Characterization of On-Orbit GPS Transmit Antenna Patterns for Space Users

ION GNSS+
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Agenda

- Introduction
- History of High Altitude GPS
- GPS ACE Overview
- GPS Receiver Design
- Generation of Antenna Patterns & Results
- Uses of Antenna Pattern Data
- Conclusions & Future Work

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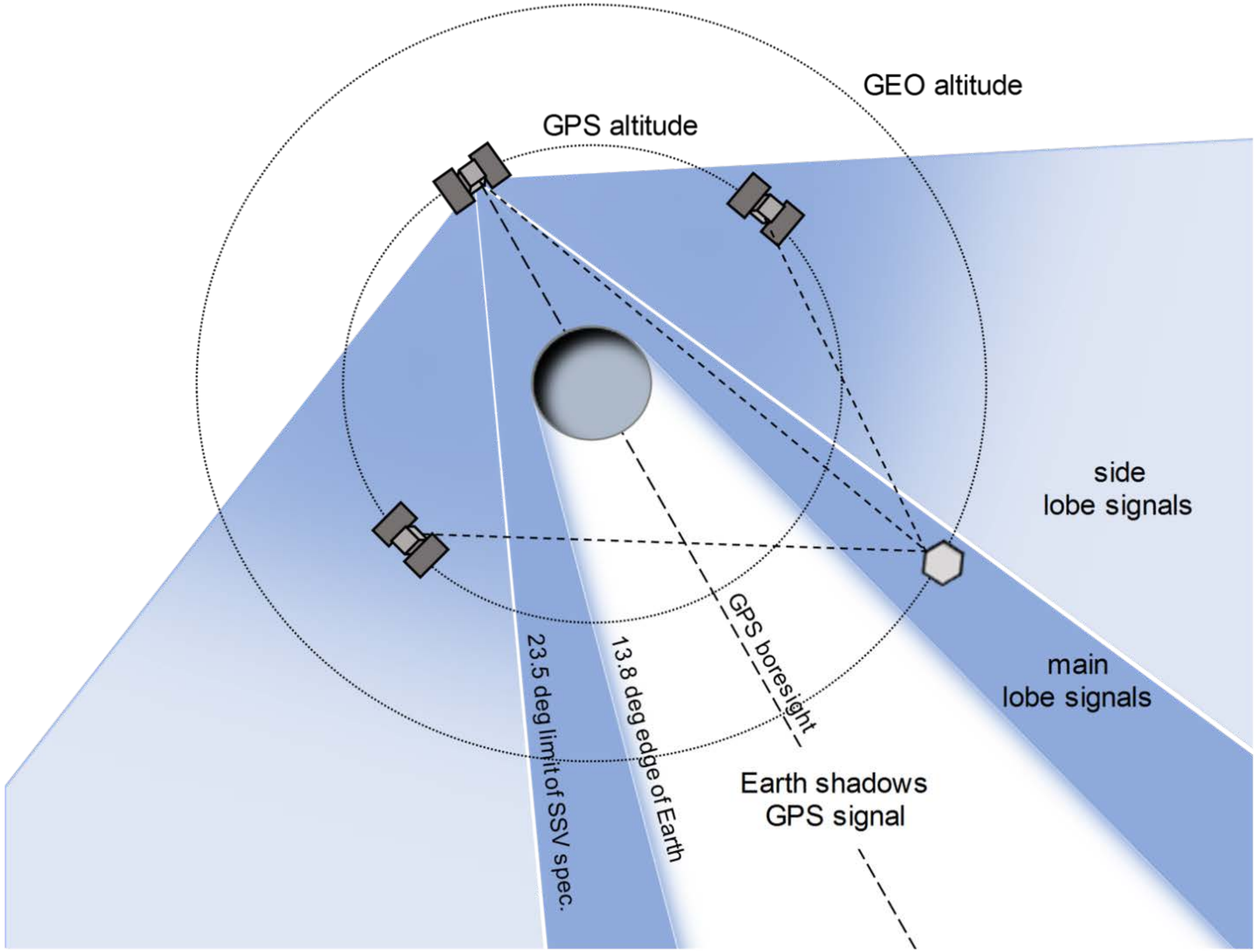
Introduction

- Problem Statement
  - *Vehicles operating in Space Service Volume (SSV, 3000-36,0000 km alt) have very limited visibility of GPS main beam*
  - *Expanding GPS usage to side lobes greatly enhances availability and accuracy of GPS solution*
  - *Side lobes are poorly characterized*
  - *Unknown side lobe performance results in lack of confidence in usage*
- GPS ACE Contribution
  - *GPS L1 C/A signals from GEO are available at a ground station through a “bent-pipe” architecture*
  - *Map side lobes by inserting advanced, weak-signal tracking GPS receivers at ground station to record observations from GEO*



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Brief History of High-Altitude GPS

- Bent-Pipe GPS
  – *First applications in early 1980's were transponded*
    - GPS signal is captured at the spacecraft and relayed to the ground on an intermediate frequency
    - GPS signal is then sent to a remote processor on the ground
  – *Kronman described a bent-pipe architecture in 2000*
- Notable flight experiments to record GPS in SSV
  – *Air Force Academy Falcon Gold*
  – *NASA Goddard / AMSAT OSCAR-40*
  – *ESA EQUATOR-S*
  – *ESA GIOVE-A*

  ➢ *Limited pattern coverage*
  ➢ *No azimuthal resolution*
- Missions using GPS in SSV
  – *In-flight: ANGELS, SBIRS, Magnetospheric Multiscale (MMS), GOES-R, SmallGEO, and more*
  – *Upcoming: cubesats in GEO, lunar exploration*

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GPS ACE Project

- IR&D collaboration between NASA Goddard Space Flight Center (GSFC) and The Aerospace Corporation
- Goals:
  - *Characterize GPS transmitter gain and pseudorange performance in side lobes*
  - *Perform real-time OD experiments from GEO platform*
- Record bent-pipe GPS signal measurements
  - *Record output GPS data (C/N_0, pseudorange, carrier phase)*
  - *Post process GPS measurements to recover GPS side lobe gain and measurement quality*
- Interest to GPS community
  - *Exhaustive dataset provides insight into performance and limitations of GPS side lobe signals, permitting improved performance modeling*
  - *Extensive measurements of IIF antennas previously not available*
  - *Provide operational platform for conducting real-time navigation experiments*

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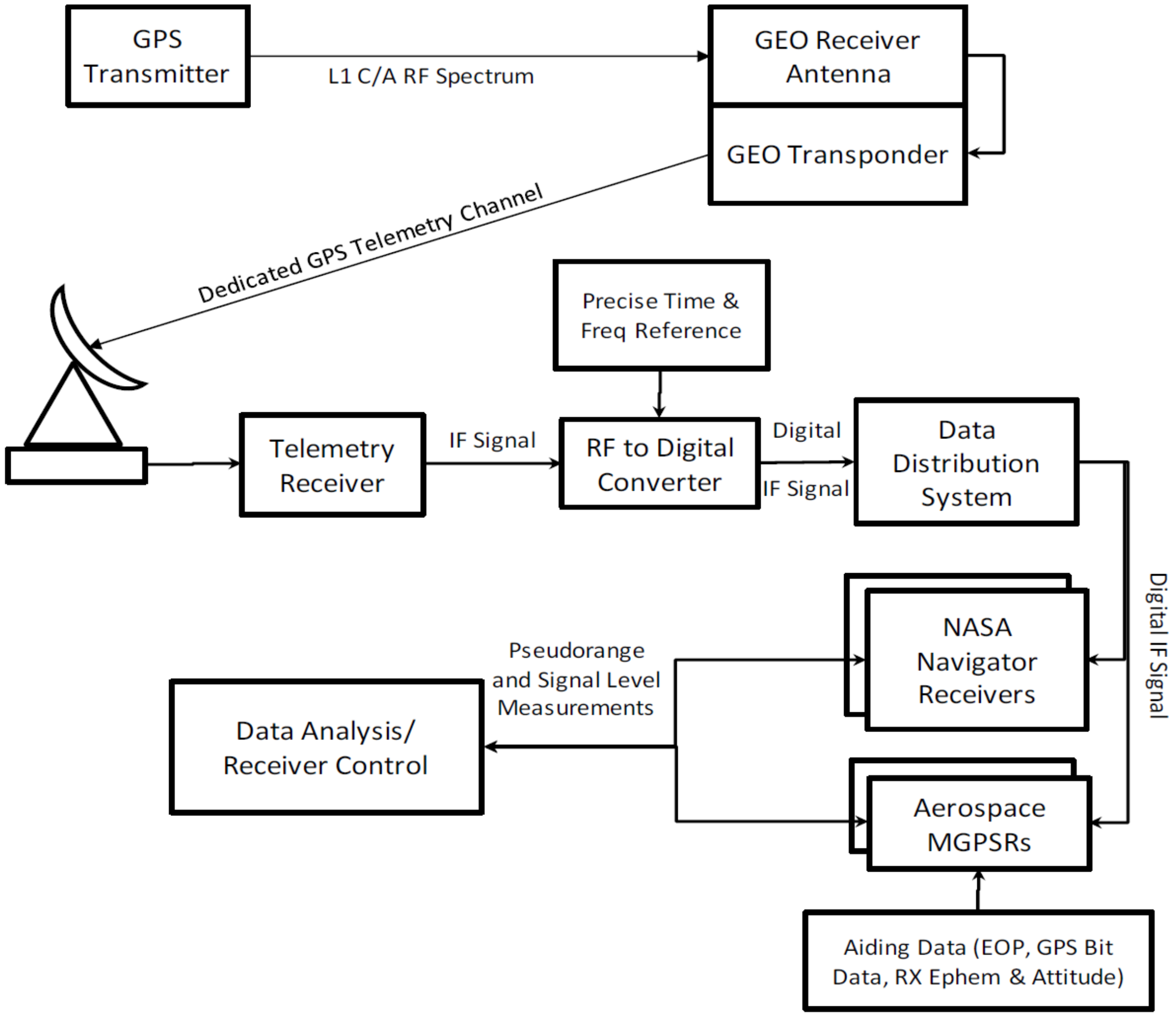
GPS ACE Implementation in Bent-Pipe Architecture

- GEO vehicle transponds GPS L1 spectrum to ground
- Digitized data is sent over network to GPS receivers
- Two versions of receivers installed:
  - *NASA Navigator receiver*
  - *Aerospace Mariposa GPS receiver*
- Record GPS pseudorange and signal level observations
- Gather daily measurement files over time for batch processing
  - *Full transmit gain patterns*
  - *Pseudorange residual assessment*



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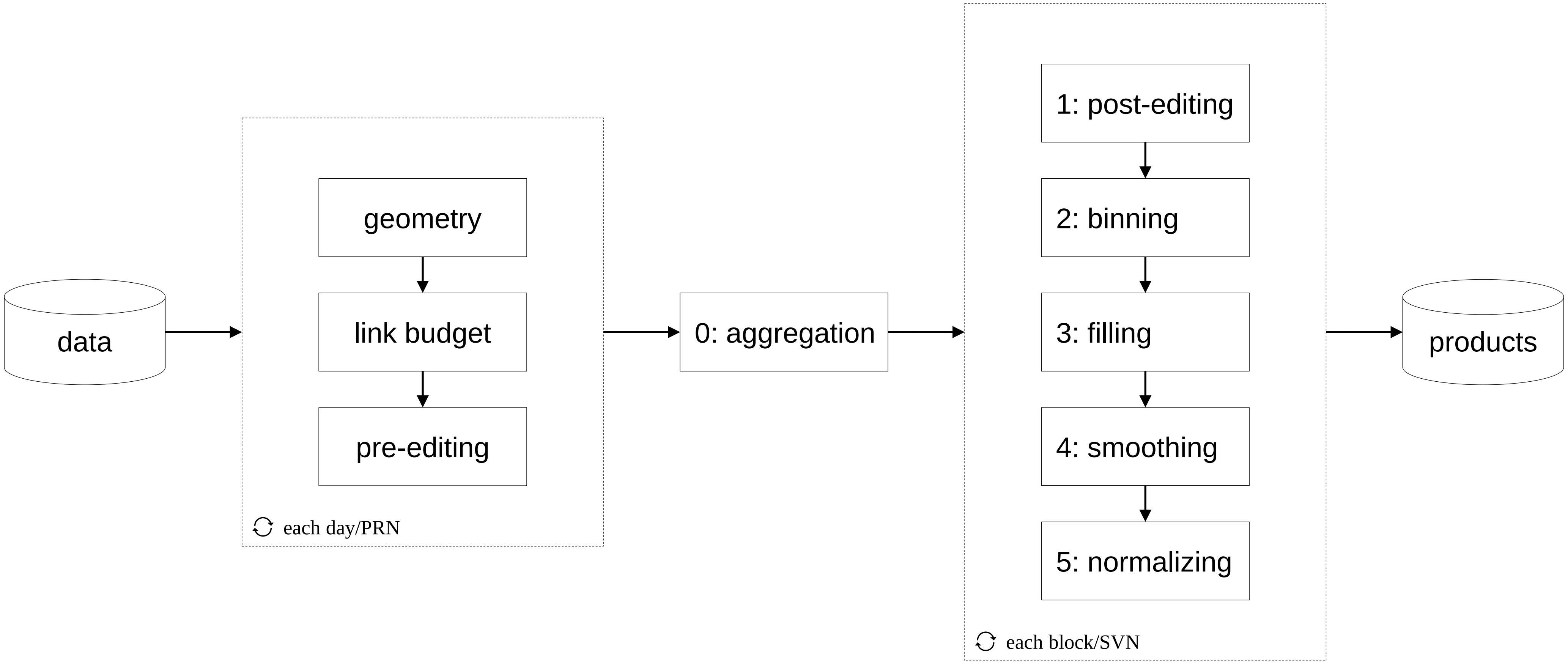
GPS ACE Receiver Implementations

Two Versions: Flight and Ground

- NASA software GPS receiver – common software base with NASA's flight Navigator GPSR
  - *Designed to operate on-board in real-time*
  - *Acquisition to ~25 dB-Hz, tracking to ~22 dB-Hz*
  - *Coherent integration times up to 20 ms (no data wipe-off)*
  - *Hardware implementation of receiver also deployed via FPGA development board installed in workstation*
- Aerospace implemented ground-based, aided weak-signal tracking GPS receiver algorithm
  - *Mariposa GPS Receiver (MGPSR) uses bit and ephemeris aiding with adjustable long integration times (1 msec to 120 sec)*
  - *GPS RF baseband data stored in 24 hour FIFO with 3-hr delayed processing to accommodate latent aiding data*
  - *Tracking to < 0 dB-Hz with 30-sec integration*
  - *All-in-view tracking, pseudorange, carrier phase*
  - *This paper uses MGPSR C/N_0 and pseudorange for results generation*

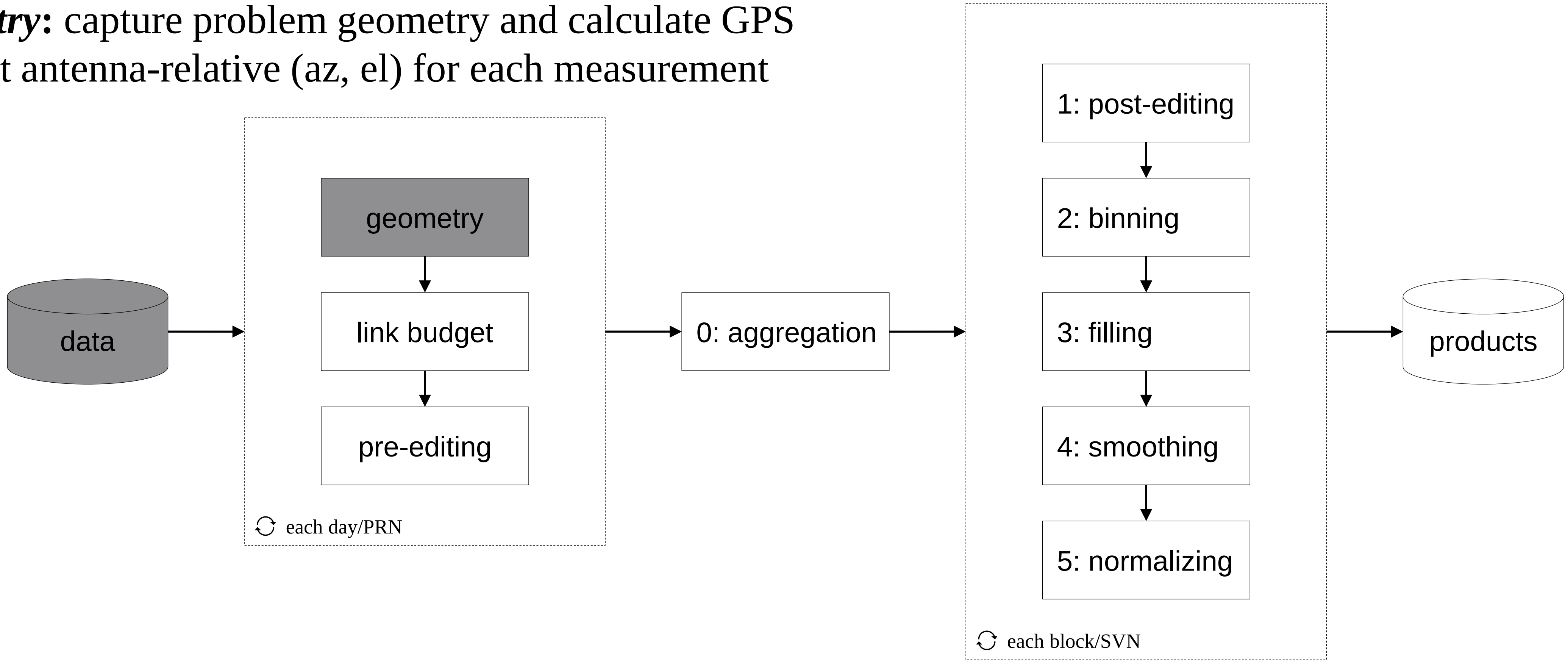
Antenna Pattern Reconstruction

NASA GSFC OD Toolbox (ODTBX) Framework



Antenna Pattern Reconstruction
Geometry

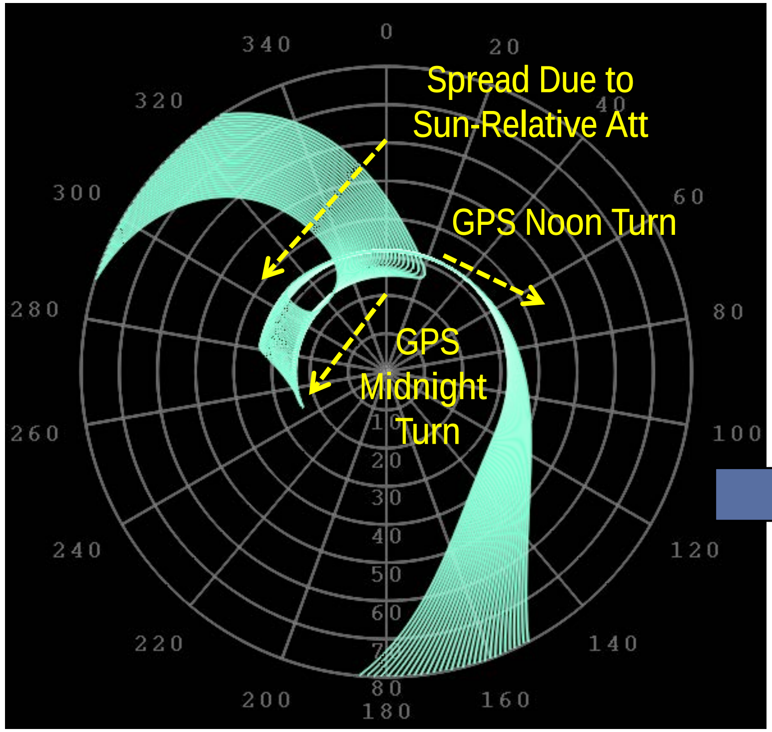
Data: collect GPS L1 C/A C/N0 and pseudorange observables
Geometry: capture problem geometry and calculate GPS transmit antenna-relative (az, el) for each measurement



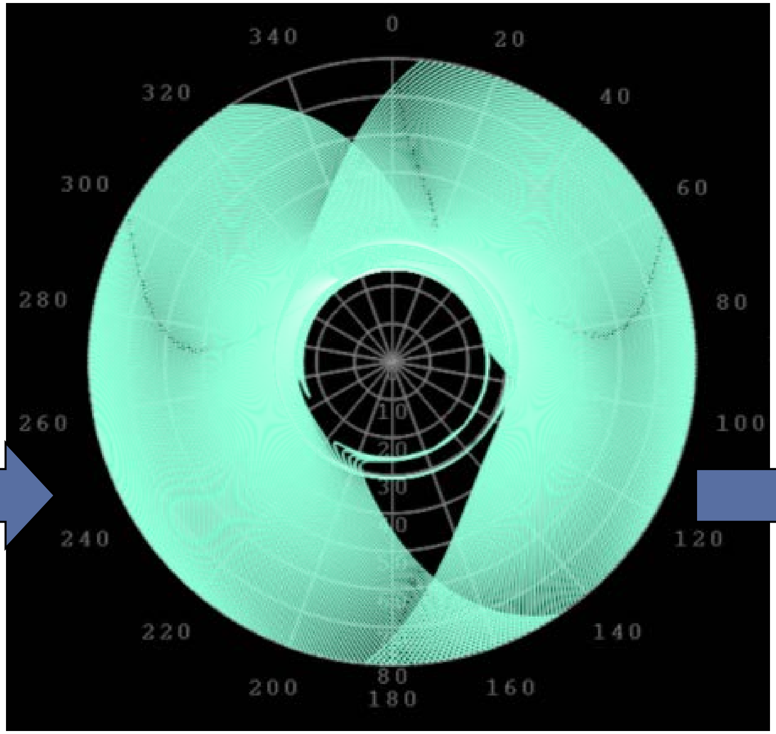
Visualization of Data Collection

- Trace path of GEO vehicle in antenna frame of each GPS vehicle
- Reconstruct full gain pattern after months of tracking

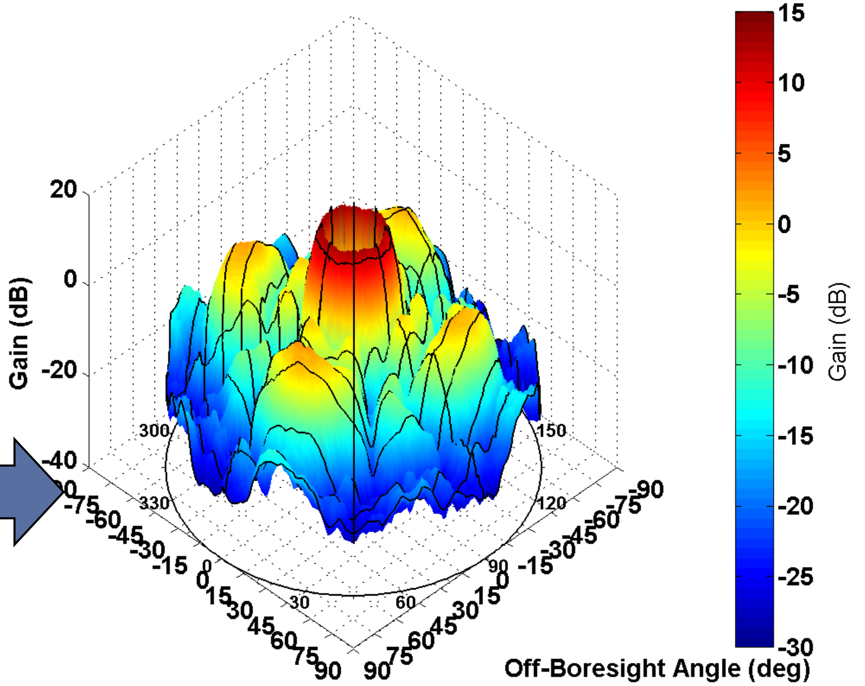
Coverage after One Month



Nearly Full Coverage after 6 Months



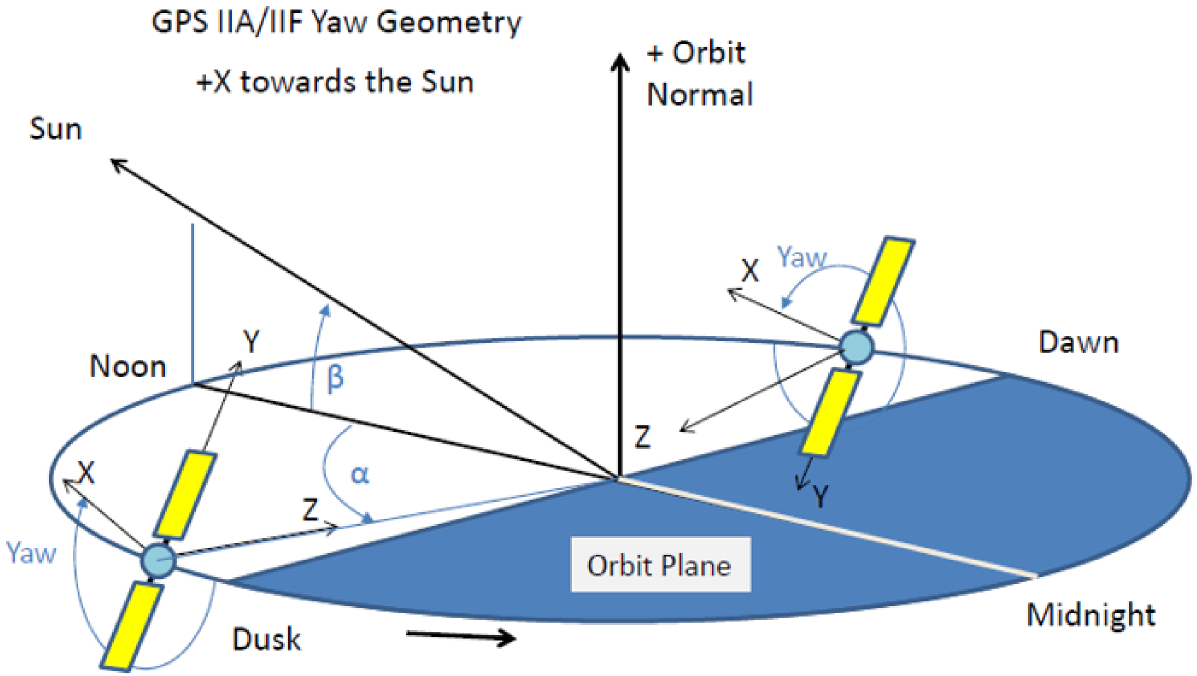
Reconstructed Gain Pattern

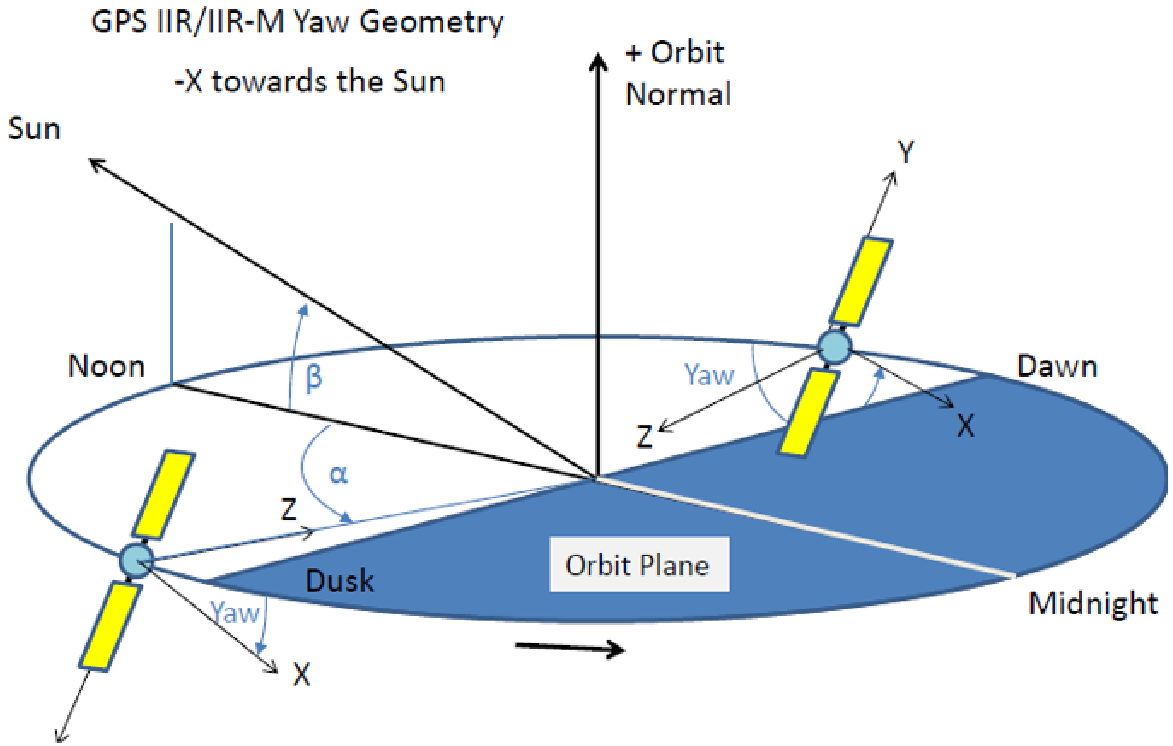


View from GPS Antenna Frame

- Shows path of GEO vehicle in azimuth & off-boresight angle relative to GPS frame
- Path changes due to Sun-relative yaw of GPS vehicle attitude
- Azimuth is from SV +X-axis about SV +Z-axis

GPS Yaw Geometry

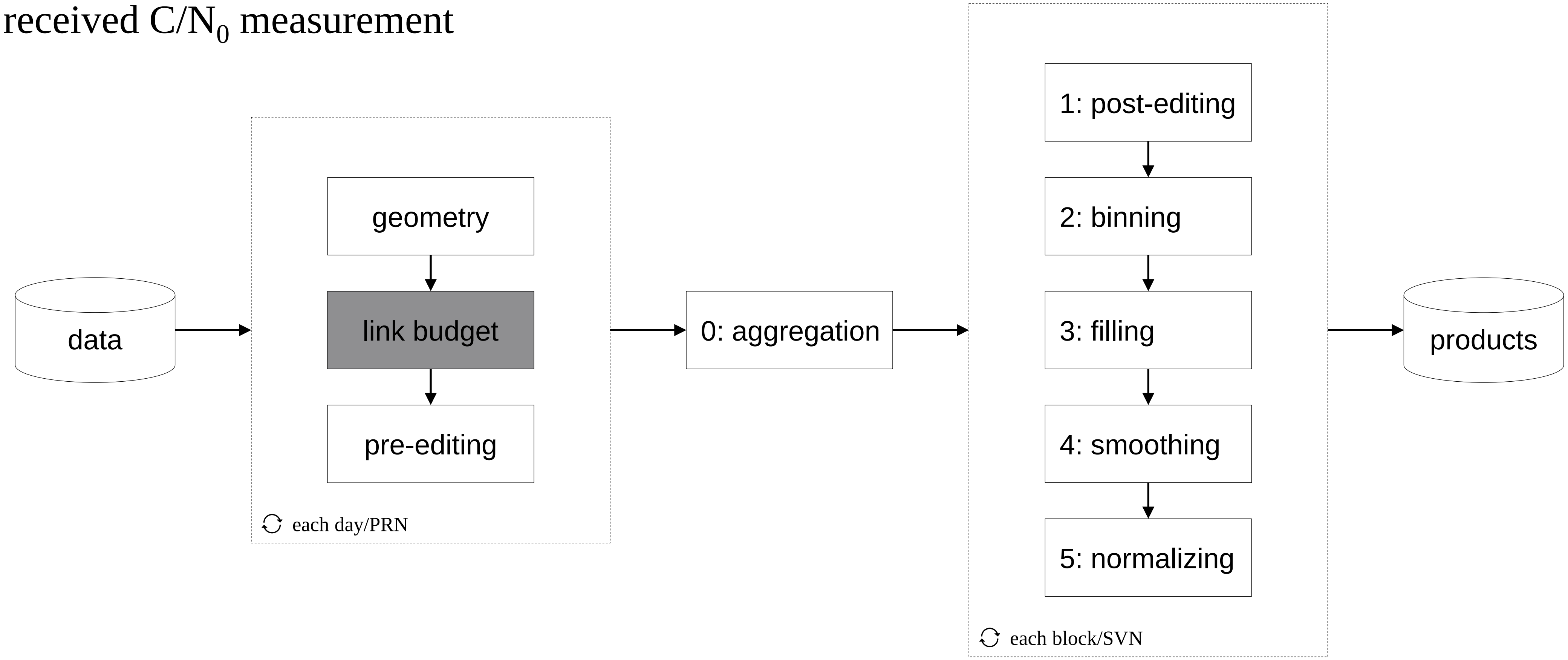




Antenna Pattern Reconstruction

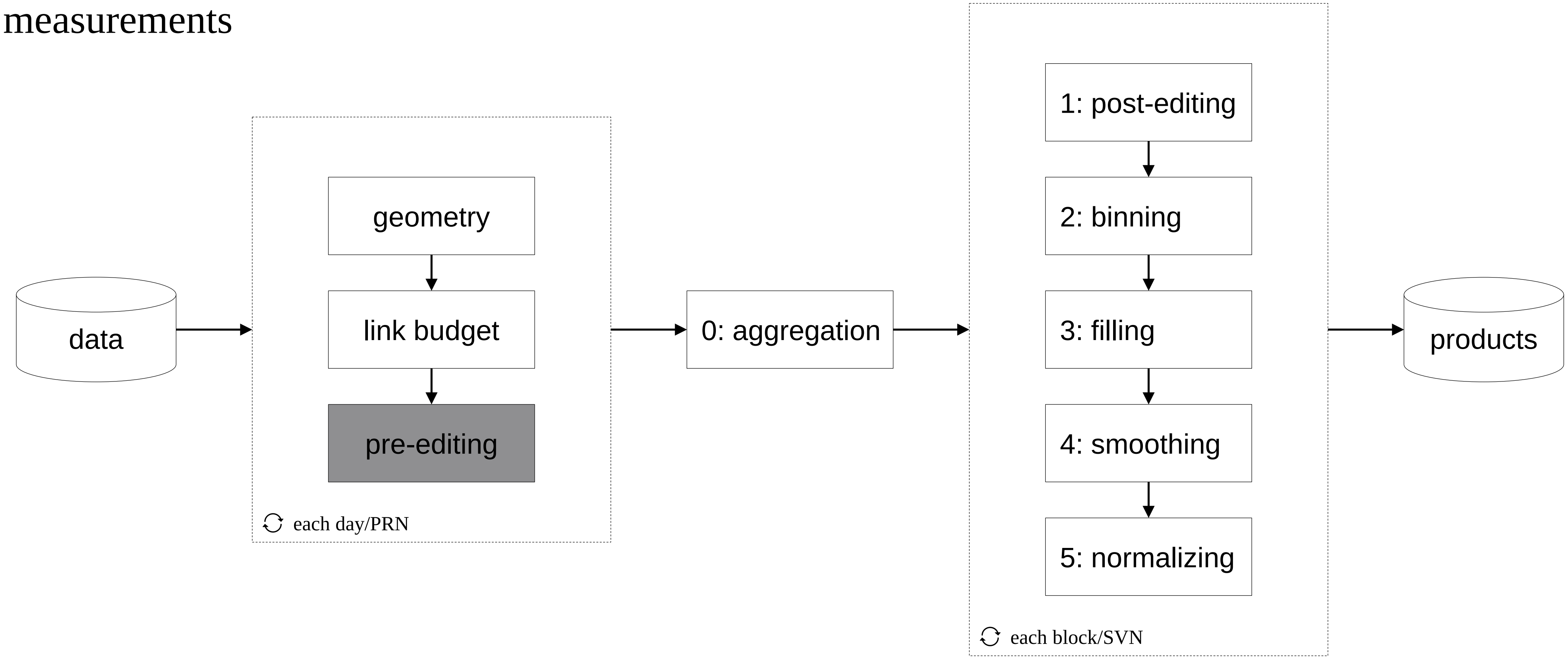
Link Budget

Link budget**:** reconstruct the transmit antenna gain value from a received C/N_0 measurement



Antenna Pattern Reconstruction
Pre-Editing

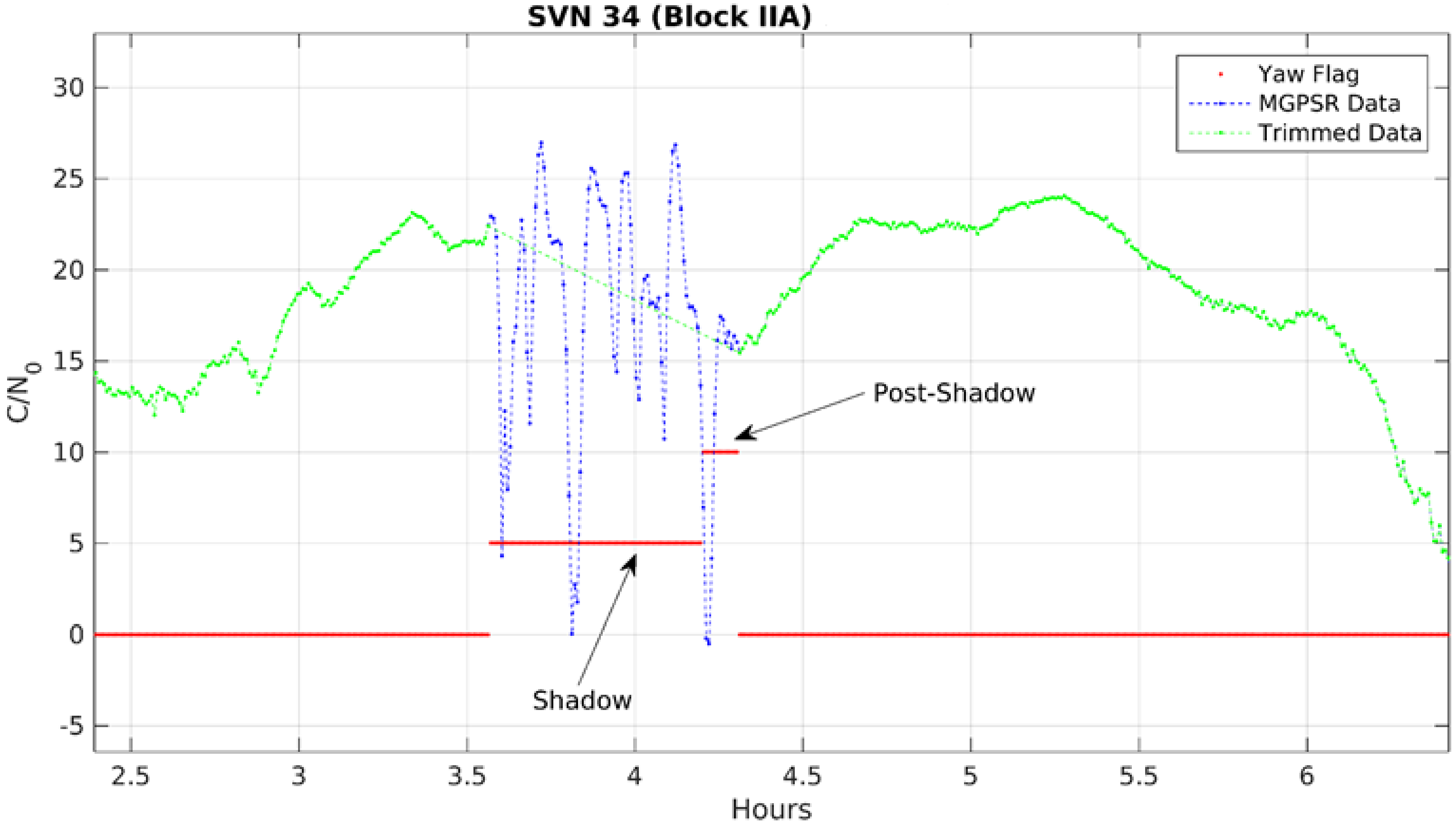
***Pre-editing*: use problem knowledge to detect and remove outlier measurements**



Data Editing: GPS SV Attitude

Eclipse Periods

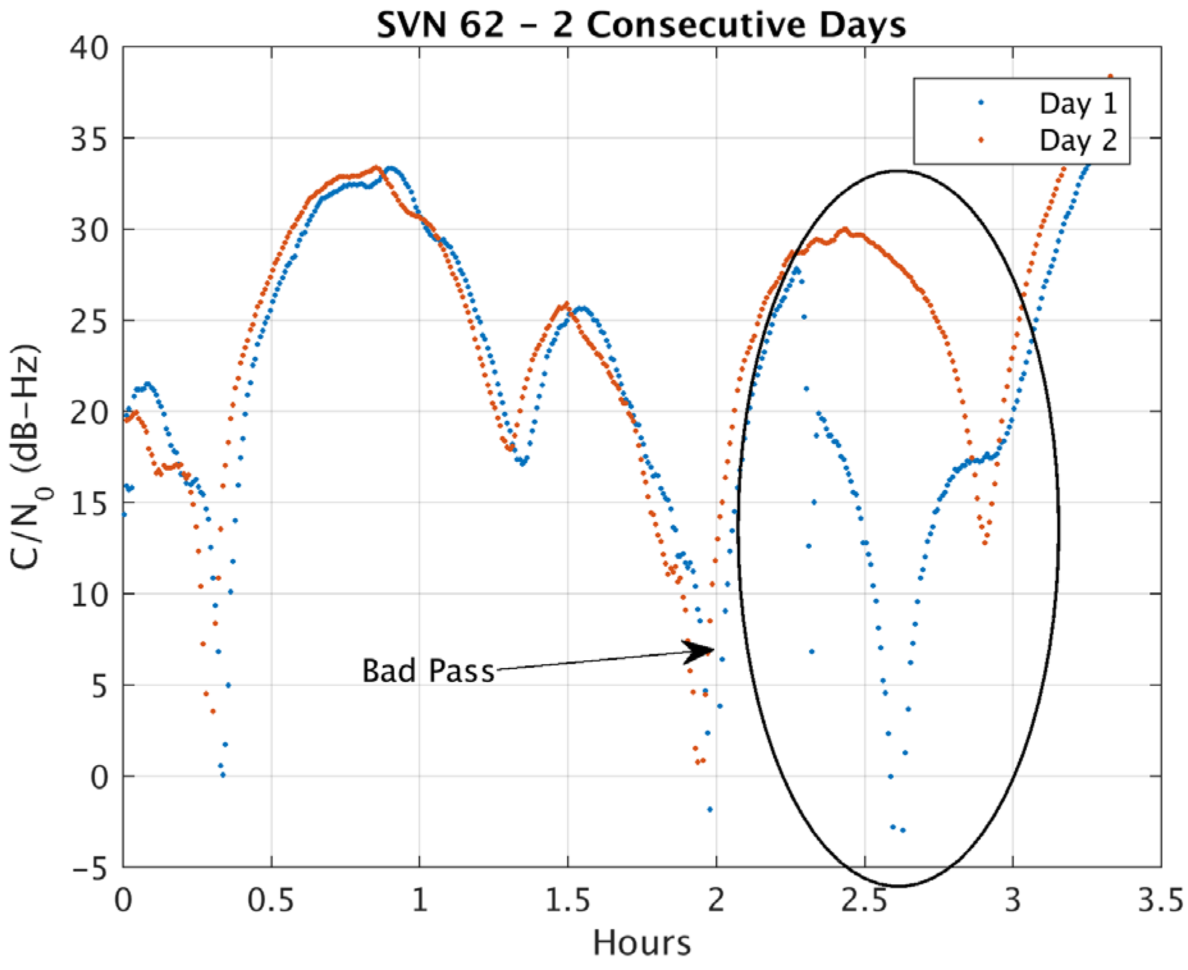
- Data was removed during noon and midnight turns
- Yaw model accurately predicts when the turns will occur based on sun angle, spacecraft position, and the beta angle.



Data Editing: GPS SV Attitude

Yaw Excursions

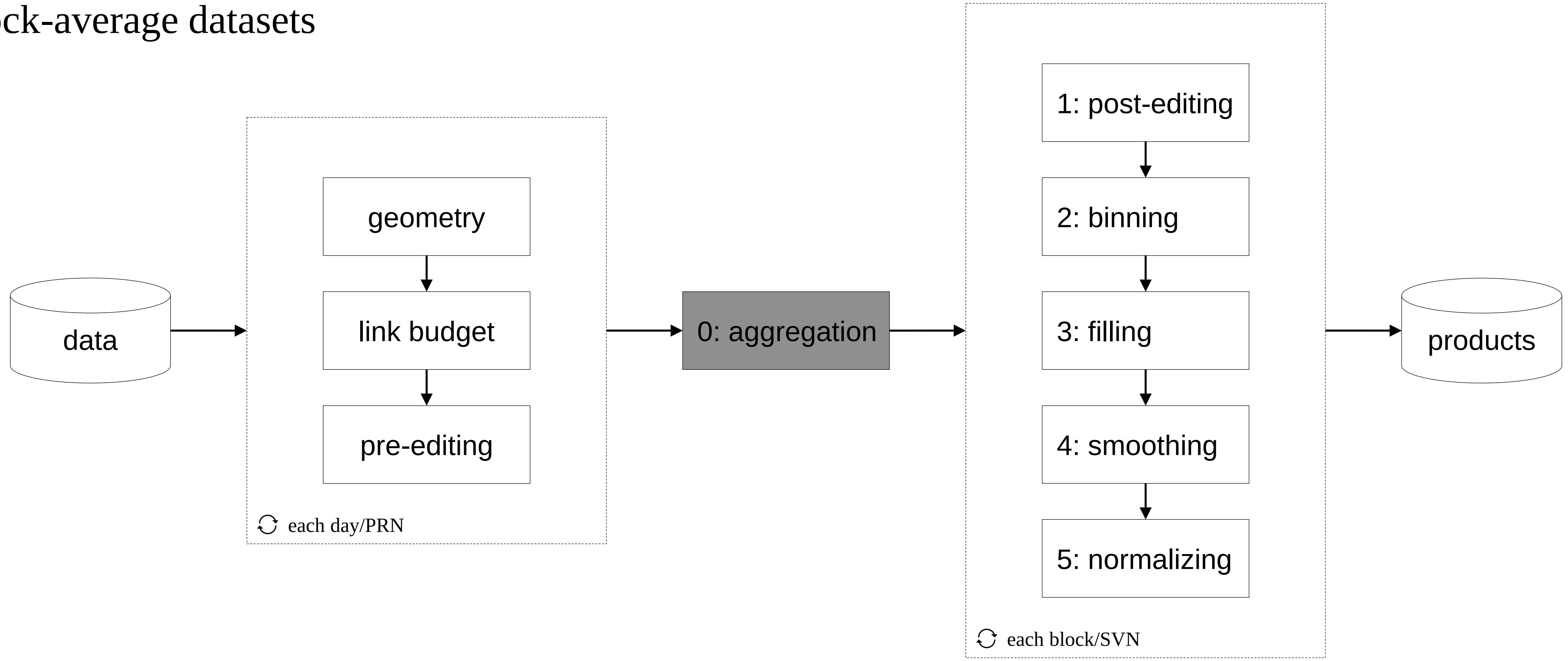
- Automatic editing was implemented to catch anomalous tracking data.
- In this case, the SV was commanded to an unexpected yaw attitude.



Antenna Pattern Reconstruction

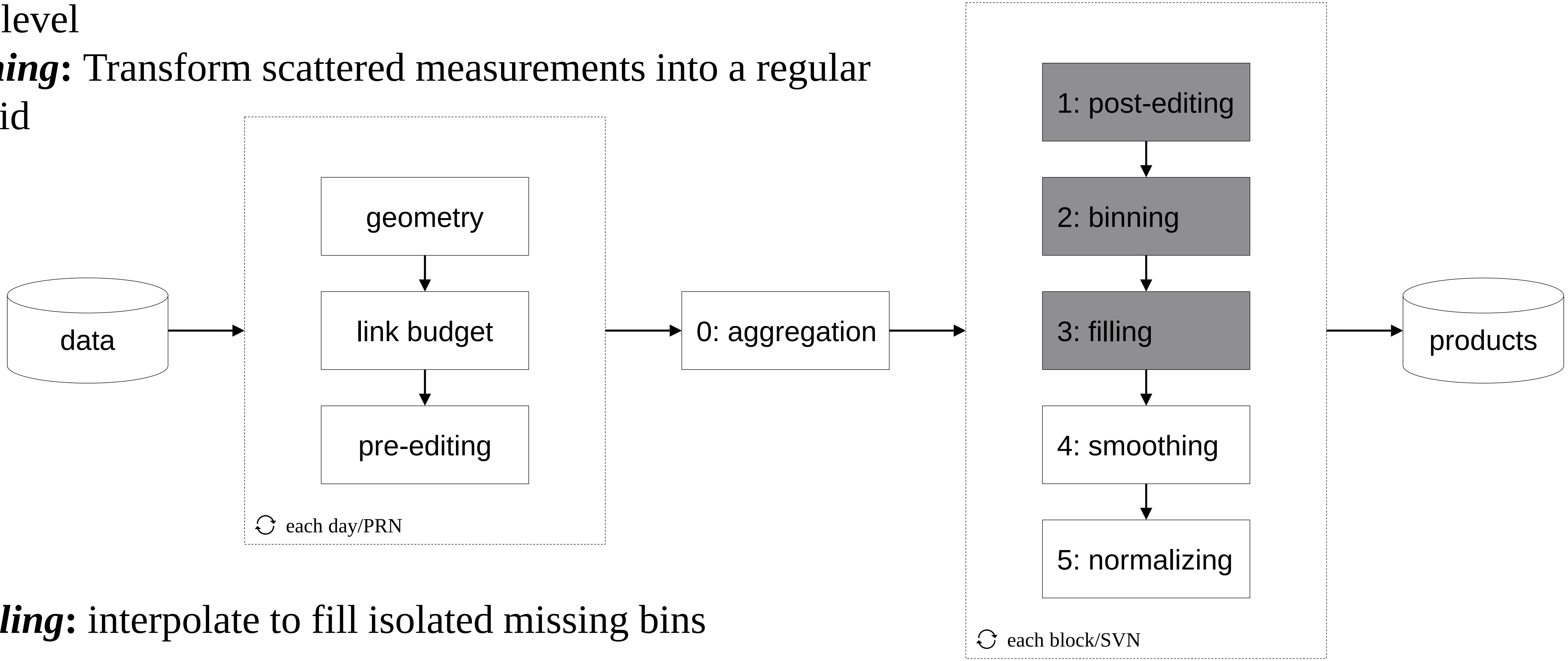
Aggregation

***0: Aggregation*: collect PRN-specific data into SV-specific and block-average datasets**



Antenna Pattern Reconstruction

1: Post-editing: perform outlier detection and removal at the pattern level
2: Binning: Transform scattered measurements into a regular az/el grid

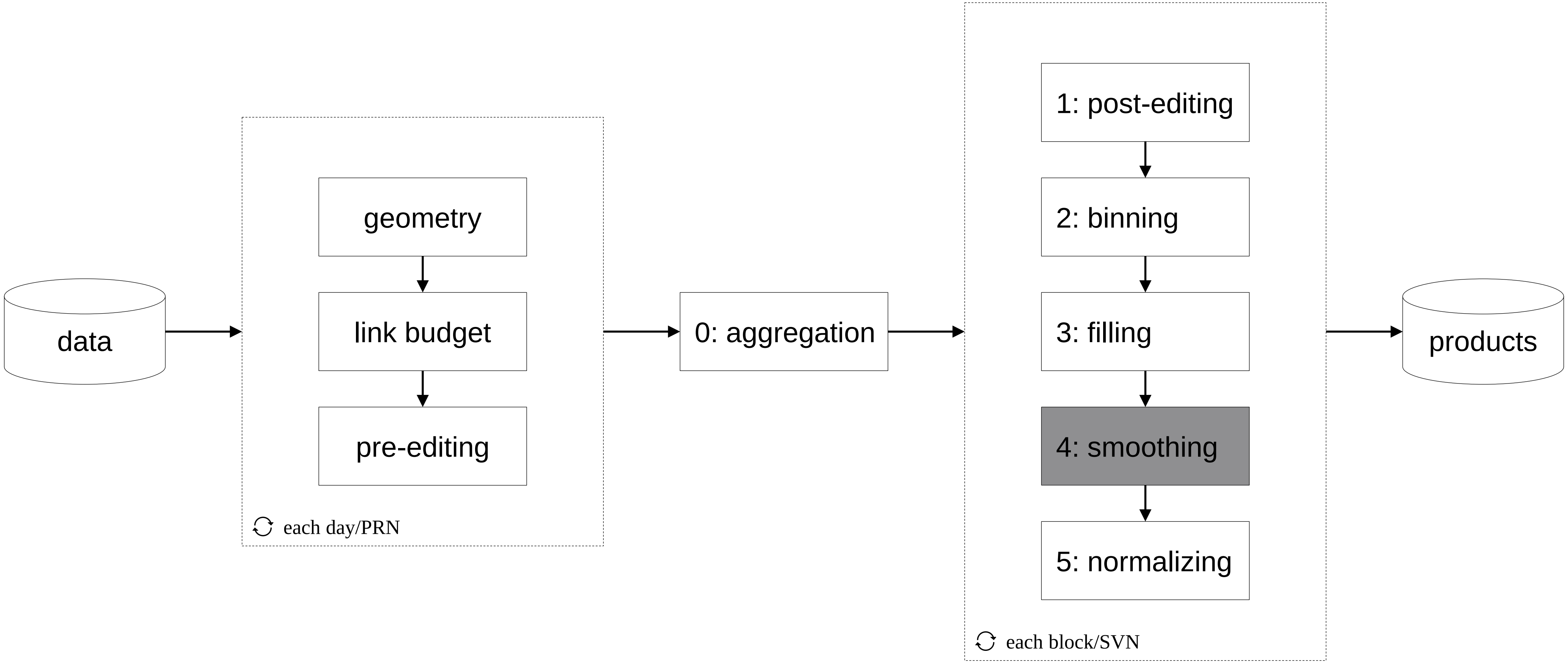


3: Filling: interpolate to fill isolated missing bins

Antenna Pattern Reconstruction

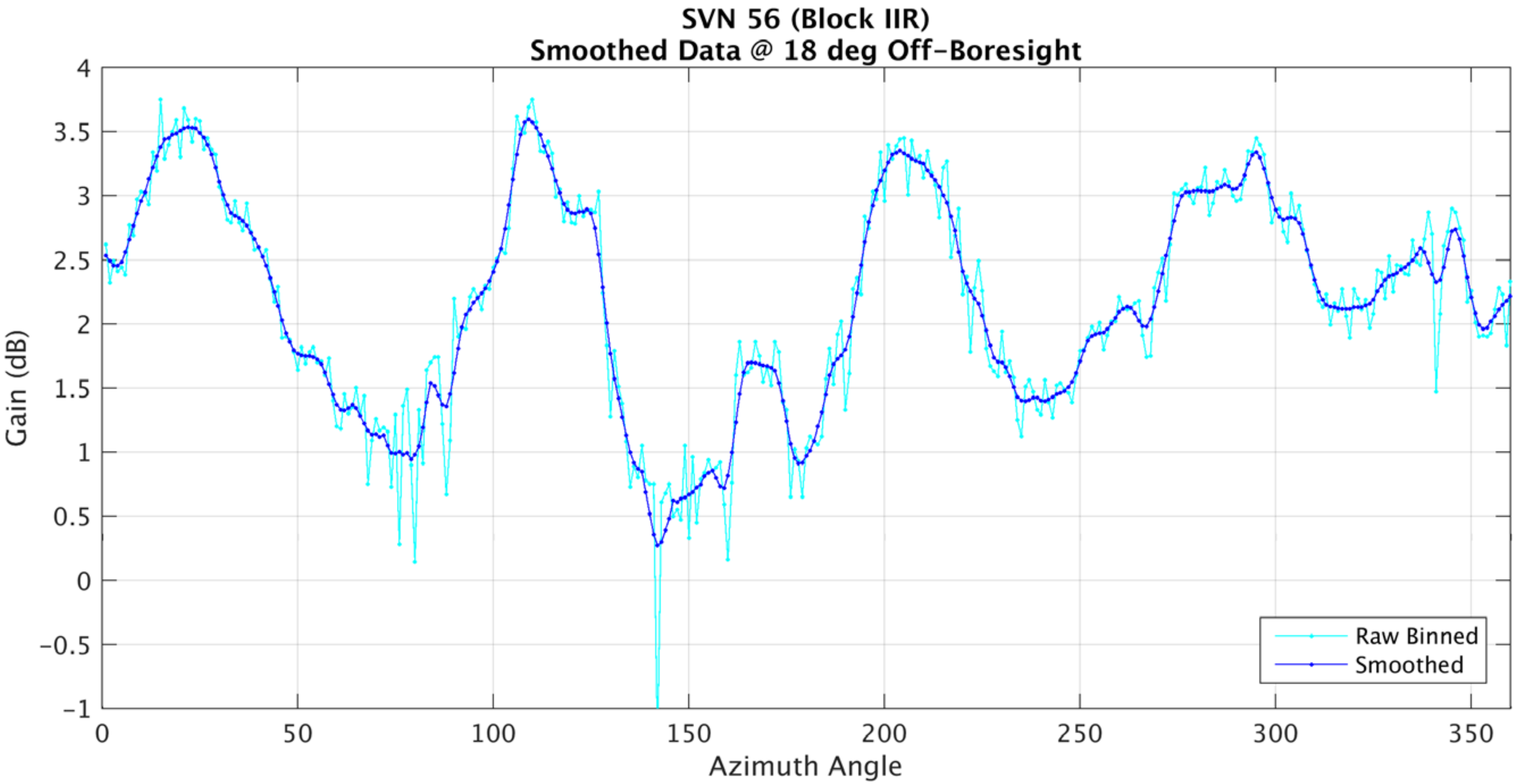
Smoothing

4: Smoothing: Reduce noise in final pattern



Antenna Pattern Reconstruction
Smoothing

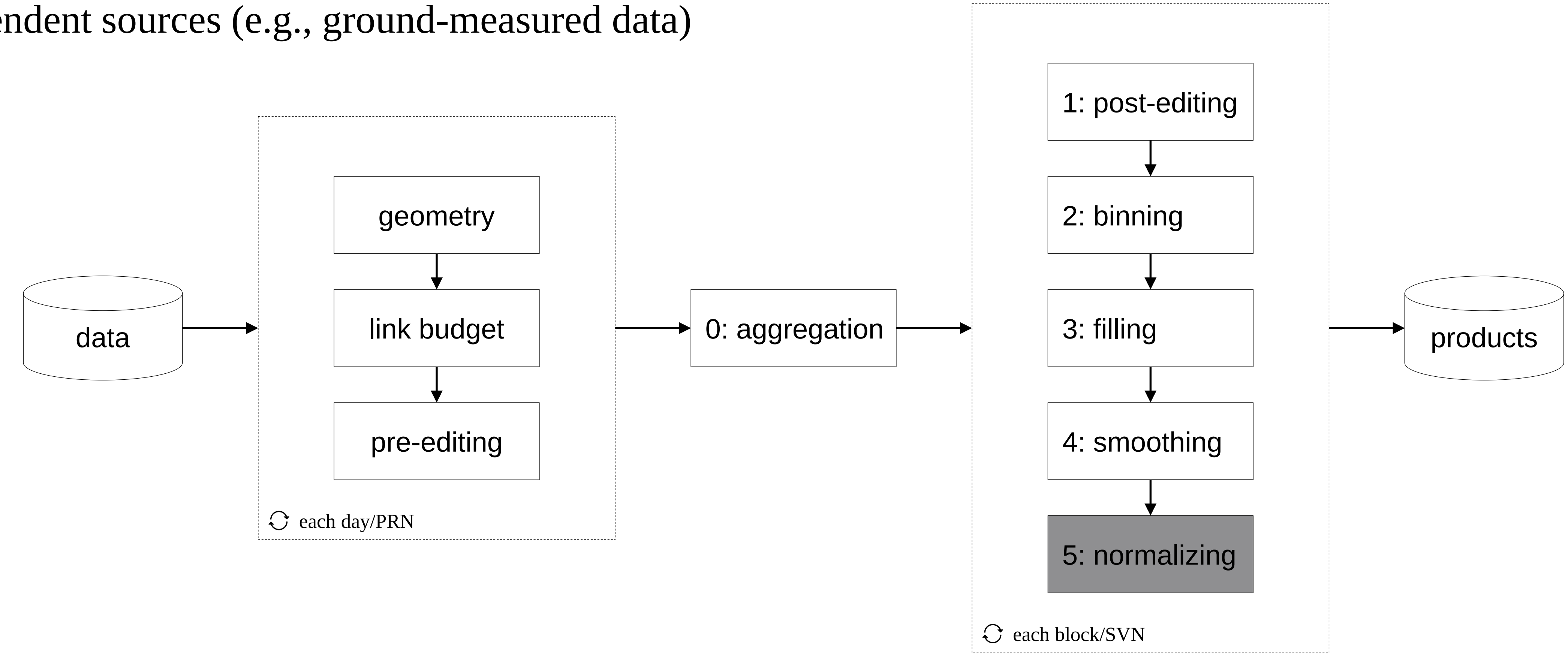
- Smoothing
  - *Binned and averaged data is noisy, used a low-pass filter to smooth*



Antenna Pattern Reconstruction

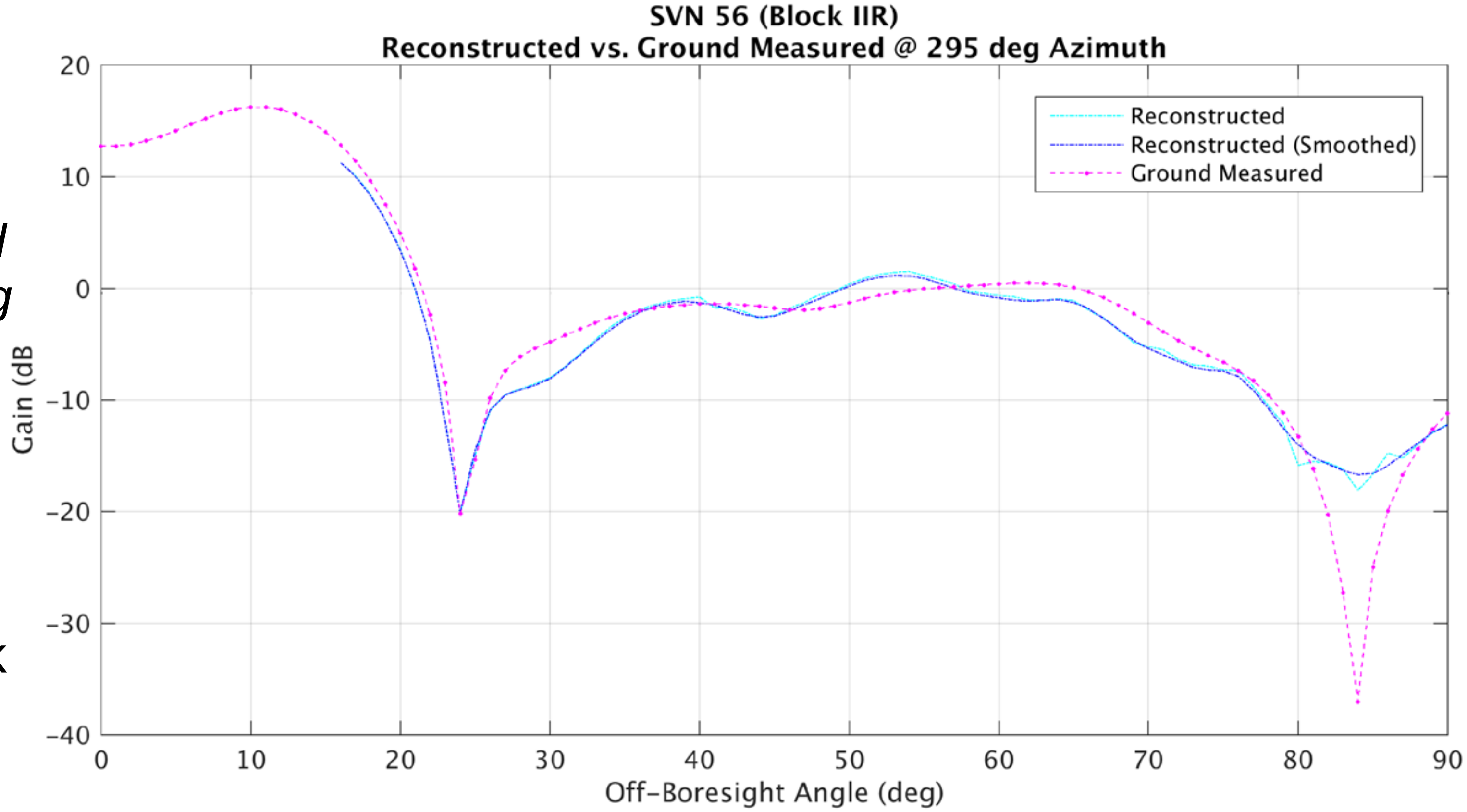
Normalization

***5: Normalization*: Calibrate the final patterns against known independent sources (e.g., ground-measured data)**



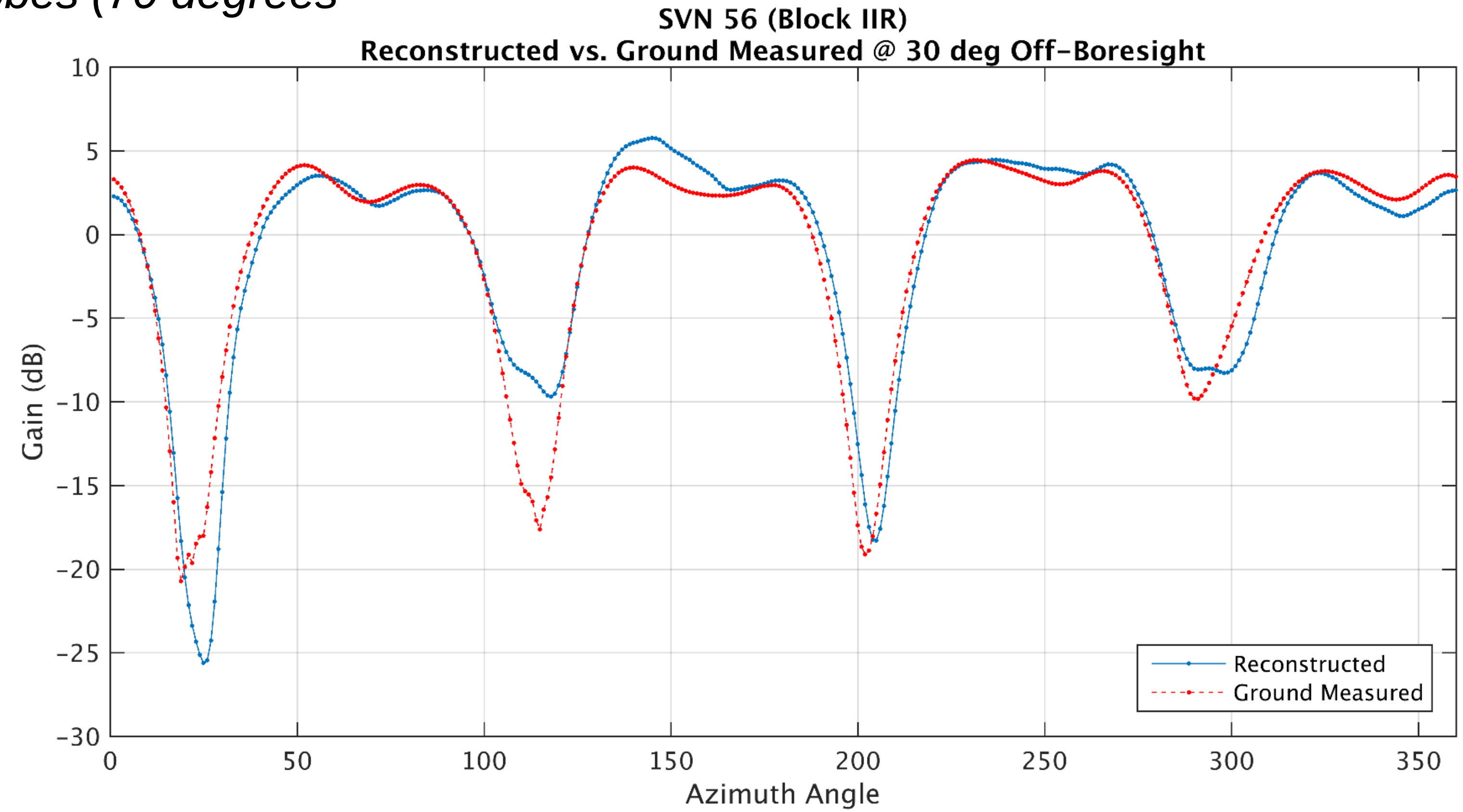
Reconstructed vs. Ground: Azimuth Cut

- Reconstructed main lobe data is aligned to vendor ground measured data
- Shallow nulls
  - *Some of these nulls are steep and narrow (in azimuth). Yaw modeling errors contribute to averaging them out*
  - *Possibly temporal effects (temperature, power variations, multipath)*
- Most GPS receivers cannot track into the nulls so this information is not needed for accurate simulations



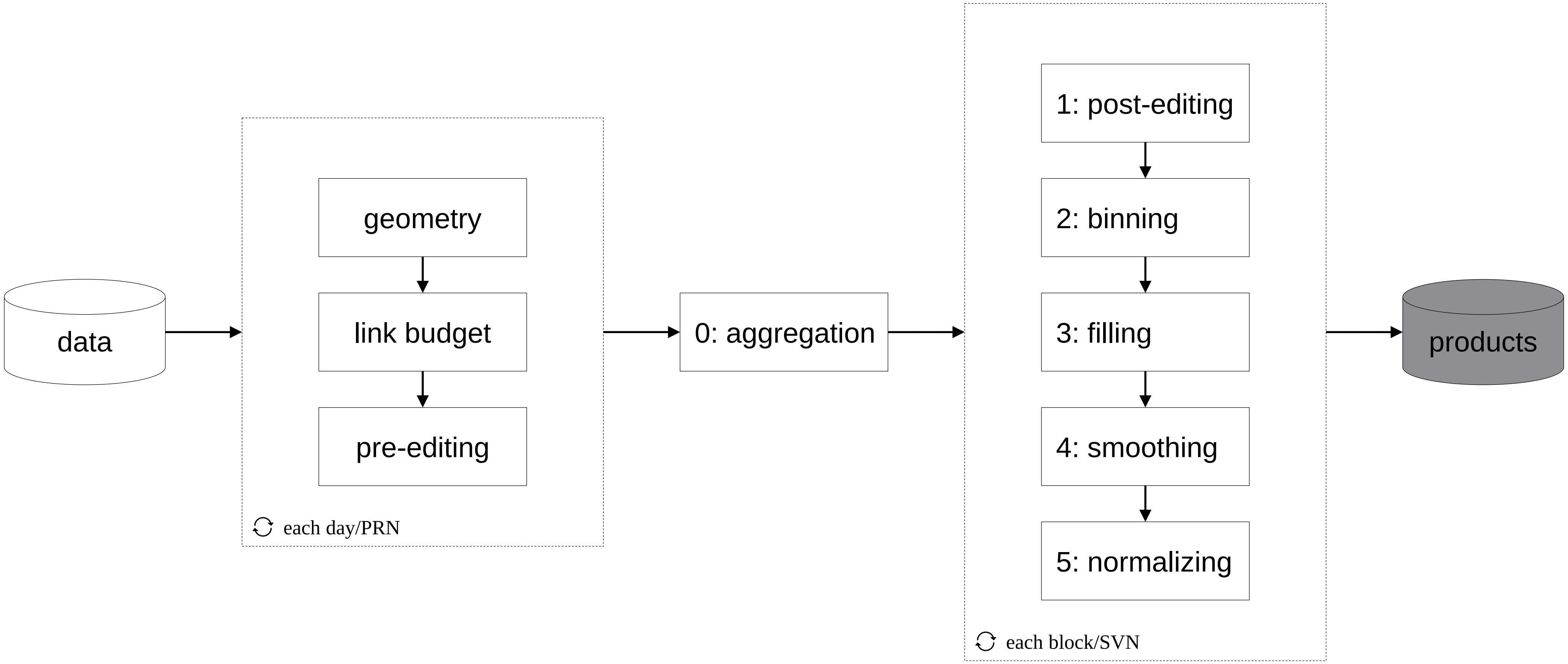
Reconstructed vs. Ground: Elevation Cut

- Good agreement in azimuth
  - *Agrees well from main lobe out to the second and third sidelobes (70 degrees off boresight)*



Antenna Pattern Reconstruction

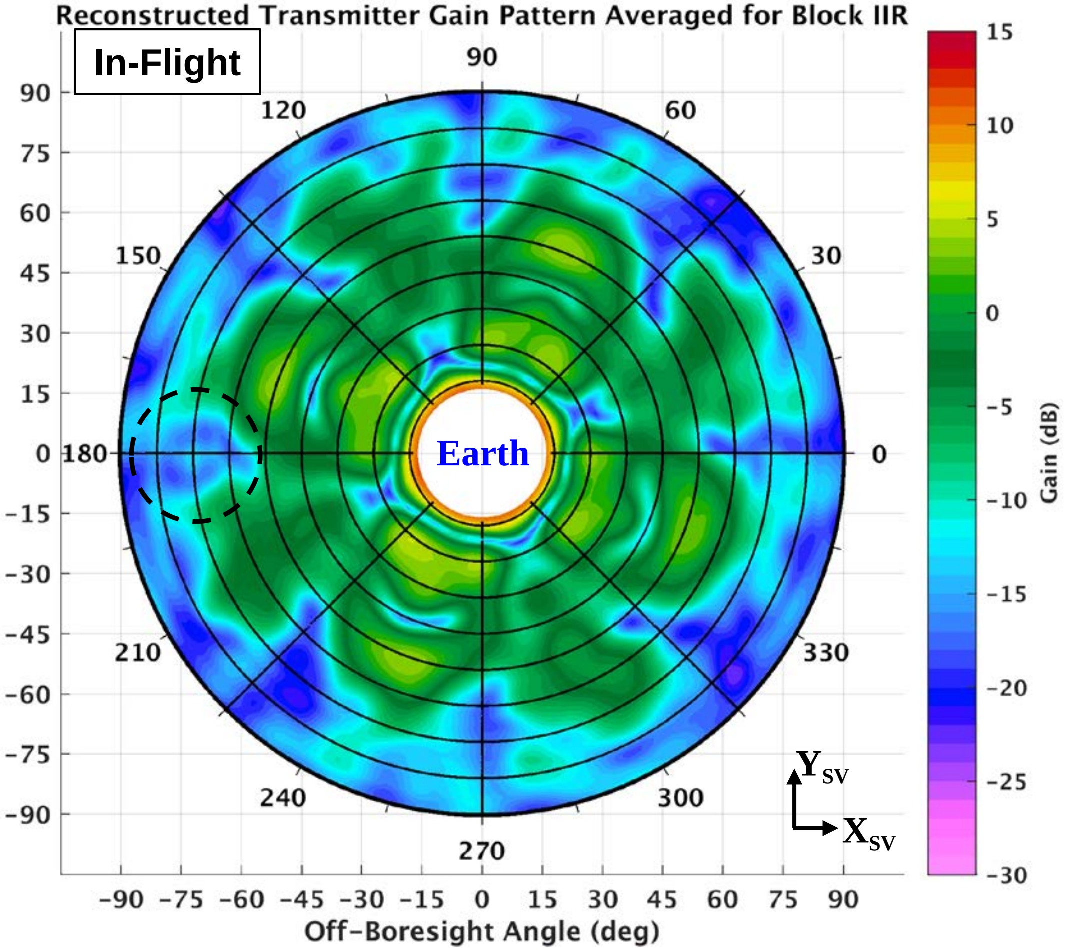
Products



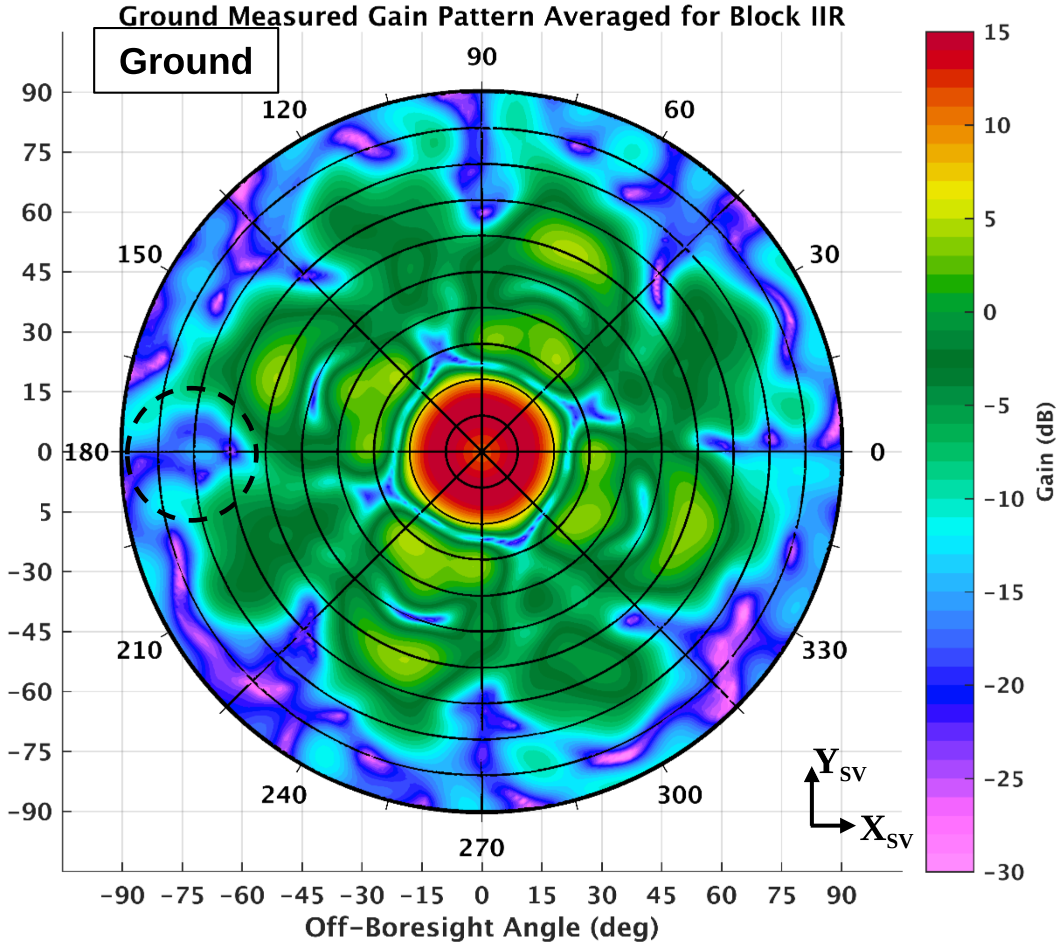
Average Transmit Gain -- Block IIR

In-Flight vs. Ground

- In-flight averaged over all SVNs in block in 1 deg x 1 deg bins
- Remarkable similarity between average flight and ground measurements
  - *Note matching patterns in nulls around outer edge*



Azimuth is from SV +X-axis about SV +Z-axis

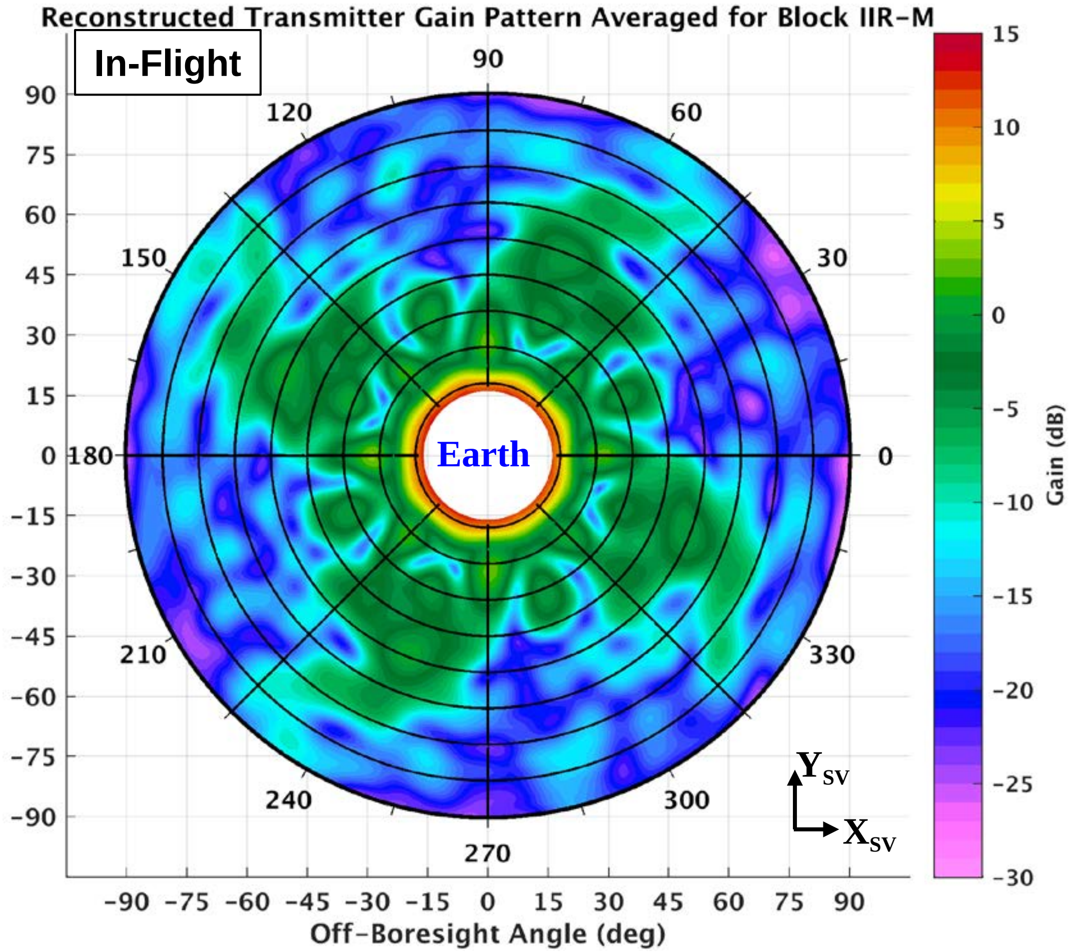


Average Transmit Gain -- Block IIR-M*

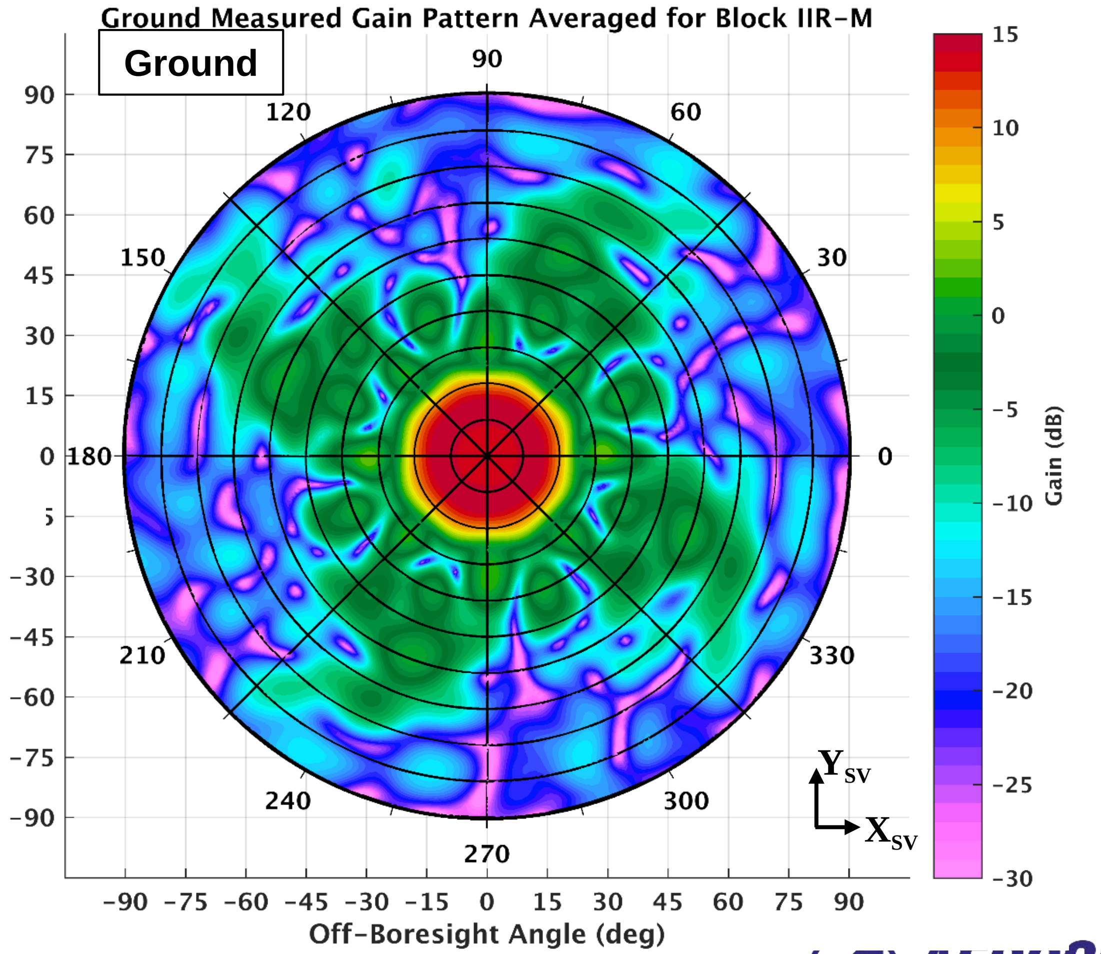
In-Flight vs. Ground

- In-flight averaged over all SVNs in block in 1 deg x 1 deg bins

** IIR-M signifies modernized antenna panel flown on all IIR-M vehicles and some IIR*



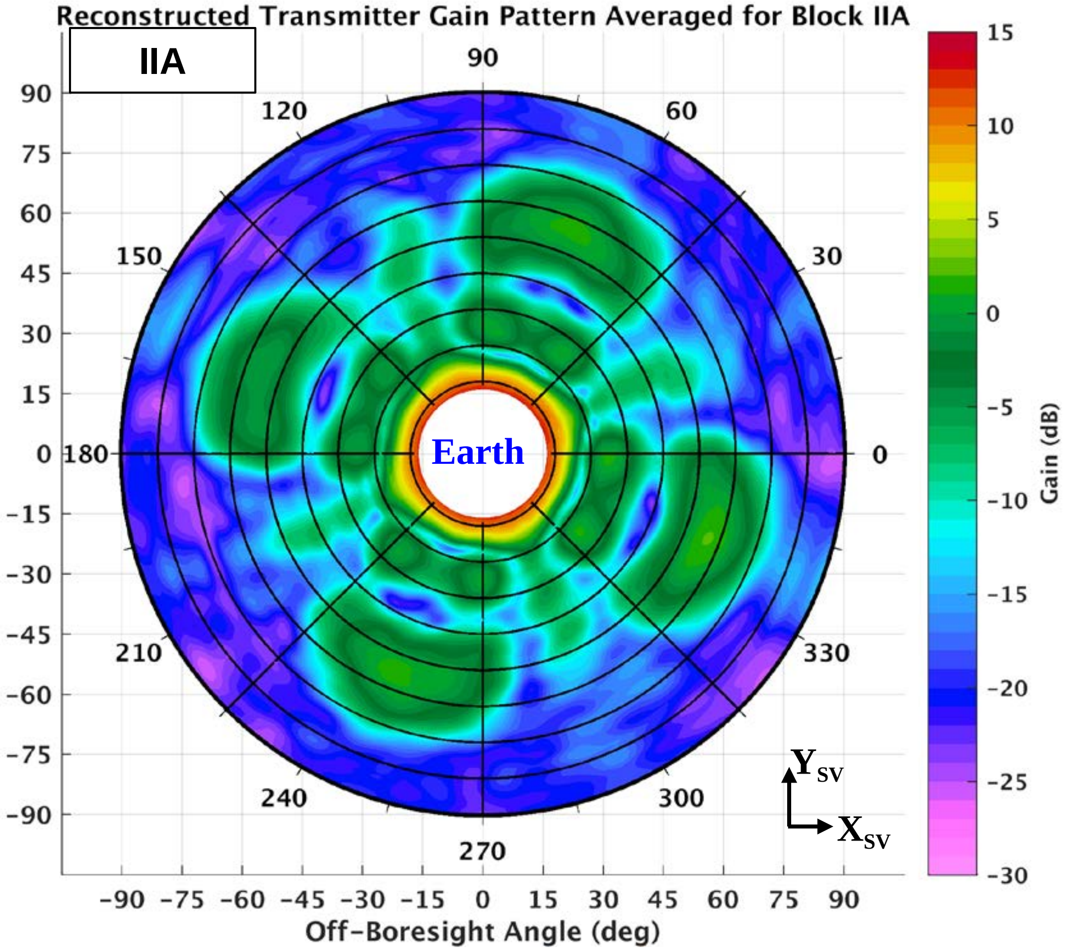
Azimuth is from SV +X-axis about SV +Z-axis

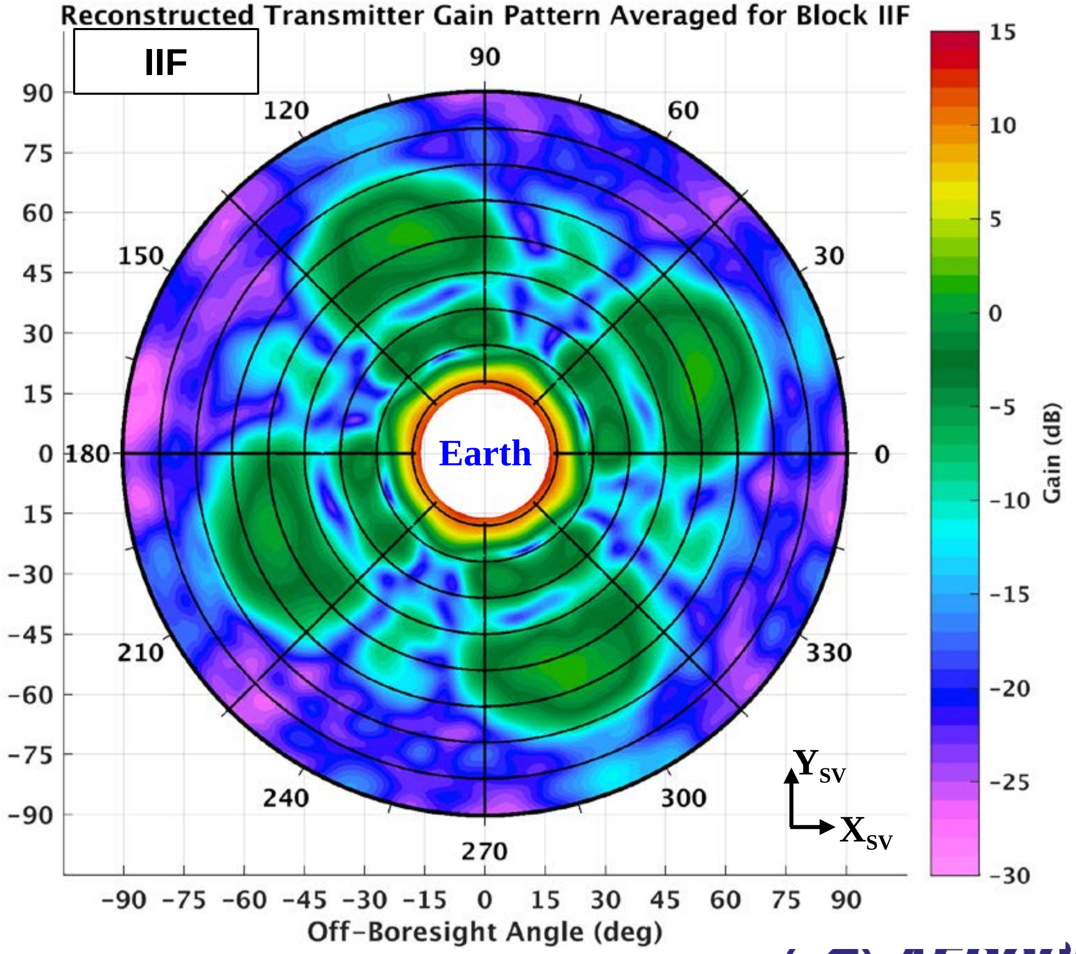


Average Transmit Gain -- Block IIA/IIF

First Characterization of Full Transmit Patterns

- Averaged over all SVNs in block in 1 deg x 1 deg bins
- IIF side lobes are shifted 45 deg in azimuth from other blocks





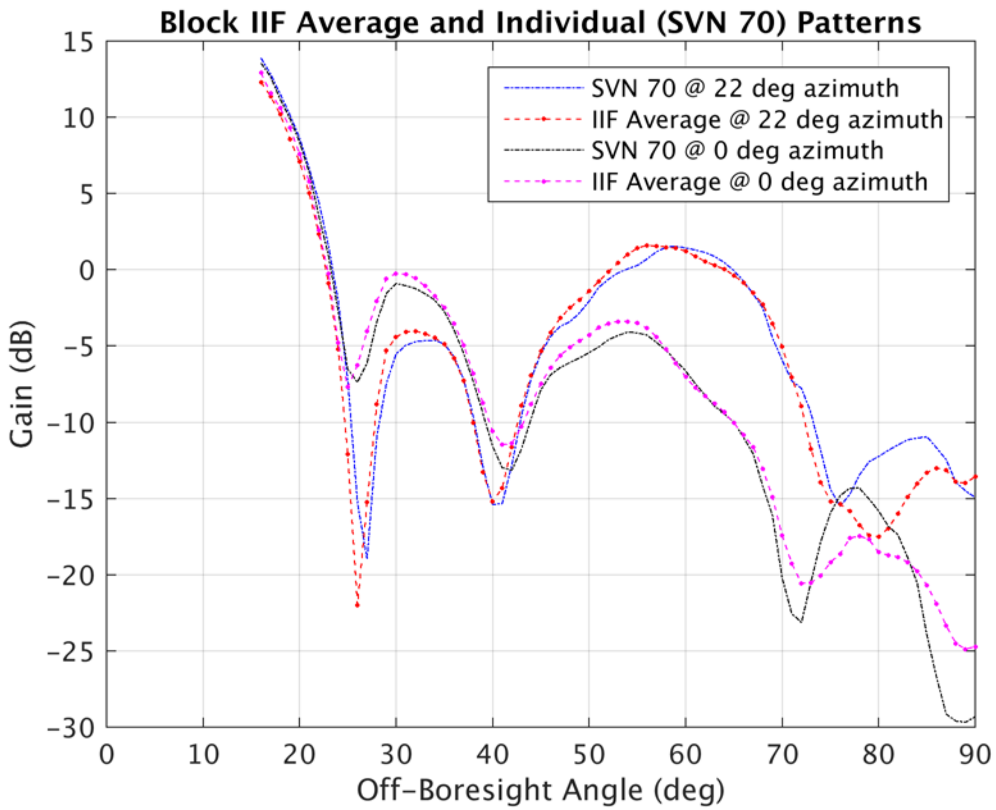
Azimuth is from SV +X-axis about SV +Z-axis

Block Average vs. Individual SVN

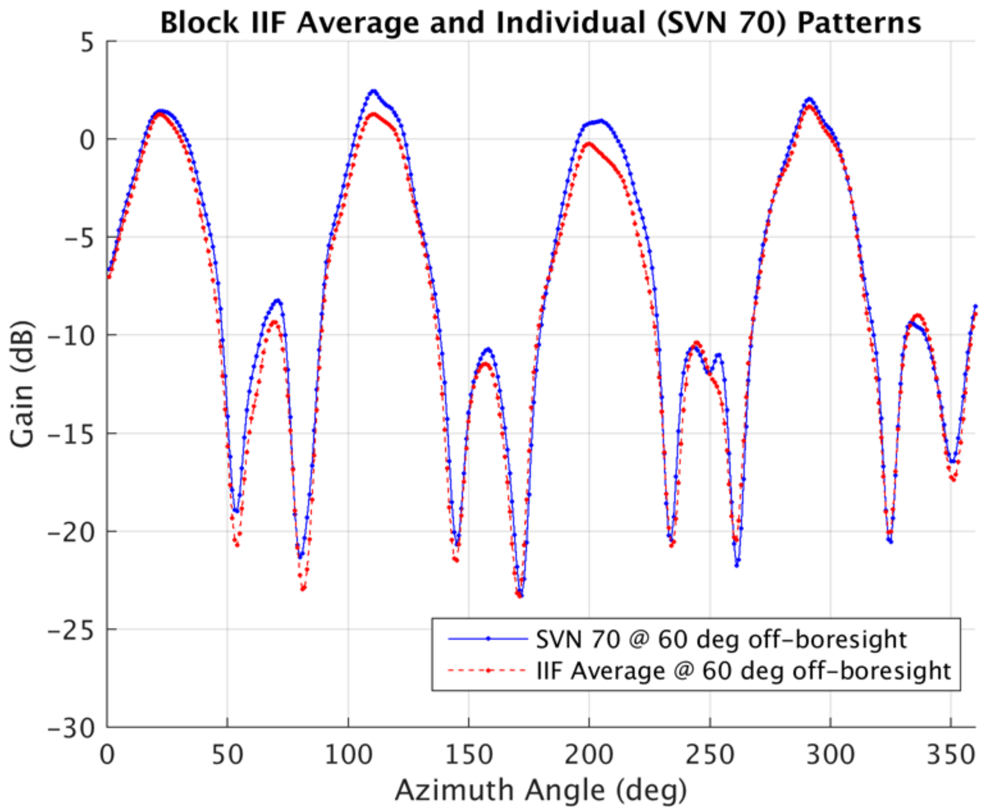
Block IIF vs. SVN 70 Gain

- Close match between reconstructed block average patterns and individual patterns

Gain vs. Off Boresight



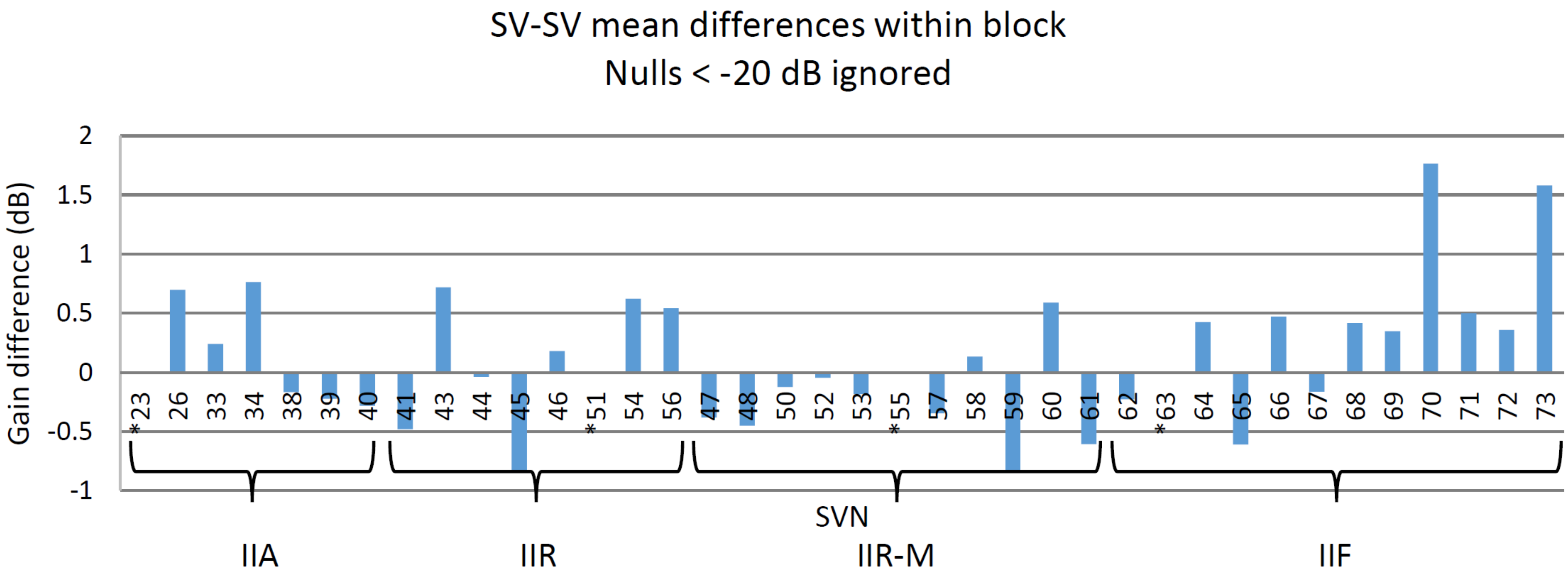
Gain vs. Azimuth



Variation in Individual SVN Gain

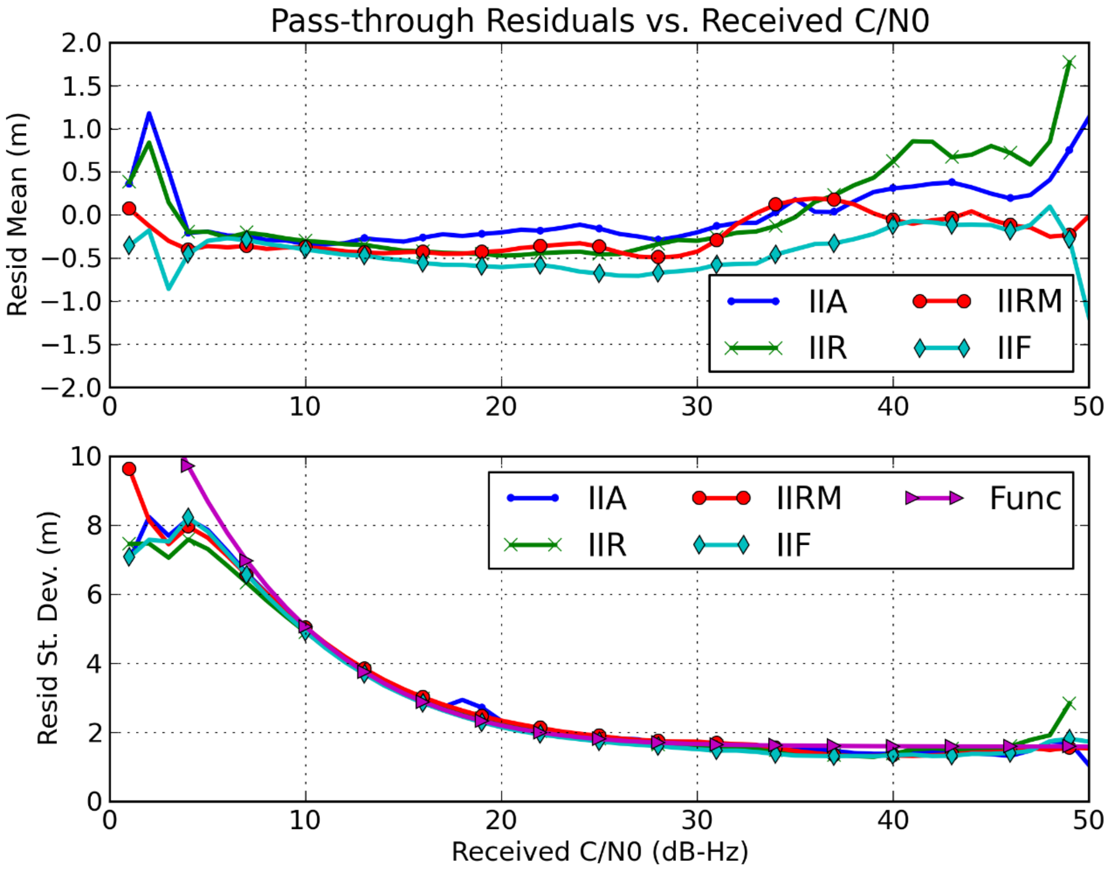
Mean Gain Difference

- There are mean differences in gain between patterns (before normalization)
  - *Transmit power was applied uniformly to each block in the link budget*
- These differences represent both the uncertainty in the link budget as well as differences in transmit power between individual satellites in a block



Pseudorange Deviation Analysis

- Evaluate pseudorange accuracy in side lobes
- Create residuals from pass-through process:
  - *Use Aerospace TRACE high fidelity orbit determination tool*
  - *Pass through external post-fit ephemeris*
  - *Compute residuals at all signal levels*
  - *Plot mean and standard deviation as a function of C/N_0 for each block*
- Mean shows values < 1 m at all but extreme C/N_0
  - *General negative trend at lower C/N_0*
  - *Spread in main beam likely due to atmosphere*
- St. Dev. shows remarkable agreement across blocks
  - *Noise function determined for relative weighting*



Conclusions & Future Work

- GPS ACE architecture permits tracking of extremely weak signals over long duration
  - *MGPSR produces signal measurements well into back lobes of GPS vehicles*
  - *24/7 GPS telemetry provides near continuous tracking of each PRN*
- First reconstruction of full GPS gain patterns from flight observations
  - *Block averages of IIR, IIR-M show remarkable consistency with ground patterns*
    - Demonstrates value in extensive ground testing of antenna panel
  - *Characterized full gain patterns from Blocks IIA, IIF for the first time*
  - *Patterns permit more accurate simulations of GPS signal availability for future HEO missions*
- Pseudorange deviations indicate usable measurements far into side lobes
- Future analyses include
  - *Signal level and measurement stability / variability over time*
  - *Comparison to GPS signals received by the highly elliptical NASA MMS Mission*
  - *Characterization of GPS Block III transmit antennas*

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Thank You

Dataset available at: https://esc.gsfc.nasa.gov/navigation

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Backup

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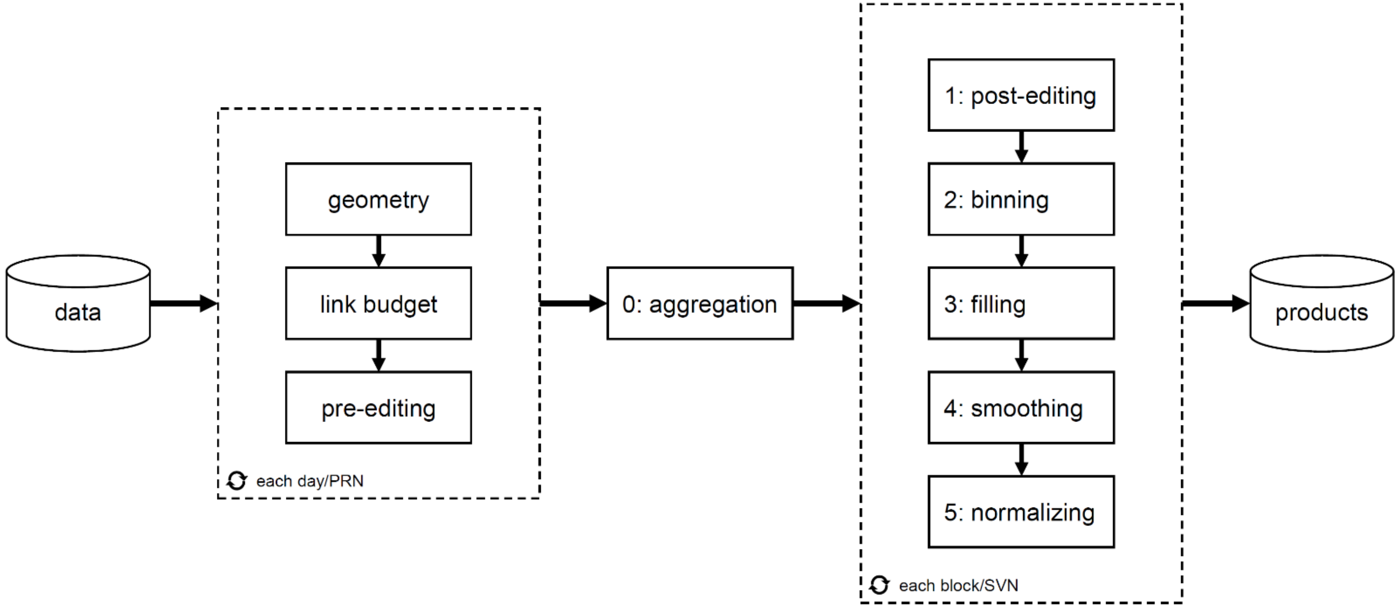
Antenna Pattern Reconstruction

NASA GSFC OD Toolbox (ODTBX) Framework

- ***Geometry***: capture problem geometry and calculate GPS transmit antenna-relative (az, el) for each measurement
- ***Link budget***: reconstruct the transmit antenna gain value from a received C/N_0 measurement
- ***Pre-editing***: use problem knowledge to detect and remove outlier measurements



- ***0: Aggregation***: collect PRN-specific data into SV-specific and block-average datasets
- ***1: Post-editing***: perform outlier detection and removal at th epattern level
- ***2: Binning***: Transform scattered measurements into a regular az/el grid
- ***3: Filling***: interpolate to fill isolated missing bins
- ***4: Smoothing***: Reduce noise in final pattern
- ***5: Normalization***: Calibrate the final patterns against known independent sources (e.g., ground-measured data)

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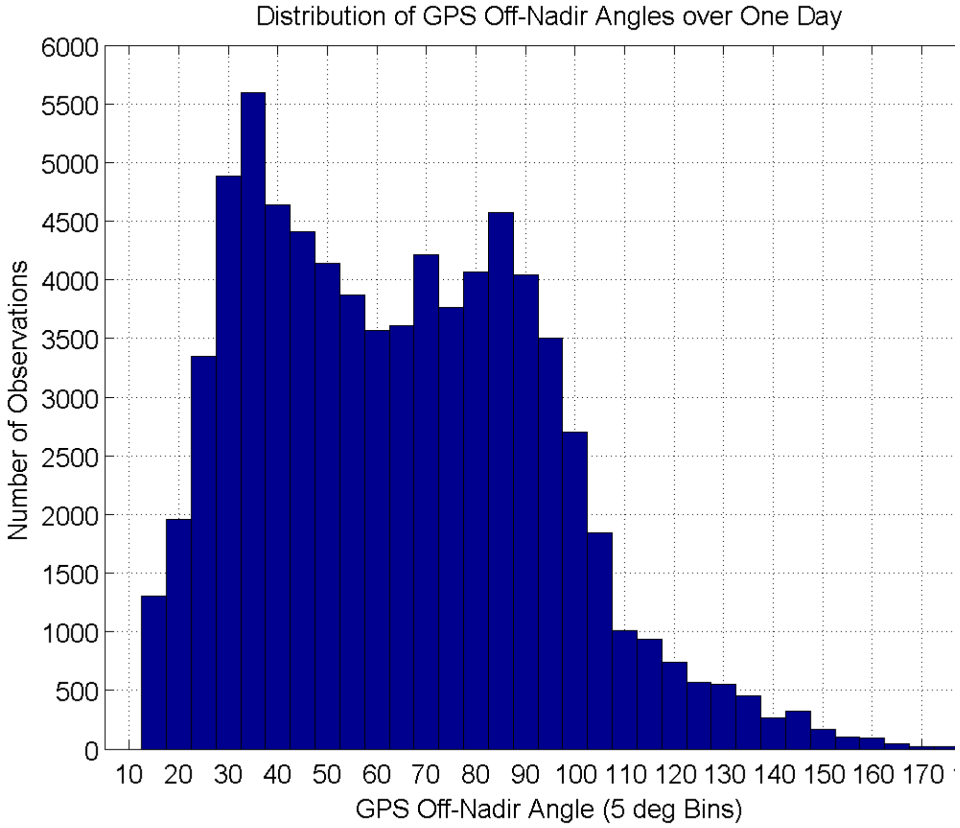
Link Budget

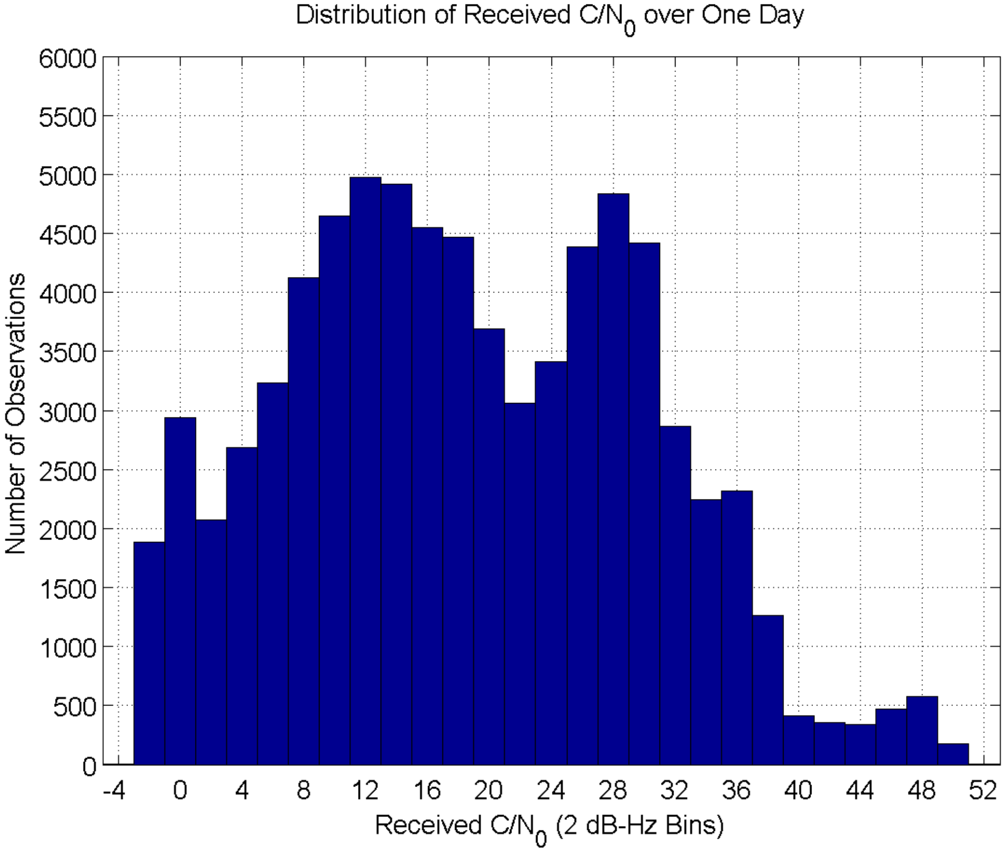
- Link Budget
  - *Knowledge of C/N0 and estimate of receiver noise temperature gives an estimate of the RX power, R_p*
  - *Estimate or calculate the R_X antenna gain , A_r, the space loss, A_d, the GPS transmit power, P_{sv}, and other losses, A_s and L_r, to find the TX antenna gain, A_t*

$$A_t(\theta,\varphi) = {}^{C}/_{N_0} - N_0 - A_r + L_r + A_s - P_{sv} - A_d$$

MGPSR Data Collection

Histograms of Single Day of Observations



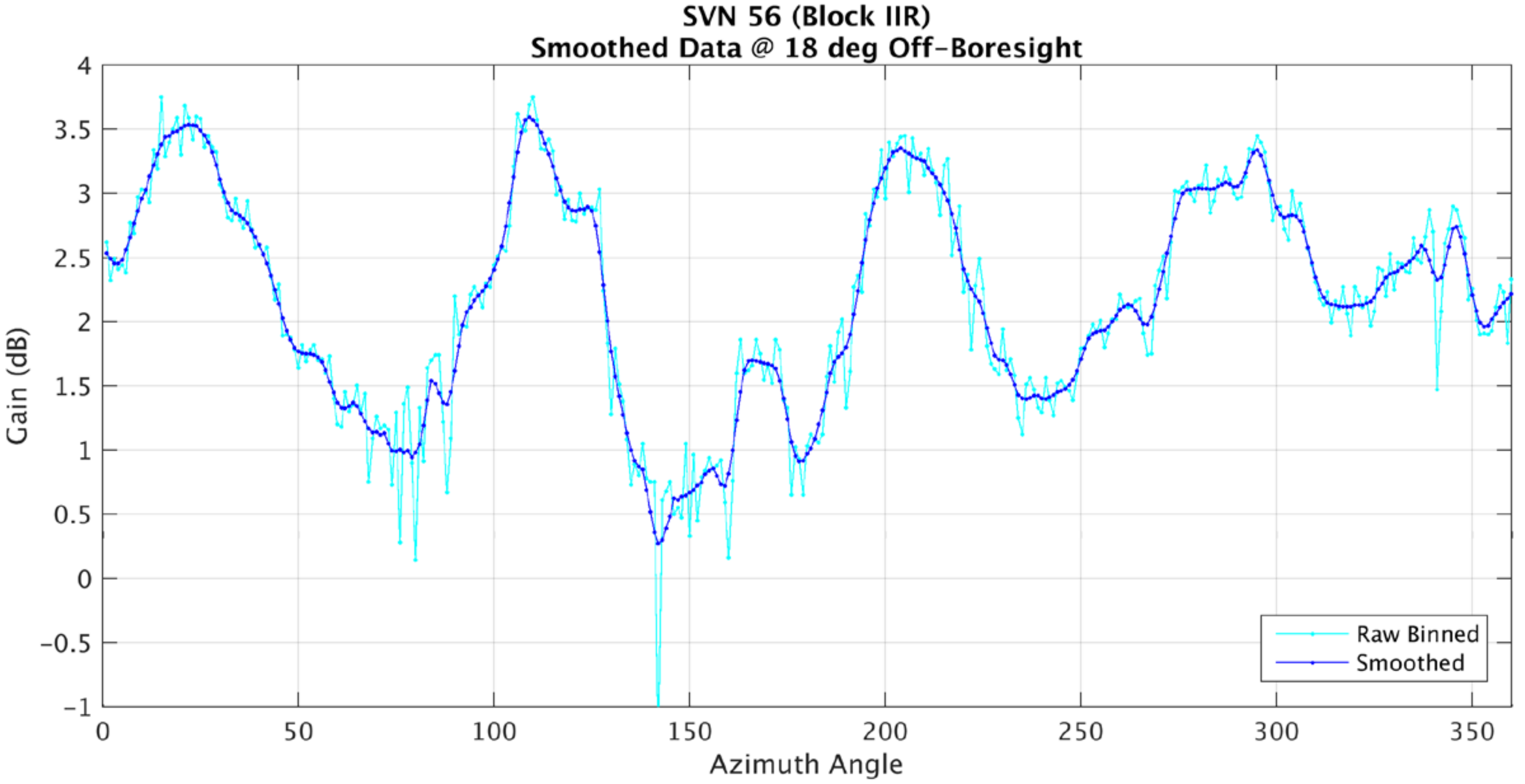


Block	Total Obs
IIA	4.8M
IIR	19.1M
IIR-M	26.3M
IIF	21.1M

- Plots show MGPSR data collection over 24 hours from GEO vehicle
  - *Demonstrates spectrum of observations available **daily** for **months***
- Left plot shows sensitivity into back lobes (> 90 deg off-nadir / off-boresight)
- Right plot shows received C/N_0 sensitivity to < 0 dB-Hz

Antenna Pattern Reconstruction

- Link Budget
  - *Knowledge of C/N0 and estimate of receiver noise temperature gives an estimate of the RX power, R_p*
  - *Estimate or calculate the RX antenna gain , Ar, the space loss, Ad, the GPS transmit power, Psv, and other losses, As and Lr, to find the TX antenna gain, At*
- Smoothing
  - *Binned and averaged data is noisy using a moving window filter*
- Normalizing
  - *The patterns are matched to ground measured data*



$$A_t(\theta,\varphi) = {}^{C}/_{N_0} - N_0 - A_r + L_r + A_s - P_{sv} - A_d$$

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GPS ACE Applications

- GPS ACE Data
  - *Mission design/requirements verification*
    - Confidence in predicted signal availability and performance
  - *Mission operations / satellite selection augmentation*
    - Improved operational navigation efficiency and accuracy
- GPS ACE System/Concept
  - *SSV monitoring*
    - Continuous monitoring of signal performance, including new launches
  - *GPS III antenna pattern verification*
    - Comparison to requirements

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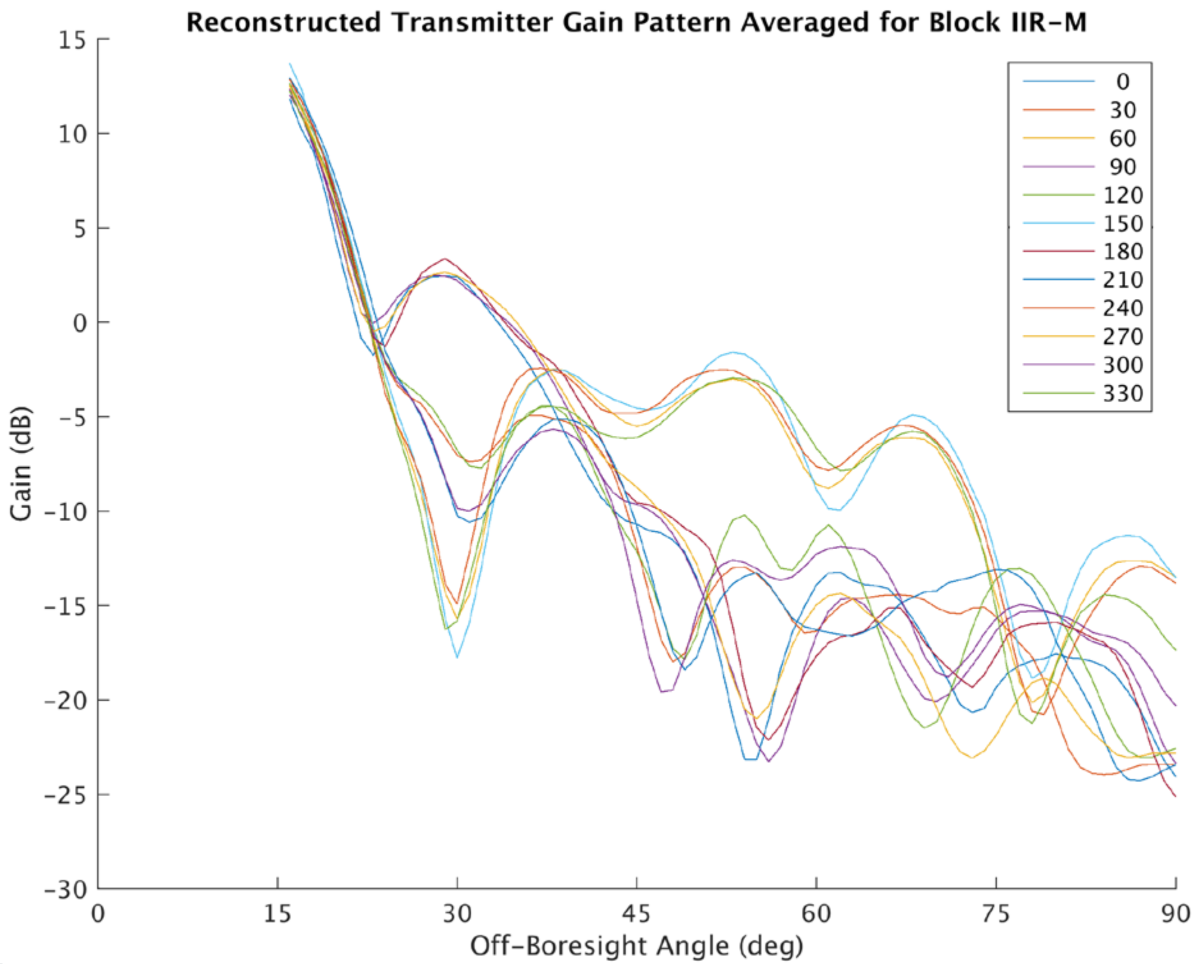
Azimuth Cuts for Blocks IIR & IIR-M



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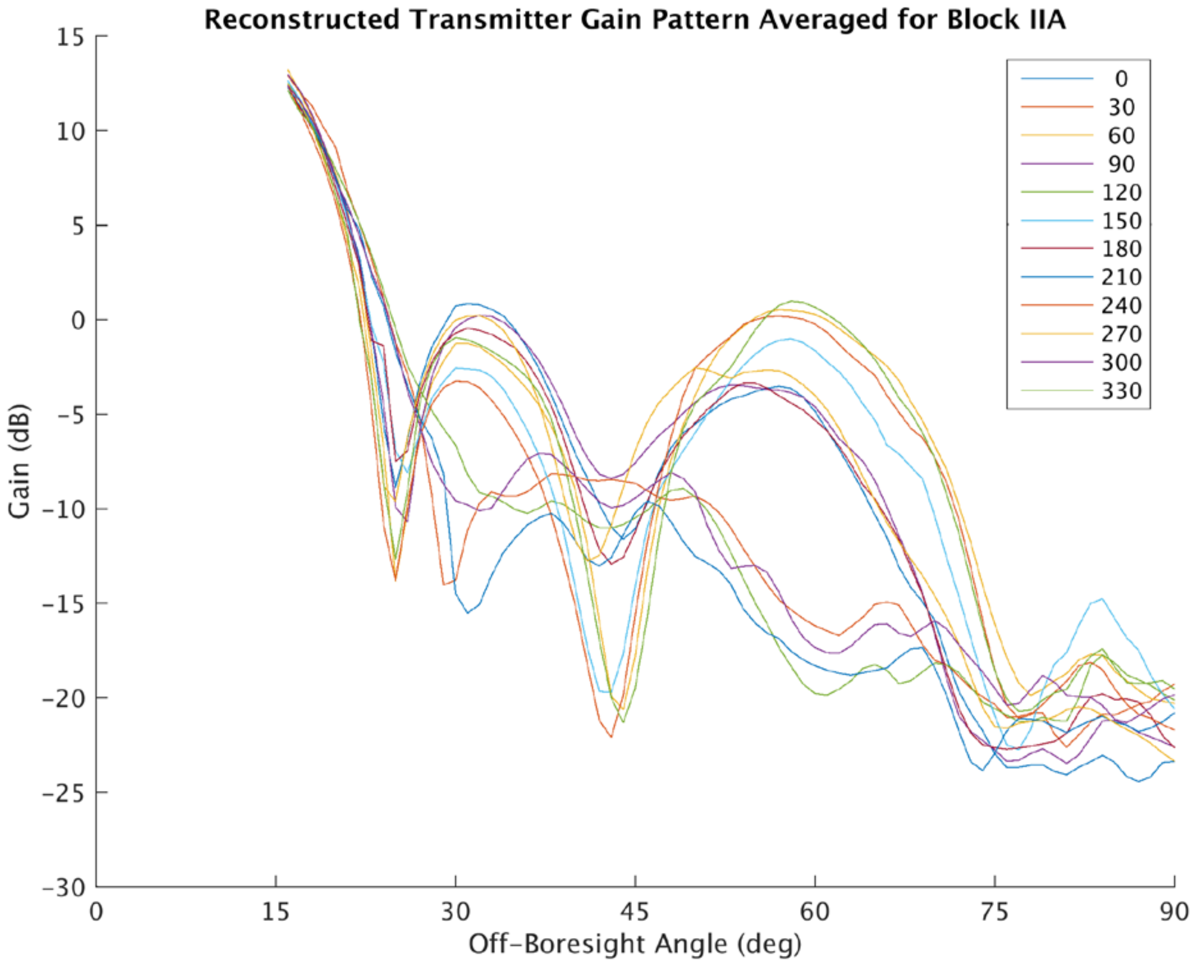
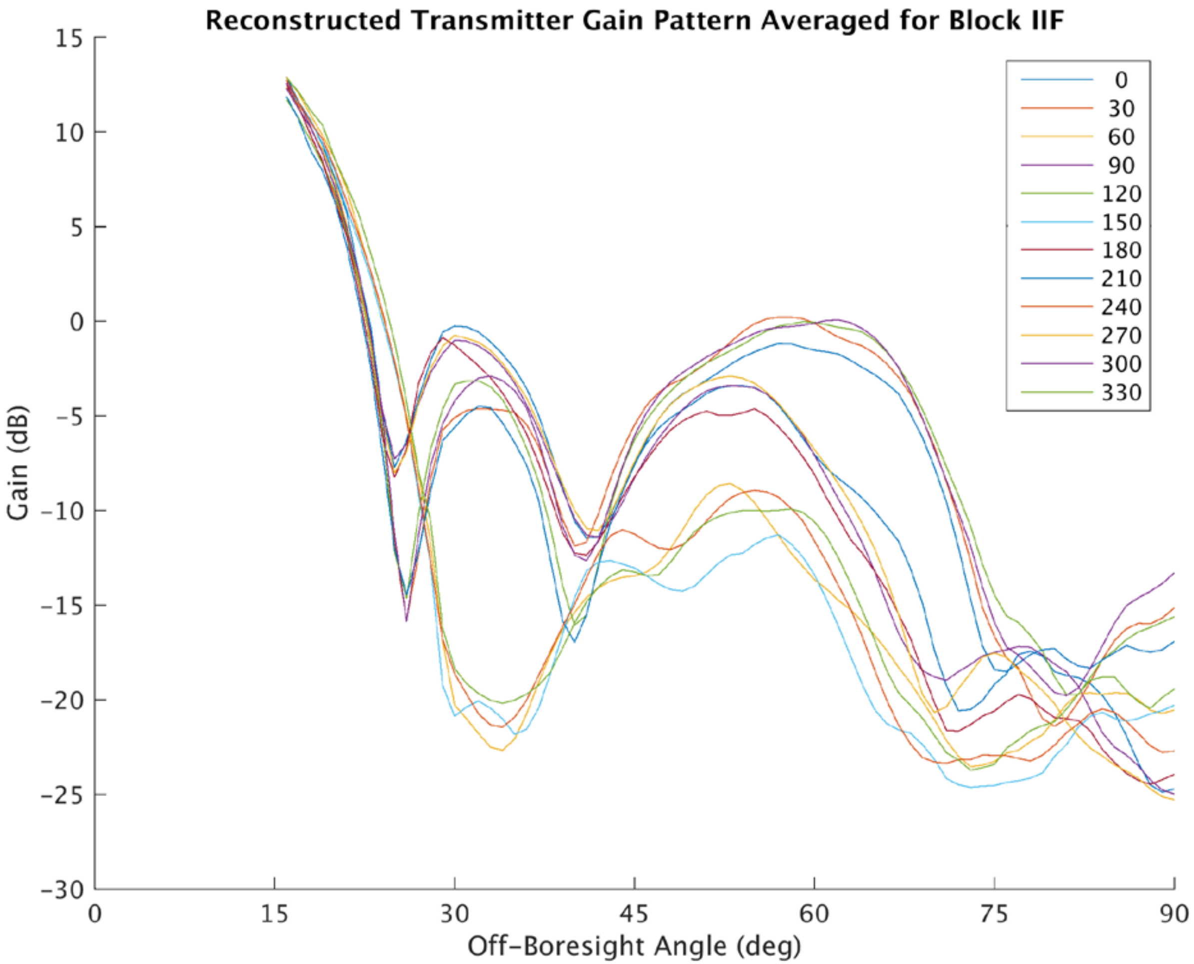
Azimuth Cuts for Blocks IIA & IIF





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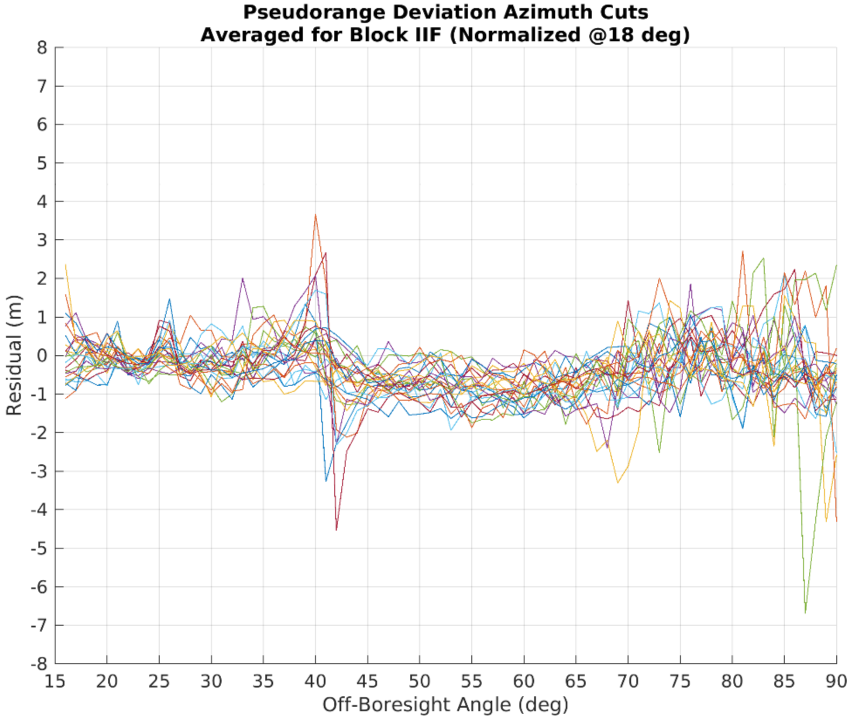
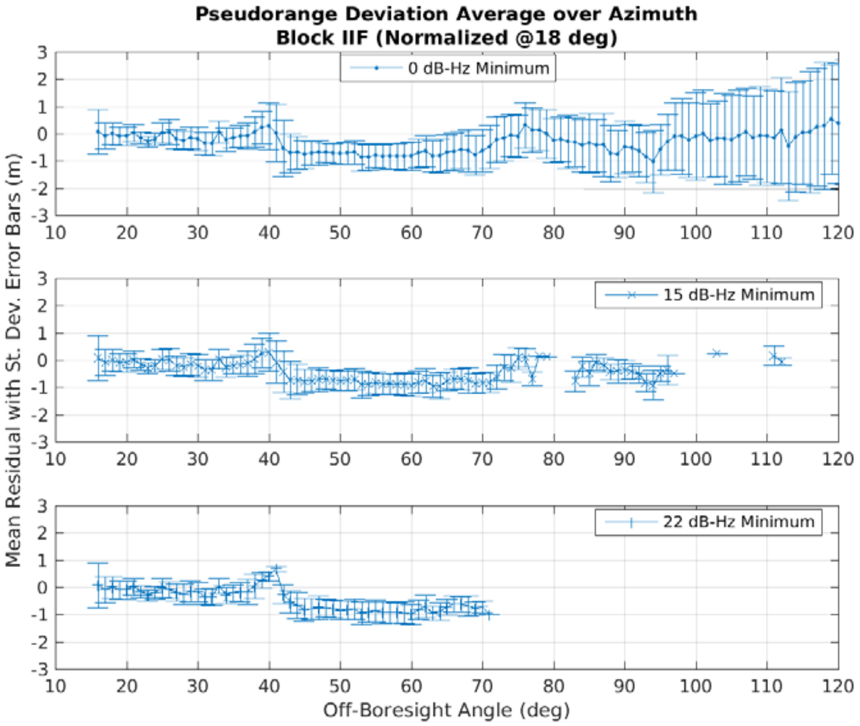
Pseudorange Deviation vs. GPS Off-Boresight Angle

Block IIF Results

- Azimuth cuts every 15 deg show variation, but reflect general trend to small negative bias in side lobes
- Average at each elevation across all azimuths
- Consistent behavior a different minimum signal levels





- Side lobe pseudoranges show small biases and predictable noise
- Clearly useful for high altitude space missions