Reverse Engineering the GPS and Galileo Transmit Antenna Side Lobes

SCPNT Symposium

November 11, 2015

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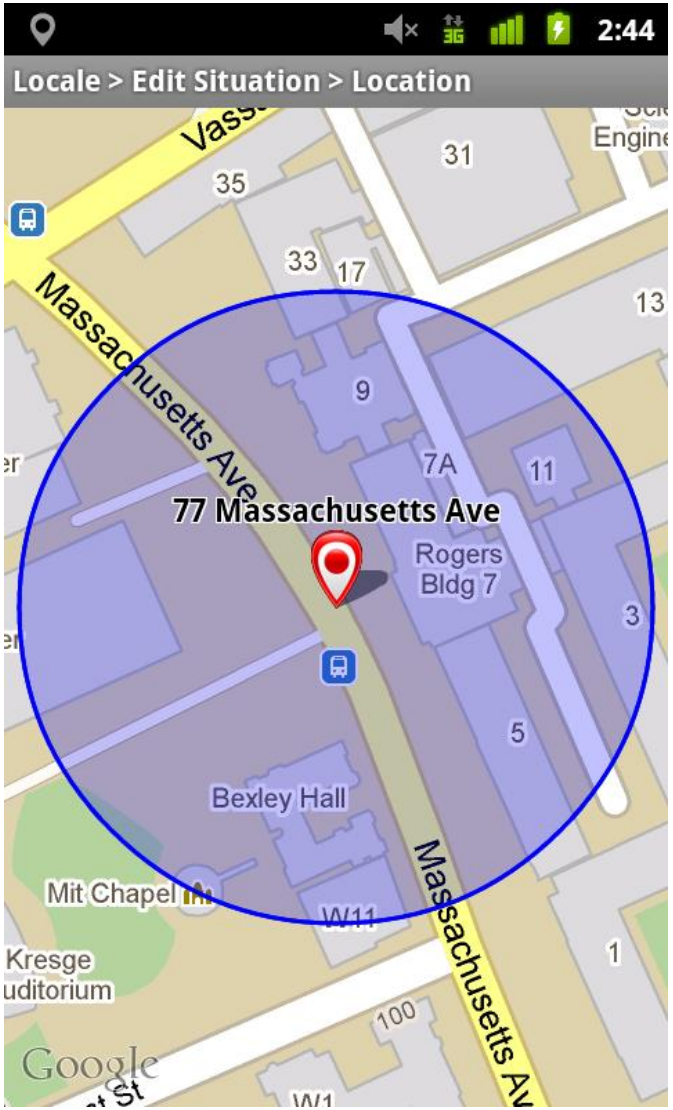
Advisor: Per Enge

Location, Location, Location!



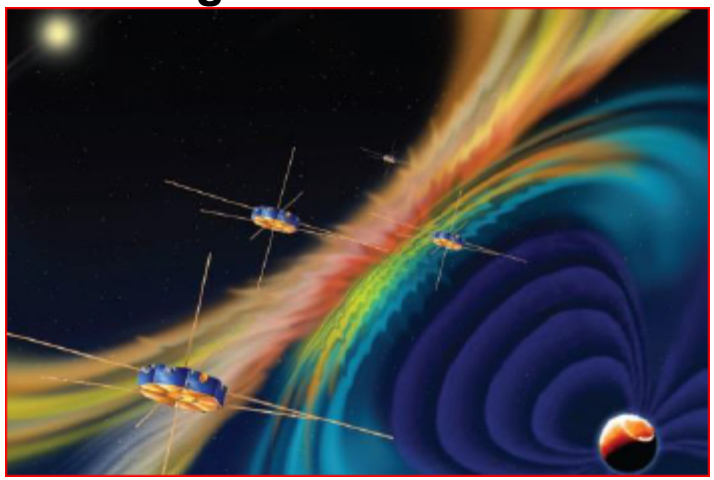
Courtesy: www.techprone.com

Space Missions Benefiting from GNSS

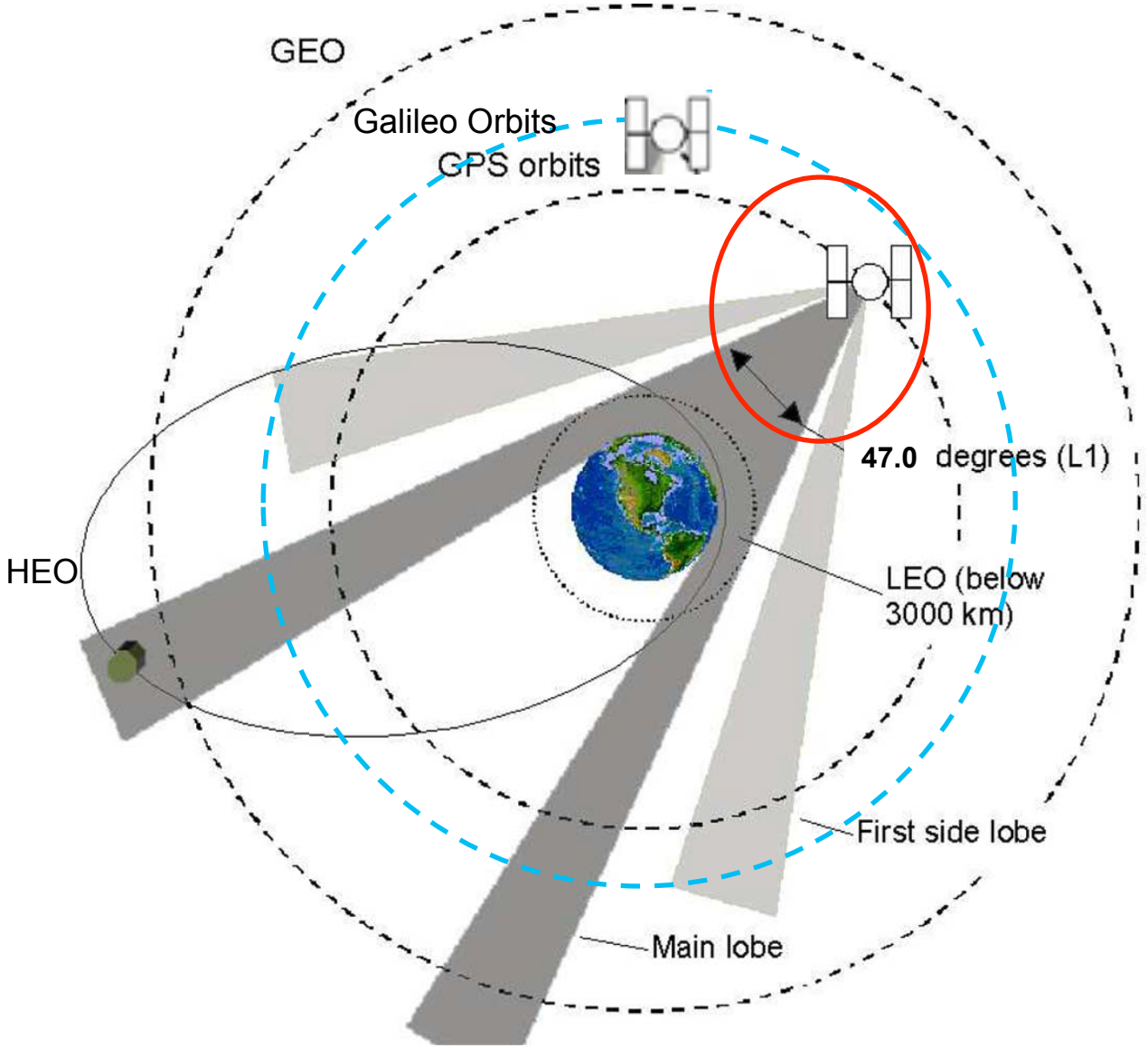
- **Low Earth Orbit Missions (LEO)**
  - Attitude Determination and Control
  - GNSS Radio Occultation

- **Geostationary Missions (GEO)**
  - Closer Spacing of Satellites in Geostationary Arc
  - GEO Satellite Servicing and Decommissioning

- **Highly Elliptical Orbit Missions (HEO)**
  - Scientific Formation Flying/Constellation Missions
  - Space Weather Observations
  - En-route Lunar Navigation Support



Using GNSS at GEO and Beyond



Bauer et.al. “The GPS Space Service Volume”, ION GNSS 2008, Savannah, GA

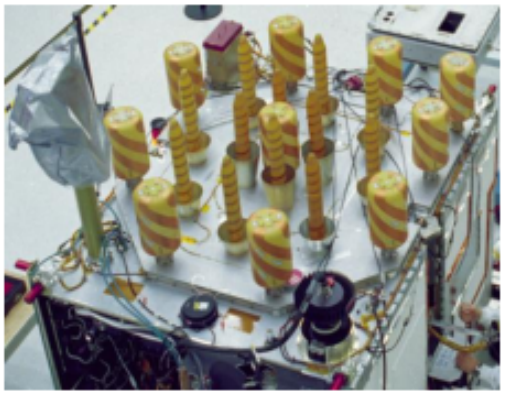
GPS in Space – Current State of Art

Use of GPS in the Space Service Volume (SSV)

- **GPS signals in High Earth Orbit and Geosynchronous Altitude utilized by multiple DOD, NASA & NOAA programs**
  - SBIRS, ANGELS, Classified Programs
  - GOES-R, MMS
- **Autonomous navigation enables new mission needs and significantly improves PNT performance over past methods**
  - GPS Ephemeris and timing data can be provided near real time with collected satellite products
  - Achievable accuracy is greatly improved over typical methods using ground based ephemeris processing via ranging and angle measurements
- **NASA activities have included:**
  - Conducting flight experiments to characterize GPS performance in SSV
  - Development of new weak signal GPS receivers for spacecraft in Geostationary or highly elliptical orbits
  - Working with the GPS Directorate and DoD community to formally document GPS requirements for space users
  - International coordination to encourage other GNSS constellations (e,g, Galileo, GLONASS, BeiDou) to specify interoperable SSV capabilities
  - Developing missions and systems to utilize GPS signals in the SSV

GNSS Transmit Antenna Array

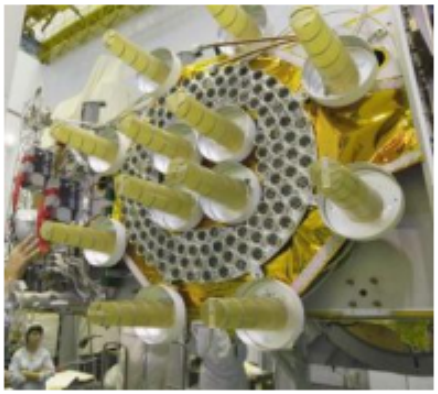
GPS IIA (Credits: Geo++)



GPS IIR (Credits: Lockheed)

GPS IIF (Credits: Boeing)

GPS and GLONASS Satellites have 12 helical antennas arranged in two concentric circles



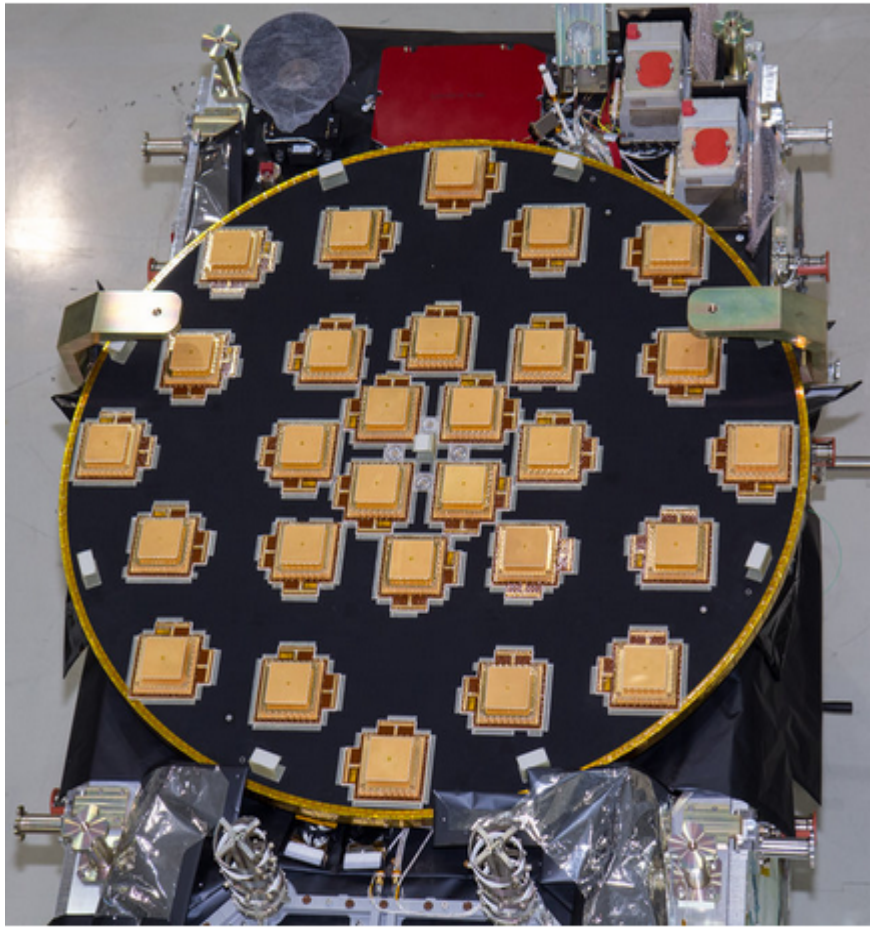
GLONASS-M (Reshetnev)

GLONASS-K1 (Reshetnev)

Czopek, F.M., S. Shollenberger (1993): Description and Performance of the GPS Block I and II L Band Antenna and Link Budget. ION GPS-93, Salt Lake City, Utah, 37-43.

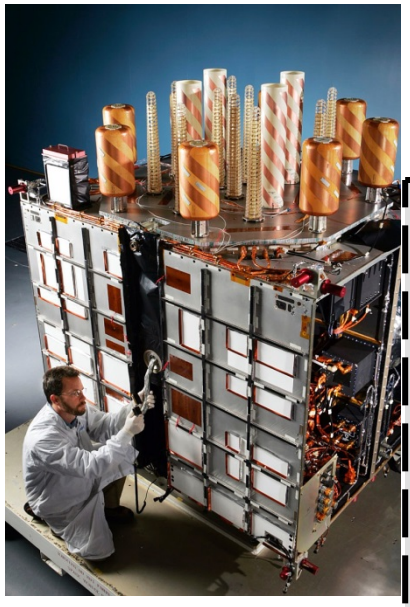
Galileo Full Operational Capability Satellite Antenna Array Design

- Uses a patch antenna array design
- No publically available information regarding design parameters.
- Side lobe characteristics unknown



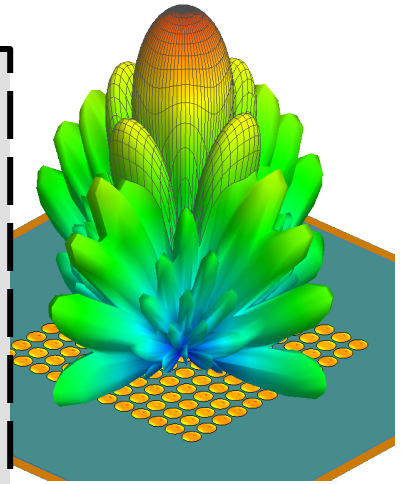
Courtesy: www.technology.org

Transmit Antenna Modeling
Design Overview



- Isoflux Radiation Pattern for the Antenna Mainlobe
- Constant Circular Polarization Axial Ratio over Mainlobe
- Good Sidelobe Supression
- Minimal Gain/Axial Ratio variation over bandwidth of interest

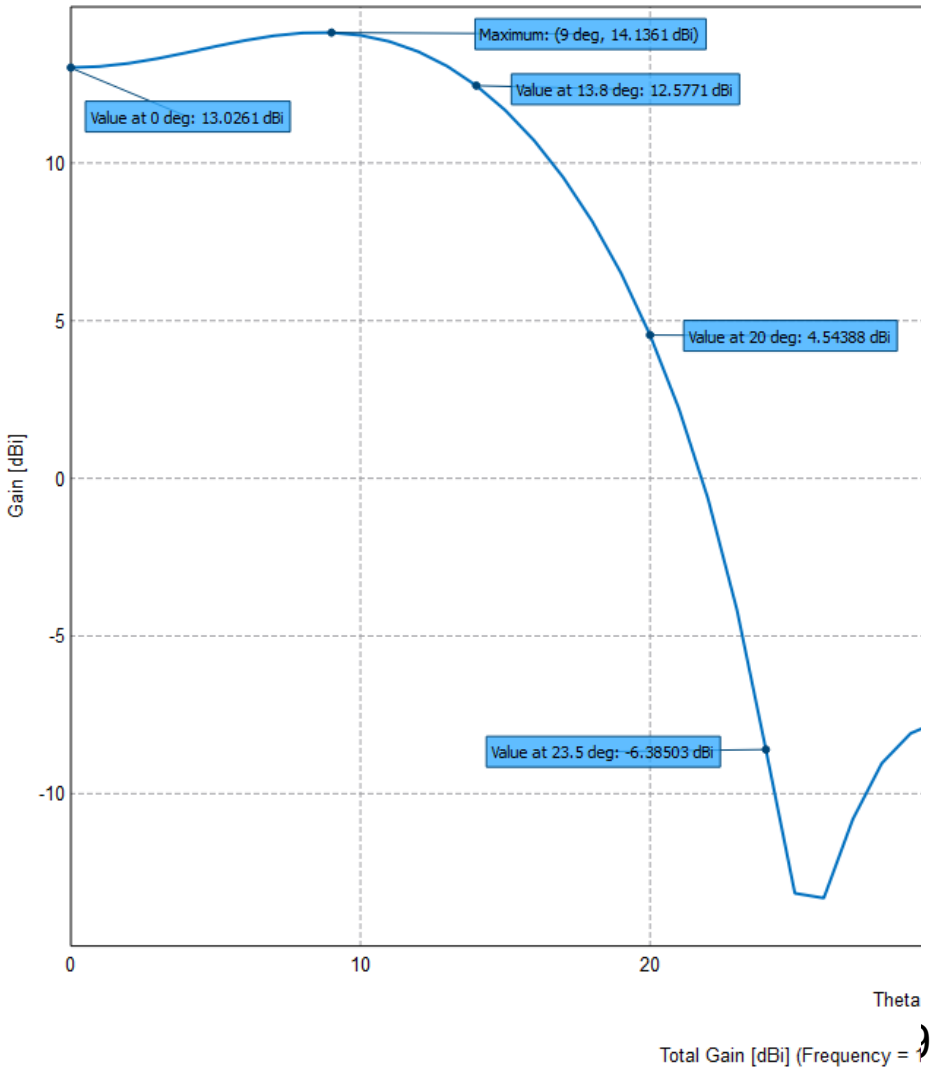
FEKO
Comprehensive Electromagnetic Solutions



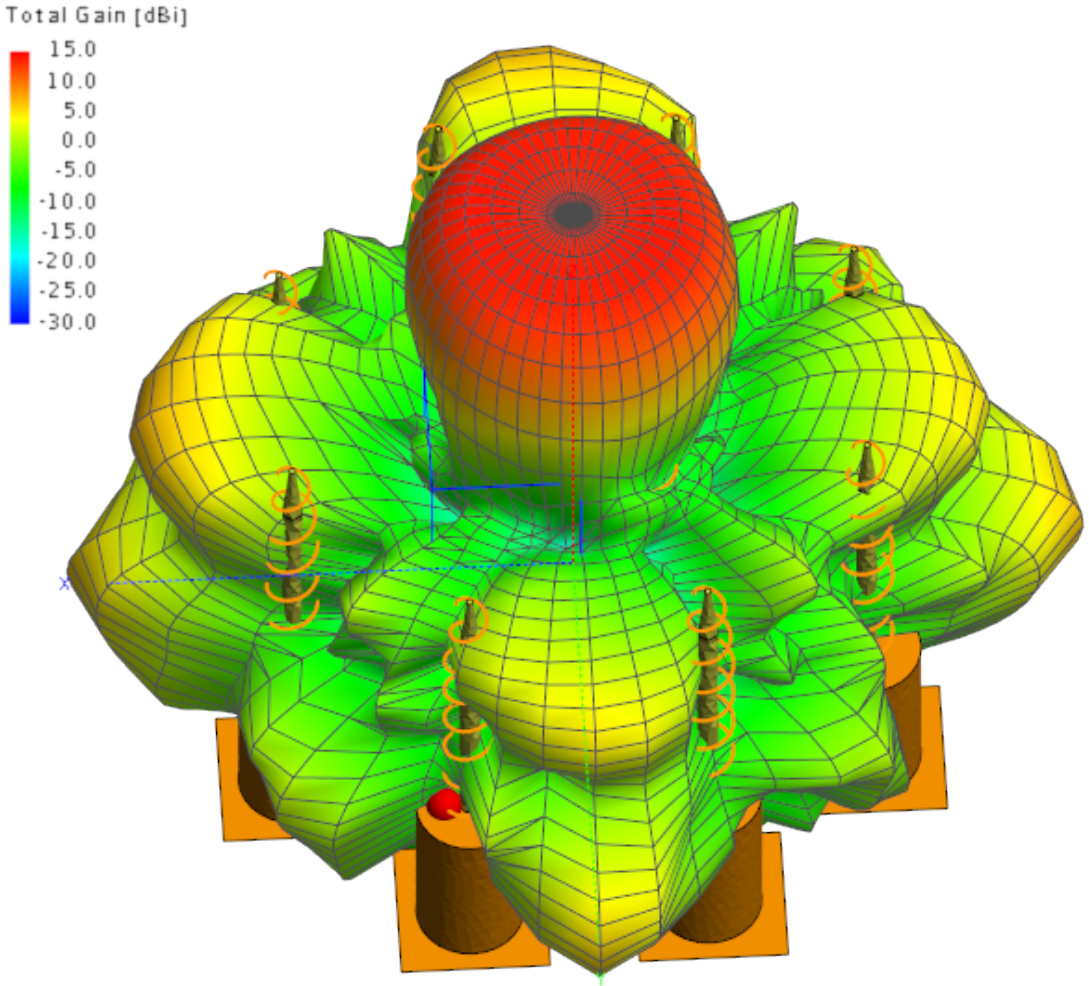
Establish transmit antenna specifications → Create CAD Model of Transmit Antenna → High Fidelity Numerically analyze array design

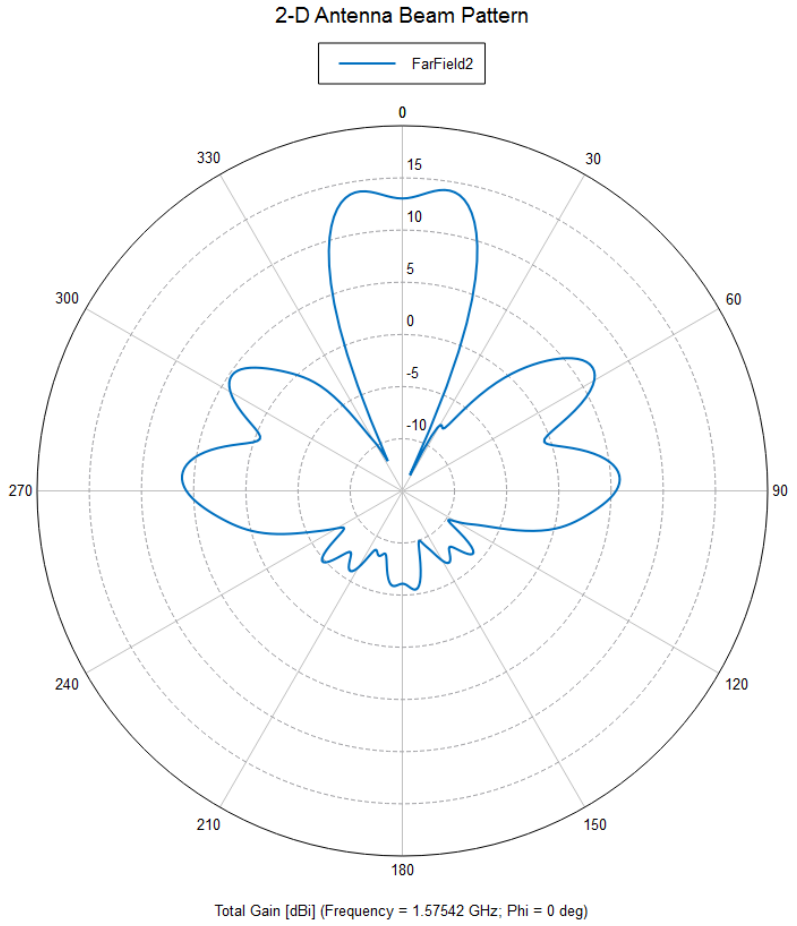
GPS III Space Service Volume (SSV) Specifications

- **L1C signal strength at EOL:**
  - Terrestrial : -157 dBW
  - At GEO Orbit: -182.5 dBW
- **Off-Axis Relative Power shall not decrease:**
  - More than 2 dB from Edge-of-Earth to nadir
  - More than 10 dB from EOE to 20 degrees off nadir
  - More than 19.5 dB from EOE to 23.5 degrees off nadir
- **Monotonic drop off in power between EOE and ±23.5 degrees off nadir**

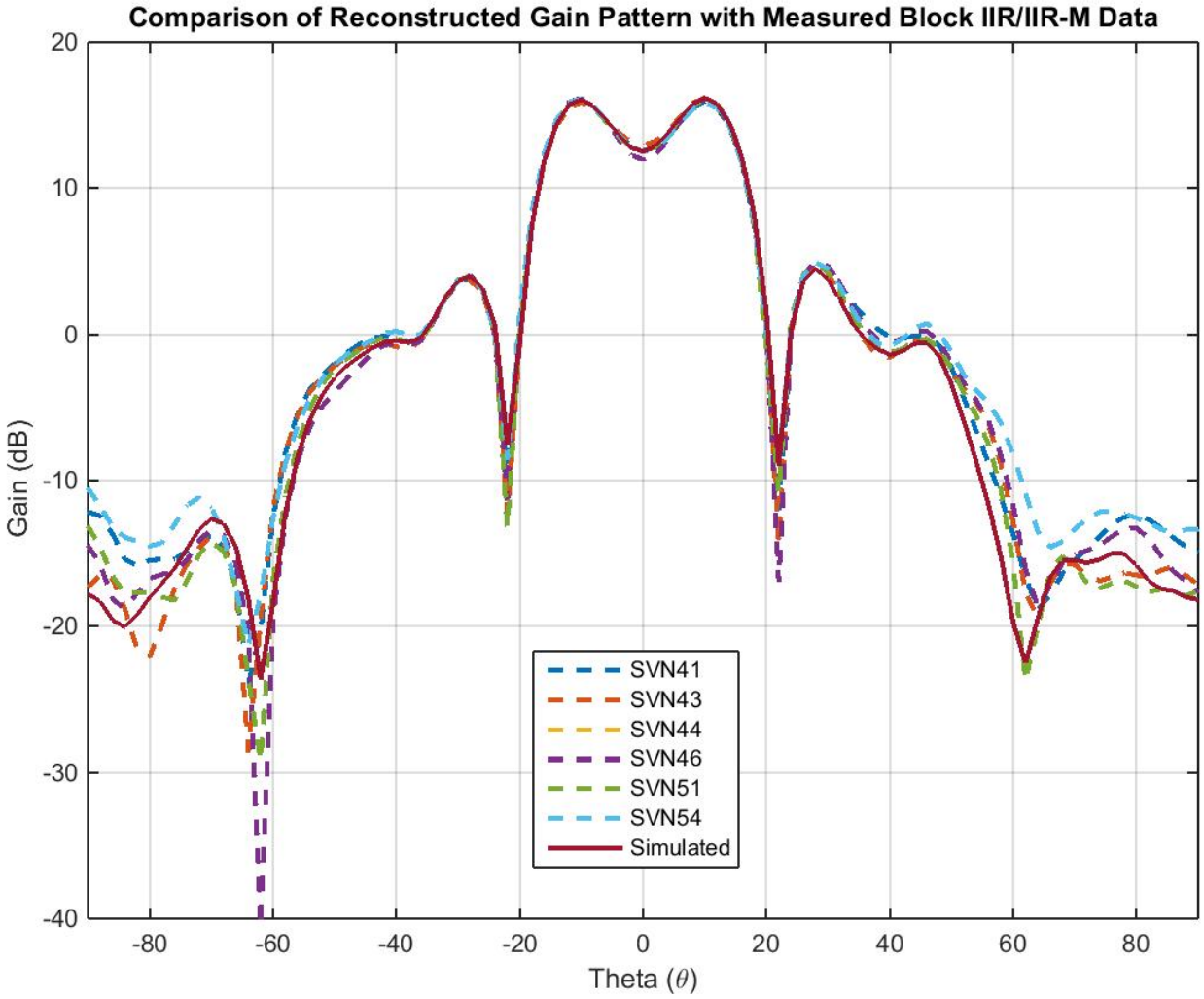


Reverse Engineered GPS Block III Transmit Antenna 3-D Beam Pattern



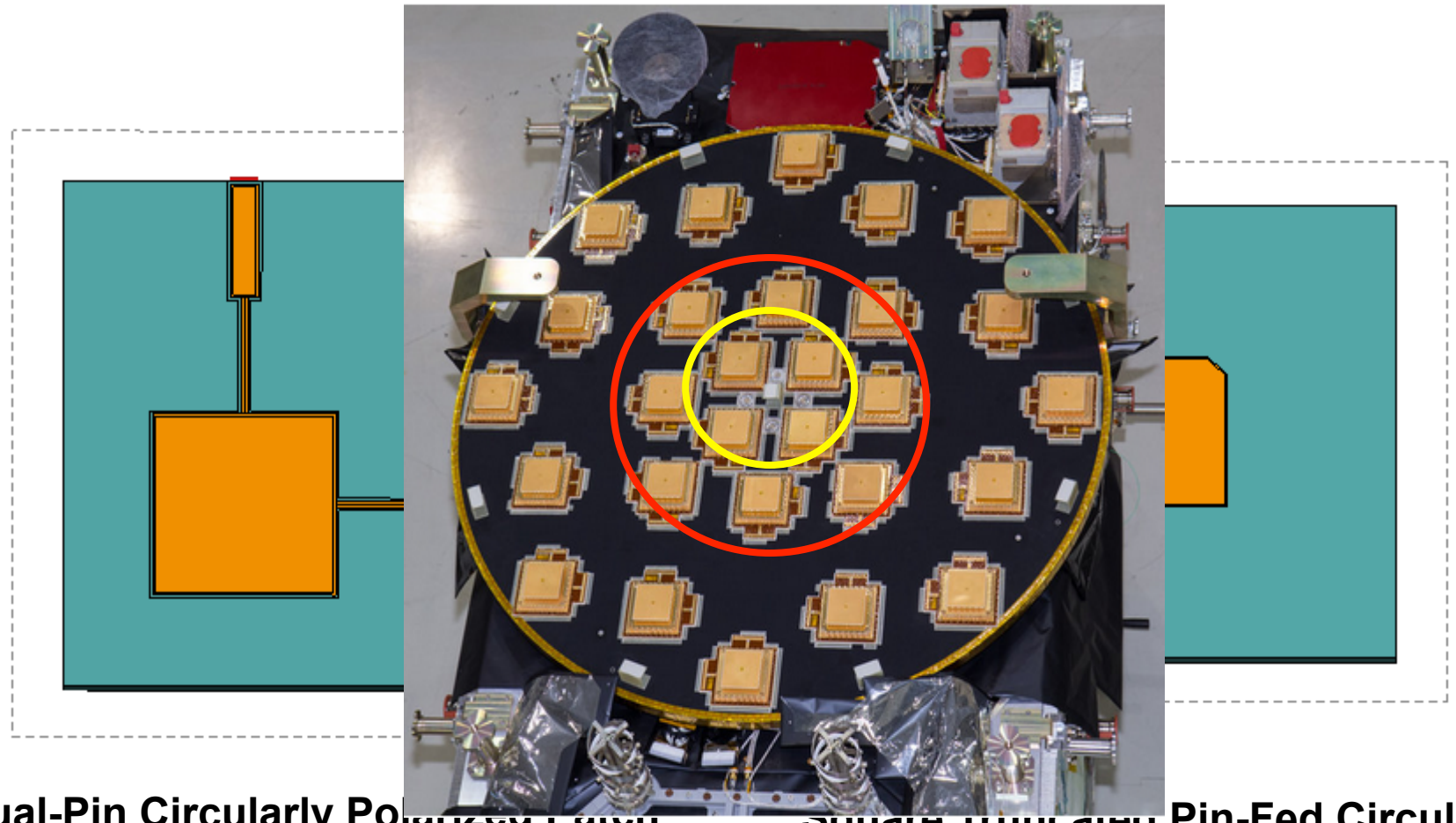


Comparison of High-Fidelity Model versus Measured Block IIR/IIR-M Antenna Data



William Marquis, *"The GPS Block IIR/IIR-M Antenna Panel Pattern"*, Lockheed Martin, 2014

Possible Single Element of Galileo Transmit Array

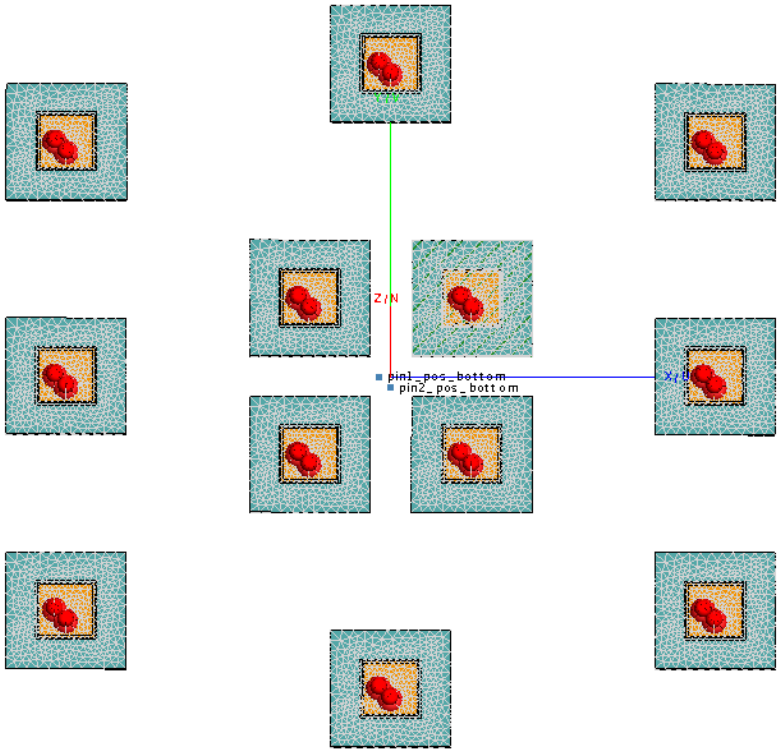


Dual-Pin Circularly Polarized Patch

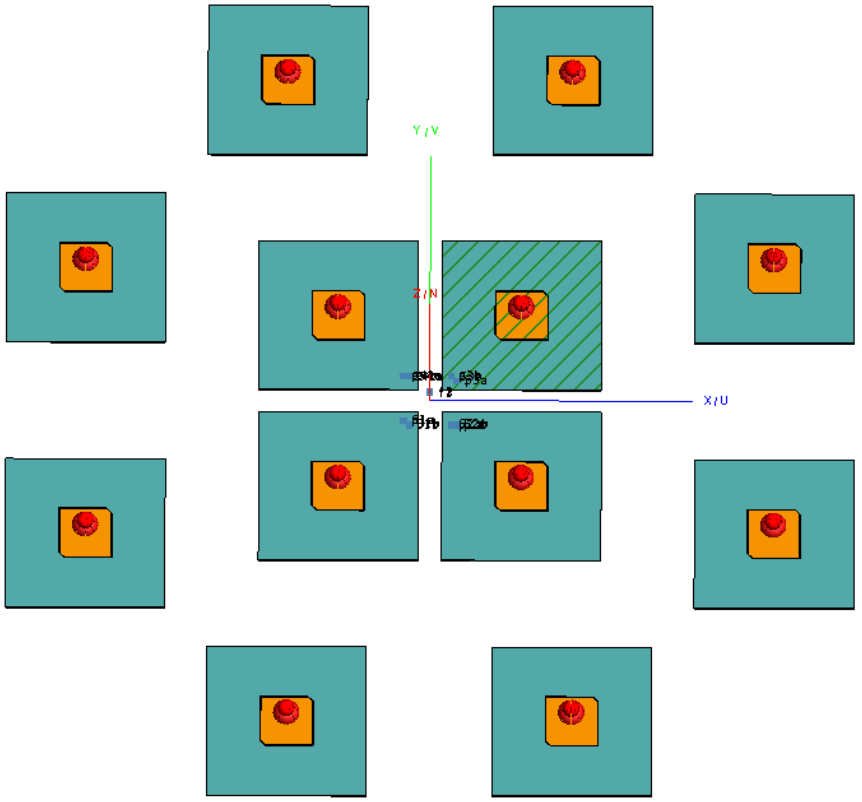
Square Truncated Pin-Fed Circularly Polarized Patch

Pozar, David (Editor), *"Microstrip Antennas: The Analysis and Design of Microstrip Antennas and Arrays "*, Wiley-IEEE Press, 1995

Circularly Polarized Patch Antenna Arrays

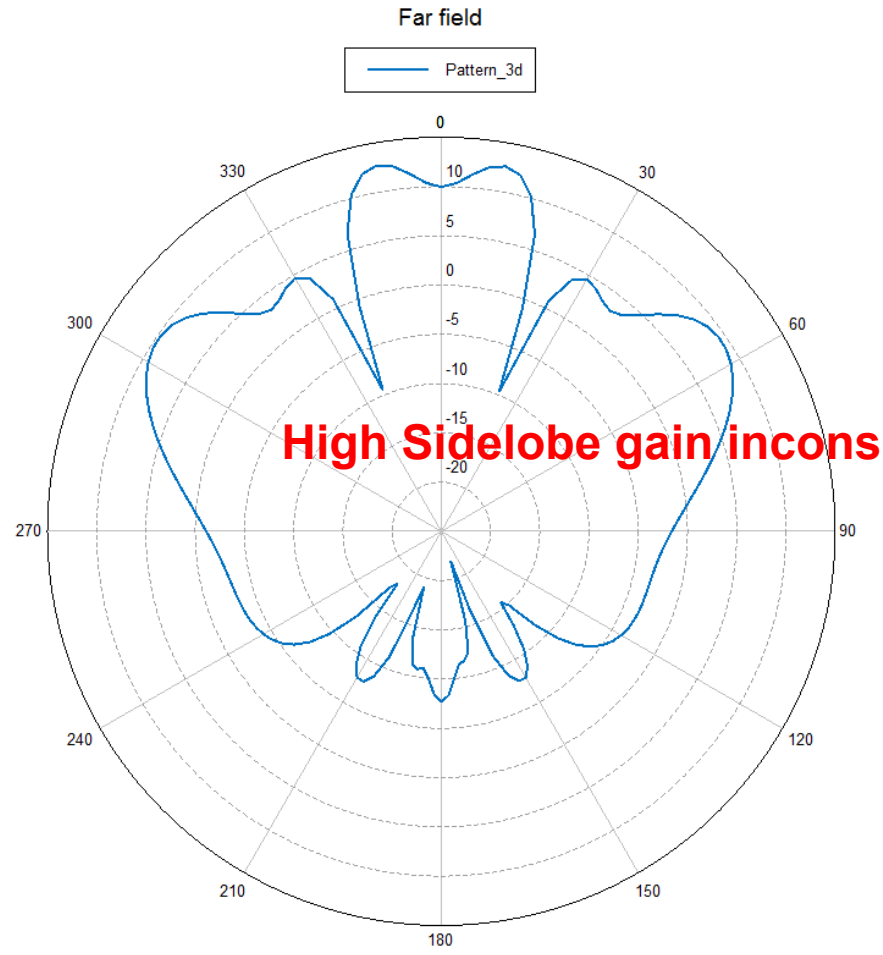


Dual-Pin Circularly Polarized Patch Array

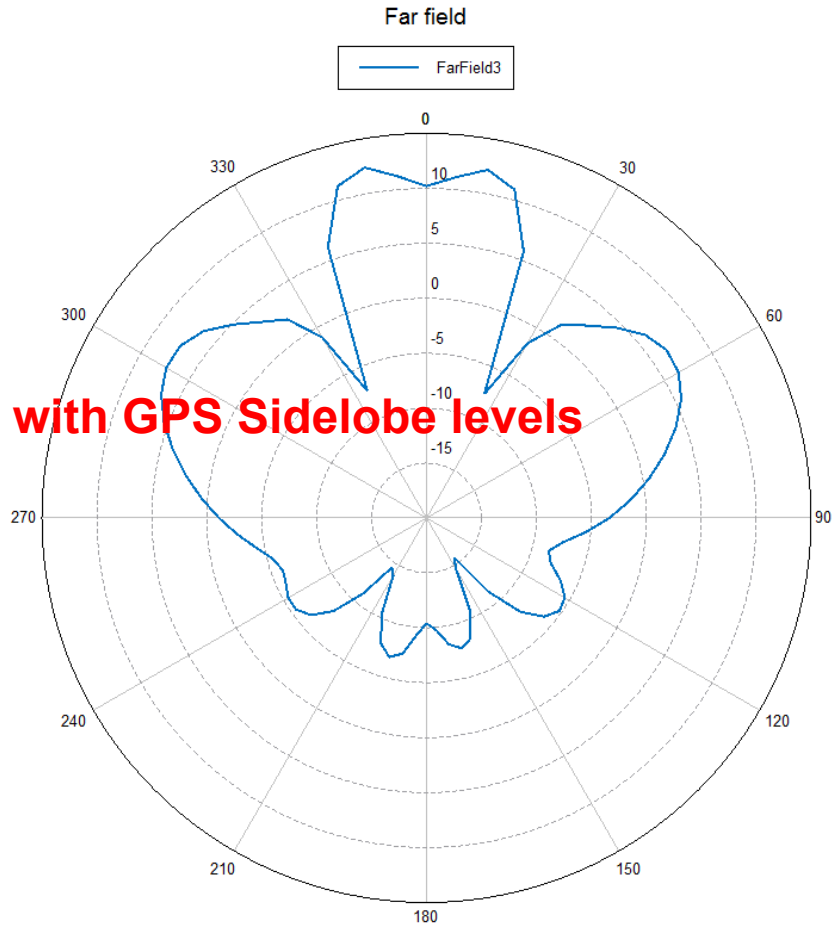


Square Truncated Pin-Fed Circularly Polarized Patch Array

Dual-Pin Circularly Polarized Patch Antenna Gain Pattern



High Sidelobe gain inconsistent with GPS Sidelobe levels



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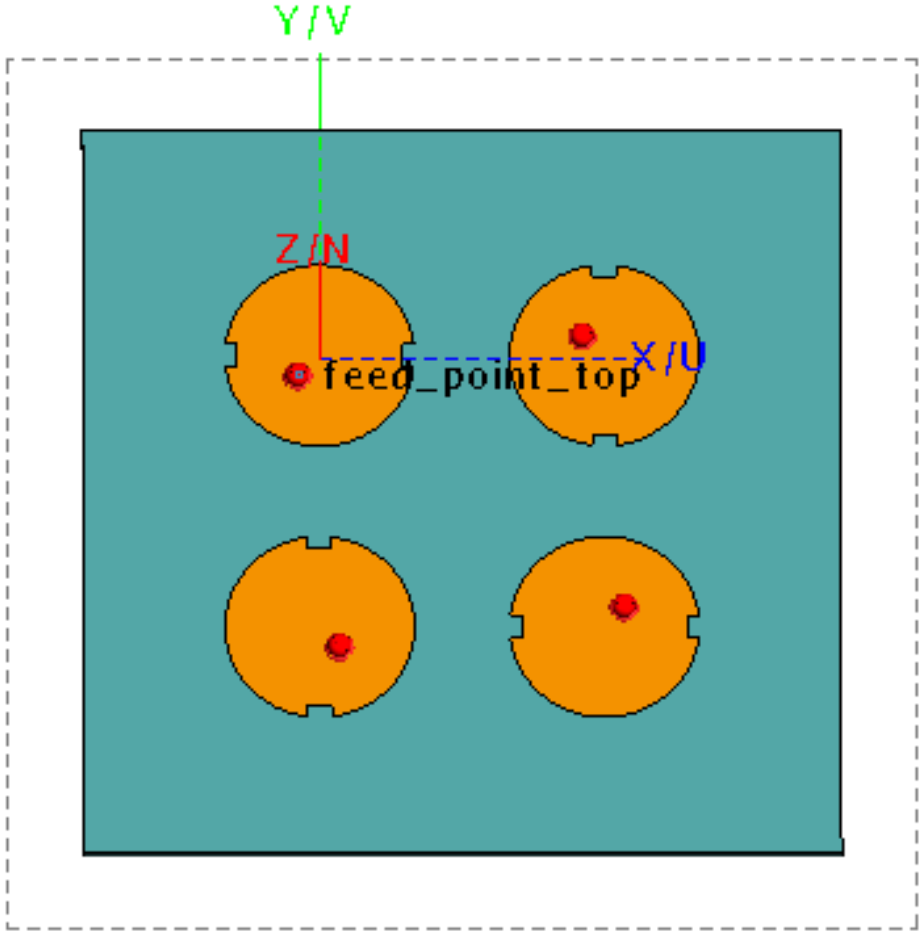
2x2 Sequentially Rotated Patch Antenna Array



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- Good Sidelobe supression
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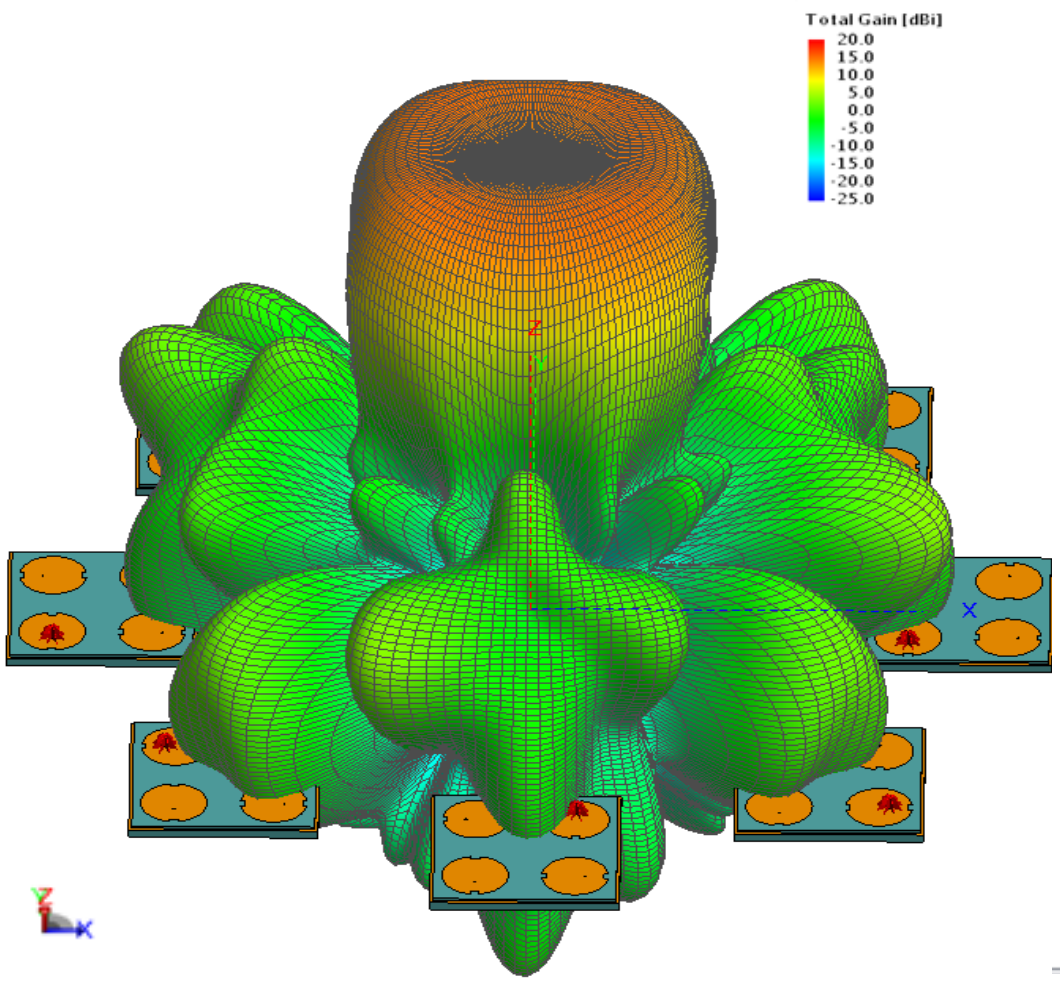
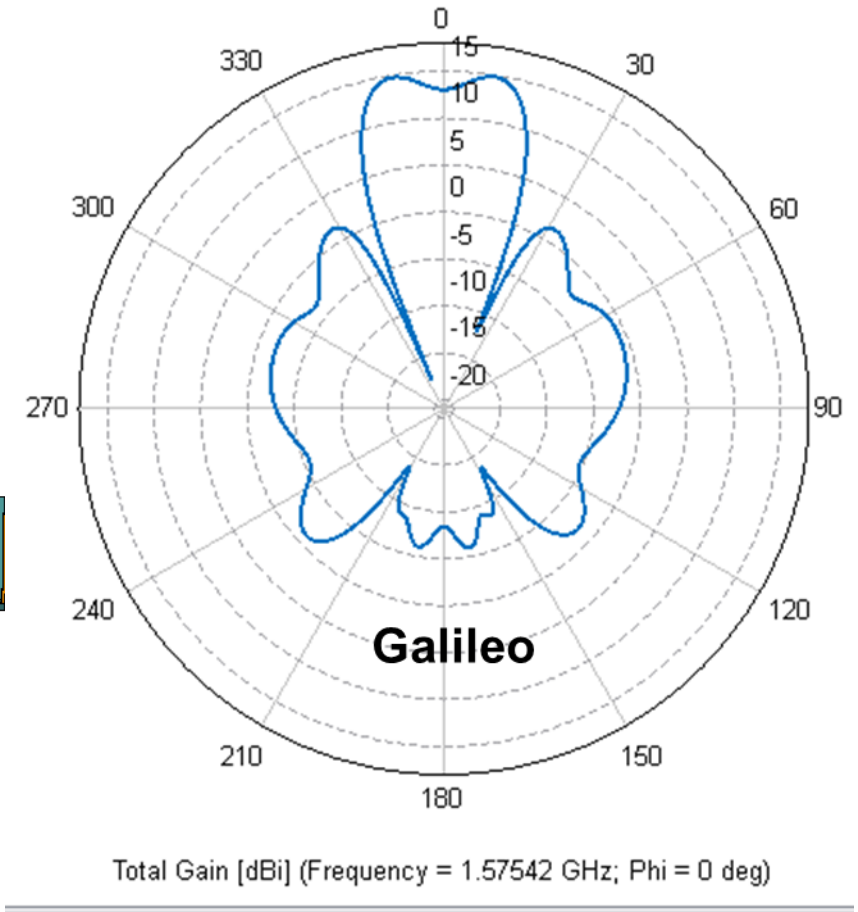
Hall, P.S.; Dahele, J.S.; James, J.R., "*Design principles of sequentially fed, wide bandwidth, circularly polarised microstrip antennas*," in Microwaves, Antennas and Propagation, IEE Proceedings H , vol.136, no.5, pp.381-389, Oct 1989

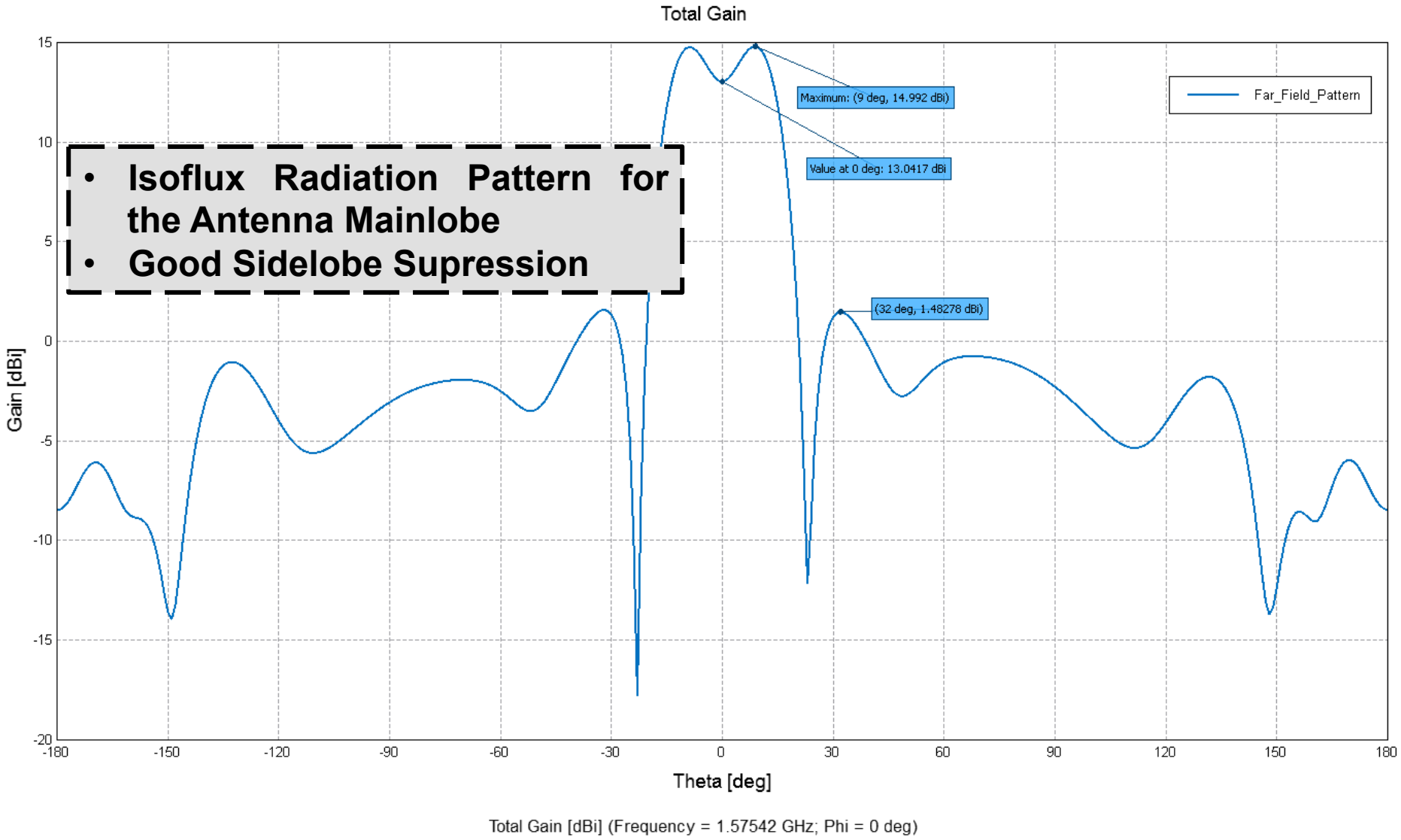
Galileo Transmit Antenna Gain Profile





Total Gain [dBi] (Frequency = 1.57542 GHz; Phi = 0 deg)

Sequentially Rotated Patch Antenna Array Gain Profile



- Isoflux Radiation Pattern for the Antenna Mainlobe
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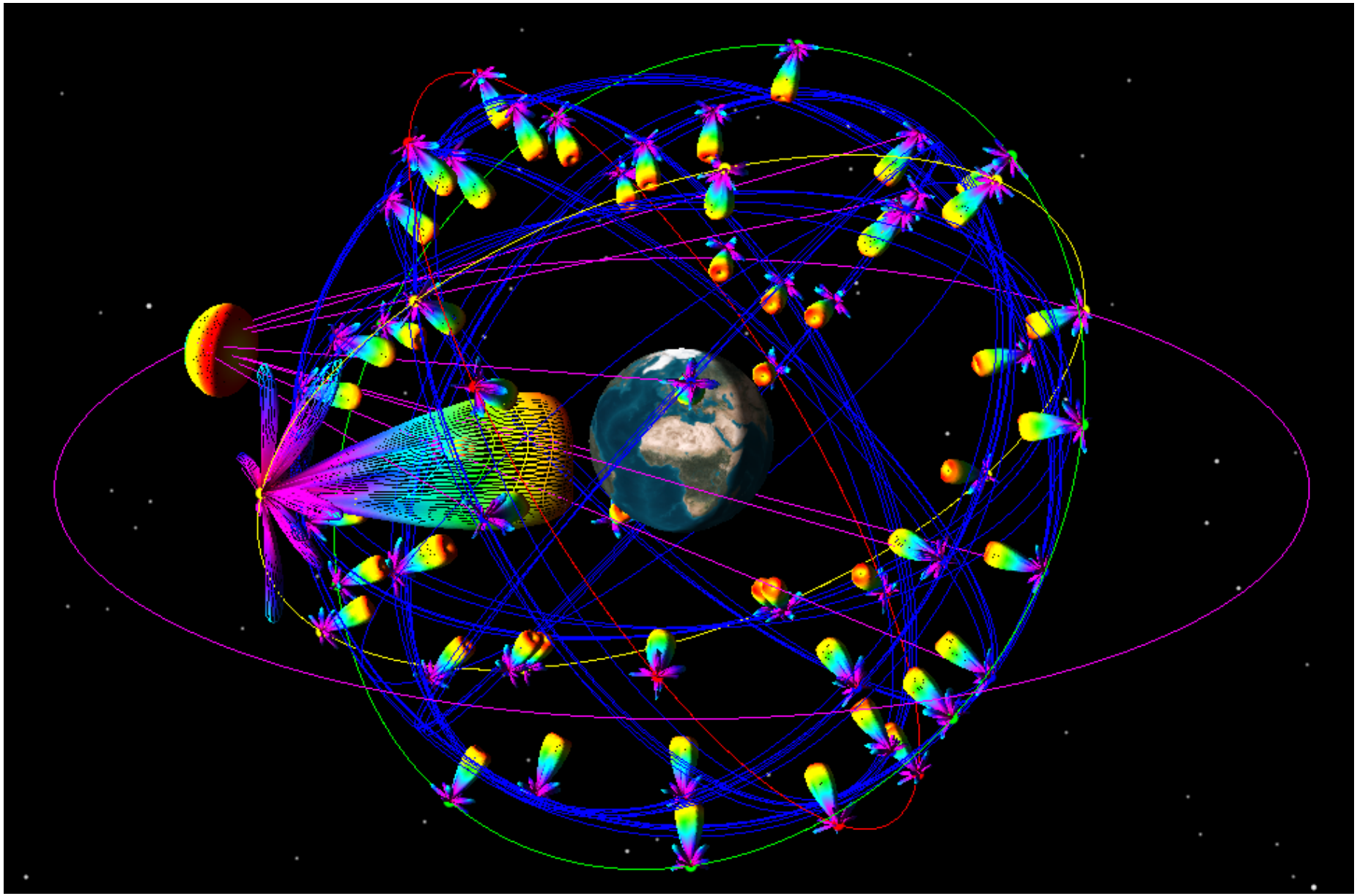
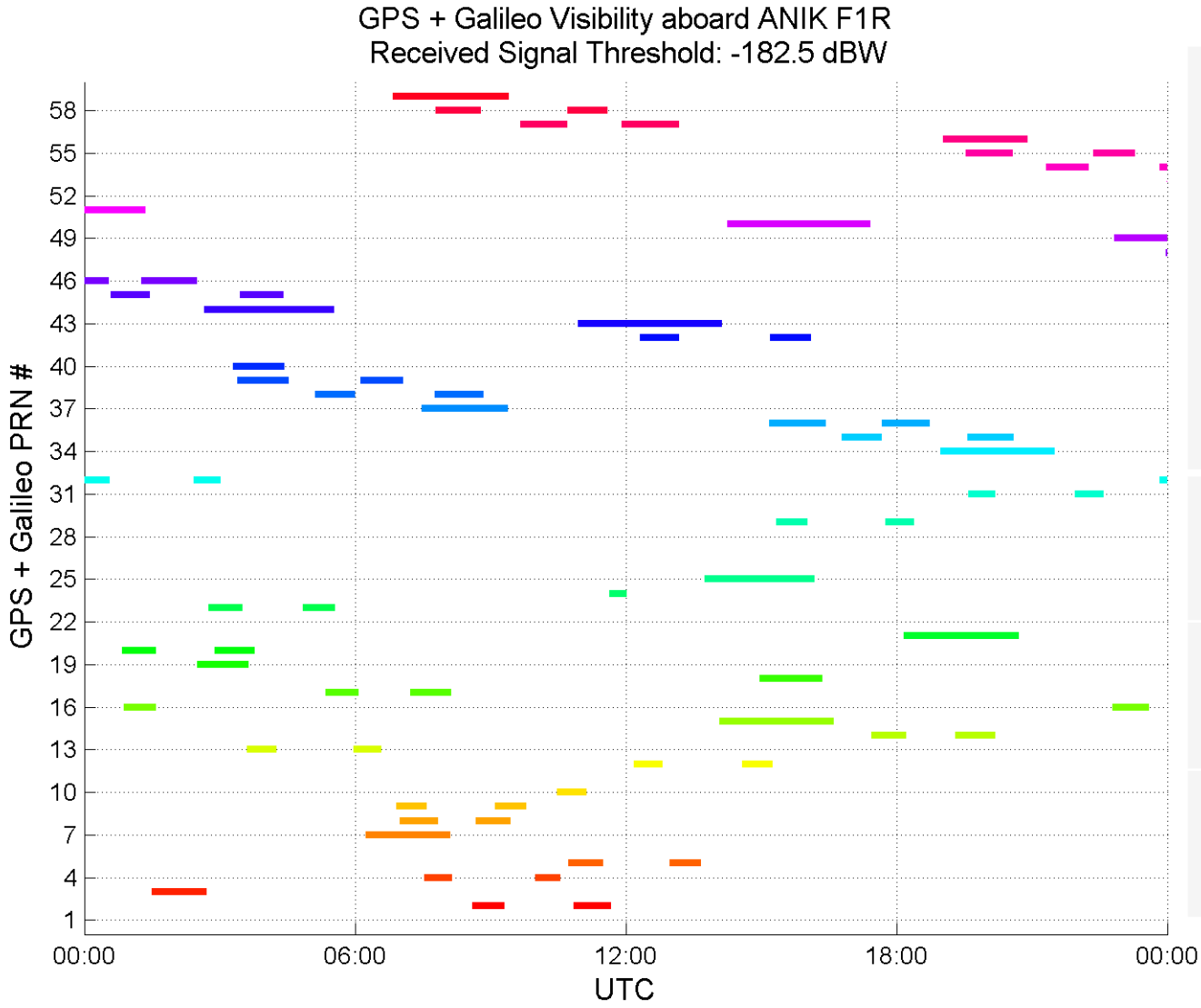
Total Gain [dBi] (Frequency = 1.57542 GHz; Phi = 0 deg)

GNSS Satellite Visibility at GEO
Main & Side Lobes

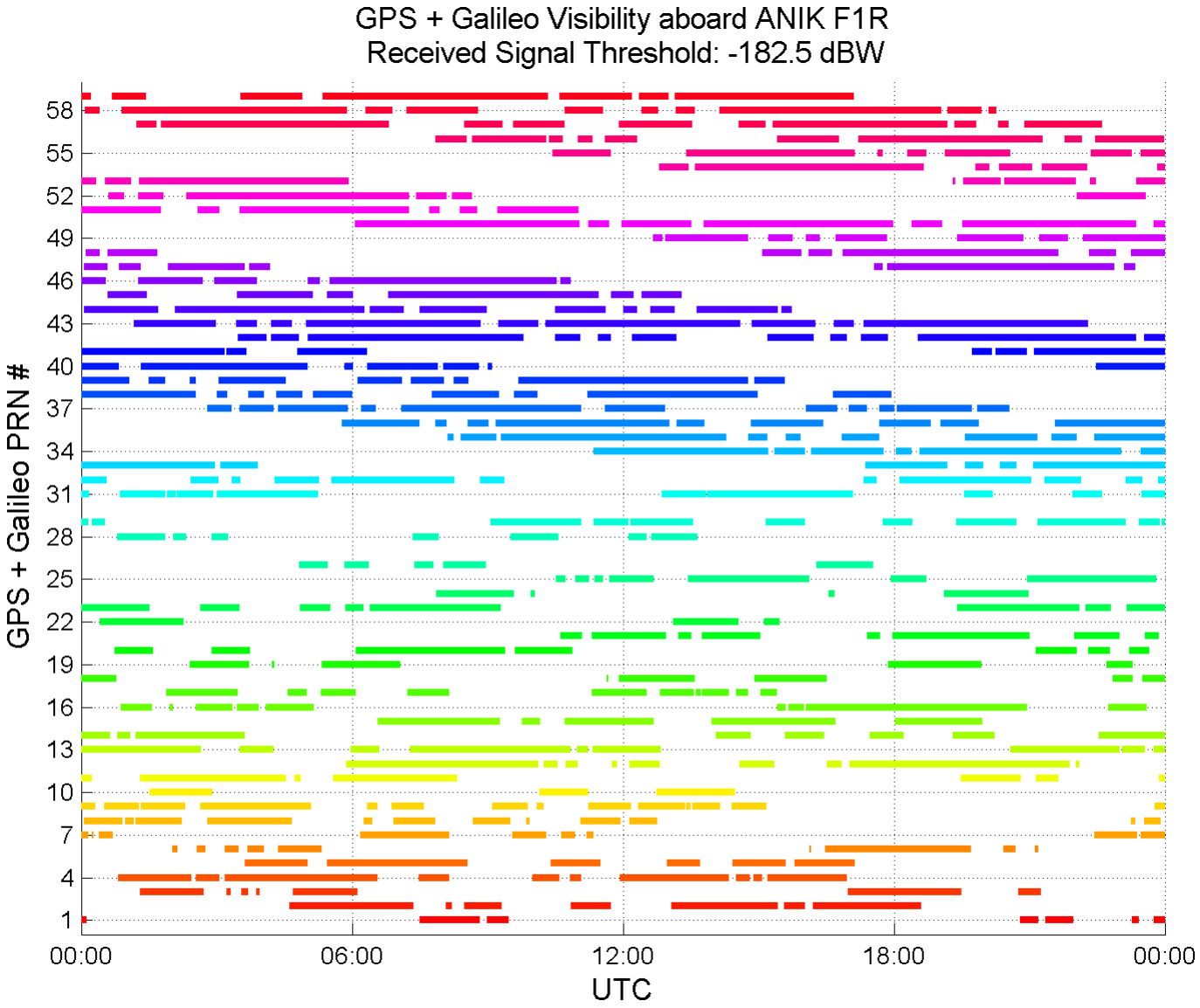


GPS + Galileo Visibility at GEO
Main Lobe Only

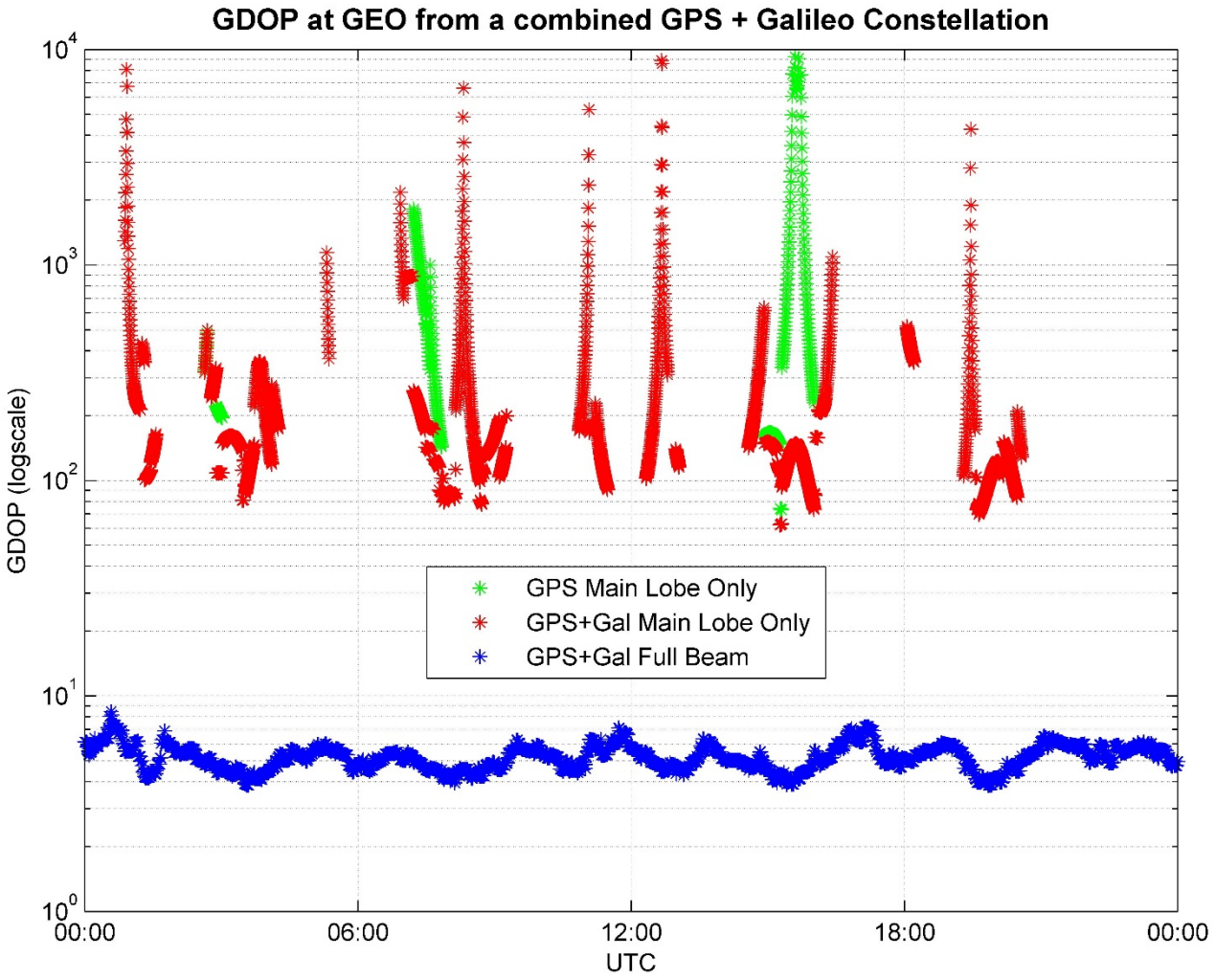


Constellation	Visibility over 24 hours	
	At least 1 SV Visible	At least 4 SVs visible
32 SV GPS Only	80.02 %	6.89 %
27 SV Galileo Only	94.51 %	12.19 %
59 SV GPS + Galileo	100 %	40.82 %

GPS + Galileo Visibility at GEO
Main & Side Lobes



GPS + Galileo Combined Constellation GDOP



Conclusion

- First to successfully “reverse engineered” expected GPS and Galileo transmit antenna gain patterns
  - Both main lobe and side lobe performance was quantified
- Evaluated satellite availability and expected performance at GEO using the main lobe only and main + side lobes
- Significant enhancement in availability and accuracy from a combined GPS + Galileo constellation enabling autonomous navigation at GEO
  - Common L1C signal allows for single receiver implementation capable of tracking both constellations