Optical testing using portable laser coordinate measuring instruments

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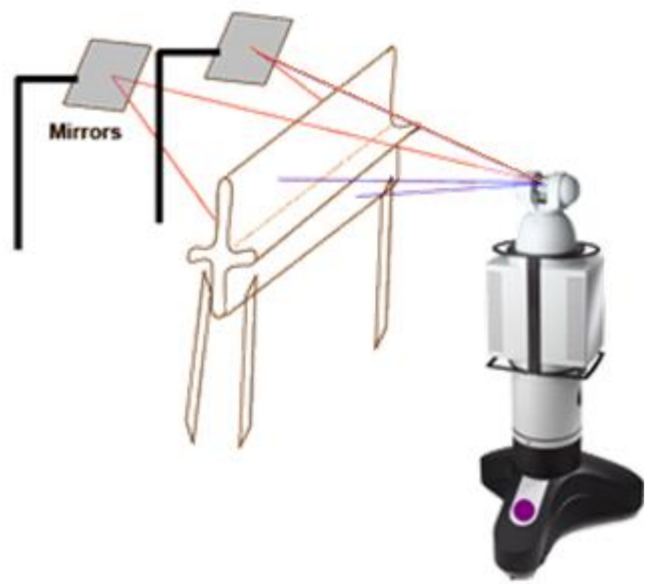
Outline

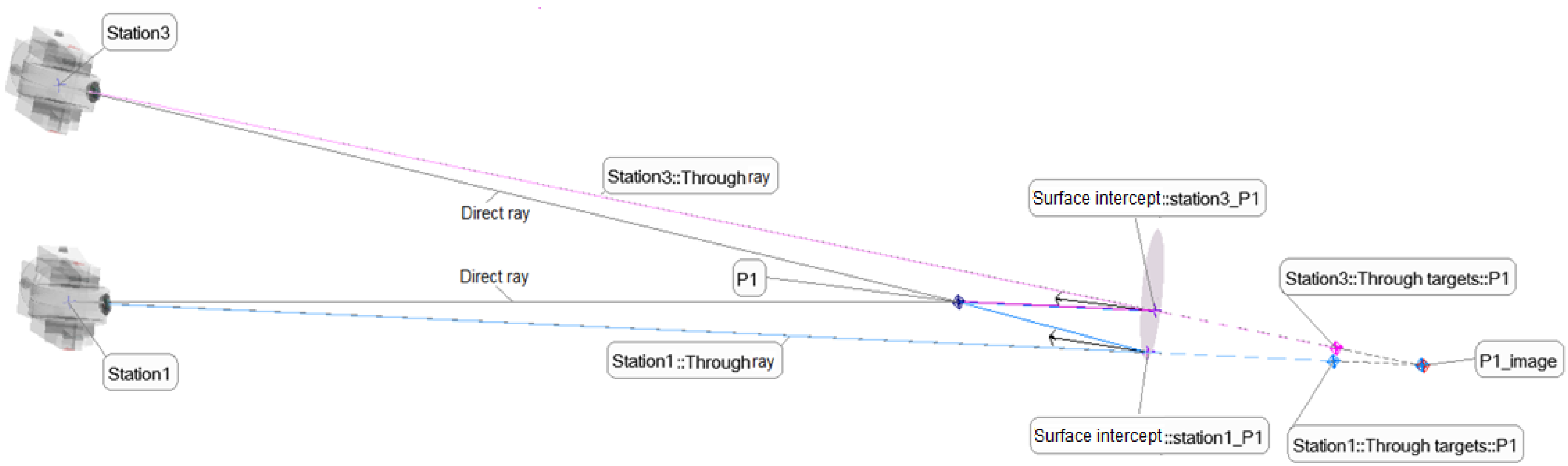
- Portable laser Coordinate Measuring Instruments (CMI) examples: Laser radars (LR) , laser trackers (LT)
- Proof-of-concept study (PoC) to characterize a mirror using CMI “direct” and “through” (D&T) shots
- Introduction
- Instruments and targets used
- Data collection
  - OAP
  - Convex sphere
- Analysis
- Results
- Summary
- Future work



“Through” measurement of objects outside the LR’s line of sight utilizing their virtual image via flat mirrors [8]

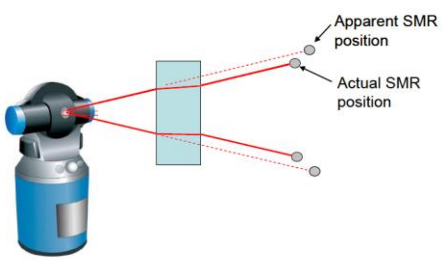
PoC study summary

- Non-contact CMI D&T measurement of calibrated target
- "Direct" measurement = actual target position
  - Measured during D&T data collection if within CMI LS
  - Transformed via reference targets if hidden
- "Through" measurement = apparent position measured along the instrument-target image line of sight (LS) (i.e. target measurement in reflection)
- "Through" ray-surface intercepts and surface normals calculated
- Data fit to conic surface formula for optimum
  - radius of curvature (RoC),
  - conic coefficient (k)
- Results crosschecked

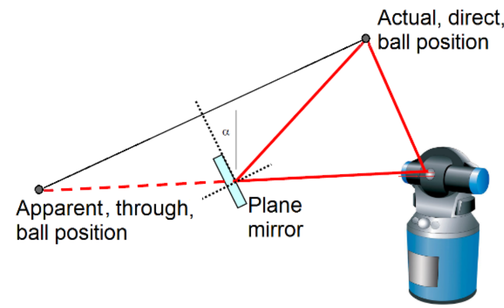


Introduction

- **LR/LT: Coordinate Measurement Machine (CMM)-like instruments**
  - Advantages: High precision, versatile, portable, commercially available, getting more advanced and less expensive
  - Usually used for mechanical metrology, particularly large-volume, and alignment applications
- **Using LT for optical shop and alignment applications examples**
  - Guide the figuring of large mirrors: Giant Magellan Telescope (GMT) and the Large Synoptic Survey Telescope (LSST) primary mirrors (PM) [1],
  - LT coupled with advanced calibration technique, Laser Tracker Plus system [2]
    - Guide large mirror fabrication process
    - Verification test for GMT-PM1 interferometric test (several low-order aberrations)
  - LT used for RoC measurement, alignment of optical elements, and image tracking [3]
  - LT used for aligning optical systems, making use of the LT's ability to measure along image LS through fold mirrors and windows [4]
    - Accurate measurement of angular orientation of fold mirrors
    - Real ray tracing code, "Laser Radar through Window" (LRTW) resolve optical path errors caused by additional materials/surfaces in LR/LT path [7]
  - Require spatial scanning by sliding/touching Spherically Mounted Retroreflector (SMR) on optical surface
    - Disadvantage: Hard, risky, time consuming, and usually requires man labor.



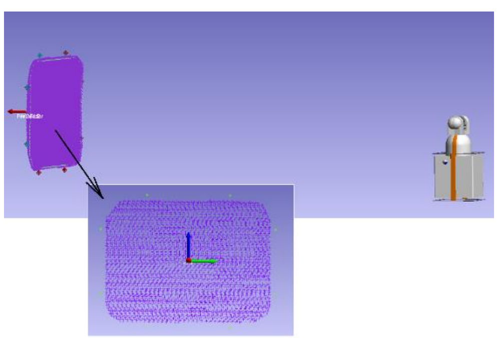
LT measurement through fold mirrors and windows previously reported by Prof. Burge [4]



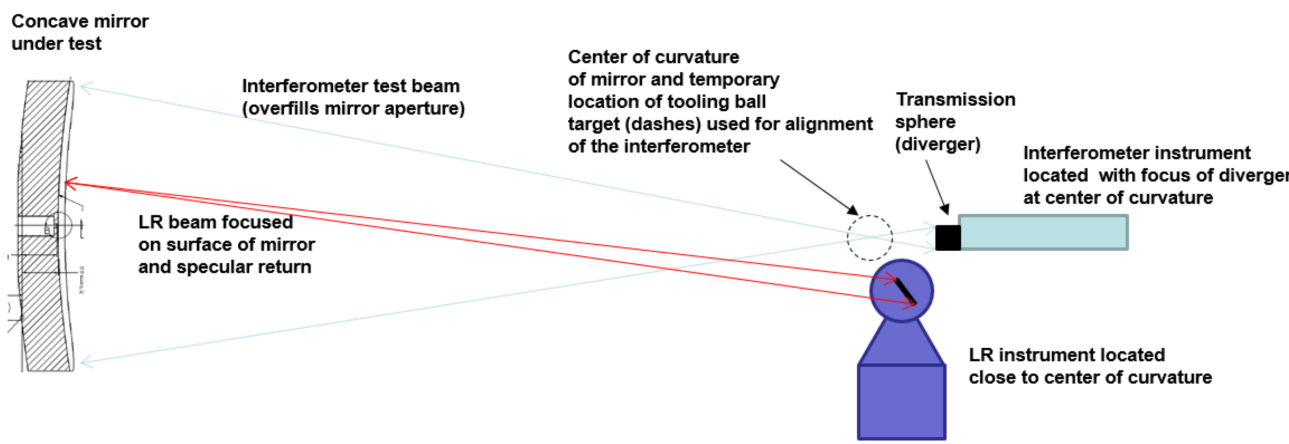
LT measurement of D&T positions of a metrology target to calculate the mirror angular orientation [4]

Introduction - continue

- **PoC study utilizing LR for prescription characterization and alignment of large mirrors [5]**
  - Test article: Ground support equipment (GSE) mirror for ground test verification of part of the James Webb Space Telescope (JWST)
    - 1.4 m x 1 m optical aperture, spherical mirror, nominal radius of curvature R = 4600mm
  - LR stationed near center of curvature (CC)
  - LR metrology RoC = 4600.075 ± 0.005mm
  - LT metrology RoC = 4600.00 ± 0.11mm
    - SMR measured touching the mirror's surface at different points
  - LR metrology advantages
    - Reduced tooling needs, non-contact, lower risk of hardware damage,
    - lower labor costs,
    - in-situ with fabrication equipment,
    - improved accuracy,
    - faster



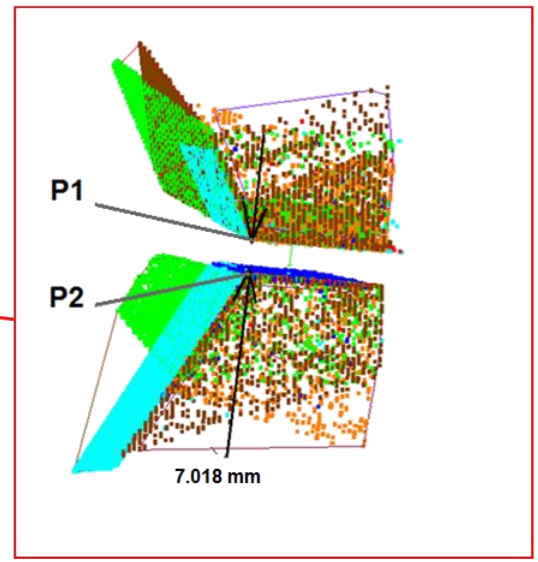
~ 4000 points LR metrology surface scan



LR positioned near CC to enable scanning entire surface [5]

Introduction - continue

- **LR unique ability to scan wide range from matte-finish/mechanical to specular surfaces allows measuring**
  - delicate surfaces,
  - tight and hard-to-reach parts,
  - or hazardous materials
- **Example: Non-contact measurement of small blind gaps between JWST Primary Mirror Segment Assemblies (PMSAs)**



Sample LR scans + fit planes
Mirror vertex = 3-plane intersection

One of LR stations used to scans to JWST PMSA vertices to calculate blind gaps between adjacent PMSAs sample LR scans [6]

Instruments and targets- LR

- **Nikon MV-224 [8]**
- **Field of view specs: Range ~1 to 24 m, azimuth ±200°, elevation ±45°**
- **Very large dynamic range enabling measurement of many different surface and target types**
  - Inexpensive, specular, tooling balls (TB) used for point-like coordinate system references (center detected based on radius save in TB measurement profile)
  - Various fast scan types possible
- **Measurement uncertainty (1-sigma)**
  - Range: ~5 µm, 1.25 ppm
  - Axes orthogonal to range direction: ~0.7 arcsec
  - Further improvement possible via SA USMN and similar algorithms
- **Control software: SpatialAnalyzer (SA)**
- **Portable**
- **Automation possible**

MV224 [8]

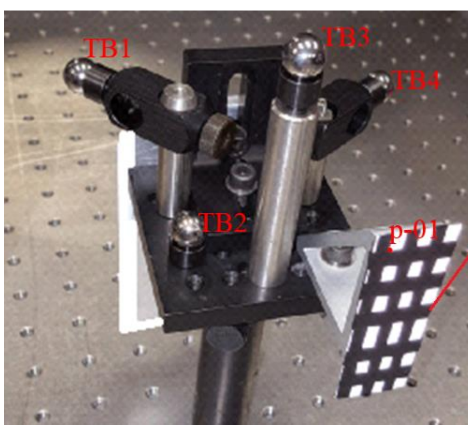
Instruments and targets- LT

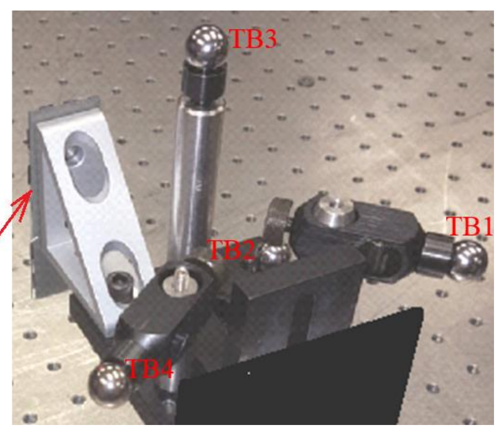
- Leica Absolute Tracker AT402 [9]
- Ultra large volume metrology: Range < 160 m, azimuth 360°, elevation 290°
- Proven Absolute Distance Meter (ADM) technology
  - ADM resolution = 0.1 μm
  - maximum uncertainty (1 sigma) = 10 μm over a full radial volume
- All-in-one system design includes key accessories; e.g. built-in camera and environmental monitoring
- Control software: SpatialAnalyzer (SA)
- Ultra portable
- Semi automation possible

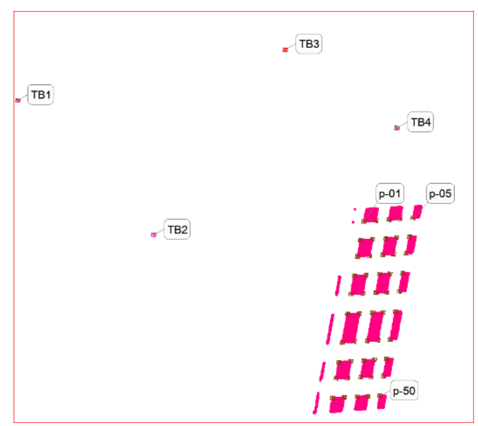
AT402 [9]

Calibrated target

- **Powered optical surface will generally cause power and astigmatism in incident "through" light limiting ability to measure in reflection**
- **LT directly measures vertex of SMR in reflection (if measurement doesn't fail)**
  - LT D&T measurement using SMRs
- **LR determines TB center based on radius saved in the TB measurement profile and will fail if TB, in reflection, magnified or distorted**
  - LR D&T measurements require point grid-like target
- **Custom made target**
  - 1"x2" reflector grid using stripes of reflective 3M and black Kapton tapes
  - Base plate supports 5 reference 0.5" TBs, replaceable with SMRs for LT measurement
  - Target reference TBs/SMRs used for transformation when points out of LS



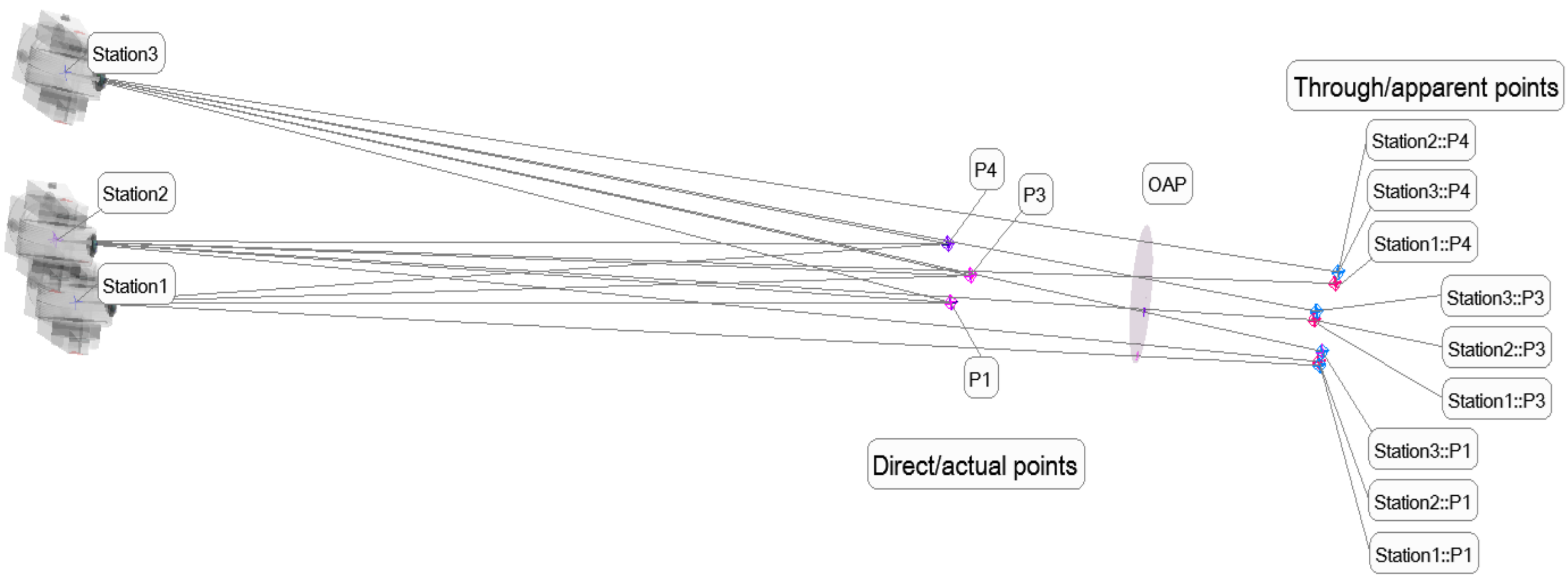




Target calibration vision scan and reference TB measurements

Data collection

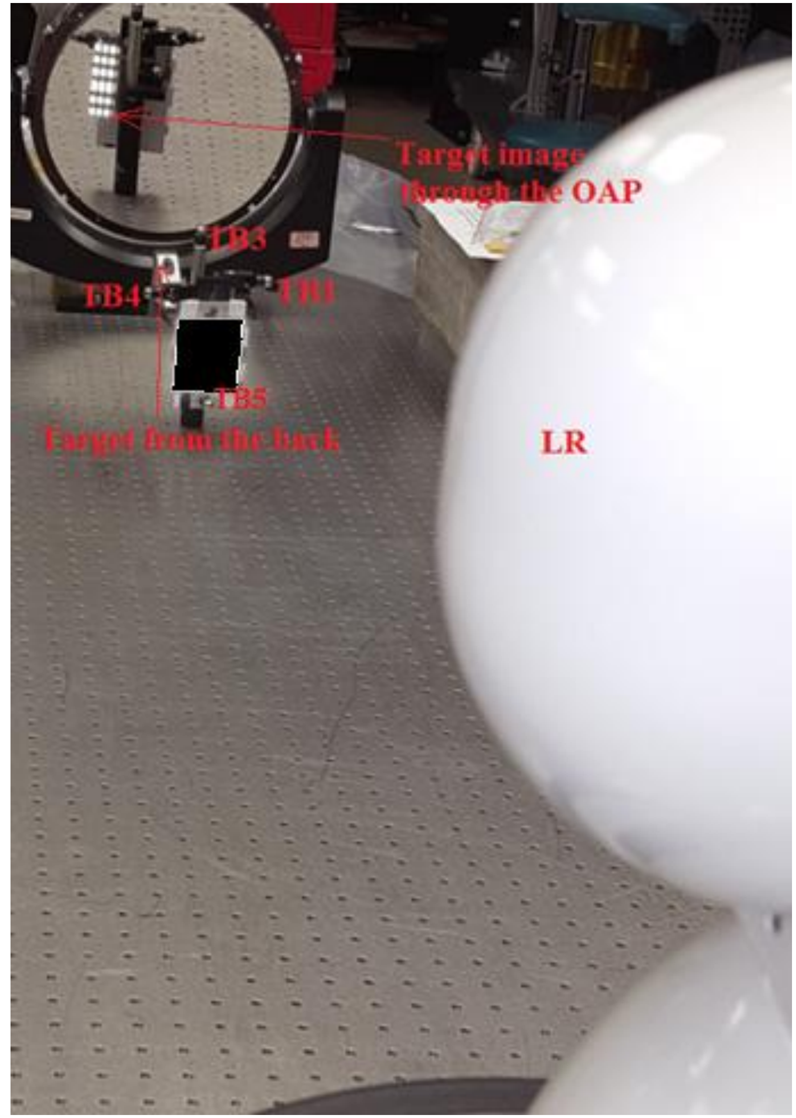
- The “direct” or actual object points measured during D&T data collection if within instrument LS
- “Through” measurements are along instrument-image LS (target measurements in reflection)
- “Through” points = CMI measurement in reflection if powered mirror were replaced by small flat mirrors tangent to surface at through ray-mirror intercepts.



AT402 D&T measurement of 3 SMRs, testing OAP mirror, from 3 stations

Data collection-continue

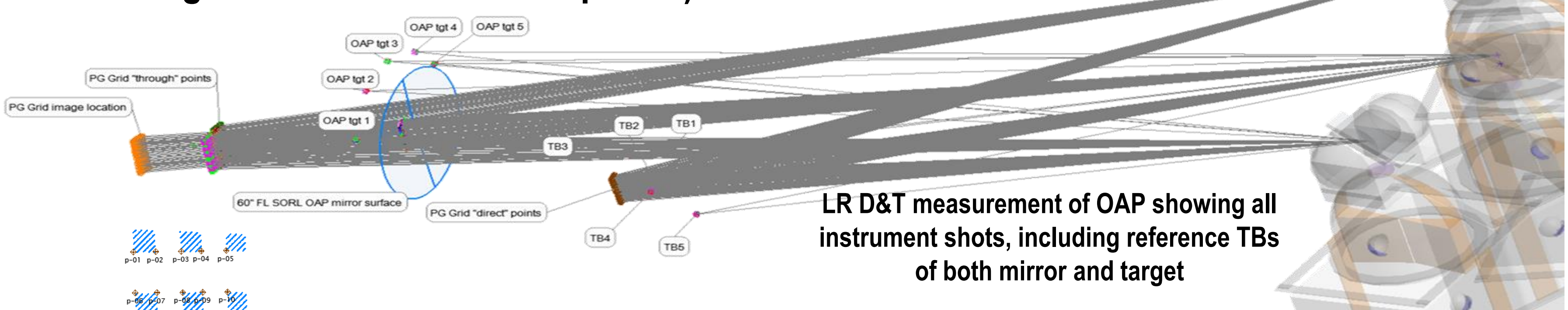
- When out of LS, calibrated target points transformed by best fitting calibration reference targets to measured ones to get “direct” target positions



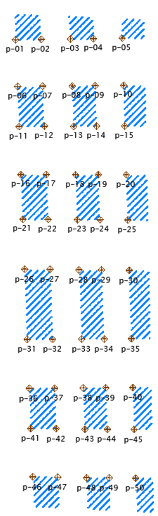
Target out of LR sight during D&T measurement as it faces mirror while enough TBs measurable and used to transform calibrated target points

Data collection-OAP

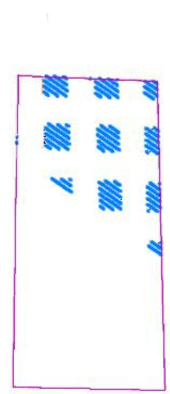
- **Vendor, Space Optics Research Lab, specs**
  - Focal length (FL) , vertex = 60.000” ± 0.300”
  - Clear aperture (CA) = 12.00”
  - Off-axis distance = 4.44” ± 0.050” to inner edge of mirror
  - Surface accuracy = lambda/8 P-V over any 99% of CA
- **3 LR stations located via Unified Spatial metrology network (USMN) (OAP and target reference TBs as tie points)**

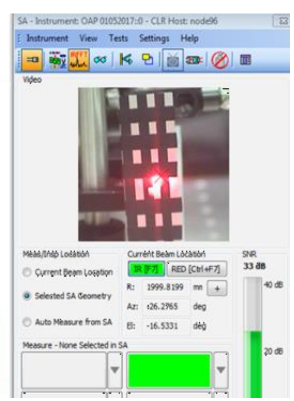


LR D&T measurement of OAP showing all instrument shots, including reference TBs of both mirror and target



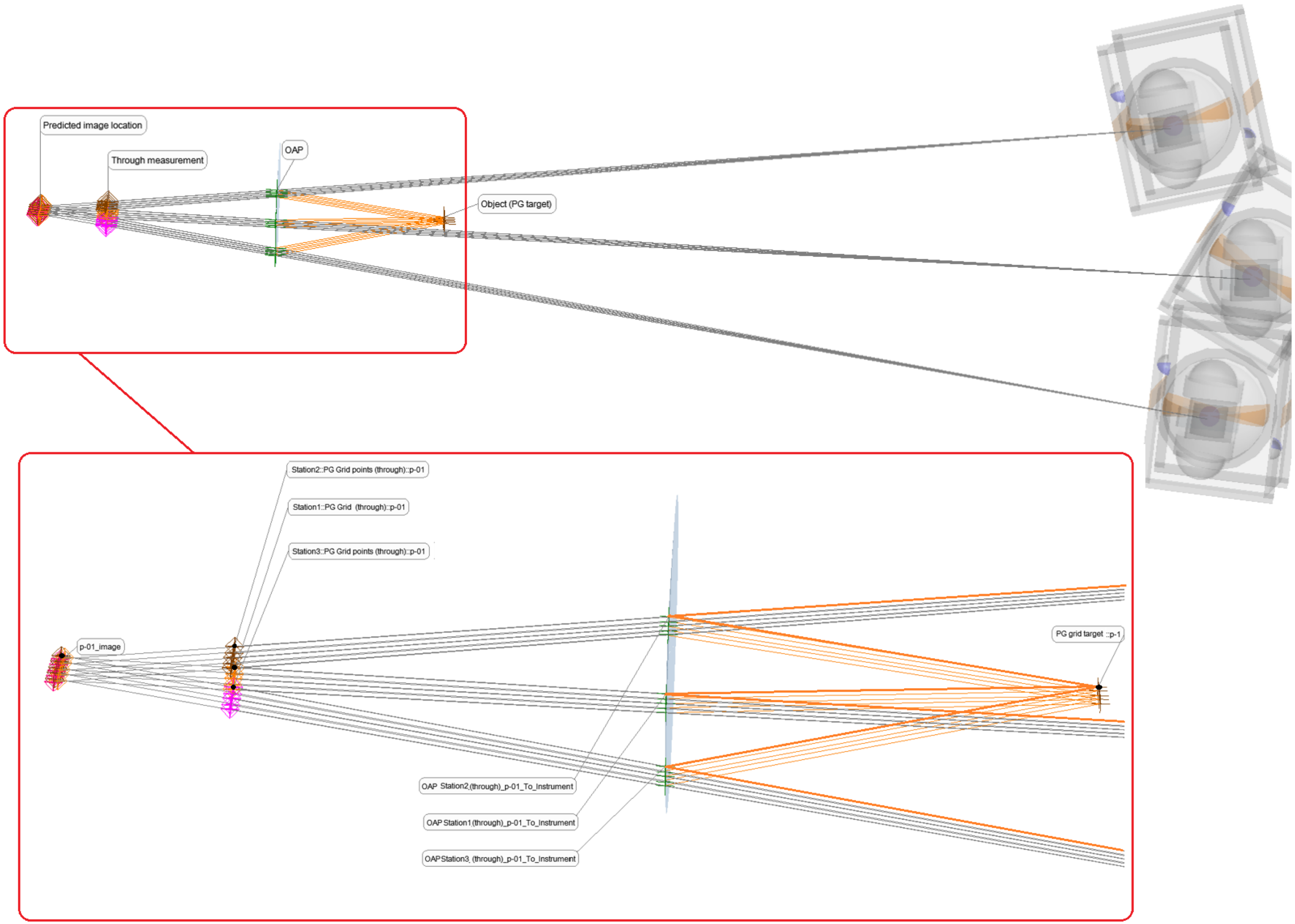
“Direct” target calibration scan and calculated grid points





“Through” target scanned by LR in reflection as seen in instrument interface

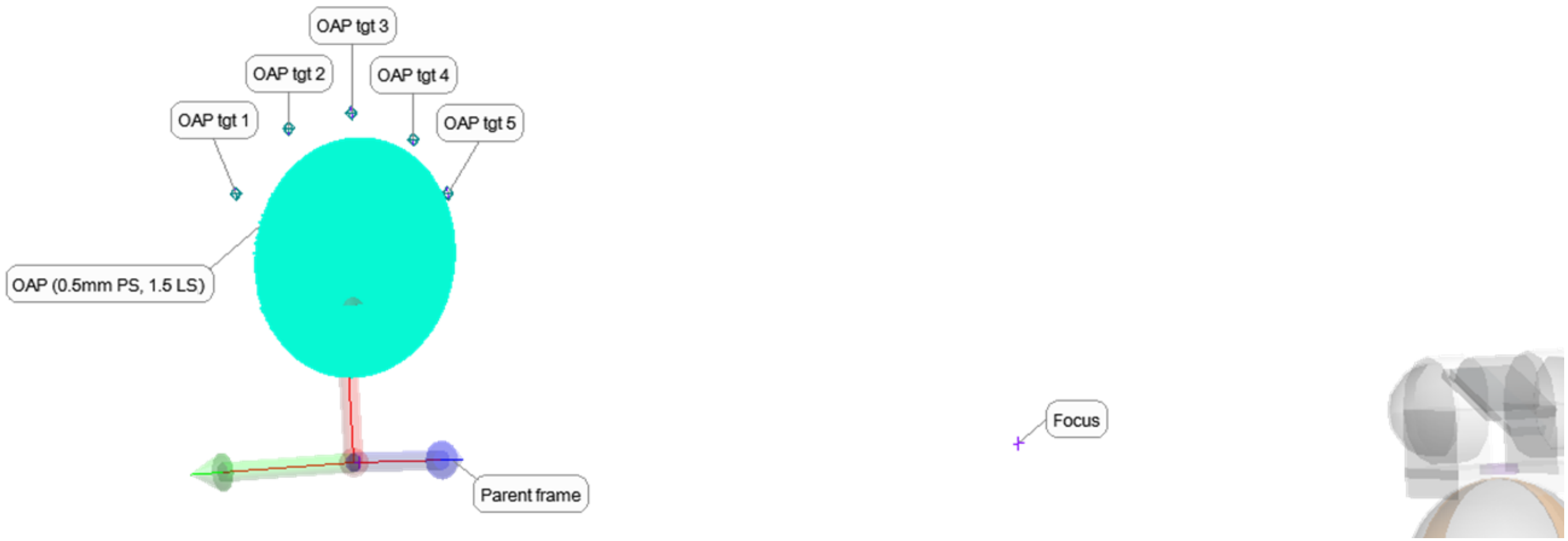
Data collection-OAP



p-01 “through” targets; actual path of LR beam in “through” measurements colored orange

Data collection-OAP crosscheck

- LR positioned close to CC to scan entire OAP
- 0.5 mm point spacing ; 1.5 mm line spacing
- 332255 points collected and fit to conic surface formula

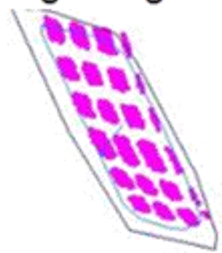


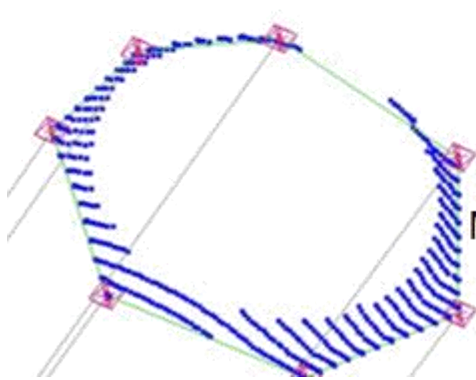
OAP vision scan with the LR close to CC

Data collection-Convex sphere

- FL = -129.20 ± 2.58 mm
- CA = 50 mm

"Through" target scan

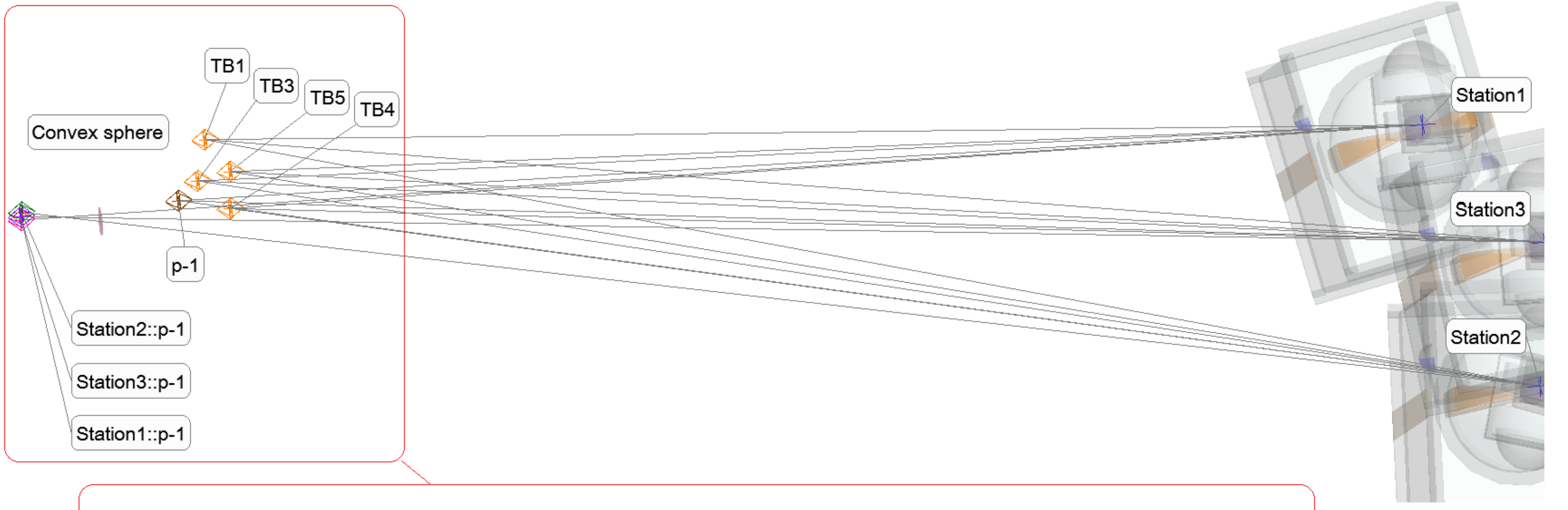


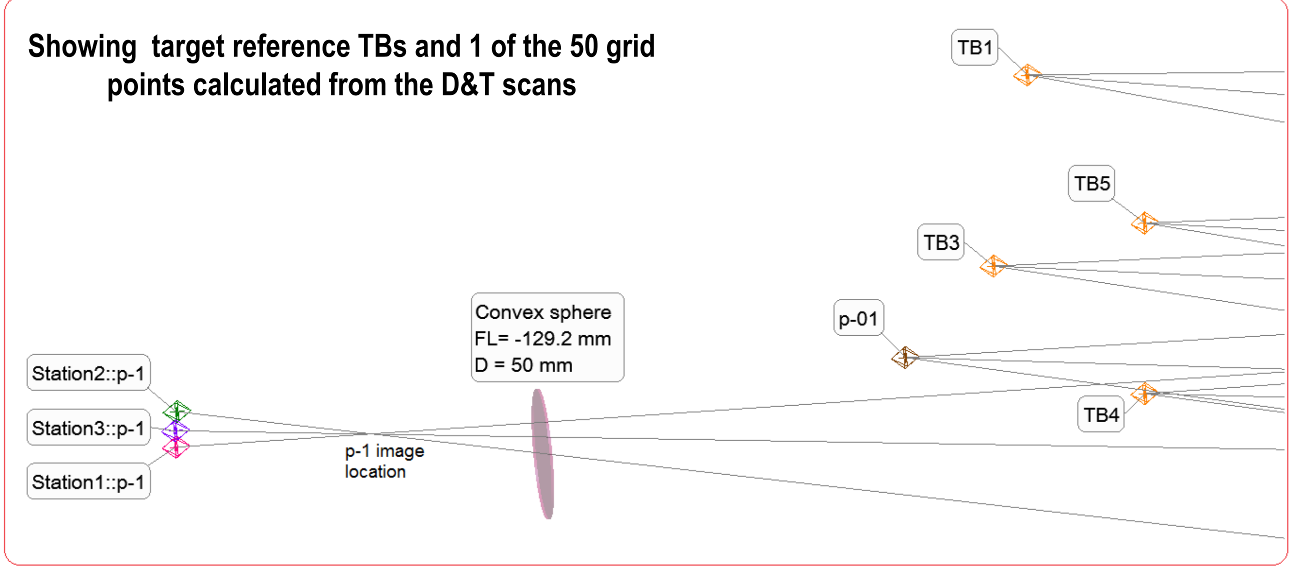


Mirror mount scan

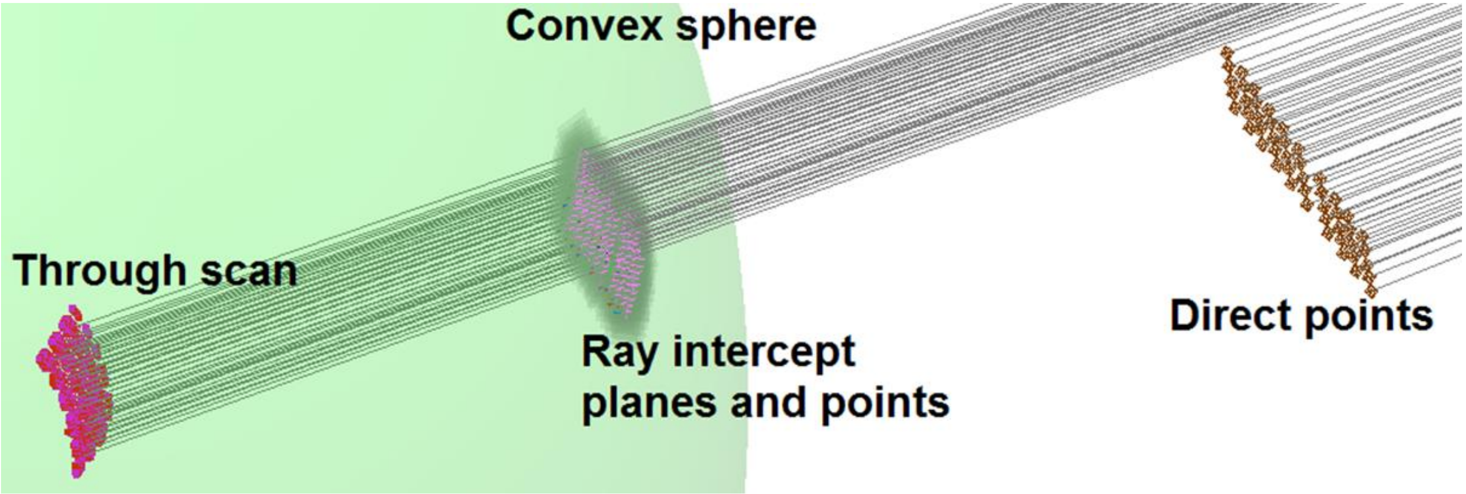
Convex sphere seen in SA interface and grid target seen in reflection

Data collection-Convex sphere

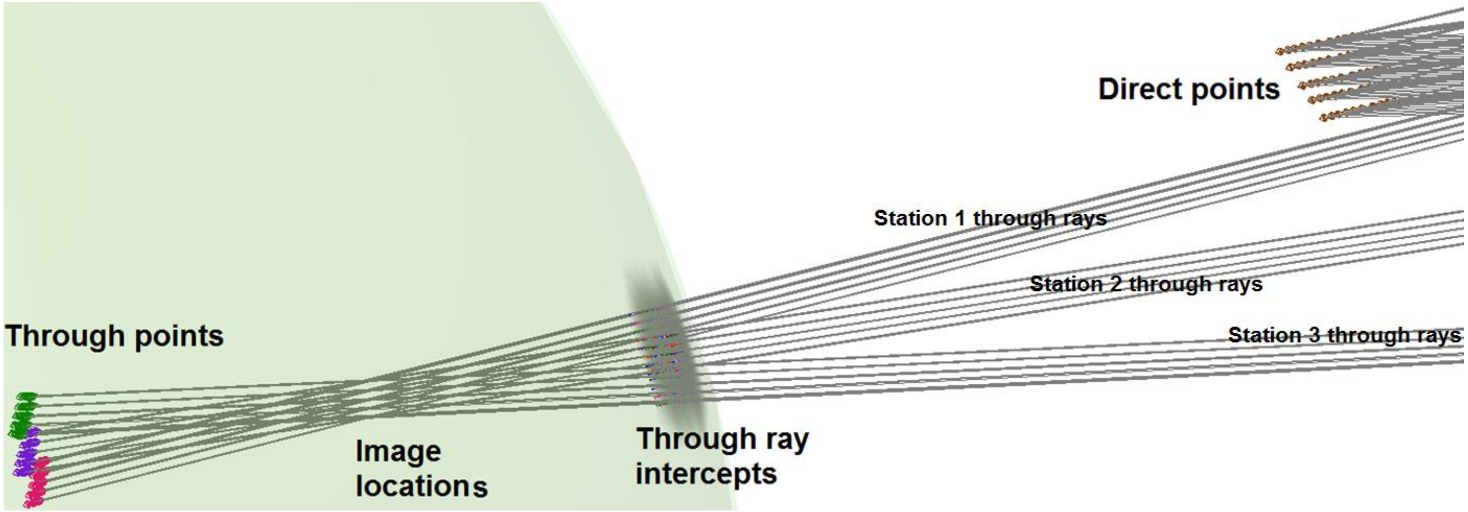




Data collection-Convex sphere



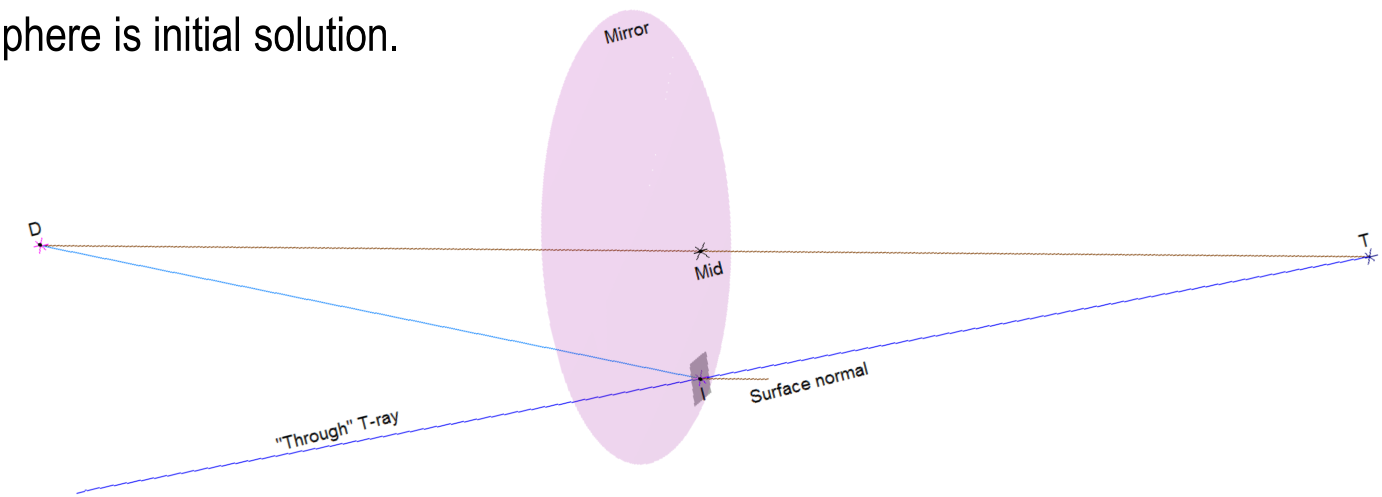
"Direct" points and "through" target LR scan measured from station1 and corresponding "through" ray-surface intercept point and fold planes



D&T grid points and ray intercepts resulting from 3 LR stations

Analysis

- **LR pre analysis**
  - Calculate grid points from target scan point clouds (LR fails to measure TBs in reflection)
  - Done with custom Measurement Plan (MP) in SA
- **Preliminary analysis**
  - Analysis and data export using custom SA MP
  - Simple law of reflection
    - Line between actual/direct, “D”, and apparent/through, “T”, points → fold plane/test surface normal
    - Mid point between D and T targets → fold plane offset
    - Intersection of instrument-image LS, T-ray, with fold plane → surface intercept
- **Surface intercept and direction cosine data processed with custom developed MATLAB optimization code**
  - Data fit to conic surface formula for optimum RoC and k
  - Sphere is initial solution.



PoC study results

- **OAP**
  - Nominal RoC = 3048 ± 7.62 mm

Method	Total # points	# Points ignored	RoC	k
LR vision scan	332255	1808	3047.501	-0.9976
LR D&T	150	27	3047.208	-1.0041
LT D&T	11	0	3047.809	-1.0000

- **Convex sphere**
  - Sphere fit in SA: RoC = -258.428 mm
  - RMS error = 0.031 mm
  - Total # points = 150; # ignored = 8
  - Nominal RoC = -258.40 ± 2.58 mm
  - **Convex sphere couldn't be tested using LT D&T or LR vision scan**

<table>
<tr><td>Sphere Fit Results:
Radius (mm)</td><td></td><td>258.4282</td><td>(free)</td><td></td></tr>
<tr><td></td><td></td><td>X</td><td>Y</td><td>Z</td></tr>
<tr><td>Center (mm)</td><td></td><td>0.2729</td><td>5.2238</td><td>258.1352</td></tr>
<tr><td>Percent Coverage</td><td></td><td>0.8333</td><td></td><td></td></tr>
<tr><td></td><td>DEVIATION STATS</td><td></td><td></td><td></td></tr>
<tr><td>Mean</td><td></td><td>0.0000</td><td>RMS</td><td>0.0307</td></tr>
<tr><td></td><td>Magnitude</td><td></td><td></td><td></td></tr>
<tr><td>|Max|</td><td></td><td>0.0944</td><td>|Min|</td><td>0.0001</td></tr>
<tr><td></td><td>Signed</td><td></td><td></td><td></td></tr>
<tr><td>Max</td><td></td><td>0.0812</td><td>Min</td><td>-0.0944</td></tr>
<tr><td>Total Number</td><td></td><td>142</td><td></td><td></td></tr>
<tr><td>Points Used</td><td></td><td>142</td><td></td><td></td></tr>
<tr><td></td><td></td><td>Measured on outside.</td><td></td><td></td></tr>
<tr><td>All offsets set to</td><td></td><td>0.0000</td><td></td><td></td></tr>
<tr><td>8 points ignored (unchecked) in fit.</td><td></td><td></td><td></td><td></td></tr>
</table>

Summary

- **PoC study to use CMIs to characterize concave conic and convex spherical mirrors**
- **Calibrated grid target position, using reference TBs, transformed to obtain "direct" positions**
- **Apparent target position measured along instrument-image LS**
- **D&T measurements yield "through" ray-surface intercept and optical surface slope by applying law of reflection**
- **Surface intercepts ad slopes are fit to conic surface formula for optimum RoC and k**

- **CMI optical testing advantages**
  - Non-contact test, lower risk of hardware damage,
  - greater dynamic range of prescriptions and increased flexibility (setups similar for different prescriptions of test mirrors),
  - in-situ, no need to remove test article from fabrication/integration setup,
  - utilizes same metrology solution, LR/LT, for multiple stages of telescope assembly and testing,
  - relatively fast,
  - can be automated to lower labor costs and reduce human error

- **Applications to large telescope development**
  - Offer alternate mirror prescription verification method that does not require additional GSE
  - Guide mirror assembly and alignment
  - Coarse co-phasing of segmented mirrors

Future work

- **Make a high precision point grid target**
  - Larger size, more grid points, and more reference targets
- **Improve point grid finder MP**
  - Enhanced functionality for both flat and curved/distorted surfaces (“through” target case with fast mirrors)
- **Automate D&T data collection**
- **Improve conic fit optimization code**
- **Evaluate uncertainties and limitations to powered surface testing using D&T method**
- **Characterize and align multiple hard-to-test surfaces using conventional methods**
  - Large conic convex mirror (space telescope secondary mirror, M2, spare)
  - freeform mirror,
  - or deformable mirror
- **Use cascaded D&T method to align fiducial-free individual surfaces in assembled optical system**
  - Individual mirrors assumed well characterized
  - Cassegrain telescope secondary mirror 6 degree-of-freedom (DOF) alignment to mechanical system under well known movement *
  - Measuring /trending effective focal length application

Acknowledgements

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  - Sierra Lobo Optics group, led by Kevin Redman, for providing technical support

References

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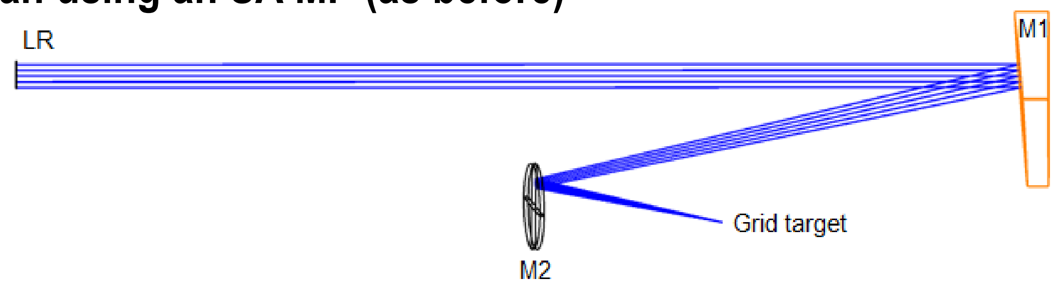
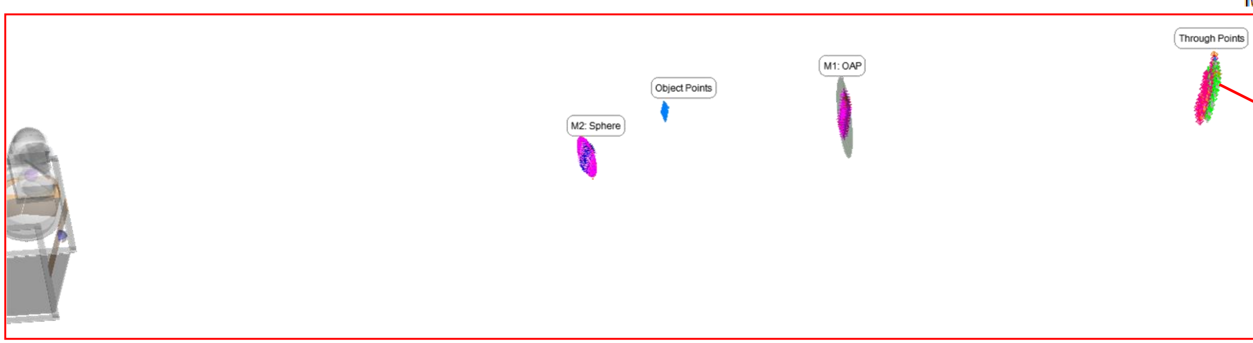
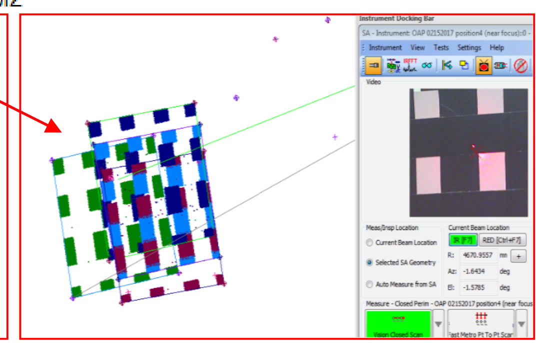
Additional slides

Cascading D&T method for aligning fiducial-free surfaces

- **PoC study: Measuring/trending effective FL**
  - Work at early stages and not published
- **2-mirror system**
  - M1 : OAP, 60” FL, 12” diameter
  - M2 : Sphere, 60” FL, 6” diameter
- **Target placed near focus, at 3 positions**
- **LR beam collimated via instrument advanced settings**
- **D&T measurement of custom grid target before and after moving M2**
- **Grid points calculated from scan using an SA MP (as before)**
  - 50 points per position

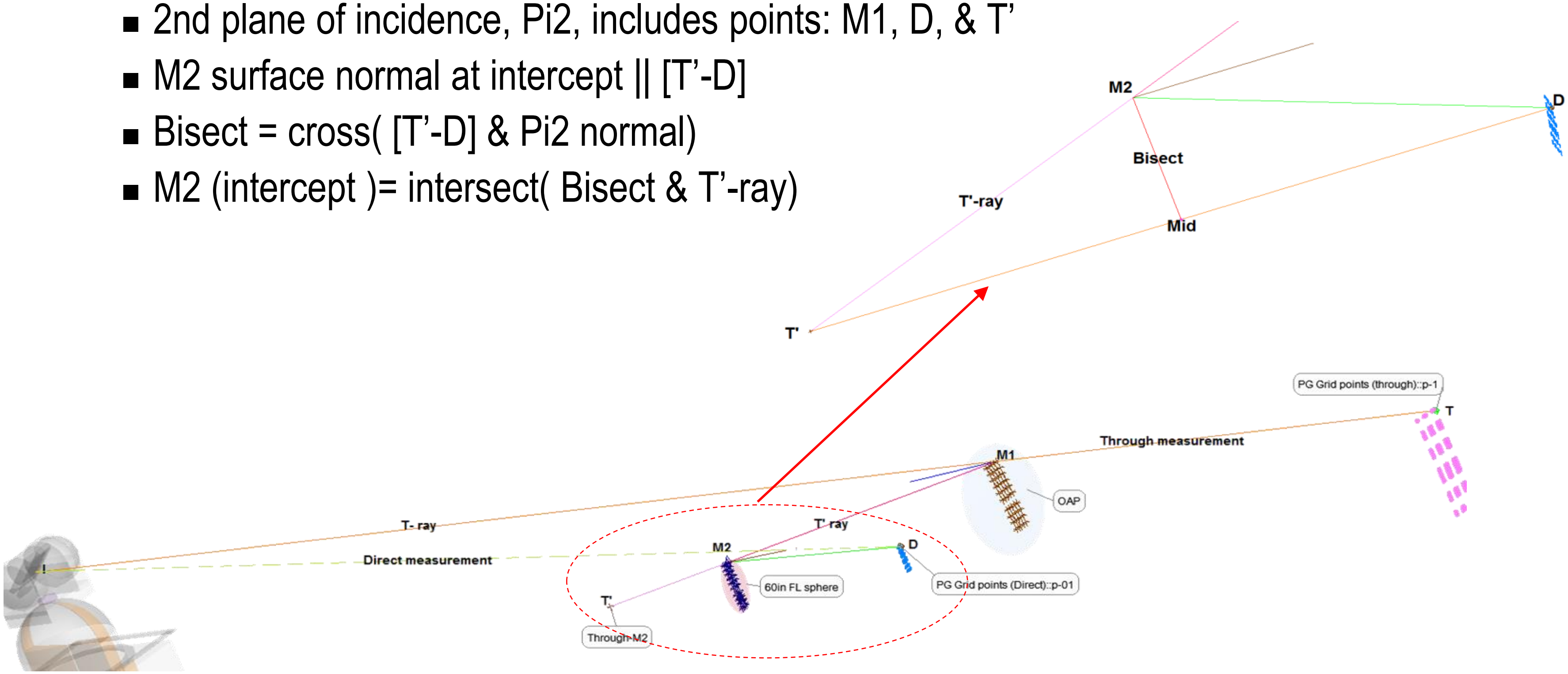






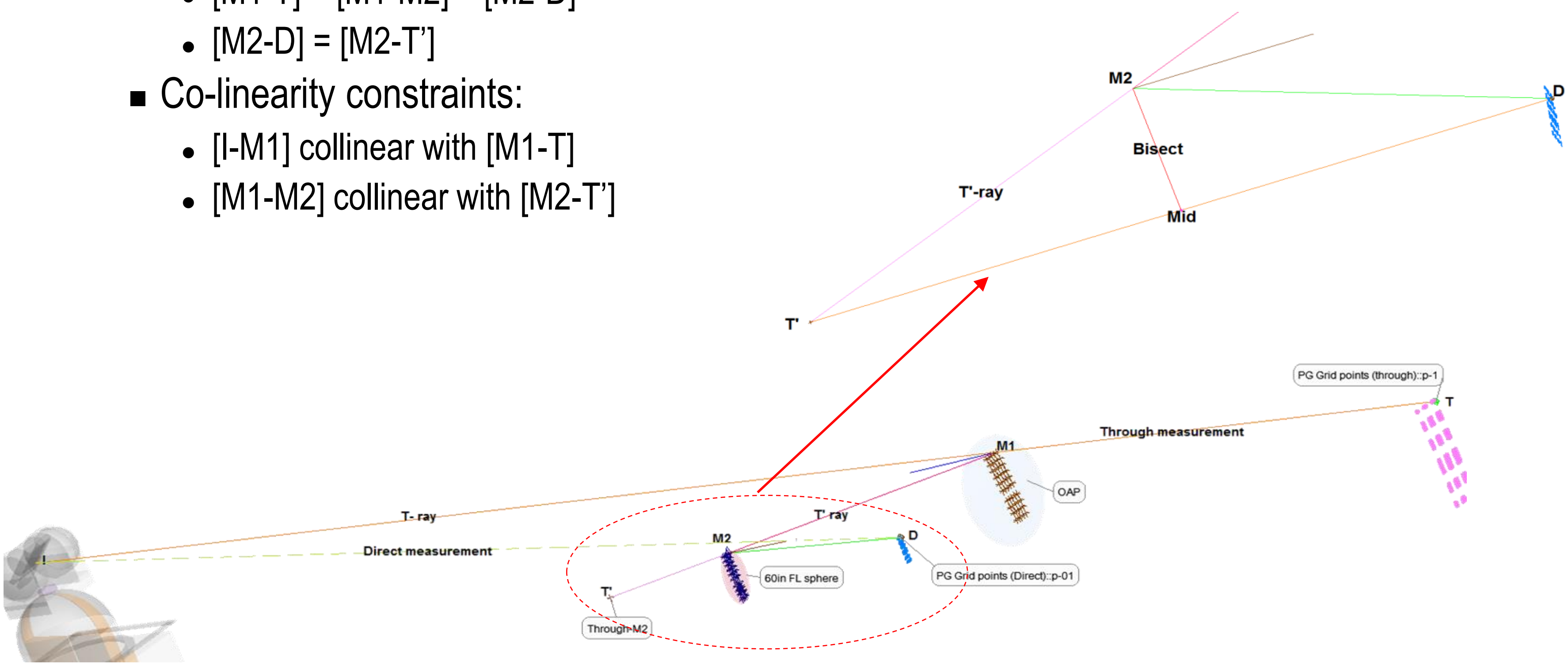
PoC measuring/trending effective FL- continue

- **Optimization code initial solution**
  - Assumes approximate knowledge of mirror 1 vertex sphere (M1-CC point)
  - 1st plane of incidence, Pi1, includes points: M1-CC, I, & T
  - T-ray (I-T line) intersect with M1 sphere = M1 (intercept)
  - T'-ray = reflected [I-M1] about M1 surface normal, line [M1-CC]
  - T' point, through M2, constructed from constraint: [M1-T] = [M1-T']
  - 2nd plane of incidence, Pi2, includes points: M1, D, & T'
  - M2 surface normal at intercept || [T'-D]
  - Bisect = cross([T'-D] & Pi2 normal)
  - M2 (intercept)= intersect(Bisect & T'-ray)



PoC measuring/trending effective FL- continue

- **Optimize M1&M2 intercepts**
  - M1 intercepts follow conic/aspheric surface formula
  - Magnitude constraints:
    - [M1-T] = [M1-T']
    - [M1-T] = [M1-M2] + [M2-D]
    - [M2-D] = [M2-T']
  - Co-linearity constraints:
    - [I-M1] collinear with [M1-T]
    - [M1-M2] collinear with [M2-T']



PoC measuring/trending effective FL- continue

- **RMS error of calculated M2 ray intercept to M2 calibrated sphere < 50 μm**

All Vectors Summary: Vector Group M2 Intercept points w.r.t M2 calibrated sphere				
Statistic	dX (mm)	dY (mm)	dZ (mm)	Mag (mm)
Min	-0.0074	-0.0022	-0.0009	-0.0843
Max	0.0808	0.0242	0.0015	0.0077
Average	0.0396	0.0121	0.0001	-0.0414
StdDev from Avg	0.0229	0.0070	0.0006	0.0239
StdDev from Zero	0.0461	0.0140	0.0006	0.0482
RMS	0.0456	0.0139	0.0006	0.0477
In Tol				50 (100.0%)
Out Tol				0 (0.0%)
Count	50			

PoC measuring/trending effective FL- continue

- **6 DOF transformation from non-contact, fiducials-free, LR D&T measurement of a 2-mirror system agrees with best-fit transformation of target reference TBs**
- **Effective focal length can be calculated based on the optical surface prescription and the calculated location/orientation using raytracing software such as ZEMAX**
- **Further improvement is possible by**
  - Improving optimization algorithm and imposing more constraints on M2 intercepts
  - Improving D&T measurement (PG Target, scan settings & point processing)

Best fit transformation of target reference TBs (Moved TBs to initial TBs)

Results	X	Y	Z	Mag
Count	5	5	5	5
Max Error	0.0009	0.0025	0.0022	0.0027
RMS Error	0.0006	0.0016	0.0014	0.0021
StdDev Error	0.0006	0.0017	0.0015	0.0024
Max Error (all)	0.0009	0.0025	0.0022	0.0027
RMS Error (all)	0.0006	0.0016	0.0014	0.0021
	Unknowns	6	Equations	15
Transformation				
Translation (mm)	0.1735	-9.4261	-9.7455	13.5594
Rotation (deg)				
Fixed XYZ	-0.6967	0.0014	-0.0105	
Euler XYZ	-0.6967	0.0015	-0.0105	
Axis-Angle	-0.999884	0.002106	-0.015105	0.6968
Matrix				
	1.000000	0.000184	0.000027	0.173451
	-0.000184	0.999926	0.012160	-9.426069
	-0.000024	-0.012160	0.999926	-9.745527
	0.000000	0.000000	0.000000	1.000000
Scale Factor				1.000000
Working frame				OAP 02032018::Frame-Parent

Best fit transformation of calculated ray intercepts (Moved M2 ray interceps to projected intercepts on initial M2 surface)

Results	X	Y	Z	Mag
Count	150	150	150	150
Max Error	0.2391	0.1123	0.0938	0.2524
RMS Error	0.1418	0.0481	0.0324	0.1532
StdDev Error	0.1423	0.0483	0.0325	0.1537
Max Error (all)	0.2391	0.1123	0.0938	0.2524
RMS Error (all)	0.1418	0.0481	0.0324	0.1532
	Unknowns	6	Equations	450
Transformation				
Translation (mm)	0.2970	-9.0838	-9.6860	13.2824
Rotation (deg)				
Fixed XYZ	-0.6927	-0.0032	-0.0185	
Euler XYZ	-0.6927	-0.0030	-0.0186	
Axis-Angle	-0.999631	-0.004517	-0.026784	0.6929
Matrix				
	1.000000	0.000324	-0.000053	0.296958
	-0.000324	0.999927	0.012089	-9.083774
	0.000057	-0.012089	0.999927	-9.685992
	0.000000	0.000000	0.000000	1.000000
Scale Factor				1.000000
Working frame				OAP 02032018::Frame-Parent