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The Cost of Accuracy

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Overview

- Discussion of accuracy versus life cycle costs

- Case studies
  - Gain methods
  - A very accurate positioner
  - Fast NF measurements to meet throughput
  - Stray signal suppression

- Summary

Defining Accuracy

- Test Article requirements lead to metrics, which lead to data collection.
- Our industry standards [1] [2] [3] define “accuracy” as a “level of uncertainty”.
- For every metric, there are associated error sources that must be quantified and/or estimated.
- The metric uncertainty is a composite of the uncertainty of the individual error sources.
- The user tolerance for the metric impacts the cost of achieving that level of uncertainty.

Test Article Life Cycle

- The life cycle of a product can generally be divided into phases:

  - Development
  - Qualification
  - Production
  - Repair

- The testing needs in each stage of the life cycle will probably differ and have different cost impacts.

Measurement System Costs

- Initial purchase/development cost
  - Higher precision to reduce random errors costs more money
- Overhead costs
  - Facilities
  - Labor
- Periodic calibration for systematic errors
  - Cost of internal/external calibration lab
  - Calibration may be done by users
- Real time correction for systematic errors will increase system costs
- Multiple measurements mean longer range time
- Post-processing to improve accuracy usually means longer range time

Case Study 1 – Gain Methods [6]

Problem Statement

- The National Laboratories have set the standards for gain measurement accuracy
- Published NIST accuracies:
    - 3 Antenna NF Extrapolation Range (Gain only)
        - Antennas < 1 m, < 50 kg.
        - 2 – 30 GHz, +/- 0.1 dB
        - > 30 GHz, +/- 0.15 dB
    - Near Field Measurements (Gain & Patterns)
        - Antennas < 3 m
        - 2 – 75 GHz, +/- 0.2 dB
    - Measurement campaigns require from 1 to 3 weeks of testing or more
- Question:
        - How much effort is required to achieve a desired accuracy?
    - or
        - Given the measurement objective (prototype validation, production QA, repair evaluation, etc.), how accurate can the measurement be in the time allotted?

Common Gain Measurement Techniques

- Absolute Methods
  - Far Field 3 antenna method
  - Near-Field 3 antenna method with extrapolation
  - Directivity Measurement with ohmic loss measured by other means

- Transfer Methods
  - Near-Field with gain insertion loss measurements
  - Far Field measurement against a gain standard
  - Near-Field measurement against a gain standard

Categories of Error Mitigation

- Minimal effort
  - Use equipment as is
  - Measure once

- Moderate effort
  - compensate for some systematic errors based on nominal values
  - Multiple measurements for random errors

- Best practices
  - Measure and compensate for systematic errors
  - More multiple measurements

Some Errors and Mitigation

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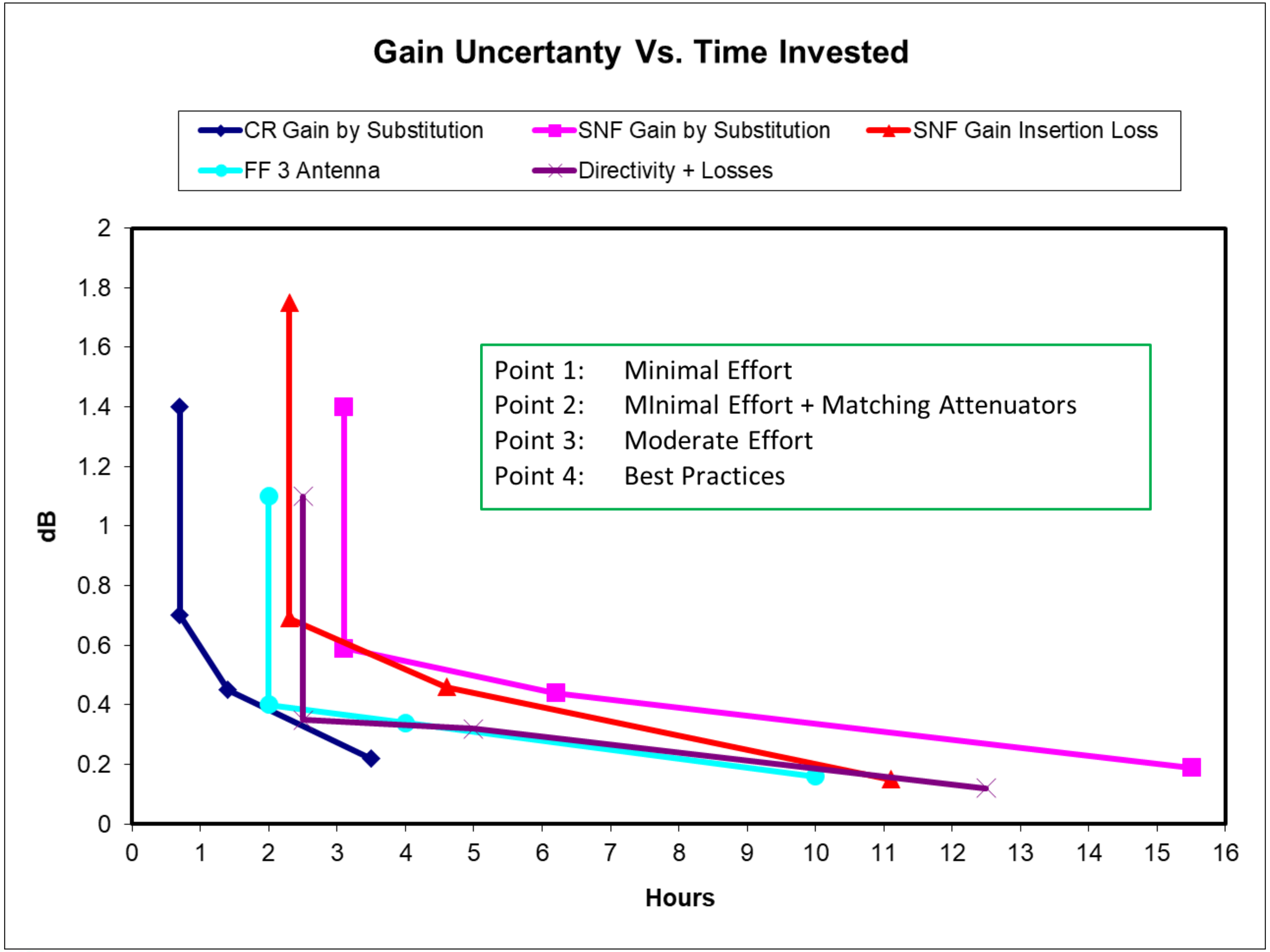
Error	Minimal Effort	Moderate Effort	Best Practices
Gain Standard gain	Accept manufacturer's tolerance	Calibrate on an A2LA certified range	Calibrate at a national standards lab
Absorber thickness	2 wavelengths	5 wavelengths	10 wavelengths
AUT alignment	Perform a plunge and rotate alignment	Plunge and rotate and small raster scan	Perform moderate effort multiple times
VSWR/Mutual Coupling	Connect antennas to the system	Add matching attenuators at each antenna port	Measure antenna and measurement system reflection coefficients and compensate
FF/CATR QZ taper	Do nothing	Adjust by nominal taper	Adjust with field probe data
NF probe pattern	Do nothing	Probe correction with nominal probe pattern	Probe correction with measured probe pattern
Connection variation	Connect everything 1 time	Connect everything for 2-3 measurements	Connect everything for 5-10 measurements
AUT S/N	Make 1 measurement	Make 2-3 measurements	Make 5-10 measurements
Polarization mismatch	Perform 1 polarization scan of the AUT for alignment	Perform multiple polarization scans and correct for range antenna nominal axial ratio	Perform multiple polarization scans and correct for range antenna measured axial ratio

Test Case

- AUT measured as a “golden” antenna
  - 24” spun aluminum reflector
  - prime focus feed, feed cover not shown
  - 26.5 – 40 GHz
  - lossy components
    - WCA
    - cable from WCA to back of reflector
    - 2.9 mm bulkhead connector
  - “catalog” gain ≈ 40 dBi
- Measured with multiple modes and mitigation levels at NSI-MI facilities

Summary of Error Estimates and Measurement Times

	Minimal Effort		Minimal Effort + Matching Pads		Moderate Effort		Best Practices	
Gain Method	Est Error (dB)	Time (hours)	Est Error (dB)	Time (hours)	Est Error (dB)	Time (hours)	Est Error (dB)	Time (hours)
Compact Range Gain Tranfser	1.4	0.7	0.7	0.7	0.45	1.4	0.22	3.5
SNF Gain Transfer	1.4	3.1	0.59	3.1	0.44	6.2	0.19	15.5
SNF Gain by Insertion Loss	1.75	2.3	0.69	2.3	0.46	4.6	0.15	11.1
Far Field 3 Antenna	1.1	2	0.4	2	0.34	4	0.16	10
SNF Directivity plus Ohmic Loss Measurement	1.1	2.5	0.35	2.5	0.32	5	0.12	12.5


Gain Uncertanty Vs. Time Invested
CR Gain by Substitution
SNF Gain by Substitution
SNF Gain Insertion Loss
FF 3 Antenna
Directivity + Losses
Point 1: Minimal Effort
Point 2: MInimal Effort + Matching Attenuators
Point 3: Moderate Effort
Point 4: Best Practices
dB
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16
Hours

Case Study 2 – A Very Accurate Positioner [7]

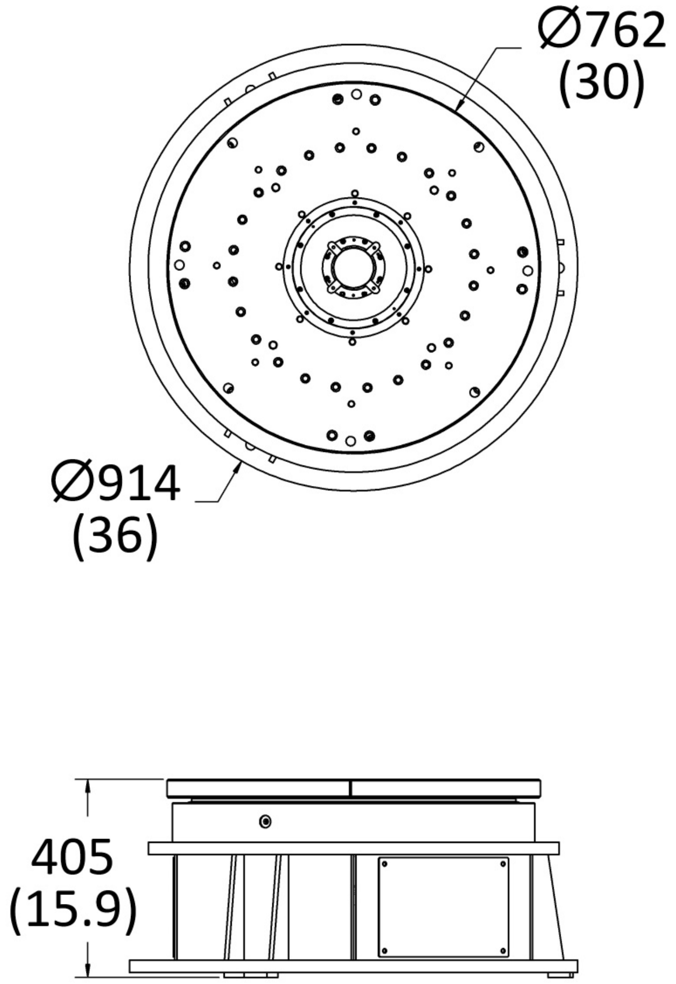
Problem Statement

- An azimuth rotator is needed to support and move a test article.
- The calibration process of the test article requires that the position of the test article must be known to a very tight tolerance.
- The rotator and the test article will be surveyed in the test area with a tracking laser.
- The requirement allocated to the azimuth rotator is that the absolute position of the rotator, within its own frame of reference, must be known within 0.004 degrees RMS.

- Solution: Increase the inherent accuracy for random errors and employ calibration to reduce systematic errors.

Standard Positioner

- For size, loading, maximum speed and other factors, the selected positioner was the NSI-MI MEC-AZ-80.
  - 76 cm turntable
  - 14,000 kg. vertical load capacity
  - 0.5 RPM maximum speed
  - Servo motor drive through right angle gear box
  - Dual speed synchro sensor standard
  - Anti-Backlash Gear included



Error Factors for Absolute Position

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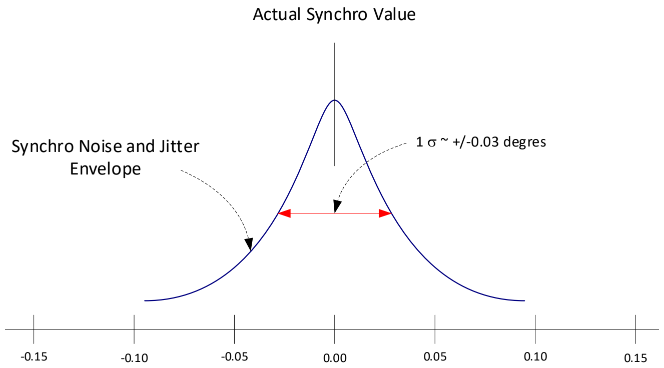
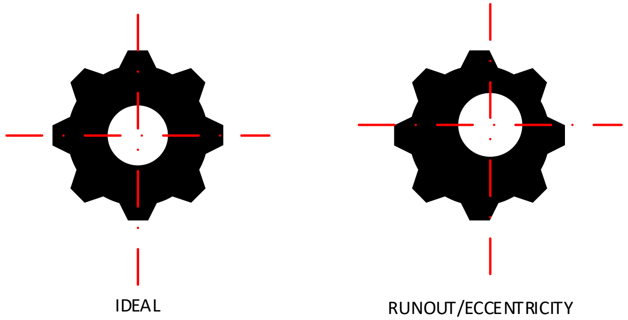
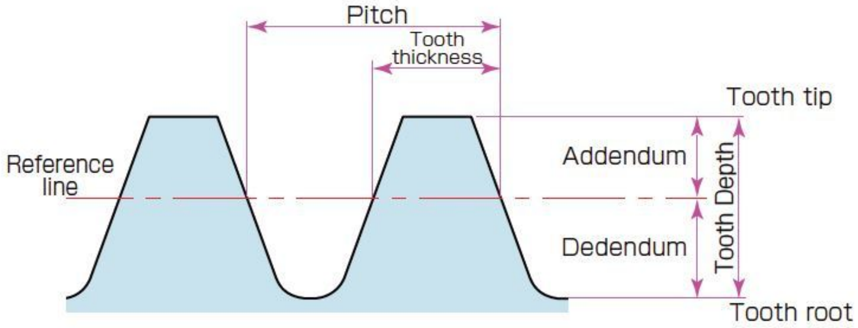
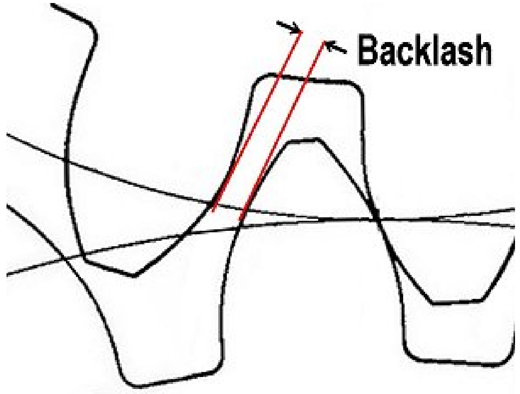
- Sensor
  - Inherent accuracy
  - Sensor radial runout
- Bearing
  - Radial runout
  - Gear tooth tolerance
- Gear Train
  - Radial runout
  - Gear tooth tolerance
- Gear Train & Bearing
  - Backlash









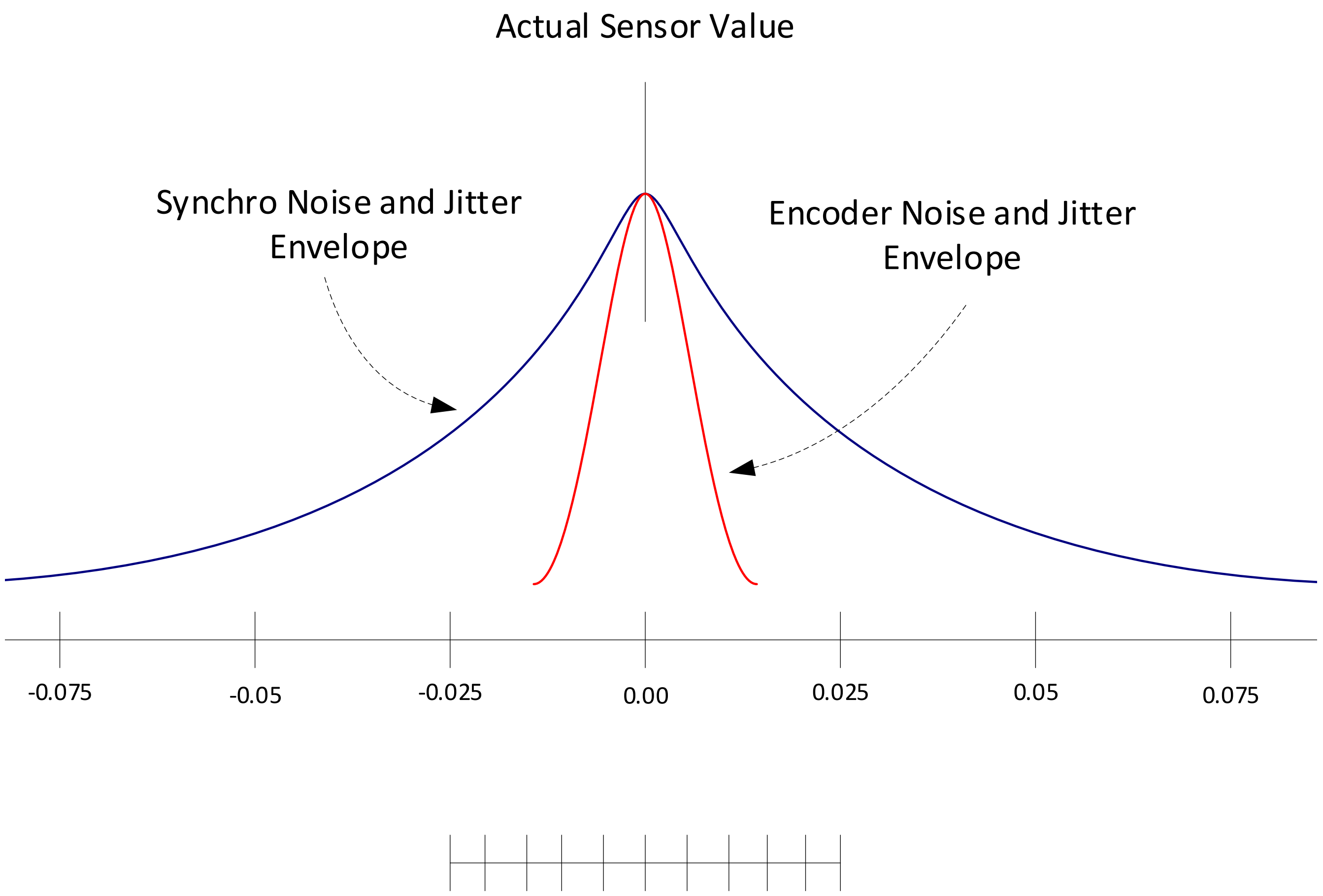
Absolute Position Error Model (Standard Positioner)

Individual Error	Error Type	Error ° peak	Error ° rms
Sensor Accuracy	random	0.05000	0.03536
Backlash	random	0.08000	0.05657
Bearing Radial Runout	systematic	0.00280	0.00198
Gear Train Radial Runout	systematic	0.00170	0.00120
Sensor Radial Runout	systematic	0.00200	0.00141
Bearing Gear Tolerance	systematic	0.00370	0.00262
Gear Train Tolerance	systematic	0.00250	0.00177
		RSS	0.06684

Error is 16X the required error

Improving Sensor Accuracy

- Replace dual speed synchros with an incremental encoder
- Inherent accuracy improves from 0.05 degrees to 0.002 degrees
- Standard option for the positioner
  - No developmental costs
  - Increased cost for the positioner
- Reduces composite error to 0.0567 degrees RMS

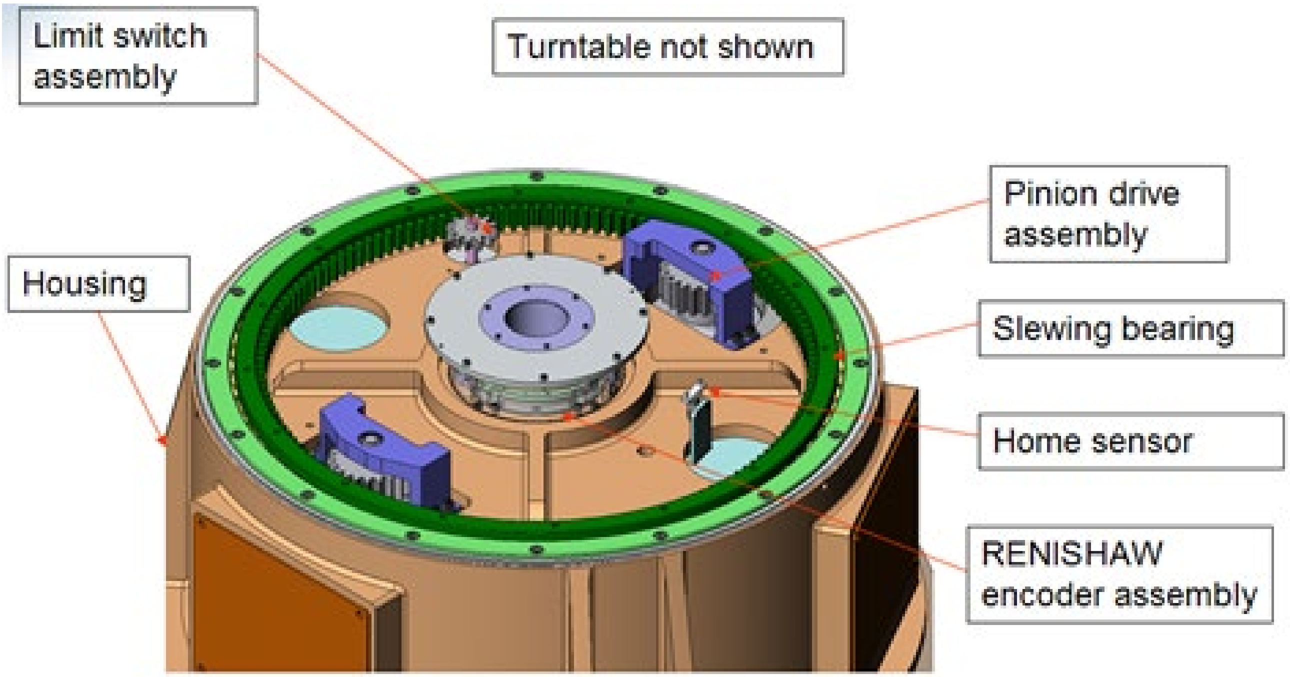


Removing Backlash

- Dual Drive Torque Bias is a well-known technique for removing backlash.
- Two motors are placed on opposite sides of the bearing. They are always driven in opposite directions with a slight difference to keep the gear teeth engaged.
- In-line gearbox instead of right-angle gearbox
- Equivalent to a limited slip differential in an automobile.

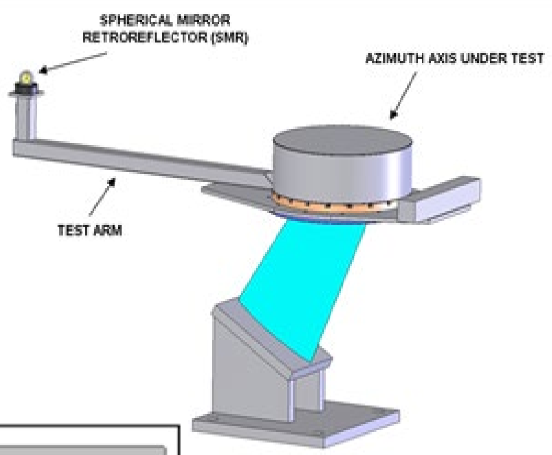
- Development cost and increased hardware cost.

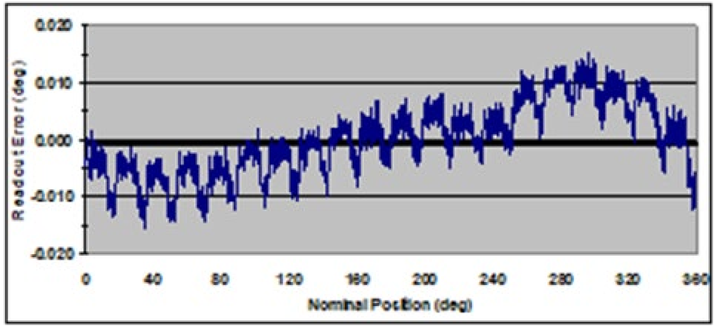
- Reduces composite error to 0.0044 degrees RMS.

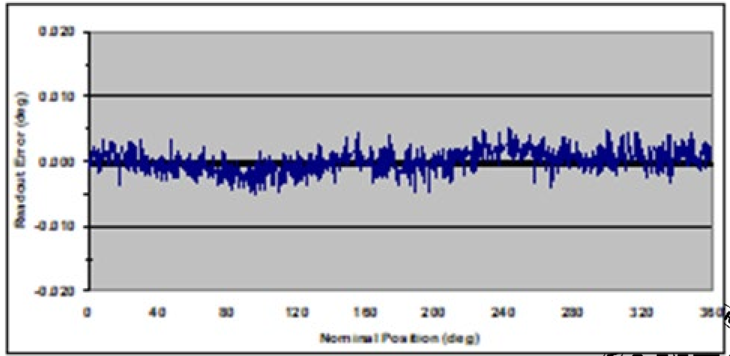


Removing Systematic Errors

- Use a tracking laser to measure the systematic runout and tolerance errors. Multiple runs in both directions are averaged. The error map is loaded into the positioner controller to correct for these errors when in use.
- No developmental cost or hardware cost.
- Initial calibration cost in manufacture.
- Periodic calibration required
    - Tracking laser must be owned or rented.
    - Tracking laser error must now be included in the error budget.
    - Procedure removes the positioner (range) from operation for 0.5 days for a laser check of the current calibration, 1 day for a re-calibration and verification.
- Reduces composite error to 0.00288 degrees RMS.







Results

- Costs are normalized to the cost of the standard positioner.
- Initial hardware cost is 2.7 times the standard cost
- Recurring calibration cost is 0.45 of the standard positioner cost over a 5-year period.

Condition or Improvement	Composite Error (° rms)	Standard Cost	Additional Engineering Cost	Additional Hardware Cost	Verification Cost	Calibration Cost	Total Cost
Standard	0.06684	1.00	0.00	0.00	0.00	0.00	1.00
Add Encoder	0.05672	1.00	0.00	0.10	0.00	0.00	1.10
Torque Bias Drive	0.00440	1.00	1.00	0.70	0.00	0.00	2.70
Laser Correction	0.00288	0.00	0.00	0.00	0.15	0.30	0.45

Case Study 3 – Sacrificing Accuracy for Throughput [8]

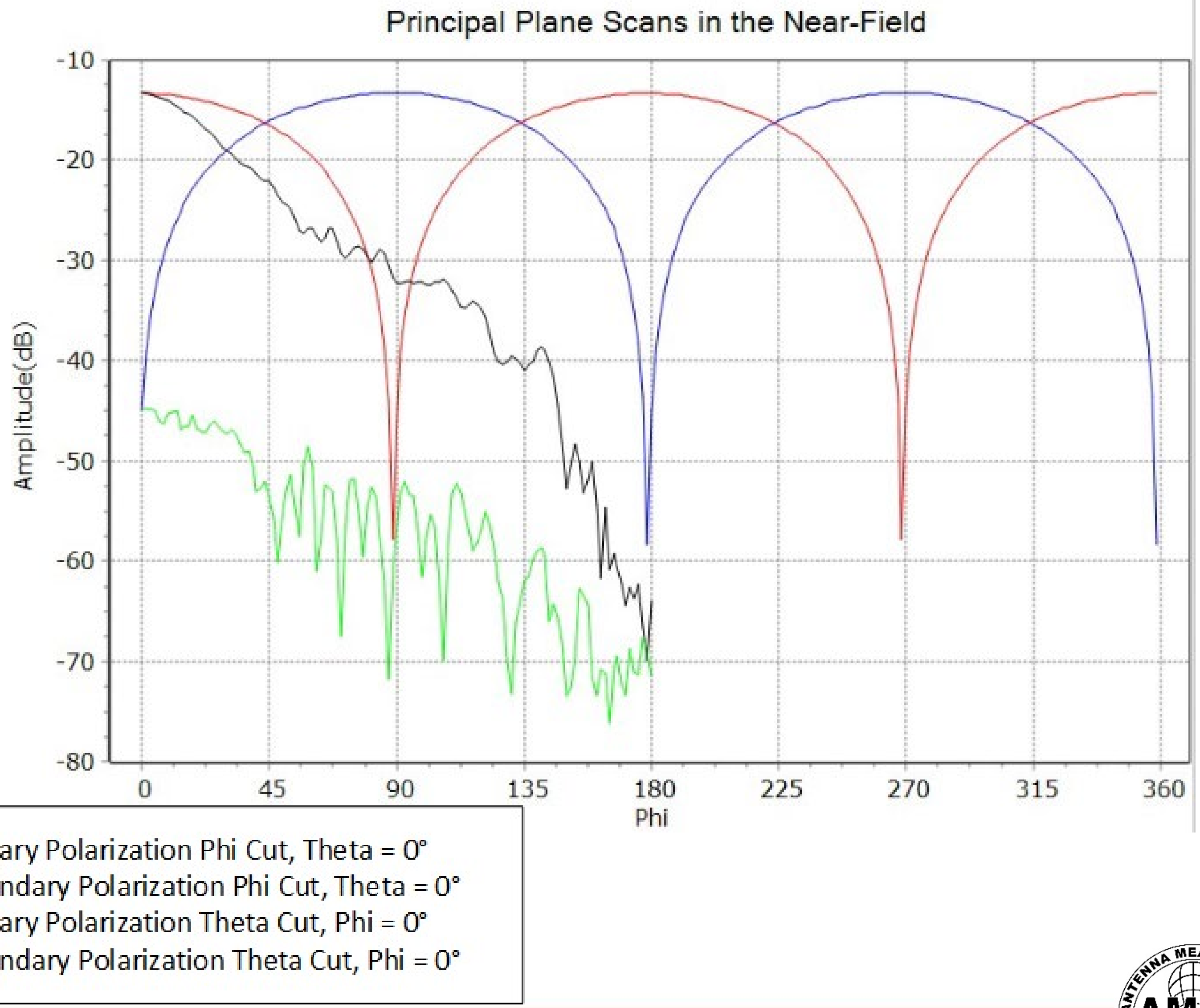
Problem Statement

- This is a case of fitting the testing into the allotted time.
- Production testing of an antenna with an allocated measurement time of one hour.
- The existing range is a spherical near-field range.
- A standard spherical near-field pattern for this antenna on this range requires 3 hours to perform. This pattern provides the qualification testing uncertainty for the antenna.
- An alternate range or building a new range is not an option.
- Functionality after manufacture is more important than specific metrics.

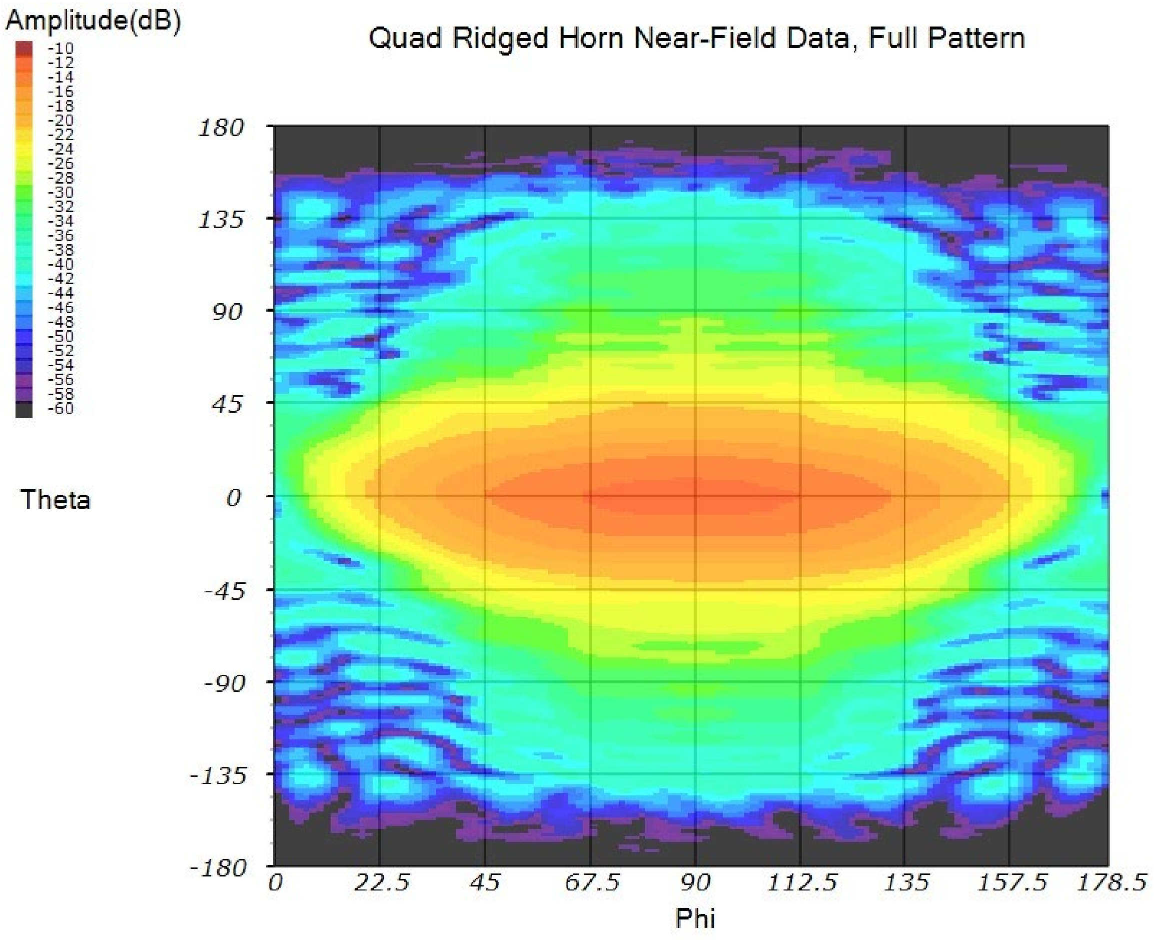
- Solution: Very sparse spherical data collection at a reduced accuracy.

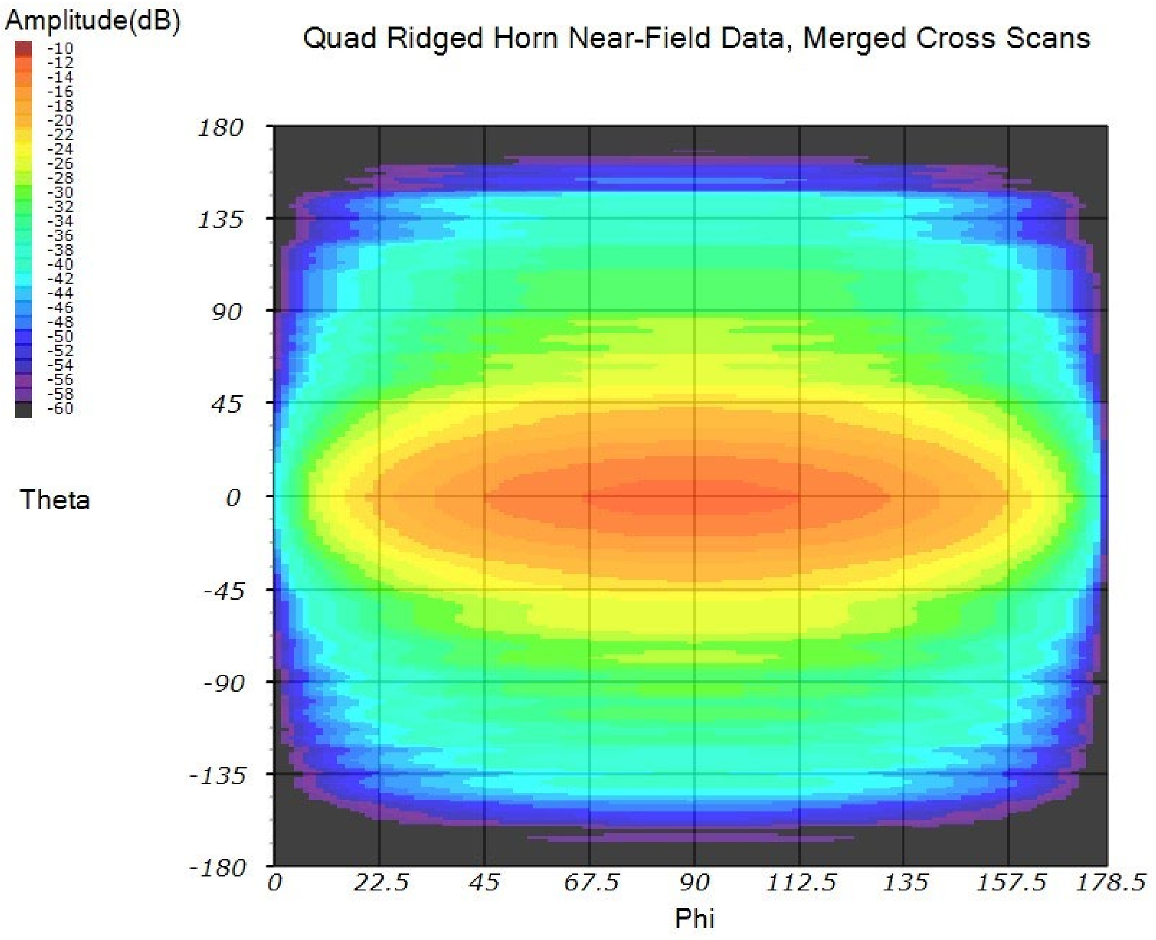
Sparse SNF Data Collection

- If principal plane scans are collected in the near-field, they can be extrapolated to a full 3D near-field pattern that can then be processed with standard SNF transforms.
- If the standard SNF pattern requires 120 scans to cover the sphere, this technique reduces data collection time by a factor of 60.
- These scans can be collected with over-sampling at little cost in time.
- Test Case: Symmetric aperture quad-ridged horn

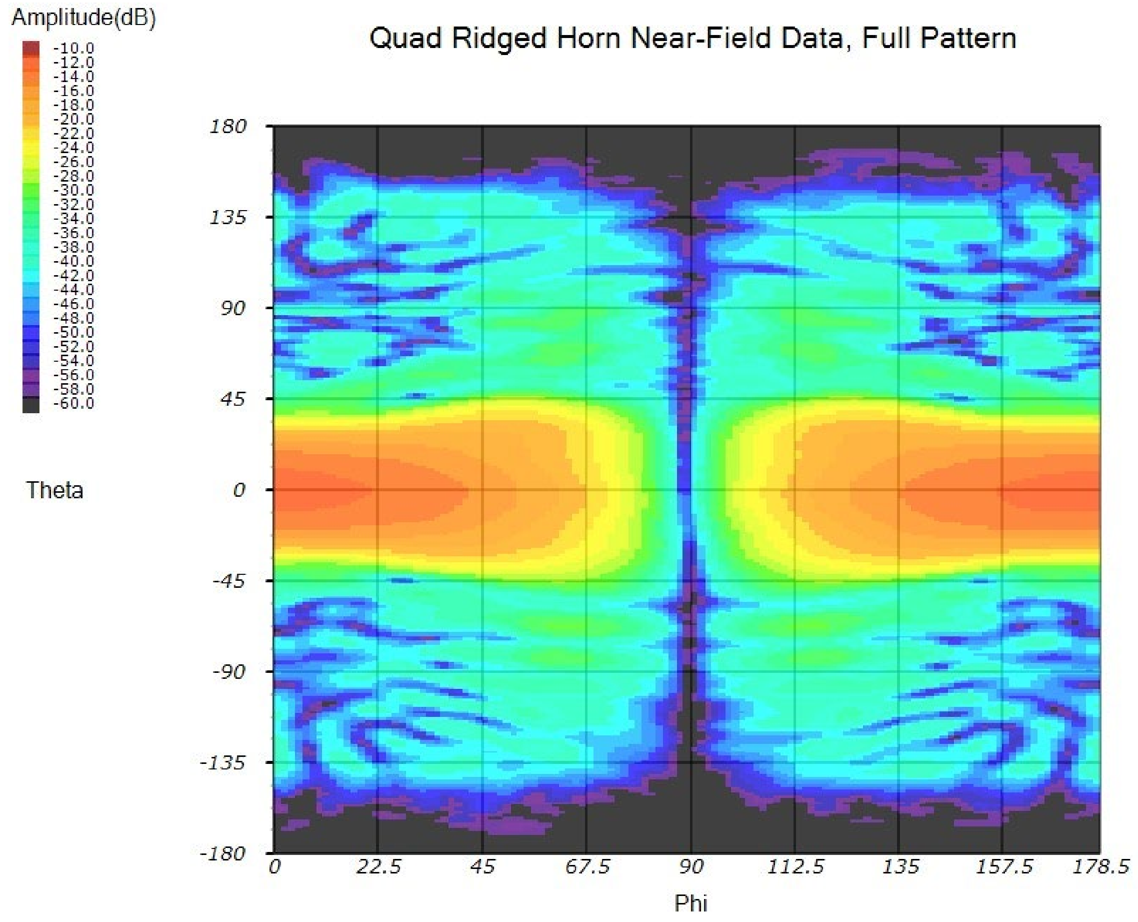


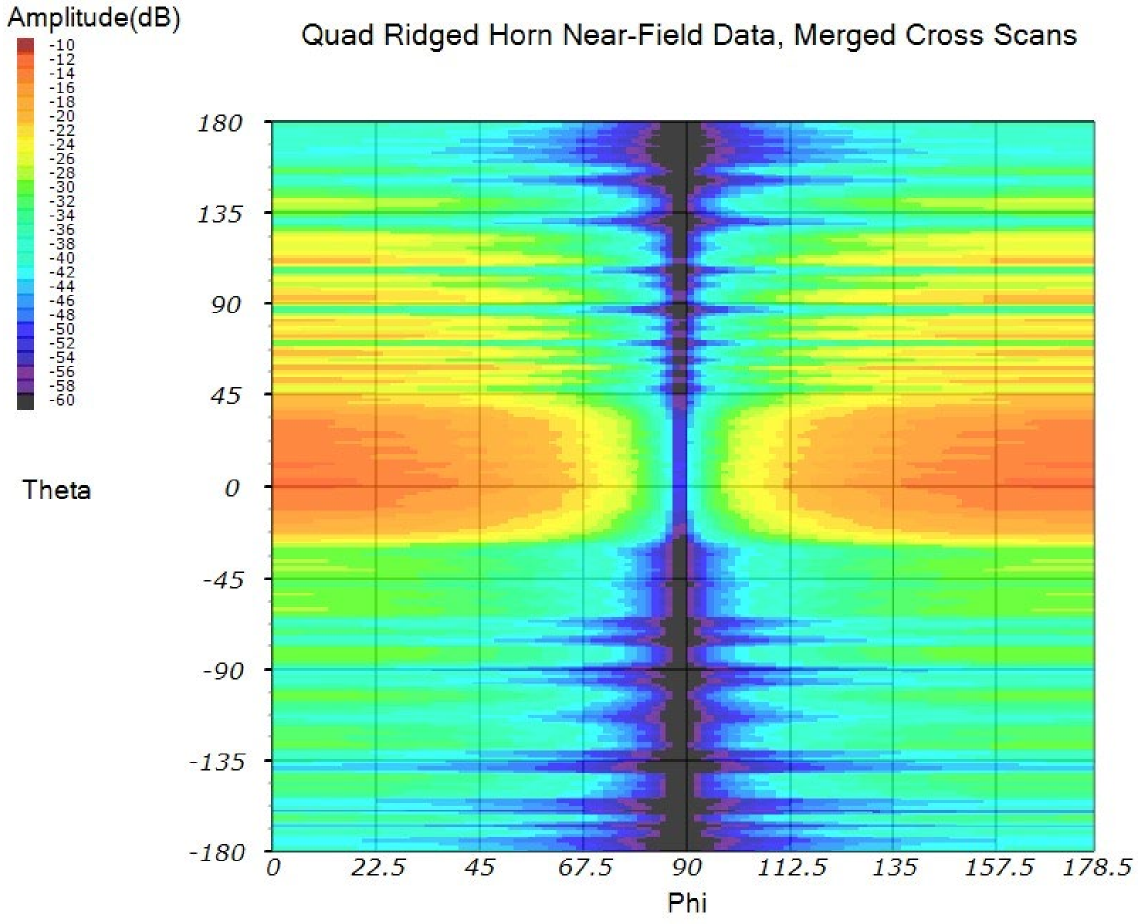
Near-Field Primary Polarization Data





Near-Field Secondary Polarization Data





Transformed Primary Polarization Data

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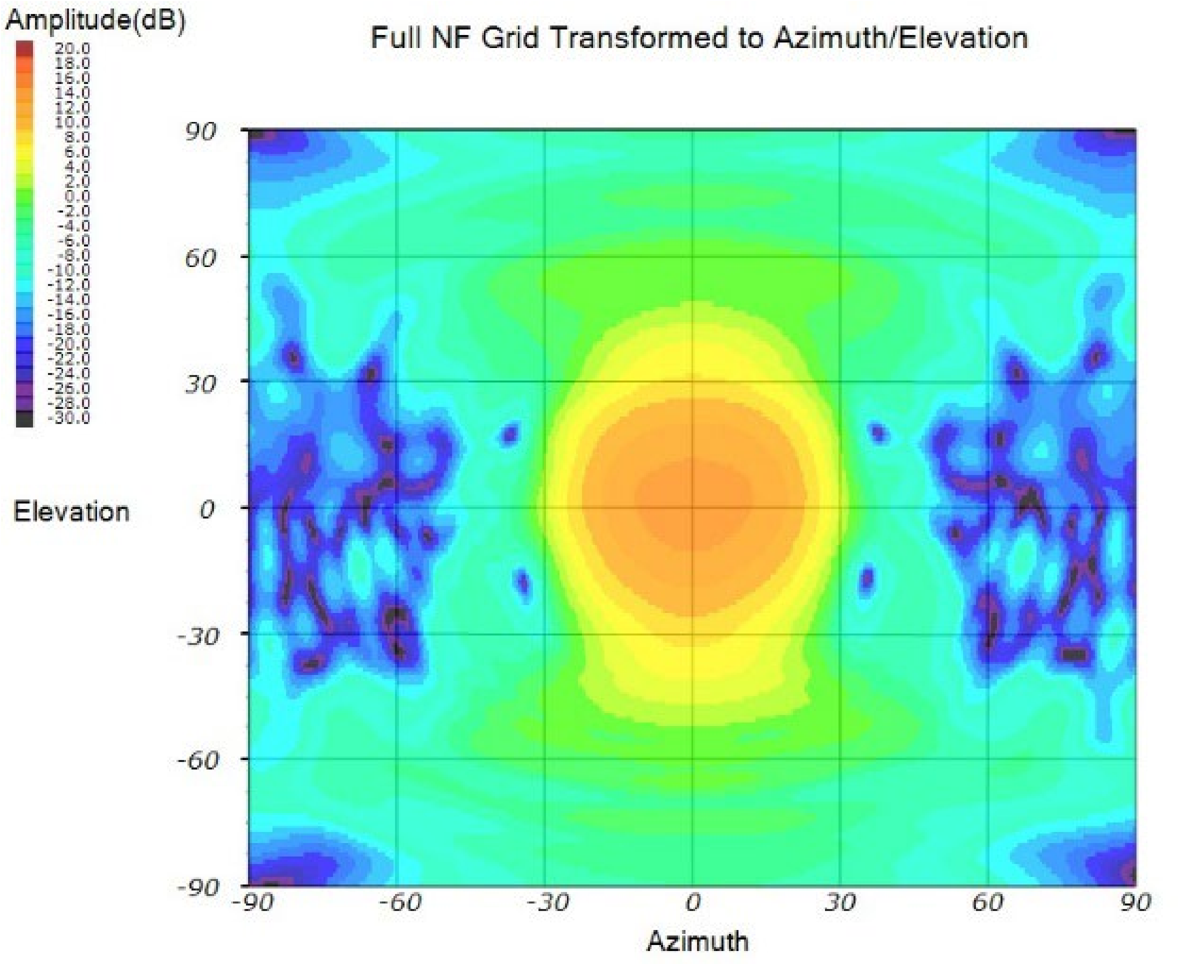
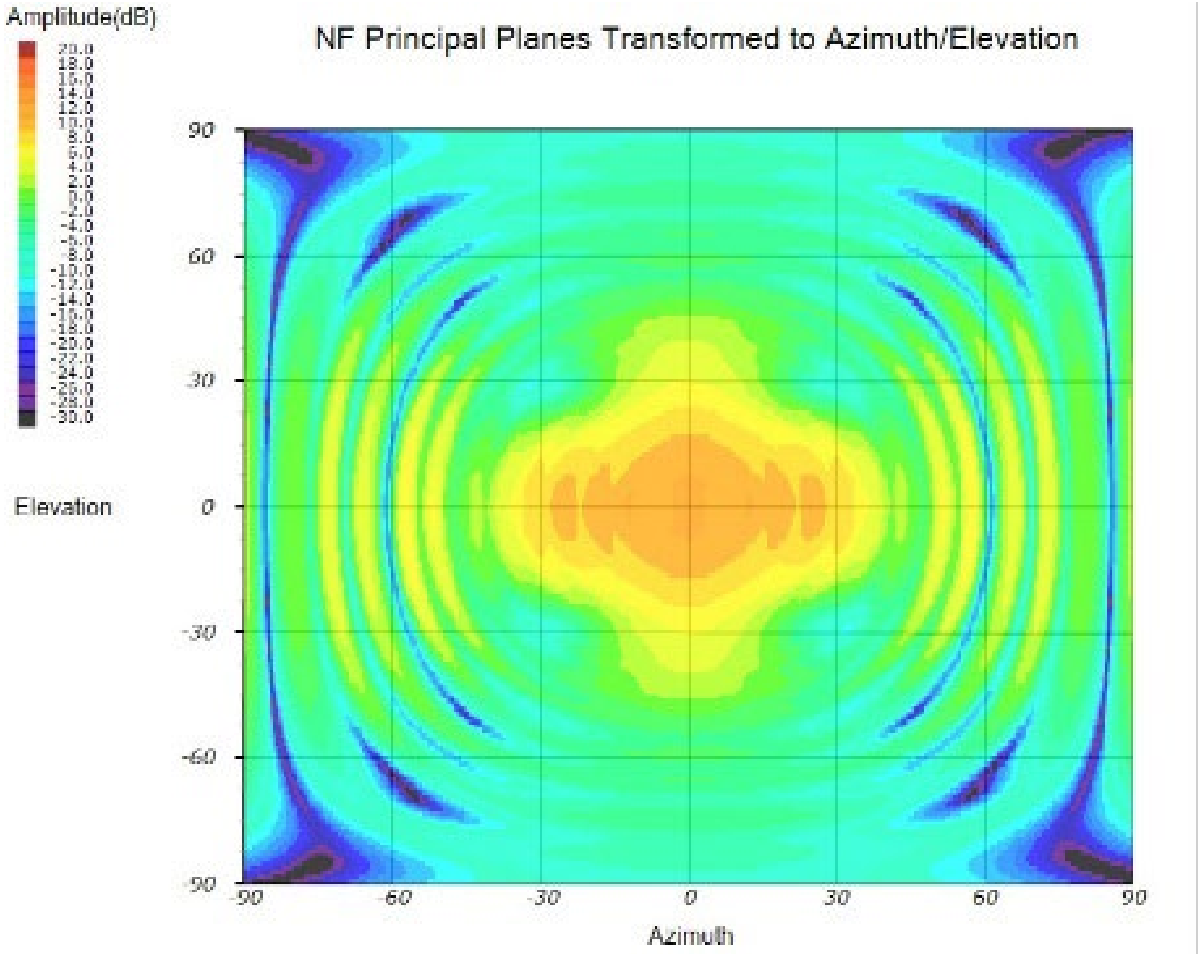
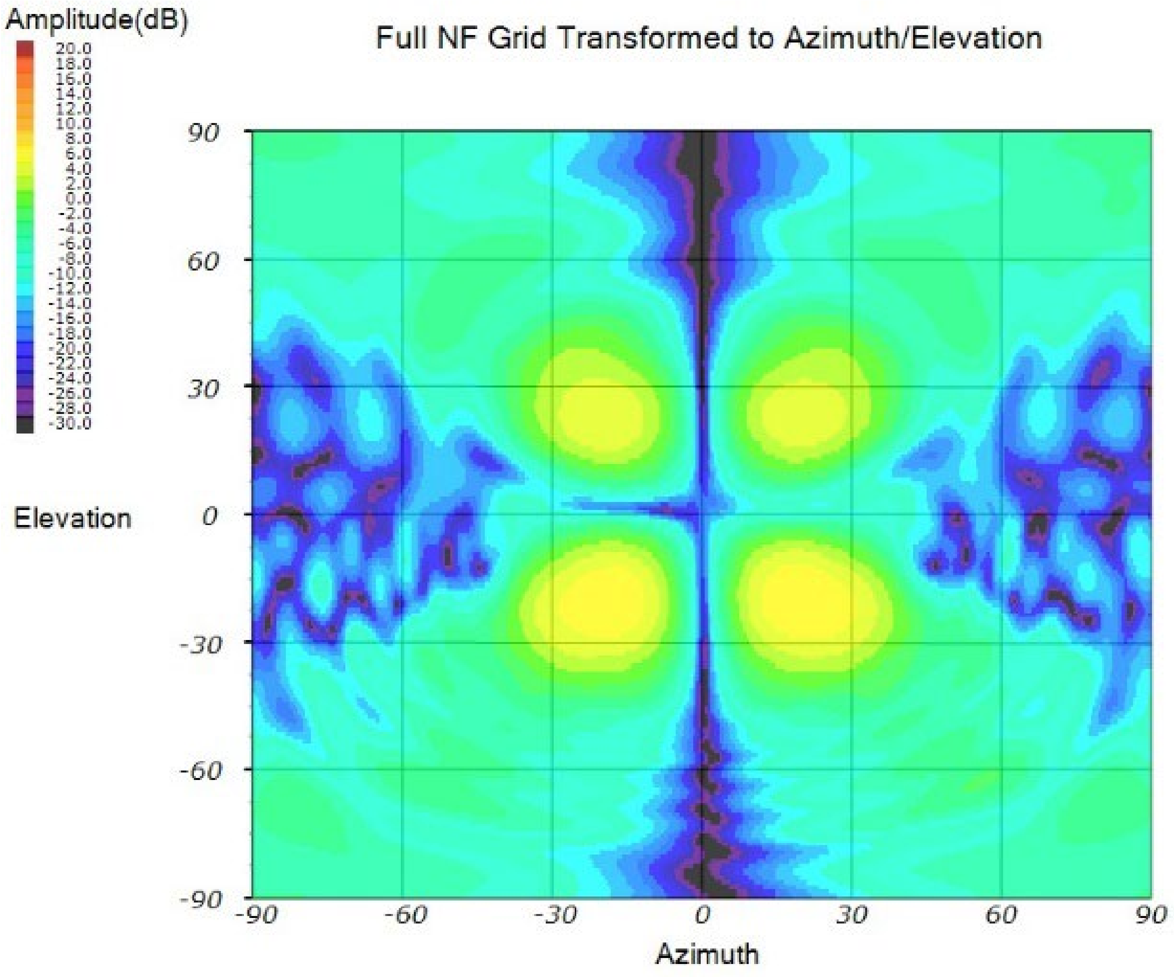
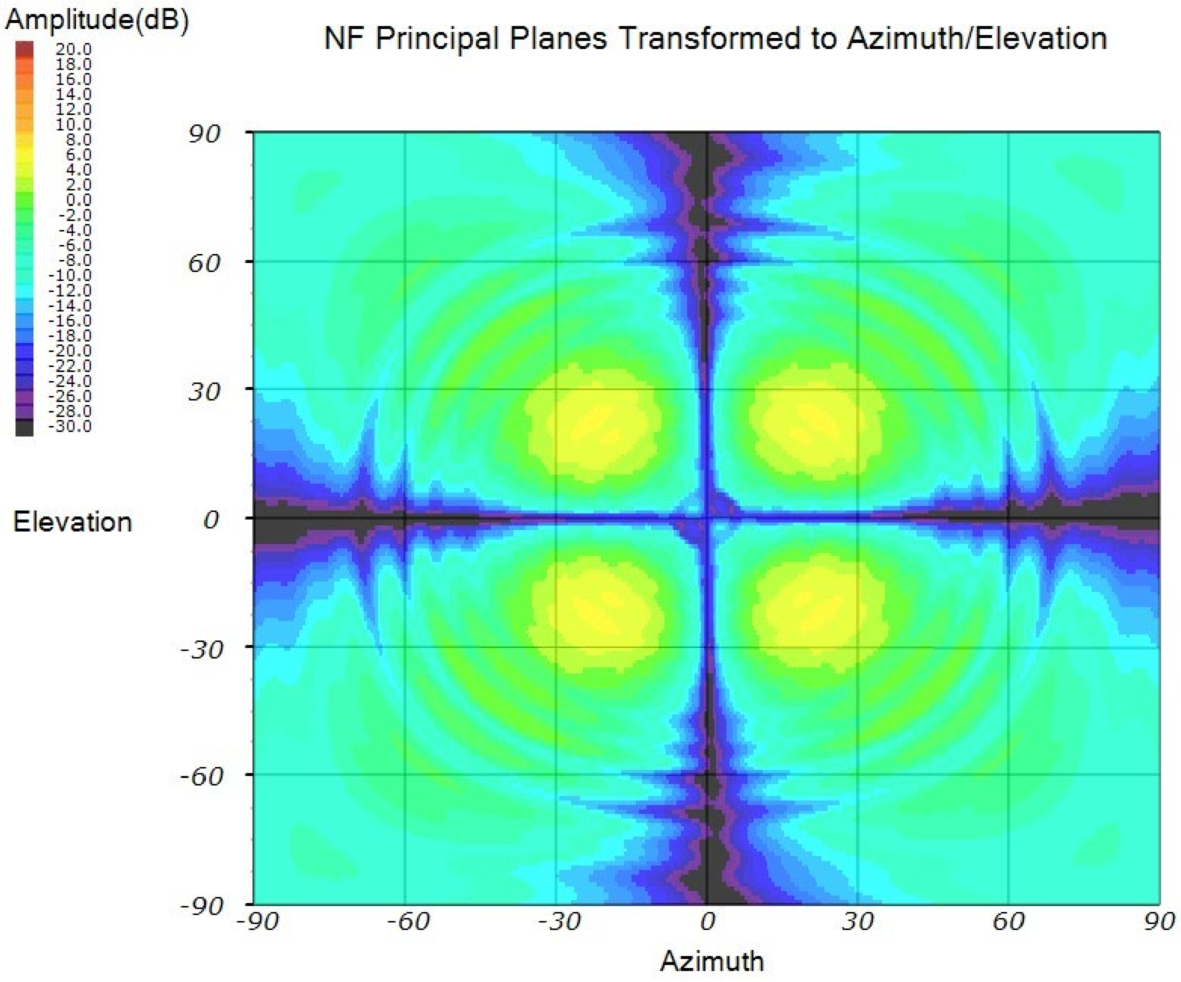




Transformed Secondary Polarization Data





Sparse SNF Data Collection

- The symmetry in the extrapolation:
  - Will always lower the directivity.
  - In the test case, the directivity dropped from 13.2 dBi to 11.7 dBi, a difference of 1.5 dB
  - Alters side lobe structure.

- Data throughput advantage is 60:1 for the test case. Different antennas and frequencies will affect the ratio.

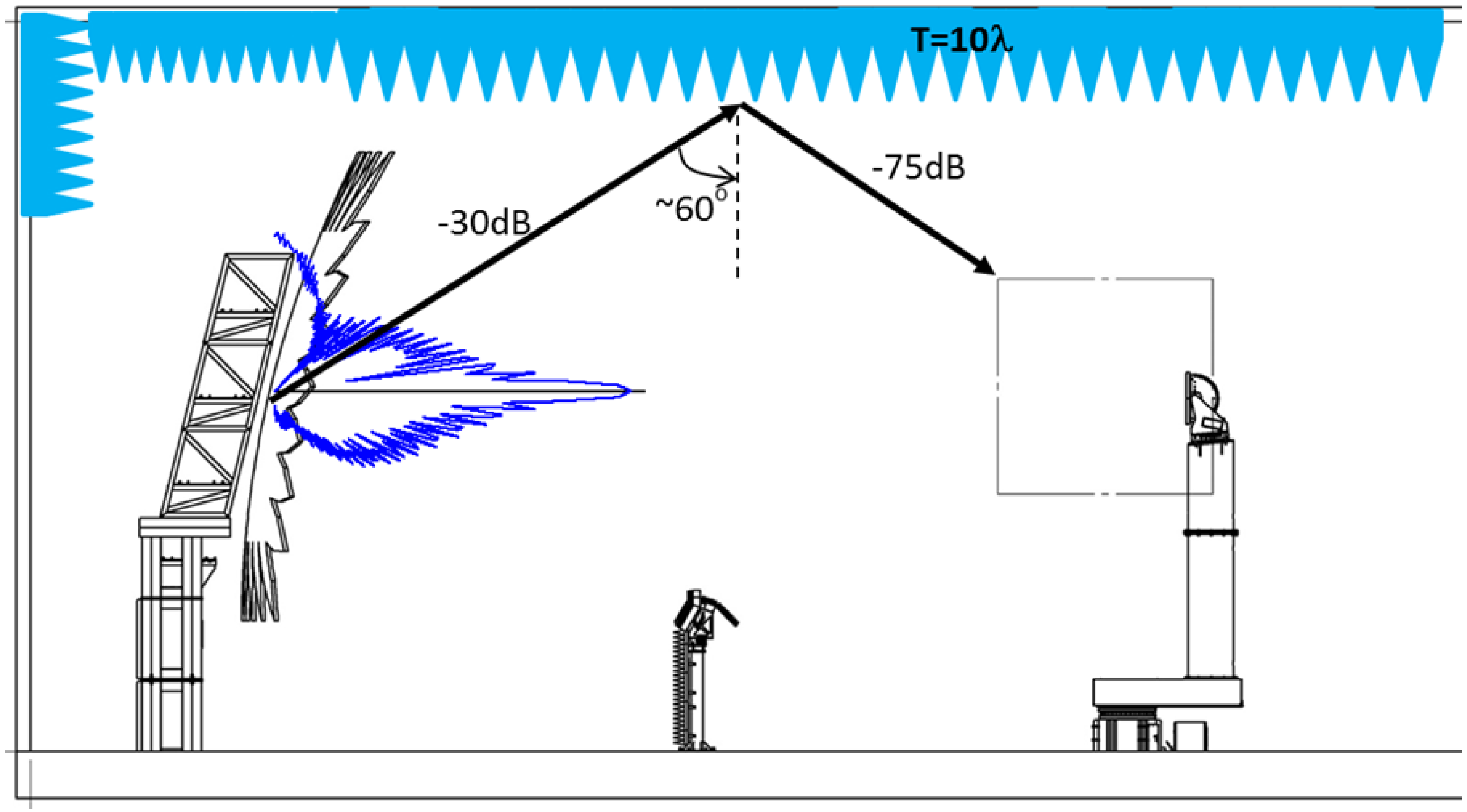
- This technique works for PNF, CNF and SNF methods.

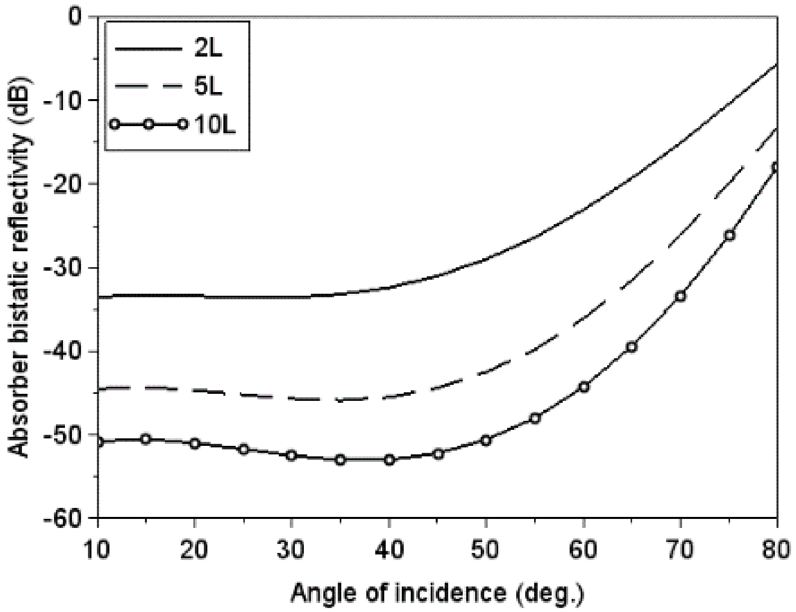
- More sophisticated sparse techniques can approach full measurement accuracy at the cost of more scans.

- Plane Polar sampling in PNF and spiral scanning in CNF/SNF are examples of more sophisticated extrapolation techniques that can improve throughput.

Case Study 4 – Stray Signal Suppression [8]

Stray Signals





Shorter and narrower rooms increase the angle of incidence.
Thinner absorber has less bi-static reflectivity.

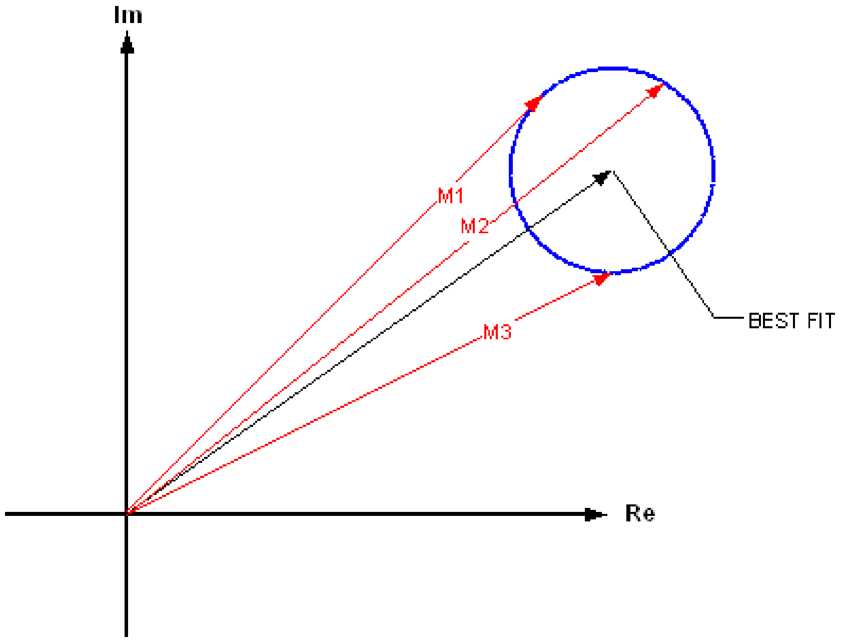
Stray Signals

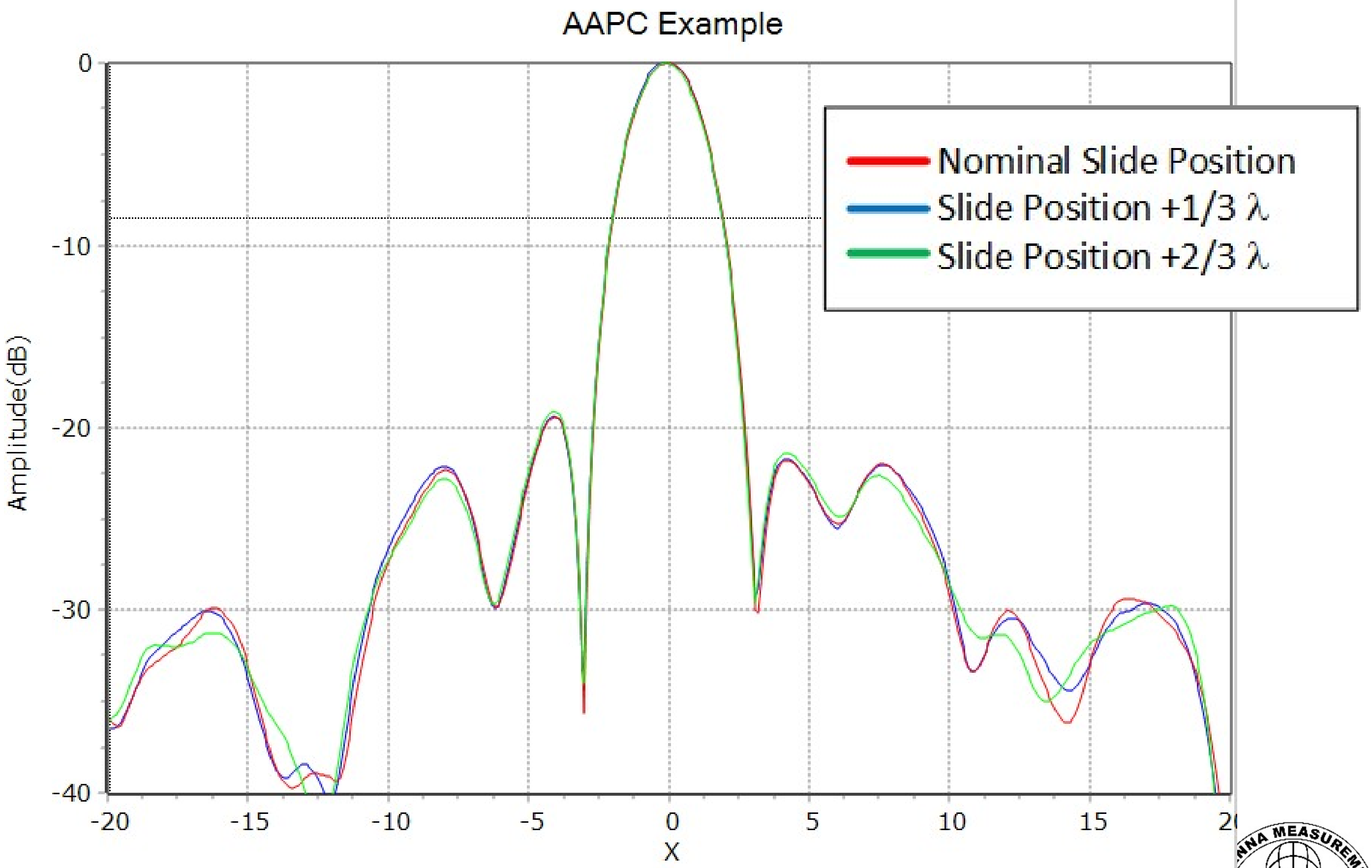
- This is a case of expanding the measurement time to achieve a desired accuracy.

- The Problem: Achieve stray signal levels low enough to meet side lobe measurement uncertainties when the chamber does not provide the stray signal levels required.
- Solutions:
  - Several post-processing techniques have developed over the years.
  - They all involve taking additional data.
  - Advanced Antenna Pattern Correction (AAPC)
  - Time domain gating
  - Mathematical Absorber Reflection Suppression (MARS™)

AAPC

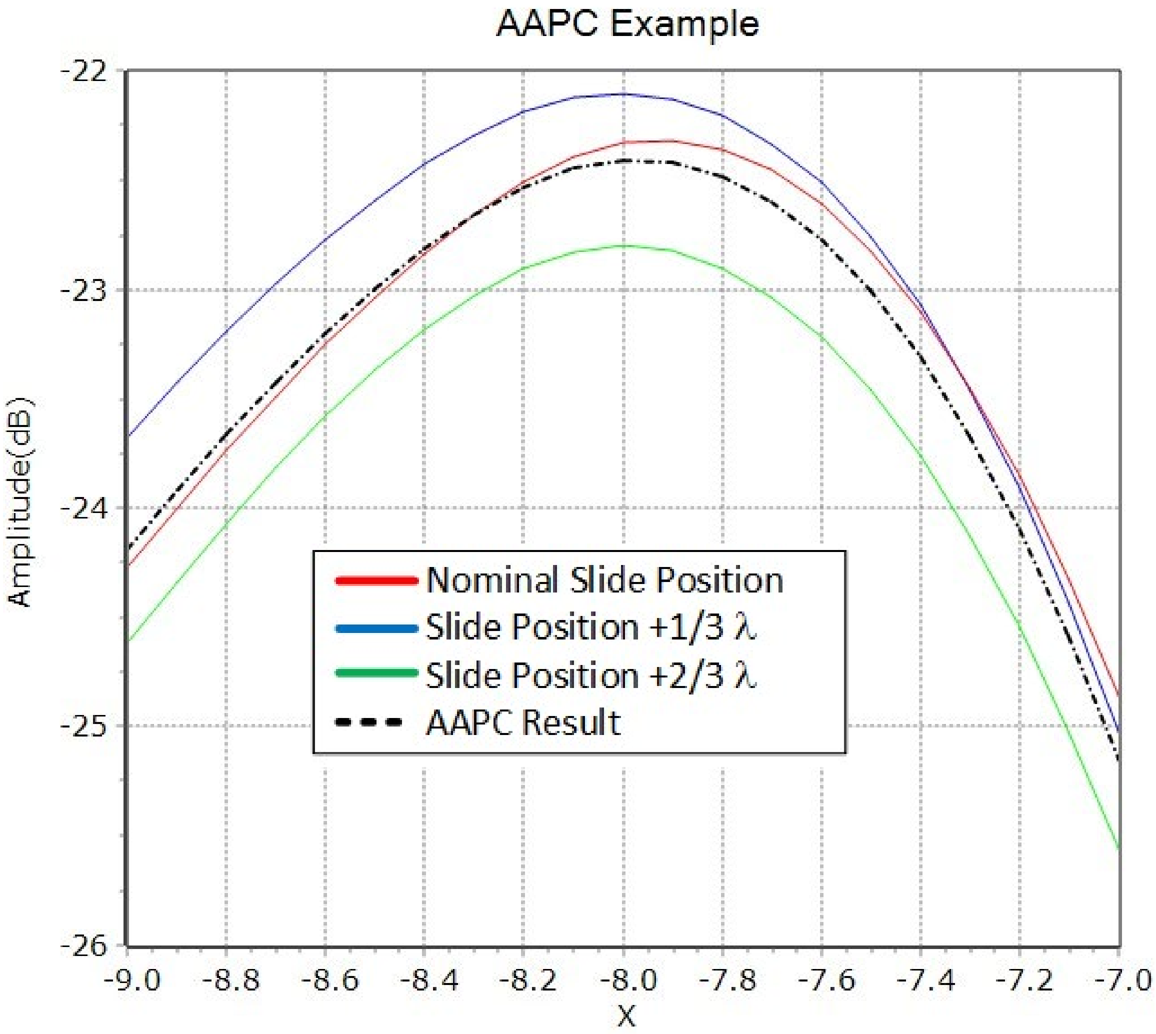
- Three to five AUT patterns are taken at different distances from the range antenna with the total distance around one wavelength.





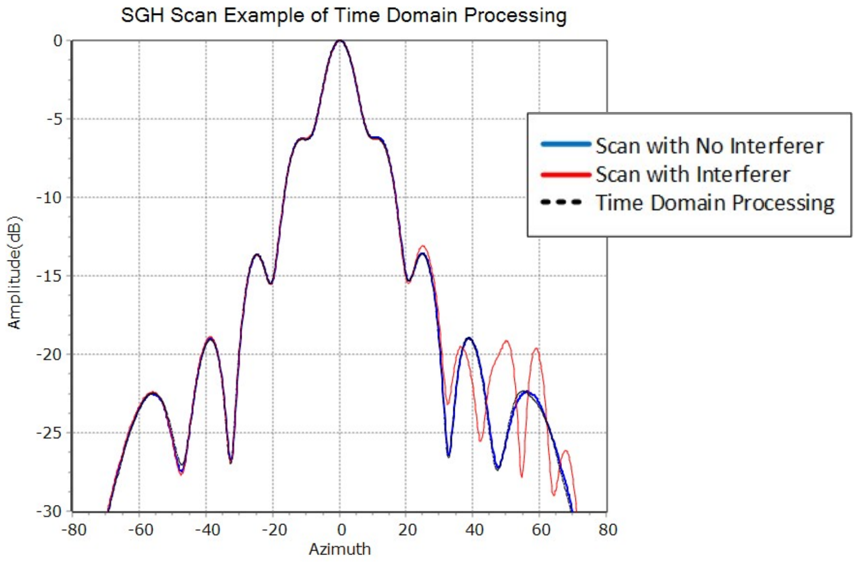
AAPC

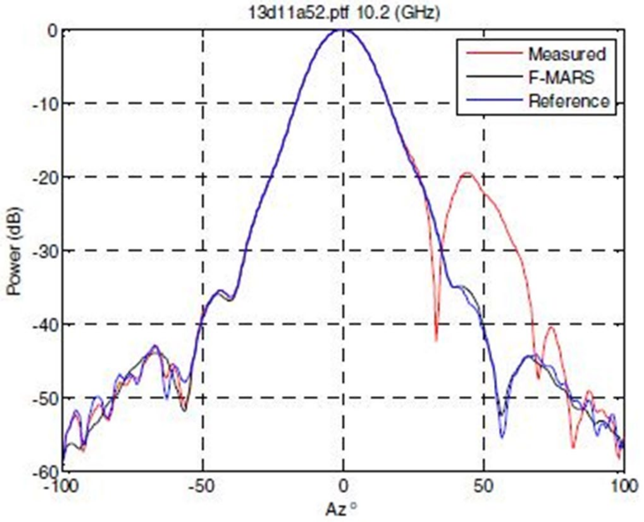
- This is an expansion of the left side lobe at -8 degrees.
- Stray signal suppression is around 20 dB at this side lobe level.
- Throughput penalty is that 3X scans are collected.



Time Domain Gating and MARS™

- Time Domain
  - Collect many frequencies over a wide band width
  - Use FFT^{-1} to the time domain
  - Gate out interferers
  - Use FFT to return to the frequency domain
  - Penalty is increased number of frequencies measured
- MARS™
  - Offset the AUT from the AUT positioner coordinate system origin.
  - Use cylindrical modal coefficients to eliminate the interferers
  - Works for PNF, CNF, SNF, FF
  - Penalty is increased sampling density





Summary

- A modern automated measurement system by itself cannot guarantee low uncertainty measurements. As expected, more effort leads to more accurate measurements
- Systematic errors can be addressed with post-processing or calibration (periodic or real-time)
- Random errors can be addressed with multiple measurements or increased precision in the instruments
- Post-Processing generally requires more data than the nominal amount
- Accuracy and throughput are generally in conflict
  - Accuracy or throughput may dominate the testing of antennas at different stages in the antenna life cycle.
  - A measurement technique may be required that sacrifices accuracy for speed. The metrologist must know the increase in measurement uncertainty that will occur.
  - A measurement technique may be required that sacrifices throughput to meet accuracy requirements. The metrologist must know the potential decrease in measurement uncertainty and the expected throughput degradation.

References

[1] IEEE Standard 1502-2020, "IEEE Recommended Practice for Radar Cross-Section Test Procedures", Clause 8, IEEE Antennas and Propagation Society, 2020.
[2] IEEE Standard 1720-2012, "IEEE Recommended Practice for Near-field Antenna Measurements", Clause 9.1 and Clause 9.4.10, IEEE Antennas and Propagation Society, 2012.
[3] IEEE P149™/D9, "Draft Recommended Practice for Antenna Measurements", IEEE Antennas and Propagation Society, Clause 15, March 2021, unpublished.
[4] NIST Technical Note 1297, "Guidelines for evaluating and expressing the Uncertainty of NIST Measurement Results", 1994 edition.
[5] JCGM 100:2008, "Evaluation of measurement data – Guide to the expression of uncertainty in measurement", Joint committee for Guides in Metrology, 2008.
[6] Marion Baggett, "Practical Gain Measurements", AMTA Annual Symposium, 2011.
[7] Marion Baggett, "The Cost of Accuracy – Mechanical Systems", AMTA Annual Symposium, 2020.
[8] Marion Baggett and Vince Rodriguez, "The Cost of Accuracy – Throughput Considerations", 15th European Conference on Antennas and Propagation, March 2021.