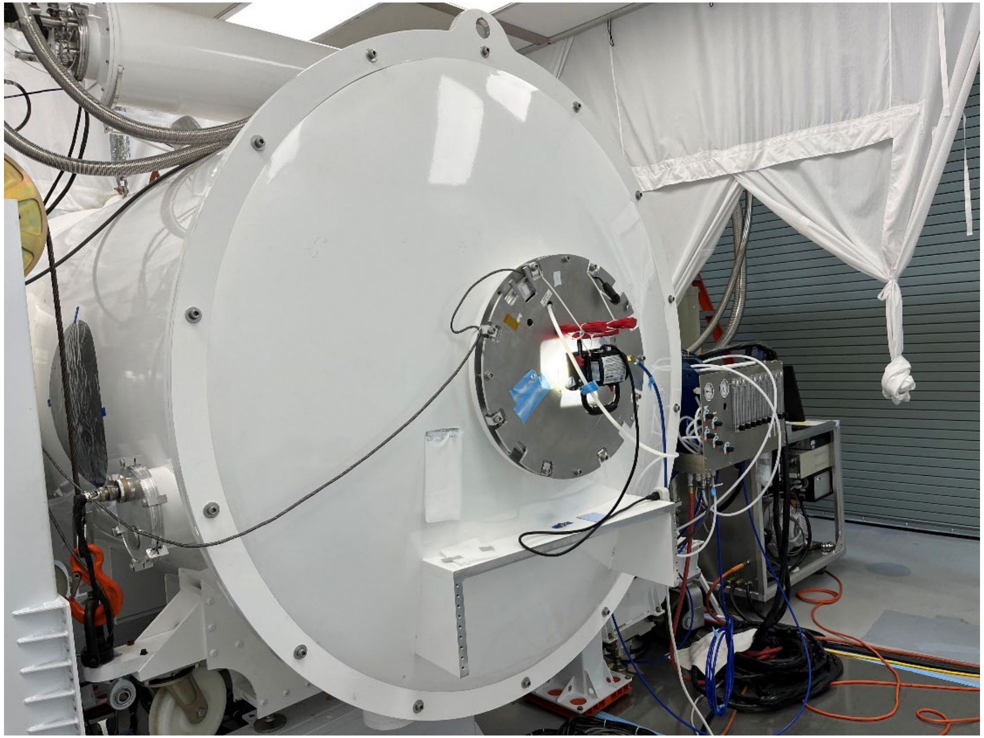
GSE Calibrator Pointing Calibrations using Theodolite (11/3/2021 – 1/23/2022)

Joe Tansock, Matthew Berghout, Aaron Davidson

Space Dynamics Laboratory
Utah State University

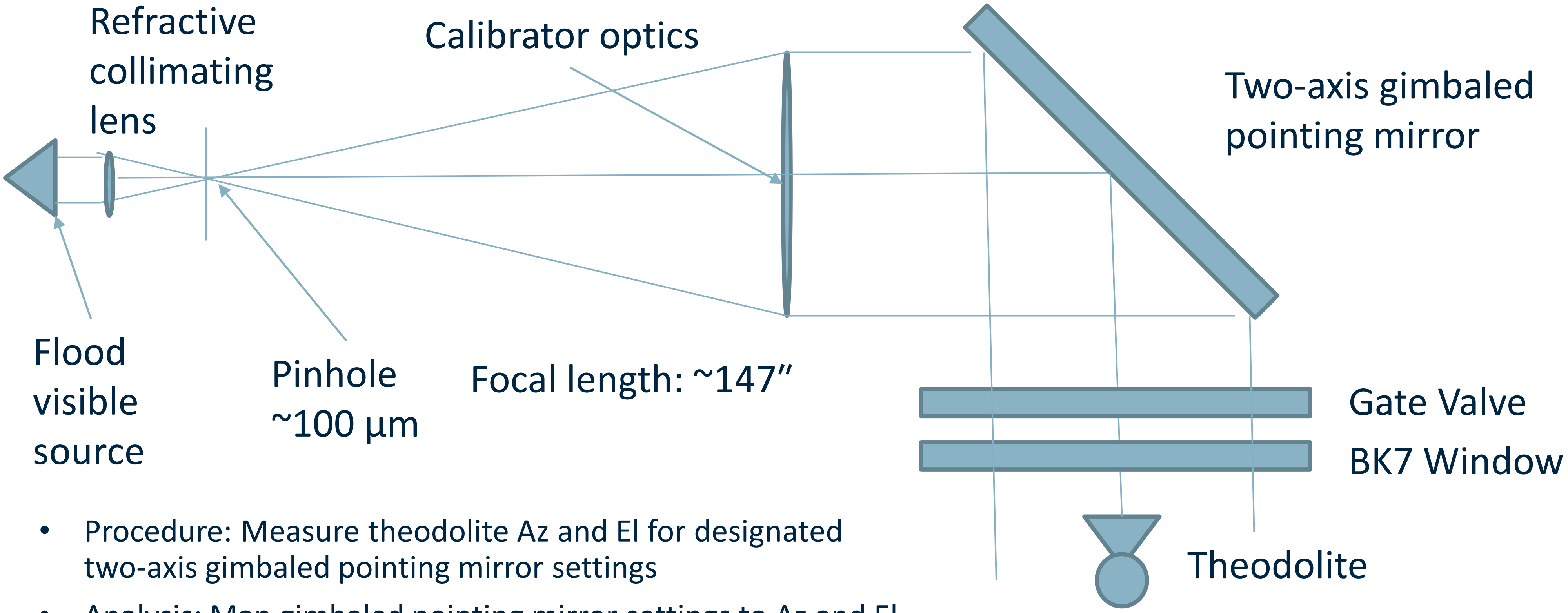
Pointing Calibration Test Configuration

- Visible flood source at entrance port
- Used to back illuminate pinhole



- Theodolite at unit under test (UUT) port
- Used to measure Azimuth-Elevation (Az-El) of the optical beam

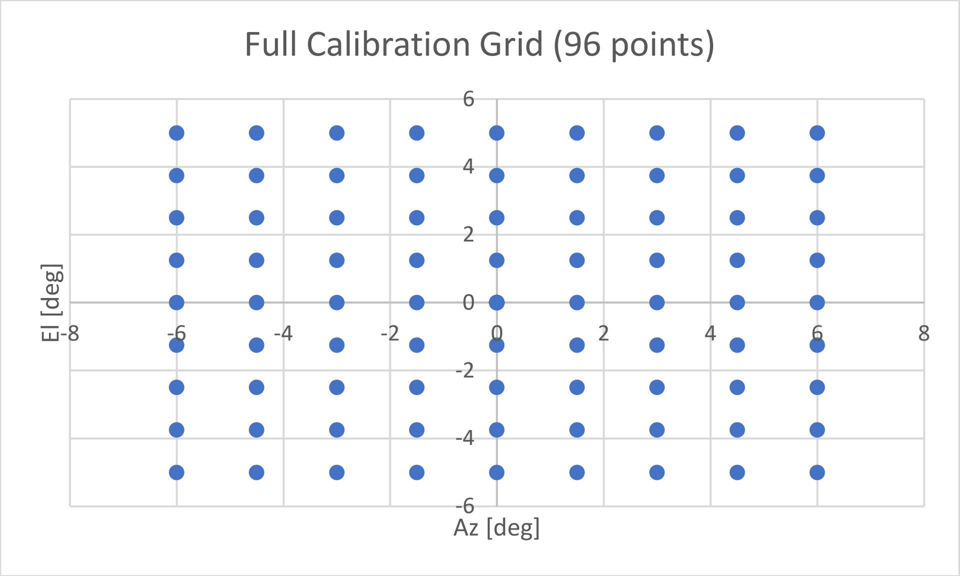
Simple Ray Trace of Pointing Calibration Measurement

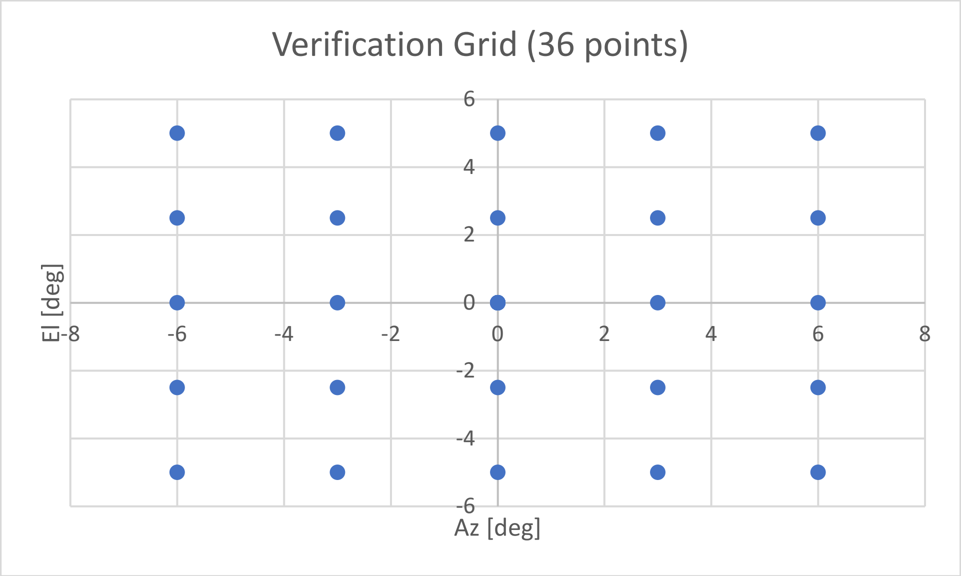


- Procedure: Measure theodolite Az and El for designated two-axis gimbaled pointing mirror settings
- Analysis: Map gimbaled pointing mirror settings to Az and El as measured by Theodolite
- Boresite: Set Az,El to 0,0 when the beam is normal of the UUT port flange

Full Calibration Grid and Verification Grid

Pointing Calibration Range: ±5° El and ±6° Az





Pointing Equation Implementation in Software

- Maps gimbal position in units of encoder counts to (1) Az and (2) El as measured by Theodolite
  - Third order polynomial equation with cross terms
  - Two equations: one for Az and one for El
- Example equations:

$$Az = A_0 + A_1 y + A_2 x + A_3 xy + A_4 y^2 + A_5 x^2 + A_6 xy^2 + A_7 x^2 y + A_8 x^2 y^2 \ldots$$

$$+ A_9 y^3 + A_{10} x^3 + A_{11} xy^3 + A_{12} x^3 y + A_{13} x^2 y^3 + A_{14} x^3 y^2 + A_{15} x^3 y^3$$

$$El = B_0 + B_1 y + B_2 x + B_3 xy + B_4 y^2 + B_5 x^2 + B_6 xy^2 + B_7 x^2 y + B_8 x^2 y^2 \ldots$$

$$+ B_9 y^3 + B_{10} x^3 + B_{11} xy^3 + B_{12} x^3 y + B_{13} x^2 y^3 + B_{14} x^3 y^2 + B_{15} x^3 y^3$$

The goal is to measure Theodolite data at multiple *x* and *y* pointing mirror encoder positions allowing for quantifying equation coefficients using multiple regression techniques.

Pointing Calibration Test Combinations

- 11/3/2021 – initial pointing calibration (full grid)
  - With UUT window, no vacuum, ambient temps
- 11/3/2021 – verification grid
  - With UUT window, no vacuum, ambient temps
- 11/8/2021 – verification grid
  - Without window, no vacuum, ambient temps
- 11/12/2021 – verification grid
  - With UUT window, with vacuum, ambient temps
- 11/20/2021 – pointing calibration (full grid)
  - With UUT window, with vacuum, @ LN_2 temps
- 11/22/2021 – 4 repeated verification grids – collected sequentially to quantify if there are pointing changes due to increasing temperature gradients of UUT window
  - With UUT window, with vacuum, LN_2 temps
- 1/23/2022 – pointing calibration (full grid)
  - 2nd cold test at LN_2 temps (~15 days later)

Verification, how well does cal repeat

Window difference, affect of ambient temp window

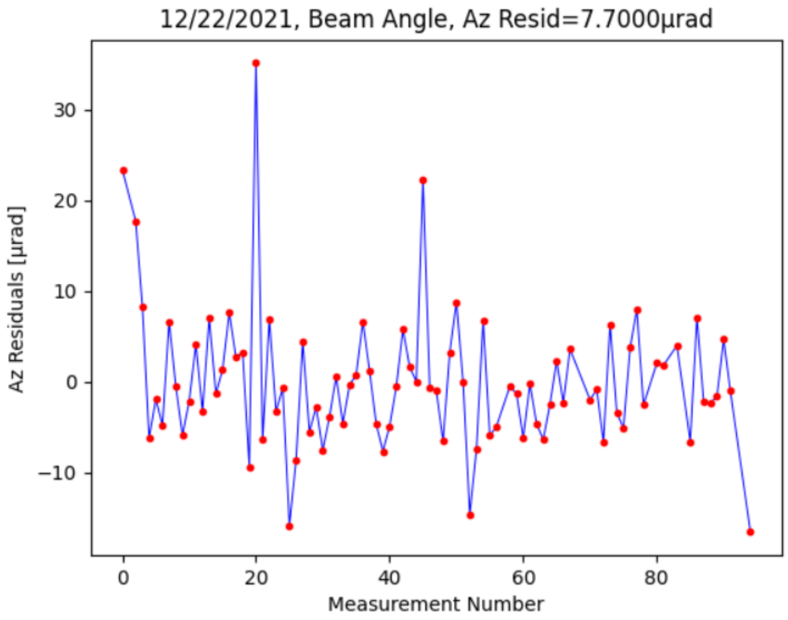
Vacuum difference, affect of vacuum

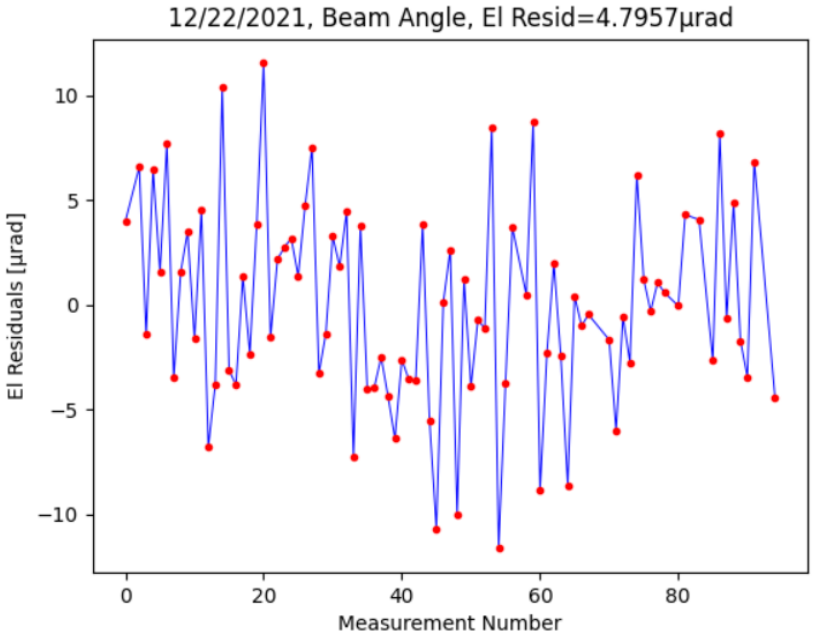
LN_2 difference, affect of cooling

Pointing cal short term repeatability (Differences within a single cold cycle)

Pointing cal cold cycle to cold cycle repeatability

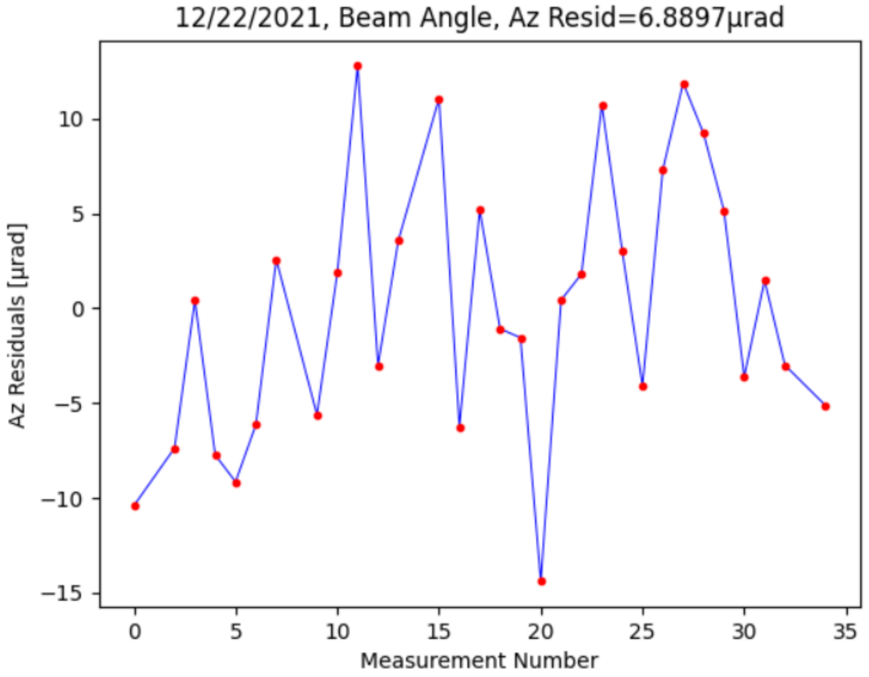
11/03/2021 Full Cal Grid Example (Ambient Temp and “with” Window)

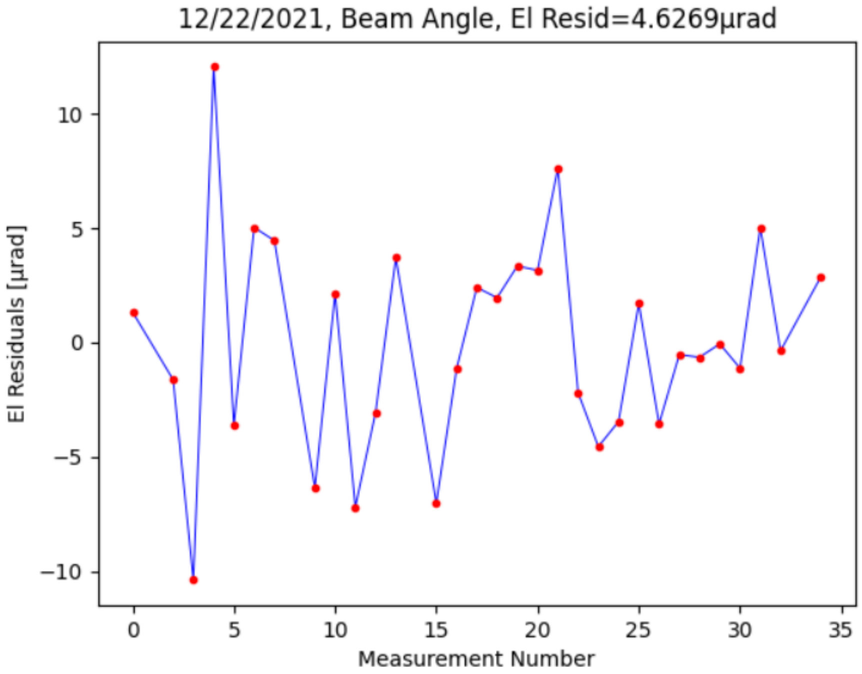




- Angular pointing calibration with residual standard deviation of 7.7 μrad Az and 4.8 μrad El
  - Over pointing mirror coverage with angle range of ±5° El and ±6° Az
  - Shows one sigma repeatability of theodolite data (~5 to 8 μrad rms) over this range

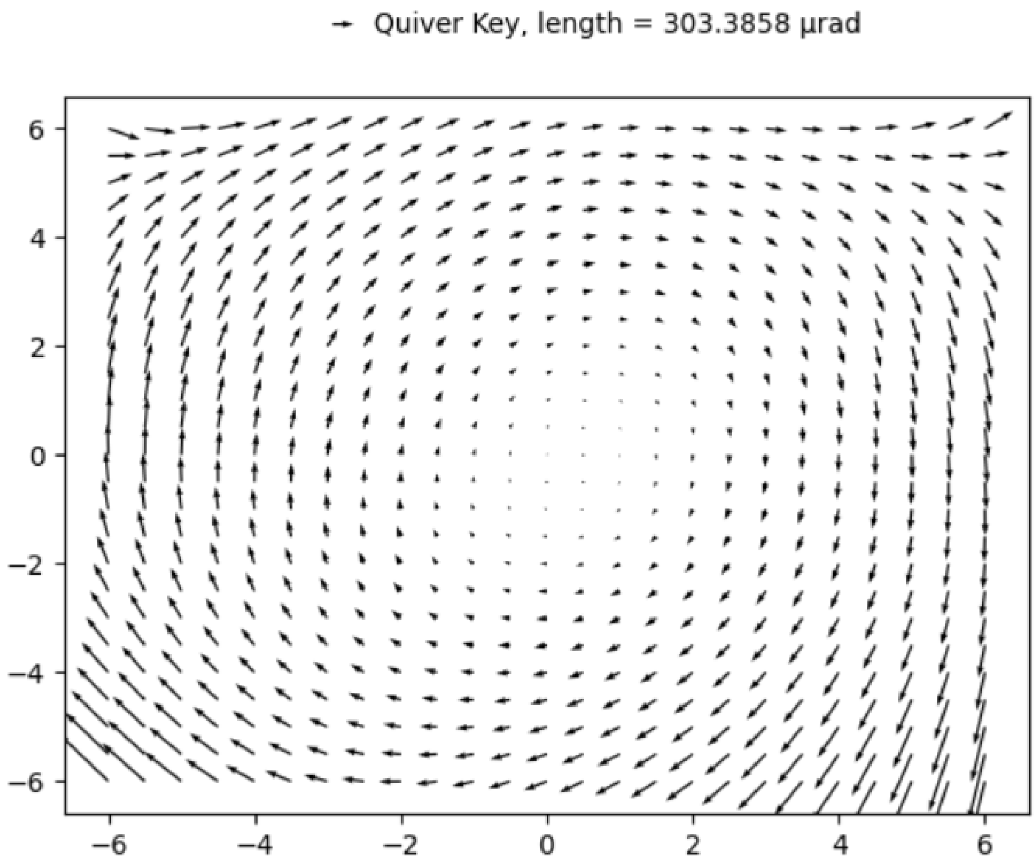
11/03/2021 Verification Grid Example (Ambient Temp and "with" Window)





- Verification grid residuals of 6.9 μrad Az and 4.6 μrad El
  - Coefficients determined from full calibration grid loaded into pointing mirror control and readout software and then verification grid performed to verify implementation
  - Residuals of verification nearly the same as the multiple regression residuals of full calibration grid

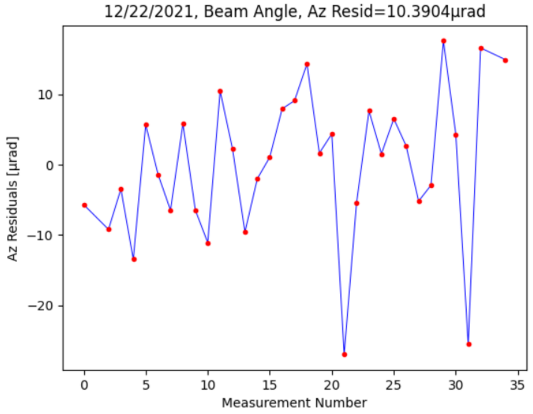
Pointing Calibration Difference Between LN_2 Operational Temp vs. Ambient Temp

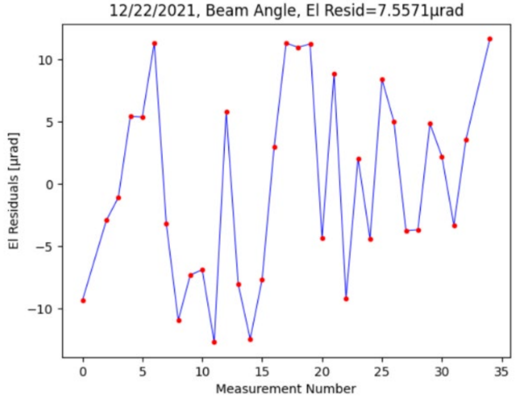


- As shown on the left, a swirling difference between ambient temp and LN_2 temp pointing calibrations are shown.
- Conclusion: pointing calibration Ambient vs. LN_2 temps
  – Is different depending on the angular coverage
    - For a ± 2°X ± 2°Y region located near the center of the grid, it is ~ 30 µrad
    - Much larger for ± 6°X ± 5°Y region, at ~900 µrad
  – It is believed this difference is due to thermal contraction of pointing mirror gimbal and possibly the encoder ring.

Short Term Repeatability of Pointing Calibration (LN_2 Temps)

- A series of 4 verification grids were performed (grids were collected one after the other to exceed the data collection time of the LN_2 calibration grid). This was done to:
  - Verify the LN_2 calibration
  - Check to see if there are changes in theodolite measurements over the data collection time of the calibration grid due to temperature gradients building on the window)
    - Gate valve open/closed: 10:26 a.m./12:53 p.m. (duration: 2 hr. 27 min.)





Grid	Start	End	Az resid rms (µrad)	El resid rms (µrad)
1	~10:30 a.m.	11:04 a.m.	10.4	7.6
2	11:07 a.m.	11:40 a.m.	10.2	12.6
3	11:41 a.m.	12:15 p.m.	14.1	12.0
4	12:17 p.m.	12:46 p.m.	8.1	11.2
Average			10.7	10.9

Individual LN_2 Pointing Calibration Uncertainty

Contribution	Source	Az (µrad)	El (µrad)	Notes:
Verification residuals	Measured	10.7	10.9	RMS residual of verification grids (includes calibration angular uncertainty, measurement repeatability, and window gradients)
Theodolite	Vendor	2.4	2.4	The angular accuracy specification of the TM6100A is defined in accordance with ISO 17123-3. The value of 0.5″ represents the uncertainty of a measured direction of the theodolite in both faces.
Total	Calculated	11.0	11.1	Total RSS 1 sigma uncertainty over ±5°El X ±6° Az

Just a data point: **relative pointing mirror cal uncertainty**
Az: 11.0 µrad rms/±6°=0.006%, El: 11.1 µrad rms/±5°=0.006%

Boresight Shift Summary [μrad]

Description	Δ Az [μrad]	Δ El [μrad]	Sign
Vacuum vs. no-vacuum	26	1500	Ambient_vacuum_window-Ambient_no_vacuum_window
Ambient vs. LN_2	3	105	LN_2_vacuum_window – Ambient_vacuum_window
Ambient_no_vacuum vs. LN_2_vacuum	29	1605	LN_2_vacuum_window - Ambient_no_vacuum_window

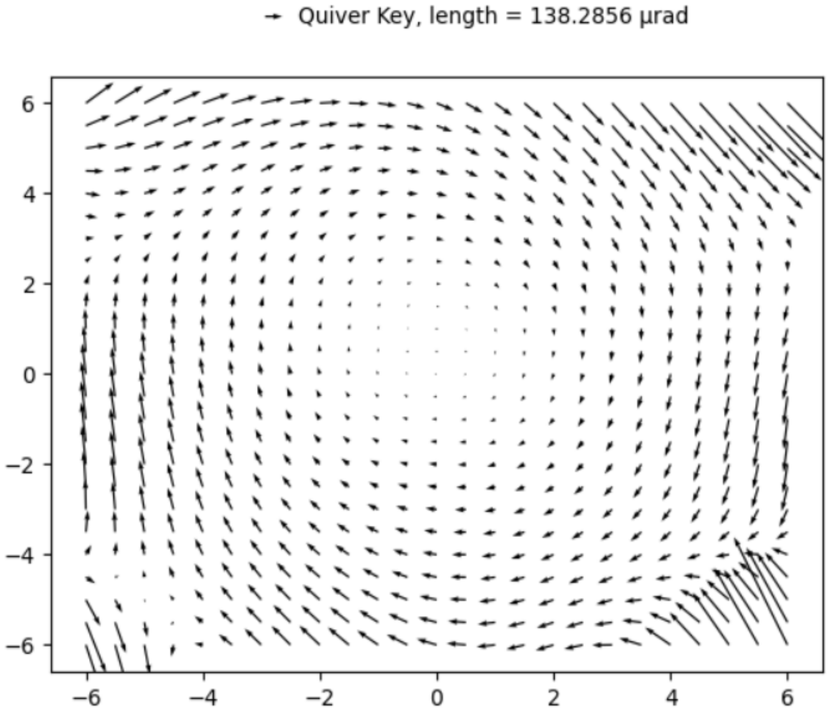
Conclusion: boresight may shift (relative to the window normal) ~0.1 deg due to vacuum and LN_2 cooling

Summary Comparison of 0,0 Setting [µrad]

Description	Δ Az 0,0	Δ El 0,0	Sign
Window vs. no-window	-785	-53	Ambient_no_vacuum_window-Ambient_no_vacuum_no_window
Vacuum vs. no-vacuum	785	105	Ambient_vacuum_window-Ambient_no_vacuum_window
Ambient vs. LN_2	-140	-384	LN_2_vacuum_window – Ambient_vacuum_window
LN_2 vs. no_window	-140	-332	LN_2_vacuum_window - Ambient_no_vacuum_no_window

These data show the 0,0 shift between LN_2_vacuum_window and Ambient_no_vacuum_no_window is -140 Az µrad and -332 El µrad [-0.008 deg, -0.019 deg]

Pointing Calibration Difference Between 1st vs. 2nd Cold Test at LN_2)



- As shown on the left, a swirling difference between pointing calibrations between LN_2 temp cold cycle
- Conclusion: Provides evidence that pointing calibration at LN_2 temps does change from cold cycle to cold cycle
  - However, this difference does depend on the angular coverage
    - For a ±2°X ± 2°Y region located near the center of the grid, it is ~ 41 μrad
    - For a ± 4°X ± 4°Y region, it is ~ 84 μrad
    - For a ± 6°X ± 5°Y region, it is ~ 117 μrad
  - The origin of this difference is unknown
    - It may be due to the gimbal thermal changes from cold cycle to cold cycle
    - It may also be due to temperature stabilization of the first pointing cal (which was ~ 2 days) vs. stabilization of the 2nd cold cycle of ~15 days

Approved for Public Release

Conclusions/Summary

- **Pointing Calibration Verification (i.e., repeatability of Theodolite calibration approach)**
  - Verification grid 1 sigma residuals nearly identical to pointing calibration at around 7.7 µrad Az and 4.8 µrad El
- **Depending on angular range, pointing calibration between Ambient and LN_2 operational temps**
  - For a ± 2°X ± 2°Y region located near the center of the grid, it is ~ 30 µrad
  - Much larger for ± 6°X ± 5°Y region, at ~900 µrad
- **Short Term Repeatability of Pointing Calibration (LN_2 temps)**
  - On the order of single calibration uncertainty during single cold cycle
- **Single calibration pointing calibration uncertainty (one sigma, using theodolite approach)**
  - 11.0 µrad Az over ±6°, 11.1 µrad El over ±5°
  - Relative: ~0.006% in Az and El
- **Boresight may shift due to vacuum and LN_2 cooling (relative to the window normal)**
  - ~0.1 deg
- **Data show the 0,0 pinhole shift between LN_2 _vacuum_window and Ambient_no_vacuum_no_window**
  - -140 Az µrad and -332 El µrad [-0.008 deg, -0.019 deg]
- **Data show evidence pointing calibration changes from cold cycle to cold cycle but it depends on the angular coverage**
  - ~ 41 µrad for a ±2°X ± 2° region to ~ 117 µrad for ± 6°X ± 5° region

Angular calibration of Pointing Mirror Gimbal will likely depend on many factors such as vacuum, operational temps, the needed angular range, and cold to cold cycle changes.