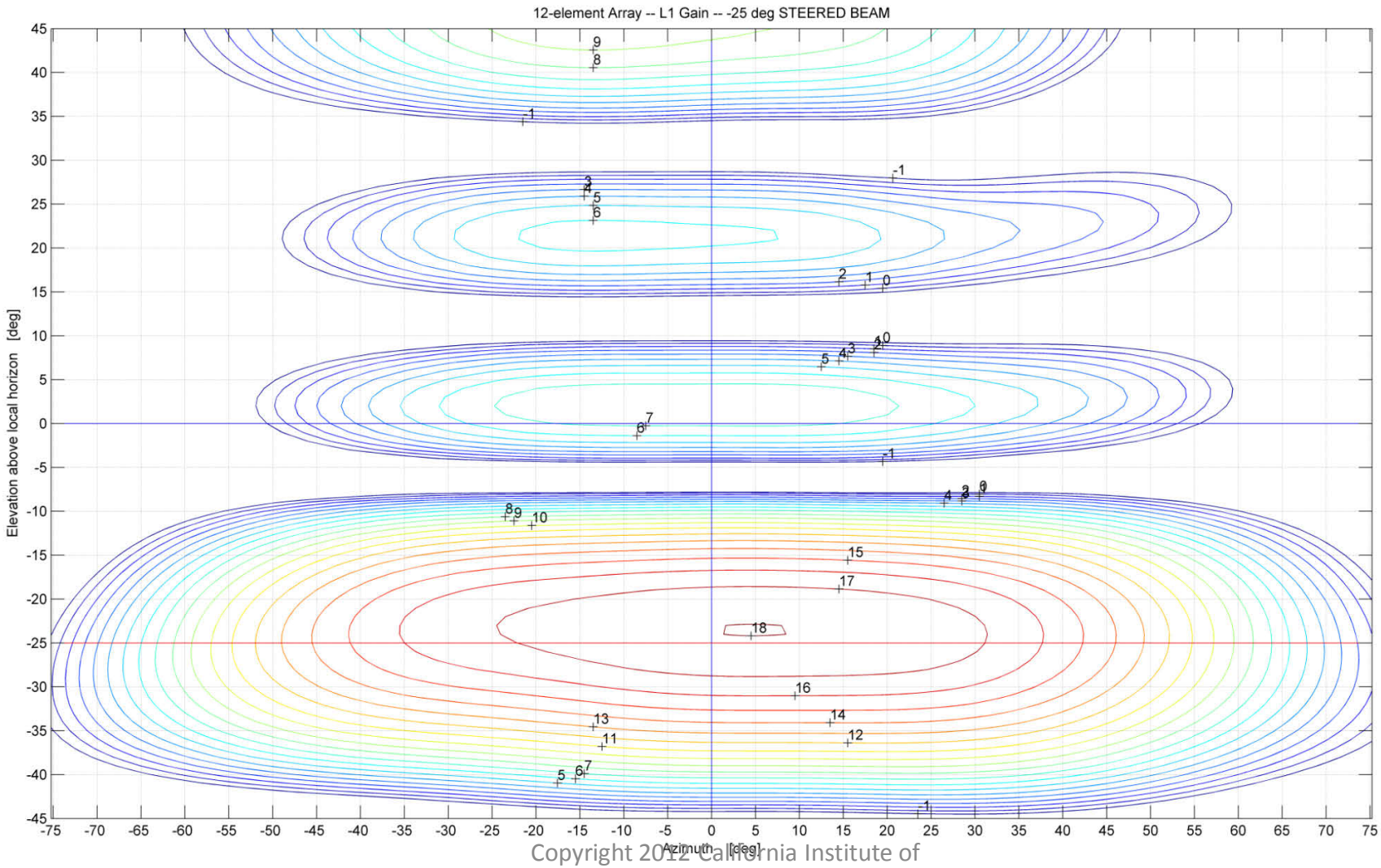
12-element Gain: PHASED



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NOVELTY: Minimum-loss Combiner Network

- Resistive losses before LNA have DOUBLE IMPACT on SNR:
  1. **Less Signal** gets into the receiver
  2. **Additional Thermal Noise** gets 'coupled-in' from the resistive losses

- COSMIC-I had about 3dB difference between Directivity and Realized Gain!
  - **Suspected culprit:** LOSSES IN THE COMBINER

- **How to achieve minimal loss:**
  1. AVOID: Impedance transformations
  2. AVOID: Transitions between transmission lines
  3. USE: Air-dielectric transmission lines.

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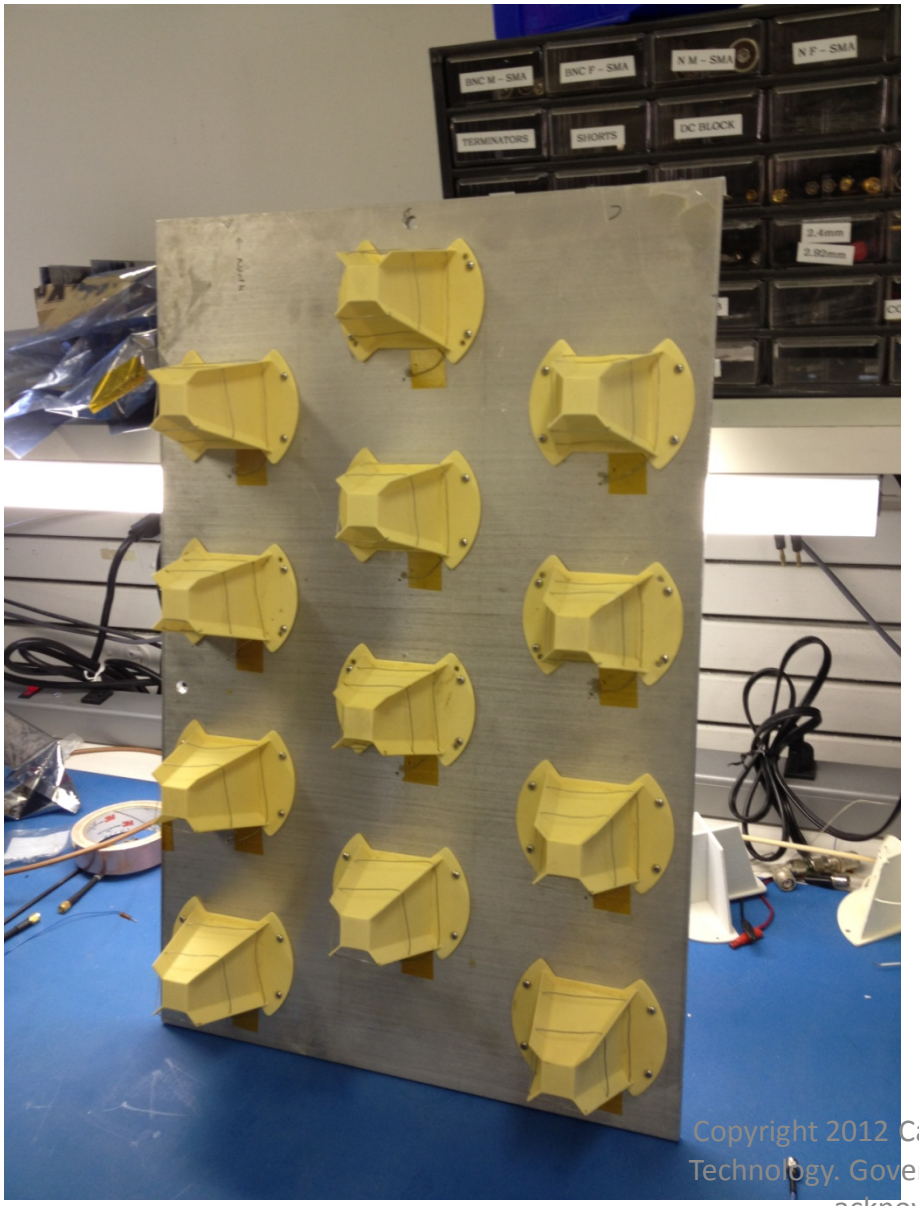
Lossy example



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Combiner Implementation

1. **Set the element's input impedance to 200 Ohm**
   - (4 elements) x (desired 50 Ohm antenna output) = 200 Ohm
   - Wire thickness controls **Series Inductance**
   - Height above Ground Plane controls **Shunt Capacitance**

2. **Use the same wire to realize both:**
   1. The helix element, and
   2. The transmission lines *(single-ended, conductor-over-ground-plane)*

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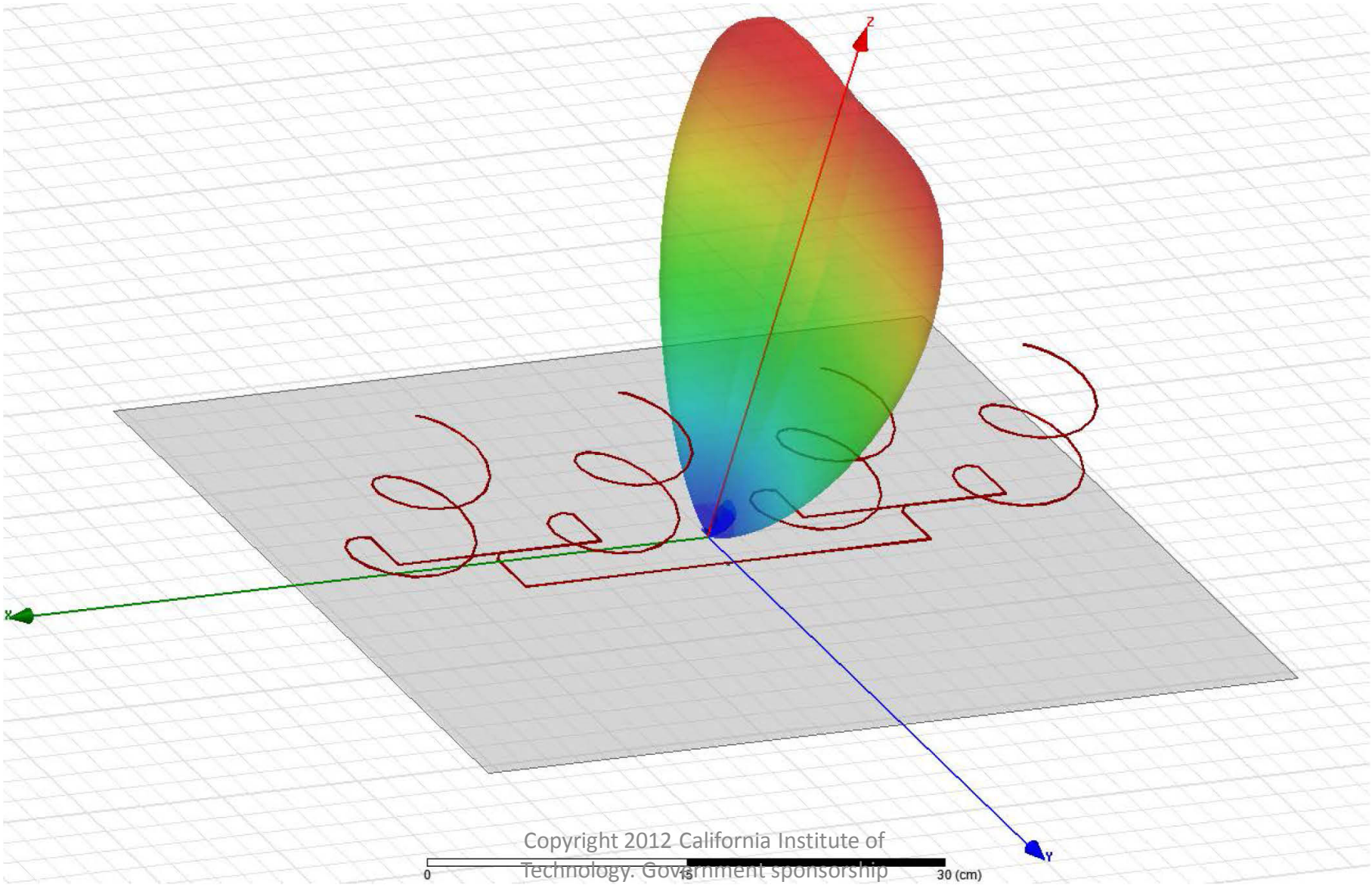
Low-loss combiner



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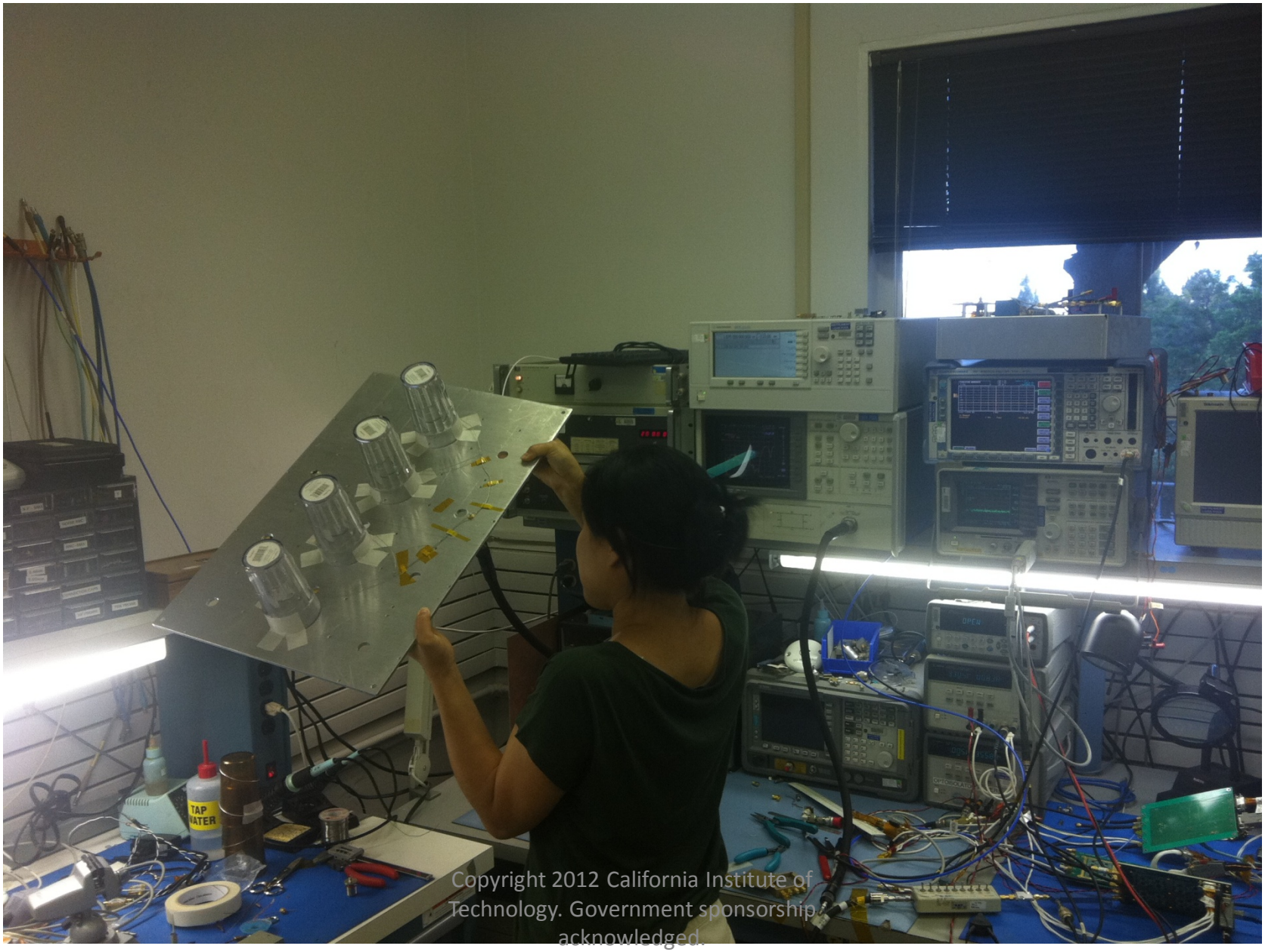
Early prototype



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BUILT PROTOTYPE: 3D-printed!

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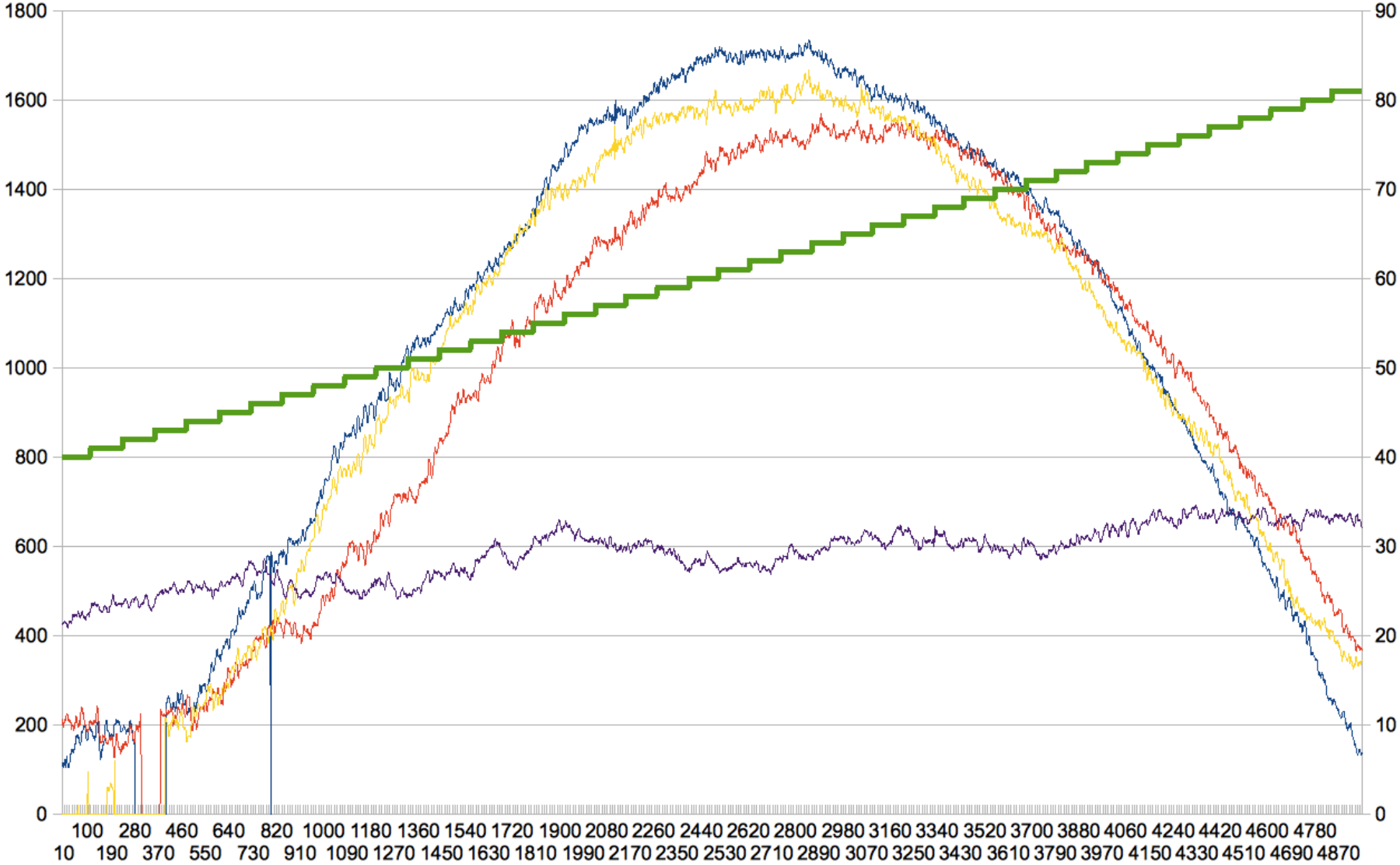
BUILT PROTOTYPE: tracking GPS VSNR



MAX COMBINED SNR = 2791 (vs 900 for COSMIC-1 ie: +9.8dB)

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Theor. Ant (100% efficiency) Effective aperture: 40 x 60 x COS(-25deg) = **$2175cm^2$**		
Frequency	**AZ = 0 deg**	**AZ = 55 deg**
L1 (1575 MHz)	**18.8 dBic**	**16.4 dBic**
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TILTED BACKPLANE (SIMULATED hfss) Effective aperture: **38 x 58 = $2231cm^2$**		
Frequency	***AZ = 0 deg***	***AZ = 55 deg***
L1 (1575 MHz)	**18.9 dBic**	**9.5 dBic**
L2 (1227 MHz)	**16.3 dBic**	**11.5 dBic**

PHASED BEAM (SIMULATED hfss) Effective aperture: **34 x 54 = $1810cm^2$**		
Frequency	***AZ = 0 deg***	***AZ = 55 deg***
L1 (1575 MHz)	**18.0 dBic**	**10.5 dBic**
L2 (1227 MHz)	**15.7 dBic**	**10.7 dBic**

PHASED BEAM (BUILT & MEASURED) Effective aperture: **30 x 51 = $1541cm^2$**		
Frequency	**AZ = 0 deg**	**AZ = 55 deg**
L1 (1575 MHz)	**17.3 dBic**	

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SUMMARY

- This antenna was selected to be **flown on the FORMOSAT-7/COSMIC-2** constellation of 12 LEO satellites *(launch: early 2016)*

- Significant improvements over antennas from previous RO missions (FORMOSAT-3/COSMIC and CHAMP):
  1. Approx. 10dB more gain
  2. Multiple simultaneous digitally-steerable beams
  3. Multi-Constellation

RESULT: Nearly an **order of magnitude more RO data** expected to be available from COSMIC-2

- ***We thank NOAA for funding this design effort.***

- ***This design is part of Caltech provisional patent 61/664,312***

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EXTRA SLIDES

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15-element BIFILAR CONICAL SPIRALS

- **PROBLEMS WITH HELIX:**
  - Needs ground plane
  - Can’t be oriented for maximum gain.

- **ADVANTAGES OF BIFILAR CONICAL SPIRALS:**
  - **NO GROUND PLANE!!**
  - Smoother phase, better Axial Ratio

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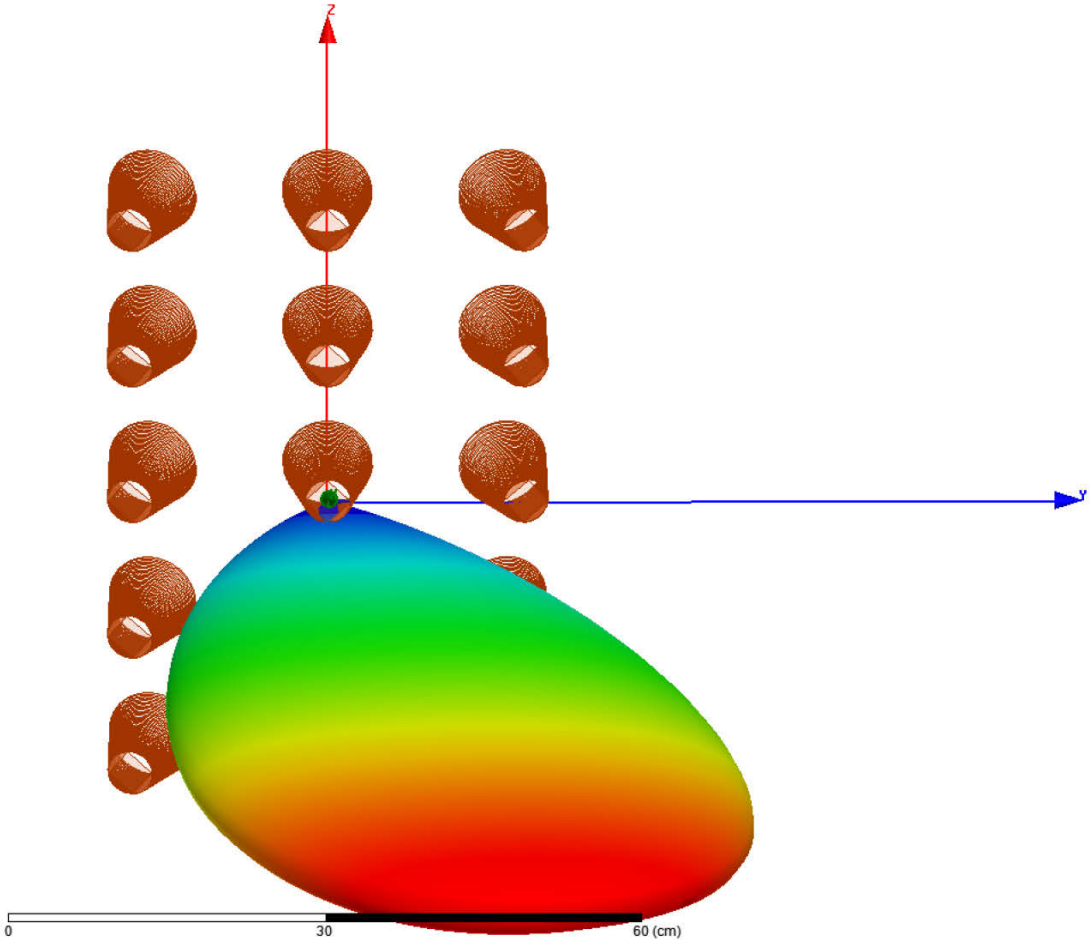
15-element



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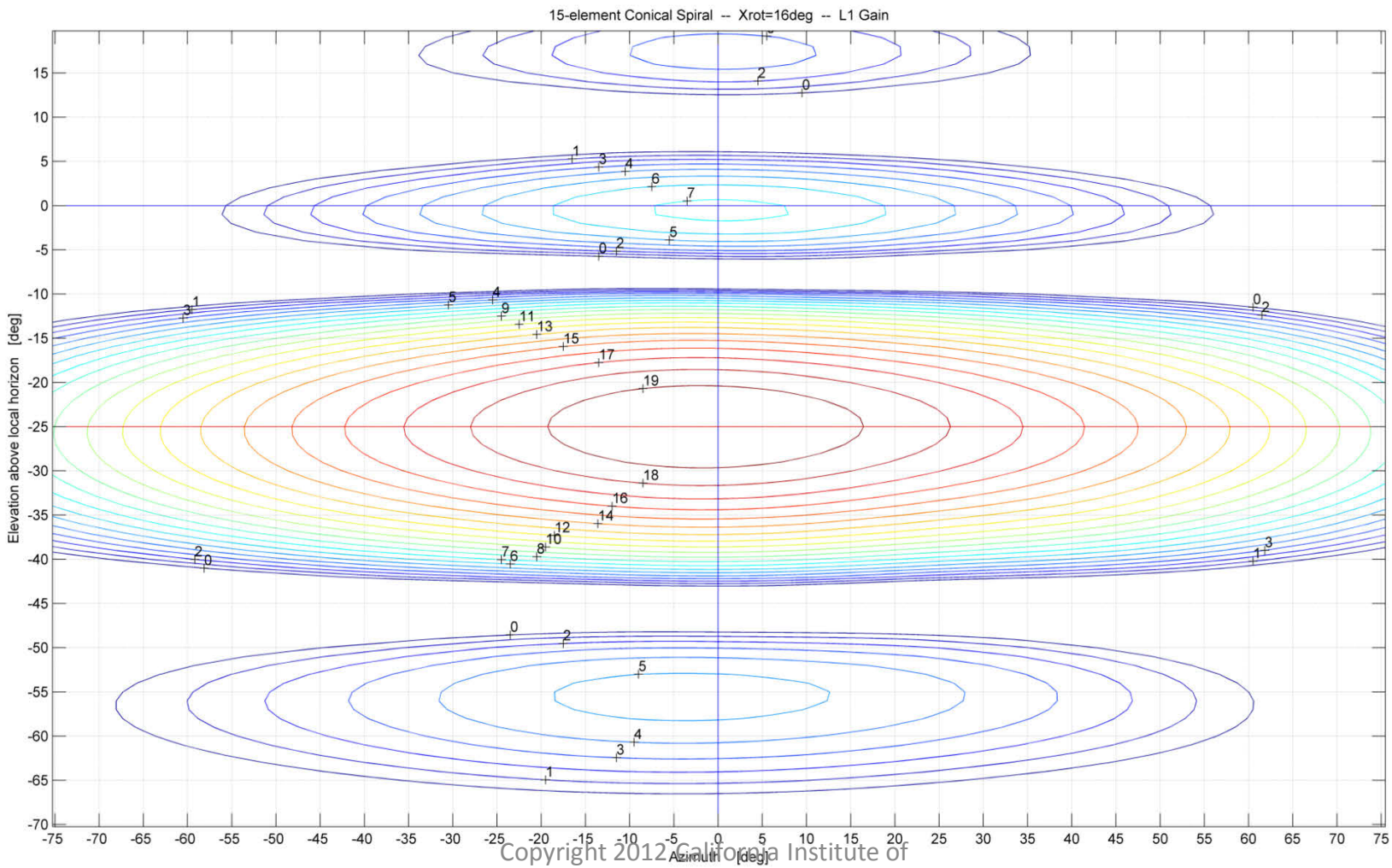
15-element Gain



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PHASED BEAM (hfss) Effective aperture: **34 x 54 = $1810cm^2$**		
Frequency	***AZ = 0 deg***	***AZ = 55 deg***
L1 (1575 MHz)	**18.0 dBic**	**10.5 dBic**
L2 (1227 MHz)	**15.7 dBic**	**10.7 dBic**

15-Element PHASED (hfss) Effective aperture: **44 x 65 = $2860cm^2$**		
Frequency	***AZ = 0 deg***	***AZ = 55 deg***
L1 (1575 MHz)	**20.0 dBic**	**13.6 dBic**
L2 (1227 MHz)	**17.5 dBic**	**12.7 dBic**
L5 (1176 MHz)	**17.4 dBic**	**12.1 dBic**

ANTENNA ENVELOPE IS STILL 40 x 60 x 10 [cm]

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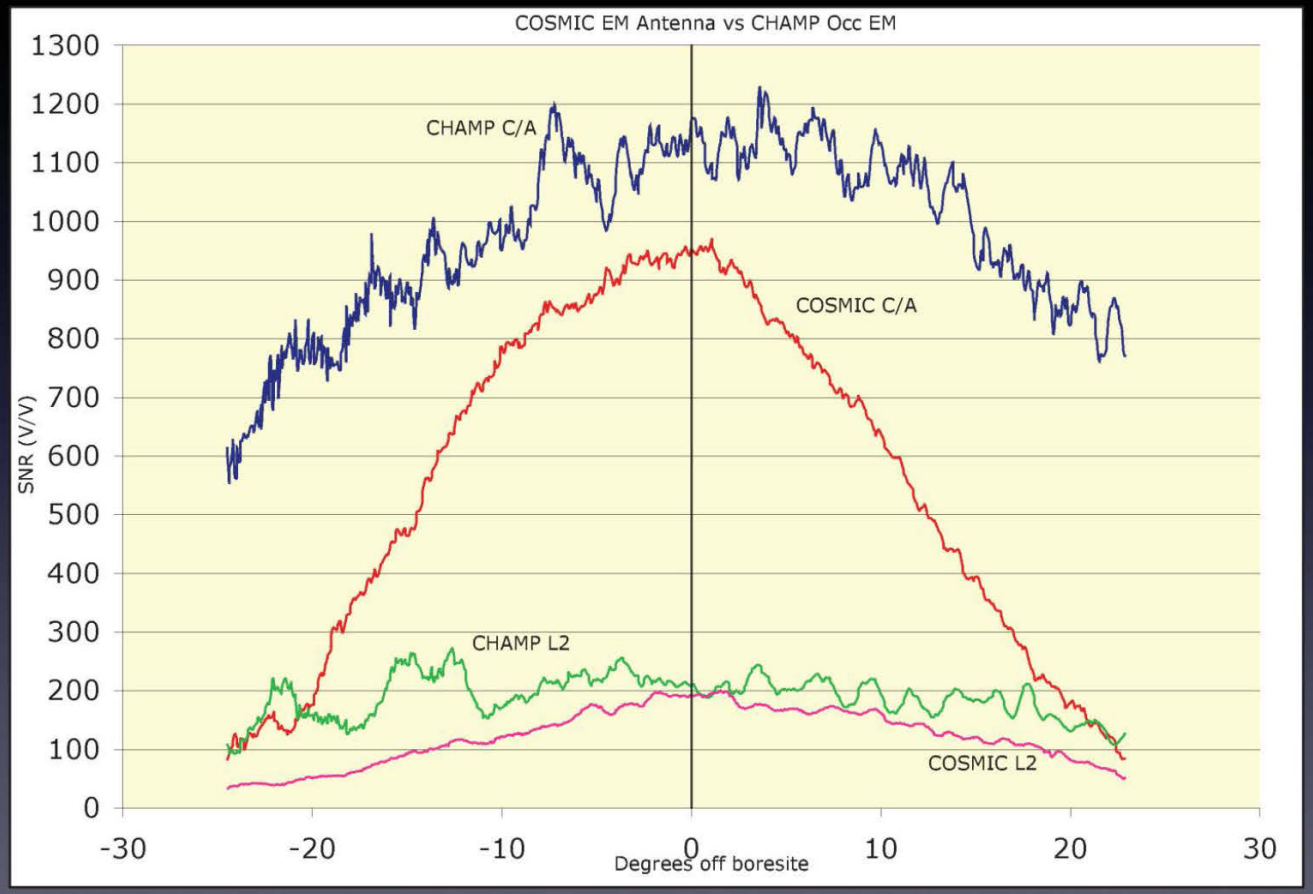
COMPARISON: COSMIC-I & CHAMP

COSMIC-1 Occ antenna vs CHAMP Occ Antenna



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