Cube Corner performance estimation using ZEMAX

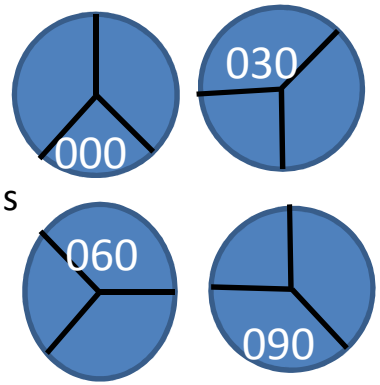
Mark Davis
US Naval Research Laboratory

David Arnold
Mike Pearlman
Harvard Smithsonian Center for Astrophysics

17th International Workshop on Laser Ranging
May 2011

Overview of Study

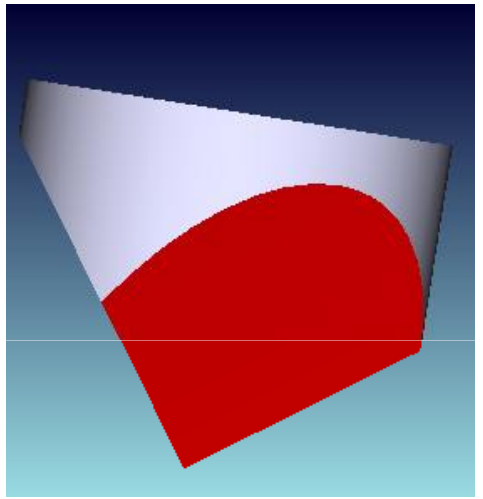
- Uncoated Corner Cubes
  - Extensive numerical comparison with David Arnold's models and results
    - Incident angles of 0 and 14 degrees for the 1.5" cube
    - Coordinate Frames (Linear Polarizations and Cube References)
    - Cube Orientation and "Clocking"
    - Quadrature Clocking Results (4 cubes oriented at 0,30,60,90 degree and summed)
    - Interpolated Annulus Response
    - Normalized (with respect to a perfect reflector)
    - Airy Units (Millions of meters^2 (MSM))
- Diameter and Spoiling Permutations
    - ZEMAX modeling and scripting
    - Custom software for interpretation, summary and extrapolations
- Results for average and worst case incident angles
    - Physical Size
    - Variation in the annulus of interest
    - Number of Cubes



All designs meet 100 MSM (on average)

What does ZEMAX Offer?

- Commercial Package “Software for Optical System Design”
  - Corner cube is defined by physical solids
    - 4 vertices (Defines the “clocking” or orientation),
    - Boolean Intersection with a cylinder constructs the solid
    - Variable Substrate , surface coating and thickness
    - Surface Tolerance
    - Aperture stops
  - Illumination Situation
    - Incident angle about any direction
    - Arbitrary wavelength
    - Laser Polarization defined via Jones Vector (H,V, circular, and elliptical)
  - Generates the Transmission Report and Huygens Point Spread Function (normalized to unity)
- Post processing software
  - Generates the annulus statistics results and converts to MSM units
  - Quadrature sum



Enormous amount of flexibility to vary the situation (sometimes to much!)

Cubes Modeled in Zemax

	aperture	radius	CLOCKING 000										
inches	mm	mm	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
1	25.40	12.70	x	x	x	x	x	x	x	x	x	x	x
1.1	27.94	13.97	x	x	x	x	x	x	x	x	x	x	x
1.2	30.48	15.24	x	x	x	x	x	x	x	x	x	x	x
1.3	33.02	16.51	x	x	x	x	x	x	x	x	x	x	x
1.4	35.56	17.78	x	x	x	x	x	x	x	x	x	x	x
1.5	38.10	19.05	x	x	x	x	x	x	x	x	x	x	x
1.6	40.64	20.32	x	x	x	x	x	x	x	x	x	x	x
1.7	43.18	21.59	x	x	x	x	x	x	x	x	x	x	x
1.8	45.72	22.86	x	x	x	x	x	x	x	x	x	x	x
1.9	48.26	24.13	x	x	x	x	x	x	x	x	x	x	x

	aperture	radius	CLOCKING 000,030,060,090										
inches	mm	mm	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
1	25.40	12.70											
1.1	27.94	13.97	x	x	x	x	x						
1.2	30.48	15.24	x	x	x	x	x						
1.3	33.02	16.51	x	x	x	x	x						
1.4	35.56	17.78	x	x		x	x	x					
1.5	38.10	19.05	x	x			x	x	x				
1.6	40.64	20.32	x			x	x	x	x	x			
1.7	43.18	21.59	x				x	x	x				
1.8	45.72	22.86	x							x			
1.9	48.26	24.13	x							x			

Colored Cells were "Best" In Some situation

990 patterns at clocking of 000 and
351 combinations of patterns quad clocked

GNSS Specifics and Assumptions

- Annulus is specific to mission
- 532.1 nm
- 0 to 14 deg incidence angle

Mission	Minimum urad	Maximum urad
GPS	23.0	26.25
GIOVE	21.75	25.75
COMPASS	22.5	26.0
GLONASS	23.5	28.0
ETS	17.9	18.4
QZSS	17.0	20.0

24.5 was used for all the GPS-III results

GNSS Optical Antenna Pattern Trade Space

- 1.0 to 1.9 inch aperture uncoated cubes at 0.1” steps
  - 0.0 to 1.0 arcsec spoiling
  - Clocking with and with out quadrature
  - Linear and circular excitation lasers
  - Incident angles 0, nominal (7 deg), and worst case (14 deg)
  - Thousands of diffraction patterns generated in ZEMAX optical design software
  - Evaluation at the working annulus
  - Validation and Comparison with Legacy Analysis Codes
- Evaluate all combinations (minimum and average in the annulus) to
  - Achieve Optical Cross Section exceeding 100 Millions of Square meters
  - Derive the number of cubes
  - Estimate the physical size (rules of thumb packing factors)
  - Measure signal variation in the annulus

ALL designs (by construction) are 100 MSM on average in the annulus

Incident 0 degree results – Rarely Used – easy to model

minimum needed to meet the 100 MSM

on average at 24.5 microradians

000 Clocking/ Quad Clock - Circular

Incidence 0 deg -000	Diameter (mm)	DAO Arcsec	Variation %	Avg #Cubes	Edge Length (cm)	Cube Normalized	Cube MSM
Most compact – mechanical size	48.3	0.7	71	19	24	0.03563	5.29193
Most stable – lowest signal variation in the annulus	25.4	0.3	23	116	32	0.07606	0.86675
Lowest number of cubes	48.3	0.7	71	19	24	0.03563	5.29193
Largest Average Cross section in Annulus	48.3	0.7	71	19	24	0.03563	5.29193
Largest Peak Cross section in Annulus	48.3	0.6	81	20	25	0.03433	5.09881

Incidence 0 deg - QUAD	Diameter (mm)	DAO Arcsec	Variation %	Avg #Cubes	Edge Length (cm)	Cube Normalized	Cube MSM
Most compact – mechanical size	48.3	0.7	7	19	24	0.03572	5.30537
Most stable – lowest signal variation in the annulus	33.0	0.0	3	43	25	0.07214	2.34789
Lowest number of cubes	48.3	0.7	7	19	24	0.03572	5.30537
Largest Average Cross section in Annulus	48.3	0.7	7	19	24	0.03572	5.30537
Largest Peak Cross section in Annulus	48.3	0.7	7	19	24	0.03572	5.30537

000 Clocking/ Quad Clock - Linear

Incidence 0 deg -000	Diameter (mm)	DAO Arcsec	Variation %	Avg #Cubes	Edge Length (cm)	Cube Normalized	Cube MSM
Most compact – mechanical size	48.3	0.7	70	21	26	0.03256	4.83603
Most stable – lowest signal variation in the annulus	25.4	0.1	49	127	33	0.06955	0.79259
Lowest number of cubes	48.3	0.7	70	21	26	0.03256	4.83603
Largest Average Cross section in Annulus	48.3	0.7	70	21	26	0.03256	4.83603
Largest Peak Cross section in Annulus	48.3	0.7	70	21	26	0.03256	4.83603

Incidence 0 deg - QUAD	Diameter (mm)	DAO Arcsec	Variation %	Avg #Cubes	Edge Length (cm)	Cube Normalized	Cube MSM
Most compact – mechanical size	48.3	0.7	46	21	26	0.03218	4.77907
Most stable – lowest signal variation in the annulus	33.0	0.0	0.9	47	26	0.06548	2.13118
Lowest number of cubes	48.3	0.7	46	21	26	0.03218	4.77907
Largest Average Cross section in Annulus	48.3	0.7	46	21	26	0.03218	4.77907
Largest Peak Cross section in Annulus	48.3	0.7	46	21	26	0.03218	4.77907

Incident 14 degree results – Low elevation and Acquisition

minimum needed to meet the 100 MSM

on average at 24.5 microradians

Quad Clocked - Linear

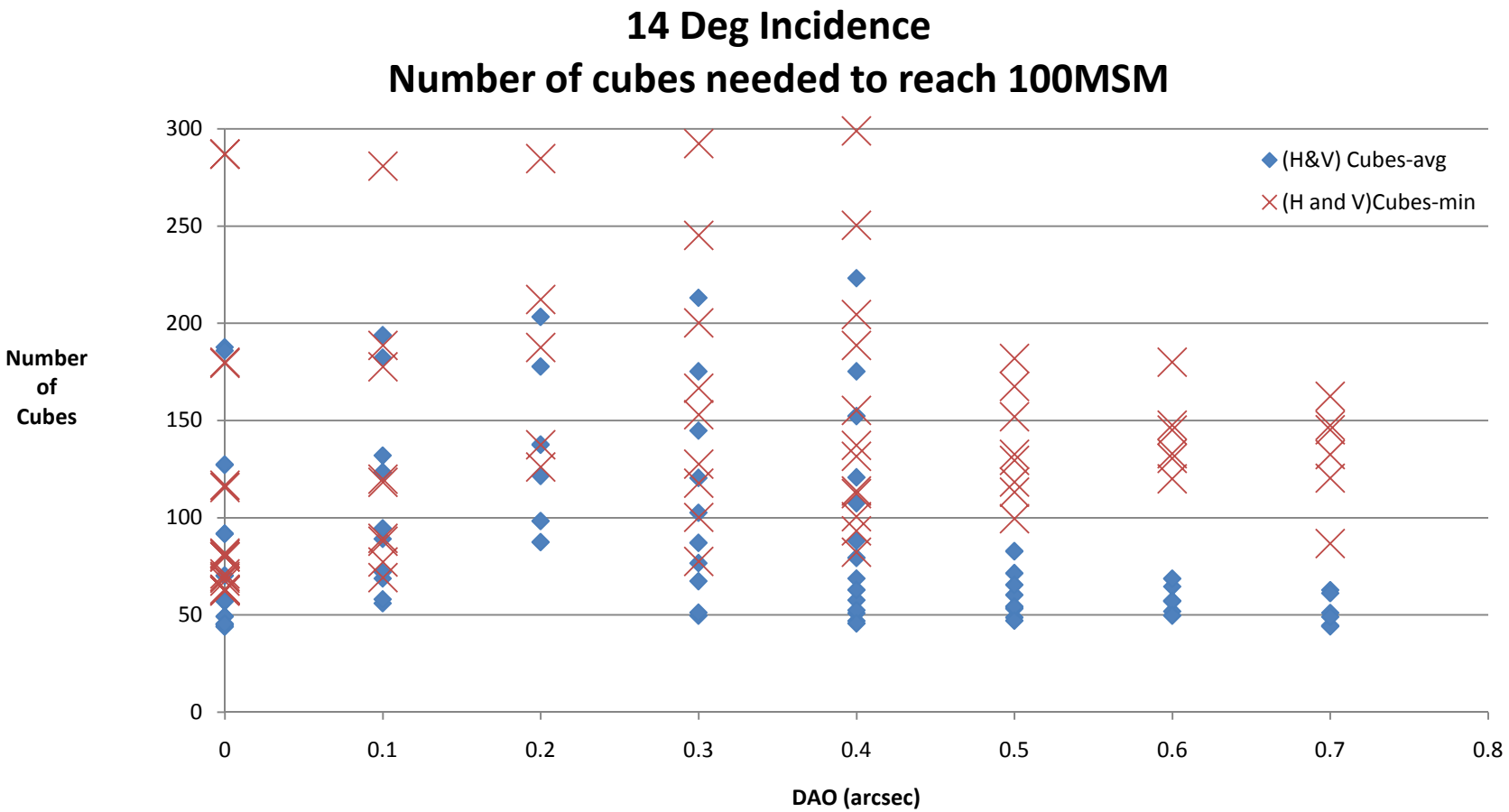
Incidence 7 deg	Diameter (mm)	DAO Arcsec	Variation %	Avg #Cubes	Edge Length (cm)	Cube Normalized	Cube MSM
Most compact – mechanical size	35.6	0.1	17%	50	29	0.04625	2.02451
Most stable – lowest signal variation in the annulus	33.0	0.0	8%	62	30	0.04965	1.6158
Lowest number of cubes	48.3	0.7	75%	31	31	0.02194	3.25786
Largest Average Cross section in Annulus	48.3	0.7	75%	31	31	0.02194	3.25786
Largest Peak Cross section in Annulus	48.3	0.7	75%	31	31	0.02194	3.25786

Incidence 14 deg	Diameter (mm)	DAO Arcsec	Variation %	Avg #Cubes	Edge Length (cm)	Cube Normalized	Cube MSM
Most compact – mechanical size	40.64	0.0	27%	50	32	0.027525	2.03531
Most stable – lowest signal variation in the annulus	35.6	0.0	15%	70	34	0.03255	1.42495
Lowest number of cubes	45.7	0.0	47%	44	35	0.02725	2.03531
Largest Average Cross section in Annulus	45.7	0.0	47	44	34	0.01903	2.27597
Largest Peak Cross section in Annulus	48.3	0.7	75%	45	37	0.01518	2.25469

Quad Clocked - Circular

Incidence 7 deg	Diameter (mm)	DAO Arcsec	Variation %	Avg #Cubes	Edge Length (cm)	Cube Normalized	Cube MSM
Most compact – mechanical size	38.1	0.0	12%	40	27.5	0.04353	2.51106
Most stable – lowest signal variation in the annulus	33.0	0.0	5%	57	28.4	0.05449	1.77333
Lowest number of cubes	48.3	0.7	23%	29	30	0.02334	3.46626
Largest Average Cross section in Annulus	48.3	0.7	23%	29	30	0.02334	3.46626
Largest Peak Cross section in Annulus	48.3	0.7	23%	29	30	0.02334	3.46626
Incidence 14 deg	**Diameter (mm)**	**DAO Arcsec**	**Variation %**	**Avg #Cubes**	**Edge Length (cm)**	**Cube Normalized**	**Cube MSM**
Most compact – mechanical size	38.1	0.1	14%	52	32	0.03300	1.90382
Most stable – lowest signal variation in the annulus	35.6	0.0	10%	65	33	0.03532	1.54613
Lowest number of cubes	43.2	0.0	27%	42	32	0.02519	2.39711
Largest Average Cross section in Annulus	45.7	0.0	36%	41	34	0.02062	2.46622
Largest Peak Cross section in Annulus	48.3	0.0	45%	42	36	0.01618	2.40213

Example of the “realm of possible solutions”



Minimum must exceed 100MSM

Incident 7 degree results – Typically elevation and Most Used

minimum needed to meet the 100 MSM

on average at 24.5 microradians

000 Clocking- Linear

Incidence 7 deg	Diameter (mm)	DAO Arcsec	Variation %	Avg #Cubes	Edge Length (cm)	Cube Normalized	Cube MSM
Most compact – mechanical size	35.6	0.0	76	48	28	0.0481	2.10569
Most stable – lowest signal variation in the annulus	25.4	0.0	45	177	39	0.04984	0.56791
Lowest number of cubes	48.3	0.7	82	30	31	0.02269	3.37012
Largest Average Cross section in Annulus	48.3	0.7	82	30	31	0.02269	3.37012
Largest Peak Cross section in Annulus	48.3	0.7	82	30	31	0.02269	3.37012

Incidence 14 deg	Diameter (mm)	DAO Arcsec	Variation %	Avg #Cubes	Edge Length (cm)	Cube Normalized	Cube MSM
Most compact – mechanical size	40.64	0.1	92	47	32	0.02889	2.15786
Most stable – lowest signal variation in the annulus	25.4	0.3	42	269	48	0.03266	0.37215
Lowest number of cubes	48.3	0.4	93	40	35	0.0172	2.55502
Largest Average Cross section in Annulus	48.3	0.4	93	40	35	0.0172	2.55502
Largest Peak Cross section in Annulus	45.7	0.1	109	43	34	0.01976	2.36351

000 Clocking- Circular

Incidence 7 deg	Diameter (mm)	DAO Arcsec	Variation %	Avg #Cubes	Edge Length (cm)	Cube Normalized	Cube MSM
Most compact – mechanical size	35.5	0.0	63	46	28	0.05034	2.20392
Most stable – lowest signal variation in the annulus	25.4	0.1	37	169	38	0.05213	0.59405
Lowest number of cubes	48.3	0.7	93	29	30	0.02348	3.48741
Largest Average Cross section in Annulus	48.3	0.7	93	29	30	0.02348	3.48741
Largest Peak Cross section in Annulus	48.3	0.6	102	29	30	0.02318	3.44308

Incidence 14 deg	Diameter (mm)	DAO Arcsec	Variation %	Avg #Cubes	Edge Length (cm)	Cube Normalized	Cube MSM
Most compact – mechanical size	40.6	0.0	82	46	32	0.02900	2.16568
Most stable – lowest signal variation in the annulus	27.9	0.0	43	186	44	0.0148	0.53651
Lowest number of cubes	48.3	0.5	134	41	36	0.01669	2.47902
Largest Average Cross section in Annulus	48.3	0.5	134	41	36	0.01669	2.47902
Largest Peak Cross section in Annulus	48.3	0.5	134	41	36	0.01669	2.47902

Discussion

- Trades
  - Number of cubes (Cost)
  - Most effective cube – Optically
  - Most compact mechanically
  - Most flexabilty for the stations
    - Linear Polarization control to “double” the cross section
    - Circular Polarizaton to automatically smooth the annulus
- Annulus Uniformity
  - How small can we make the in annulus variance?
  - What do we give up?

Next Steps and Questions

- Is 100 MSM enough for daytime AOS?
- How much bigger is needed to support routine daytime?
- What specific data is helpful from the LNF lab results
  - Model quantification
  - As built performance

- Results ZEMAX is designed for solving
  - Is an AR coating the Aperture beneficial?
  - What about Elliptical Beams?
  - Oops we clocked them backward
  - Shoulder Height impacts
  - Aperture Stops and the mechanical structure
  - Manufacturing Tolerances
  - Is the substrate the best we have today?
- Can we model Glonass 115 and CompassM1?
  - What tolerance and clocking data are available
  - How is the tray oriented wrt the body specific axis
  - Do we model the attitude accurately during noon/midnight turns?

Conclusions

- Panel Discussion

Spare Slides

ETS8/QZSS Heritage Concepts

- 1.6” Cube – Assume 100 MSM for 0 incident angle for the Average
  - strongest signal in the annulus at 0 deg --- cube clocked at 000
    - V 0.4” – need 38.2 cubes for 28.9x28.9cm --80%
    - H 0.4” – need 38.6 cubes for 29.0 x 29.0 cm – 78%
    - C 0.4” – need 35 cubes with 27.6 x 27.6 cm – 88%
    - Variation is 78 to 88% about this average
  - Strongest signal in the annulus at 0 deg – cube’s quad clocked
    - V 0.4” -- need 38 cubes for 28.8 x 28.8 cm – 49%
    - H 0.4” – need 39 cubes for 29 x 29 cm – 49%
      - At 14 deg this needs 93 (51 for avg) cubes – 40.4 % variation – size is 45 x 45 cm
    - C 0.4” -- need 35 cubes for 28x28 cm with 7% variation
      - Getting stations to add a QWP is feasable
      - At 14 deg this needs 75 (55 for avg) cubes – 30% variation – size is 38 x 38 cm

Circular solution with quad clocking works well
Still can use +49 or +80% signal if you orient the linear beam correctly

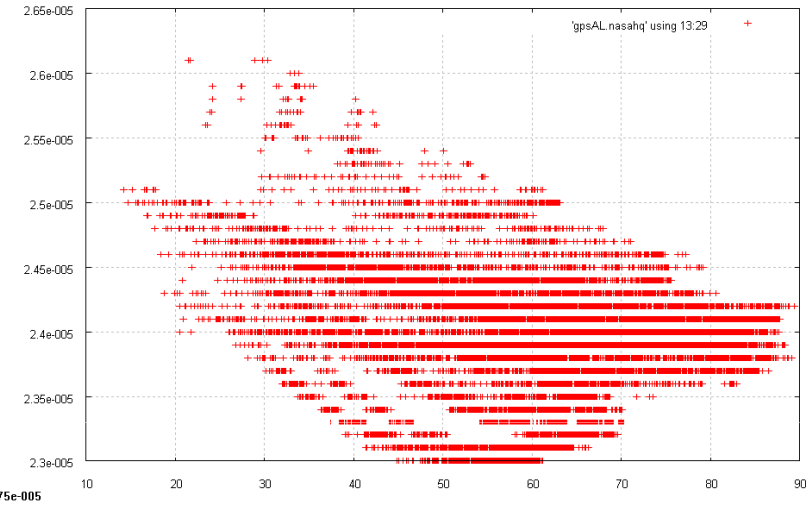
Unspoiled Concept

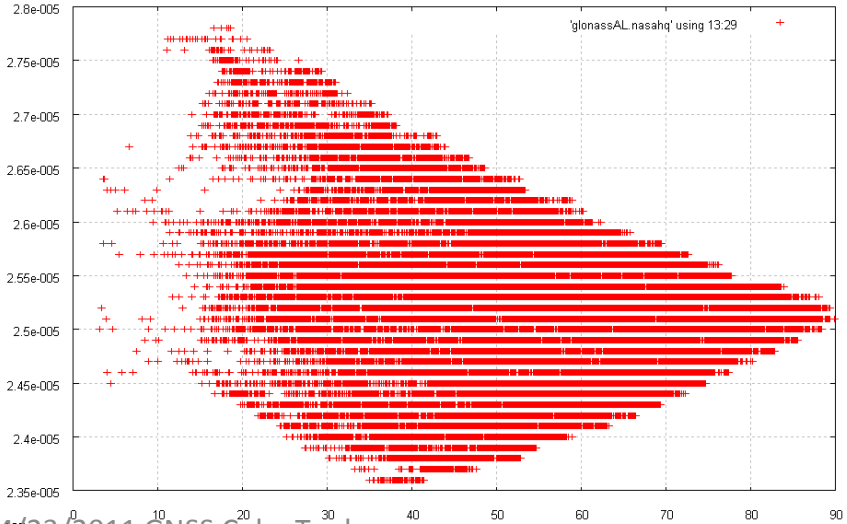
- 1.5” Cube 38.1 mm – Assume 100 MSM for 0 incident angle for the Average
  - strongest signal in the 24.5 urad annulus at 0 deg --- Assumes quad clocking
    - In terms of MSM
  - V -- 39 cubes –1.4 % variation - 27x27 cm
  - H - 40 cubes – 1.4% variation – 27.2 x 27.2 cm
    - At 14 deg we need 69 cubes and still get 18.8% variation -36 x 36 cm
  - C – 37 cubes – 3.8% variation – 26 x 26 cm
    - At 14 deg we need 61 cubes and still get 13.3% variation
- 1.1” cube - 27.94 mm Cube – Assumes 100 MSM for 0 incident angle for the Average
  - Strongest Normalized unit signal
  - V – 84 cubes for 1.0% variation needs 29.2 x 29.2 cm
  - H – 84 cubes for 1.0 % variation needs 29.2 x 29.2 cm
    - At 14 deg we need 287 cubes (187 for the average) and have 31 % variation – 54 x 54 cm
  - C – 79 cubes for 1.3 % variation needs 27.8 x 27.8 cm
    - At 14 deg we need 206 cubes and still have 13.8% variation

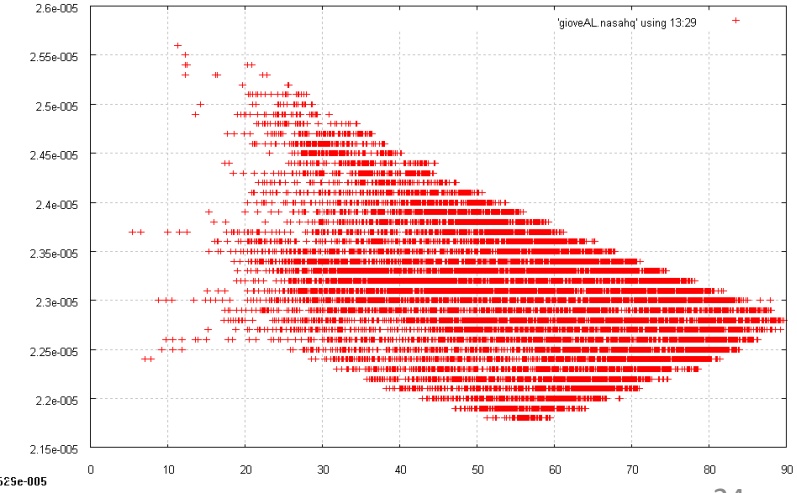
Variability grows off normal incidence

OTHER BACKUPS

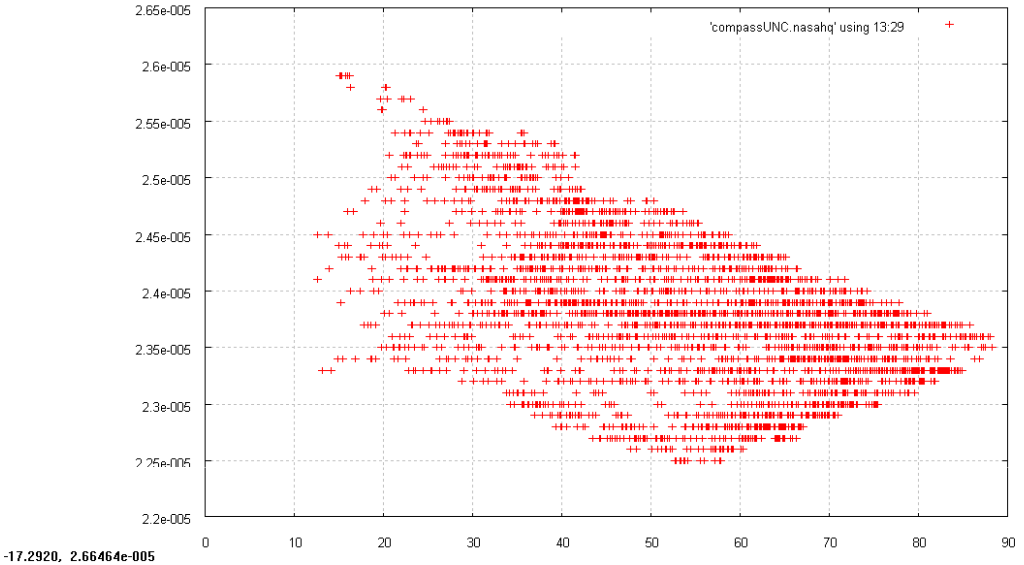
Tracking today: Aluminum Coated



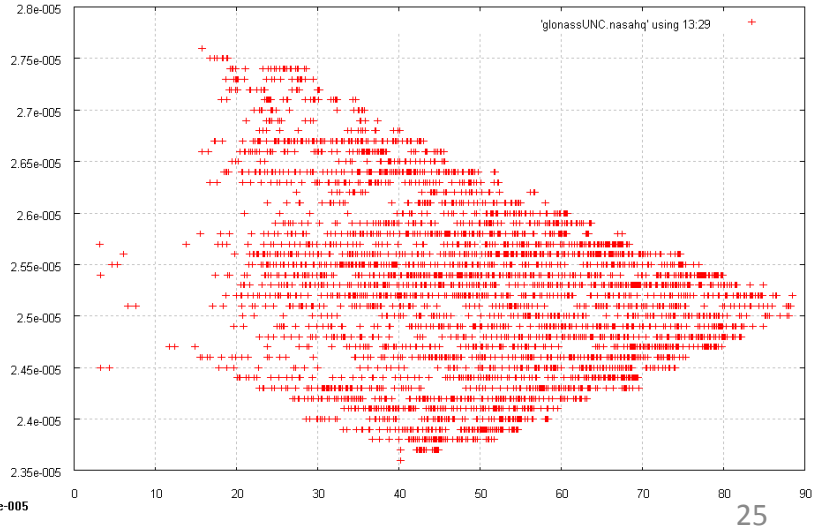




Tracking Today: Uncoated



-17.2920, 2.66464e-005



-18.1600, 2.81637e-005

Optimize for the worst case at AOS/LOS

Assumptions

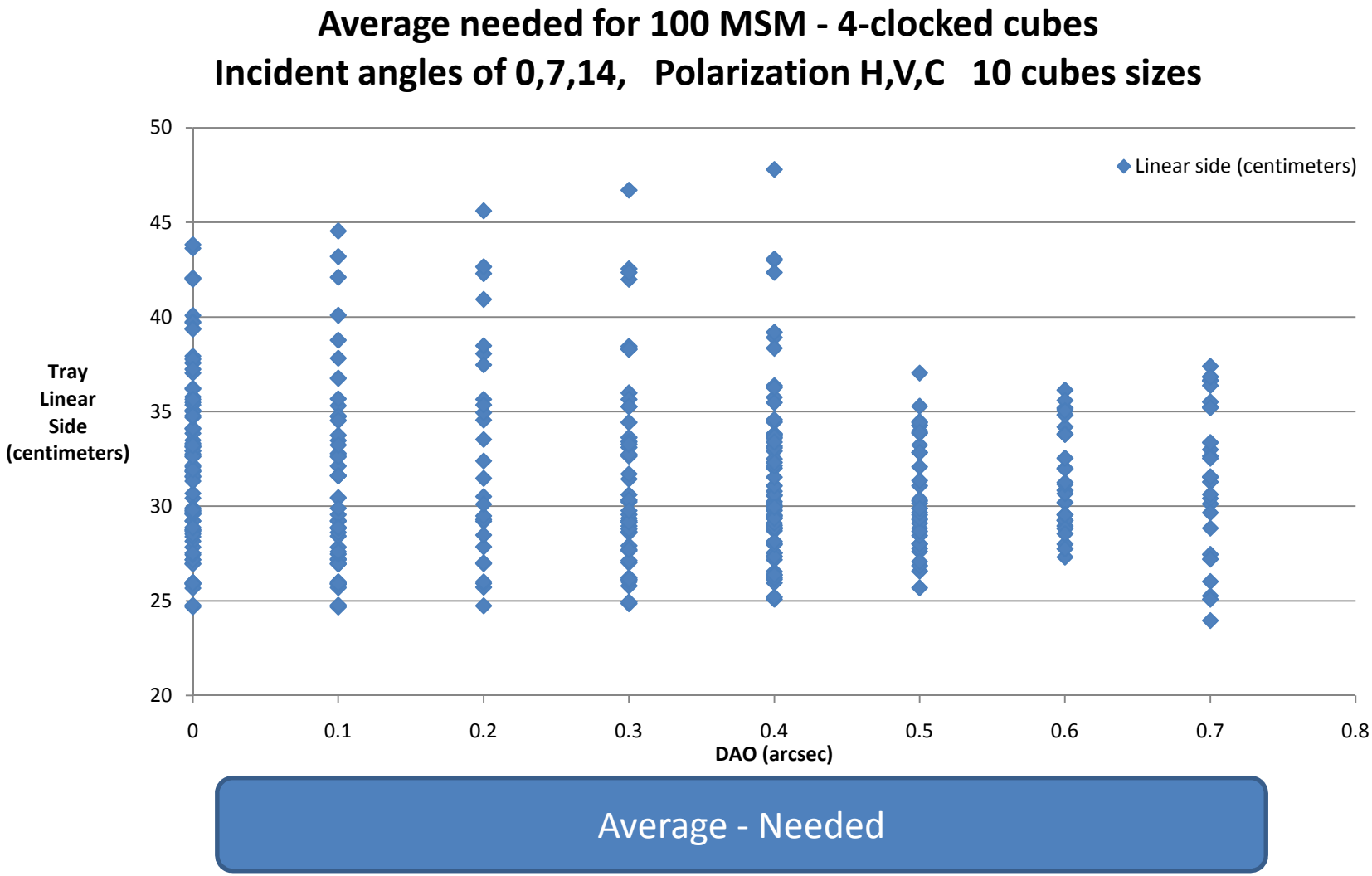
- Annulus is 24 microradians
- Uncoated cubes
  - 1 mm at aperture “extra height”
- Properly mounted to minimize thermal effects
- Maximum of 14 deg off normal
- Stations are using either Linear or Right Circular Polarization
- 100 Million Square Meters (MSM) is enough
  - All tray size and number of cubes target this limit

Array Area to achieve 100 MSM

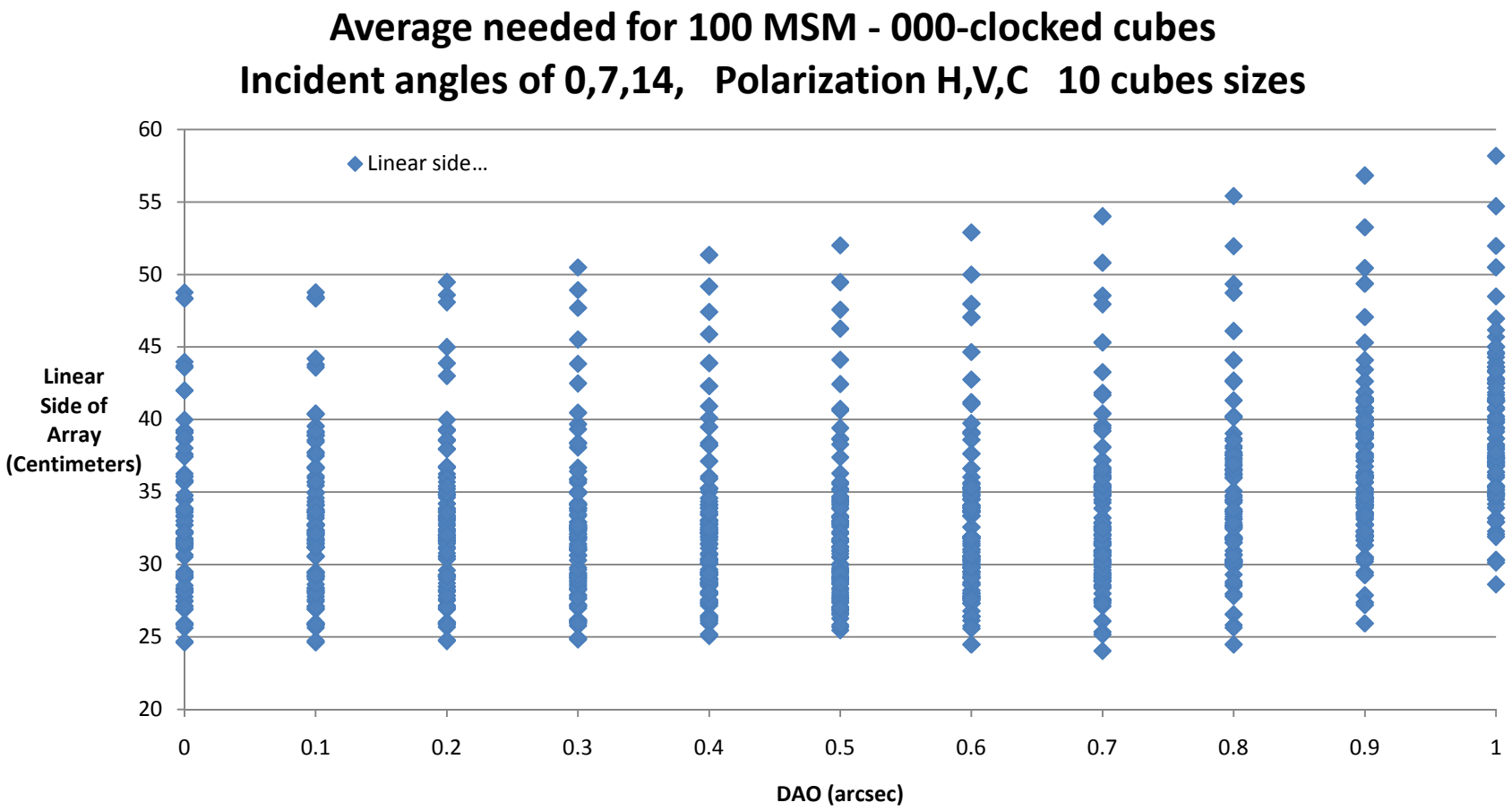
- For Each combination of
  - Incident angle 0, 7, 14 degrees
  - Dihedral Angle Offset (DAO)Spoiling [0 to 1]
  - Cube size [1 to 1.9 inch]
  - Polarization Horizontal, Vertical, Right Circular
  - Compute the Min, Average, Max within 1 urad of the annulus of interest
    - Normalized (to unity airy disk)
    - MSM (Millions of Square Meters)
    - Number of cubes needed to achieve the 100MSM for min and average
  - Array Size
    - N cubes * optical area (pi()*cuberadius^2) * scale
    - Scale chosen to be 1.67 for ETS8 style
      - Others were 2.3 GPS-blockII, 2.46 – Compass, 2.3-Optus
    - Report the linear side dimension (assumes a square solution)

By construction – ALL the designs will meet the 100 MSM

Quad-Clocked Results

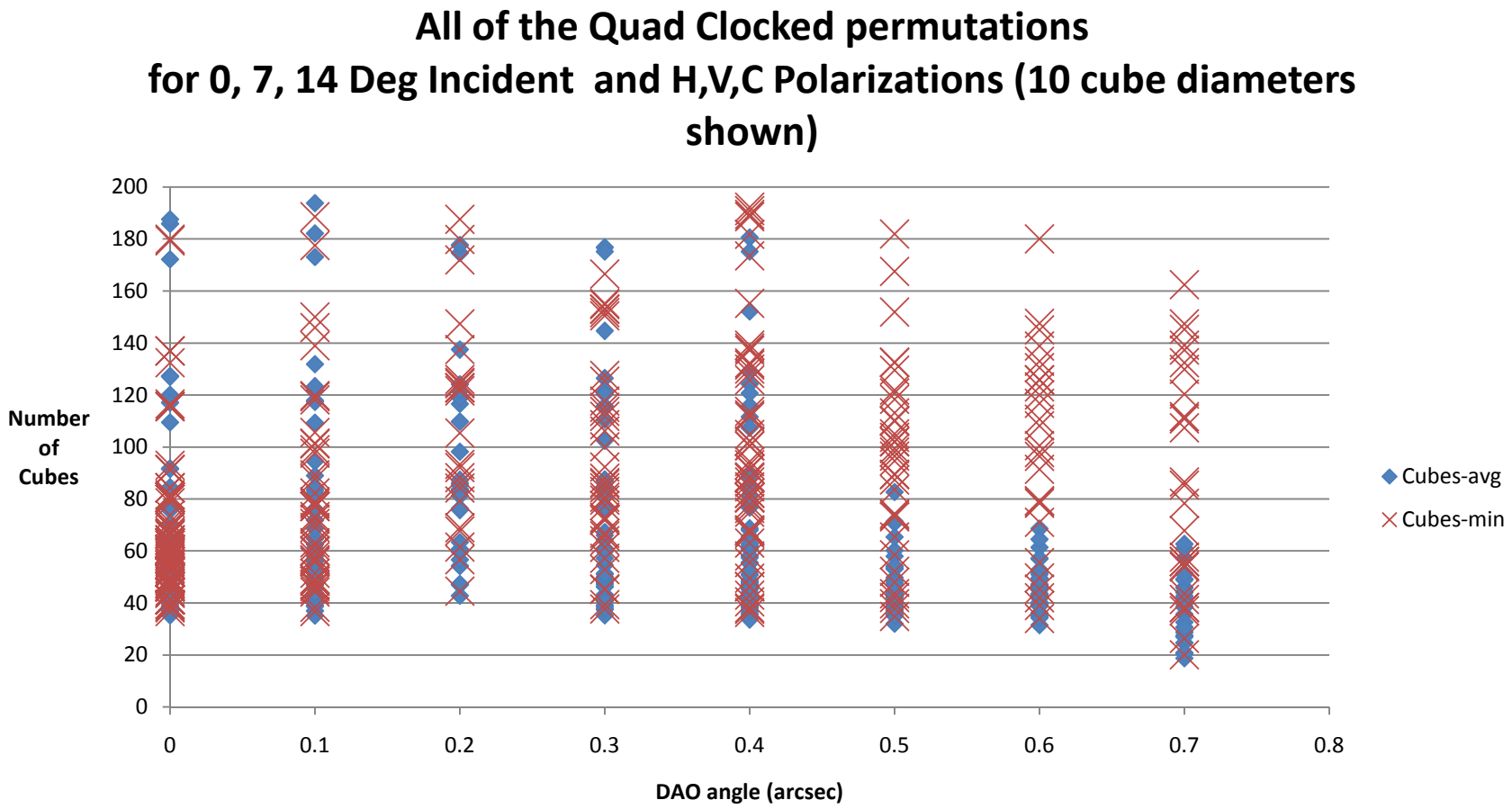


Cube at 000 results

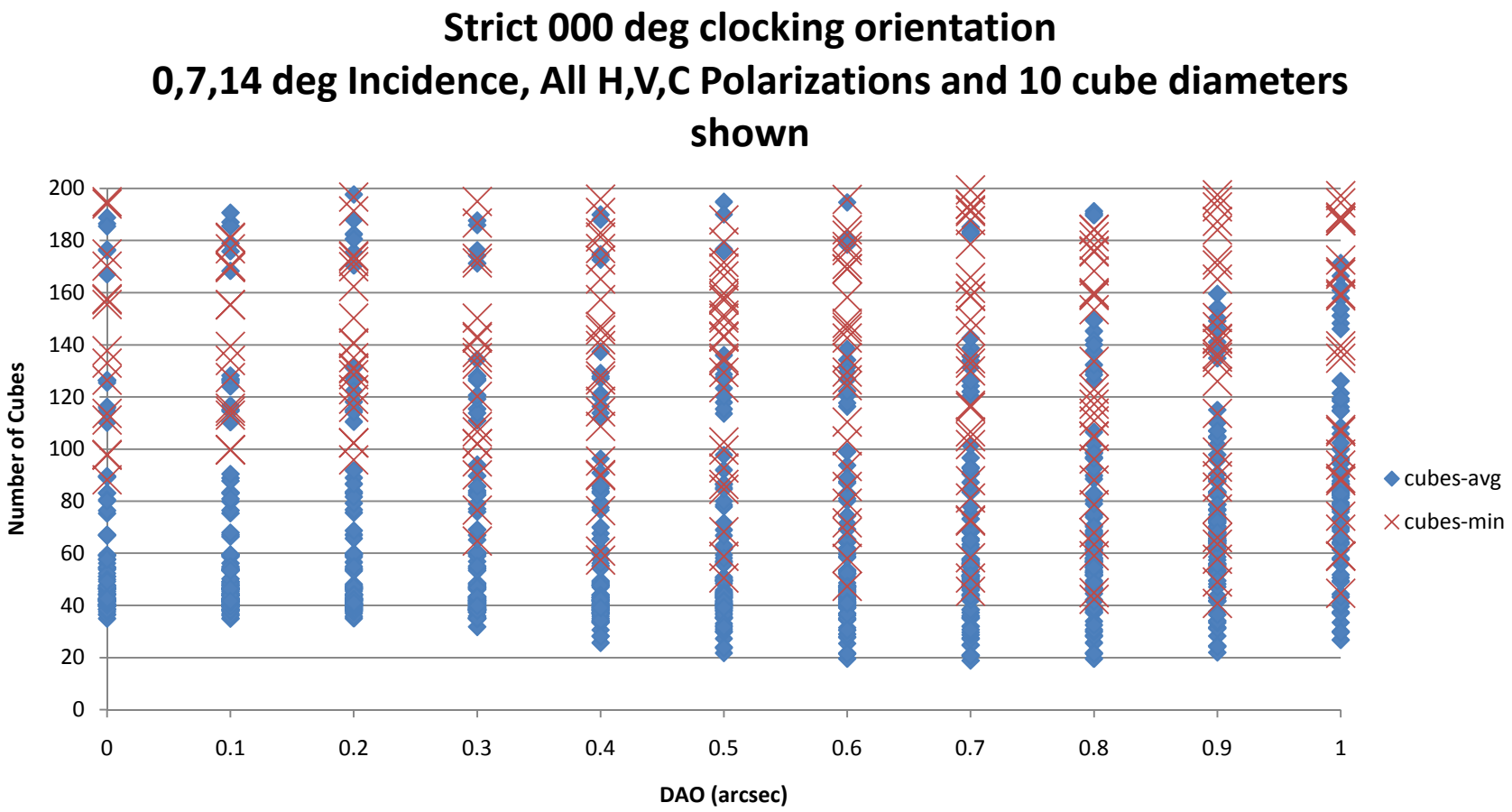


Average needed

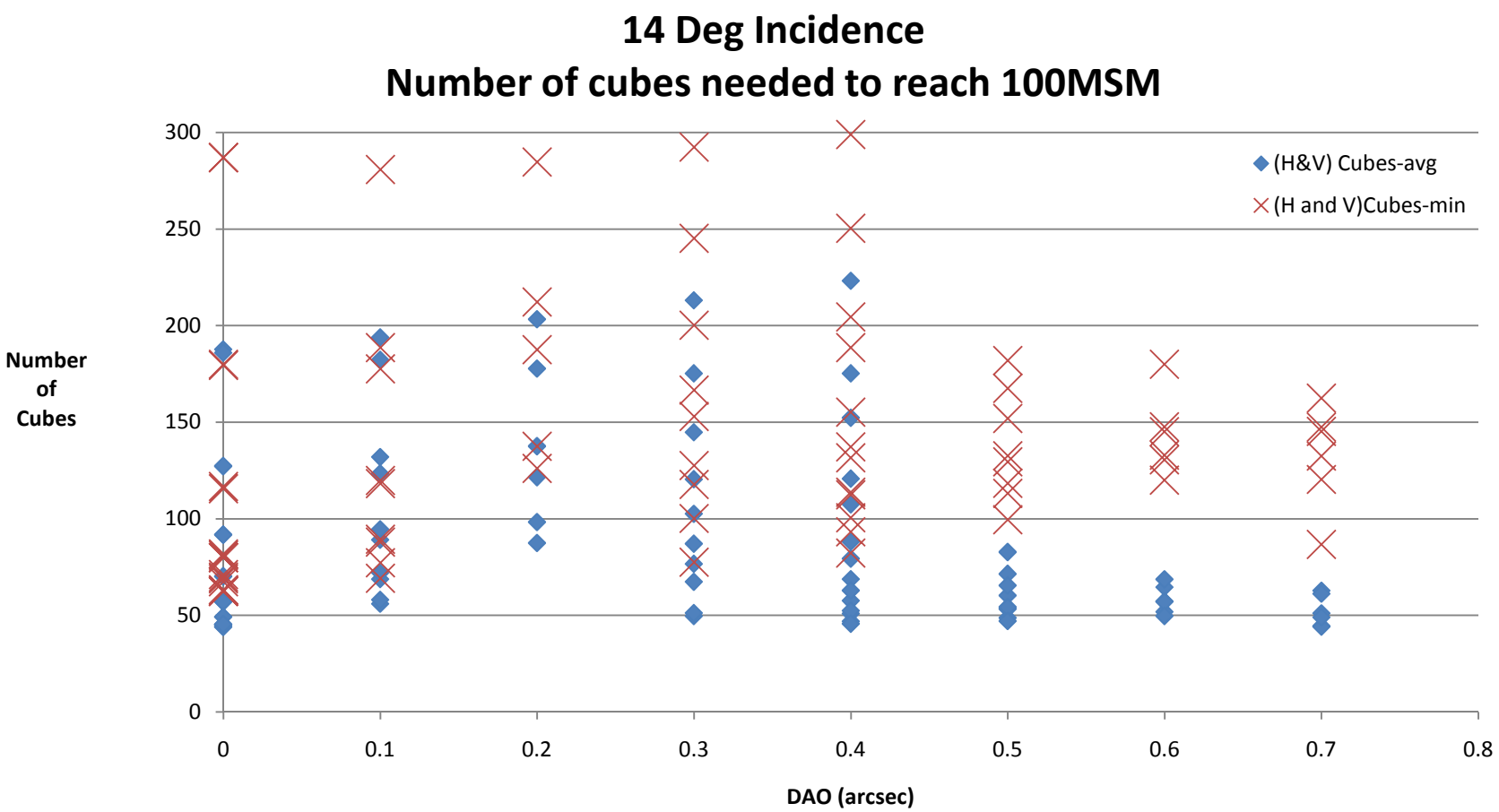
Big Picture – 4 cube clocking orientations



Big Picture – Strict 0 deg clocking

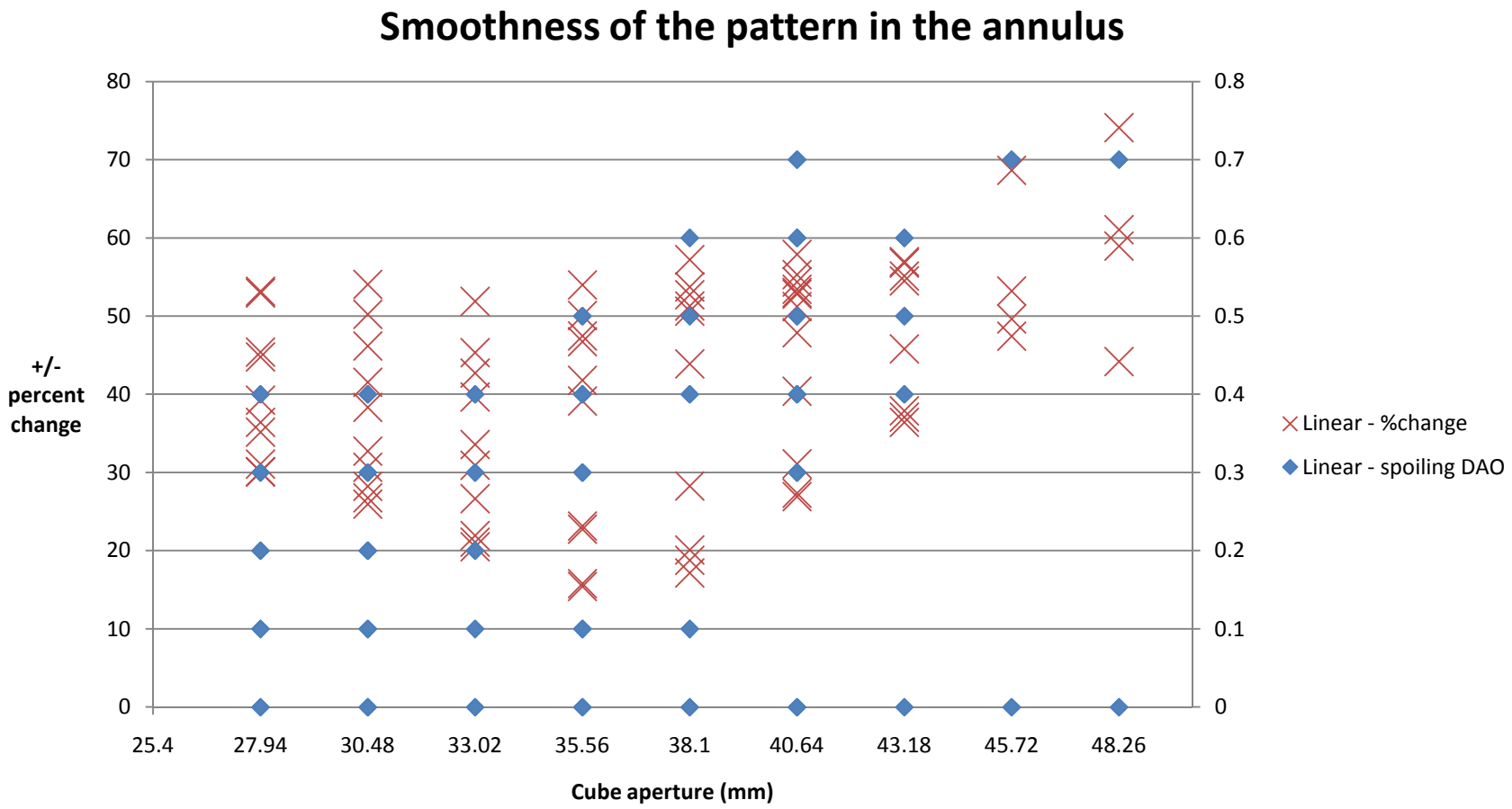


14 deg incident Angle Only



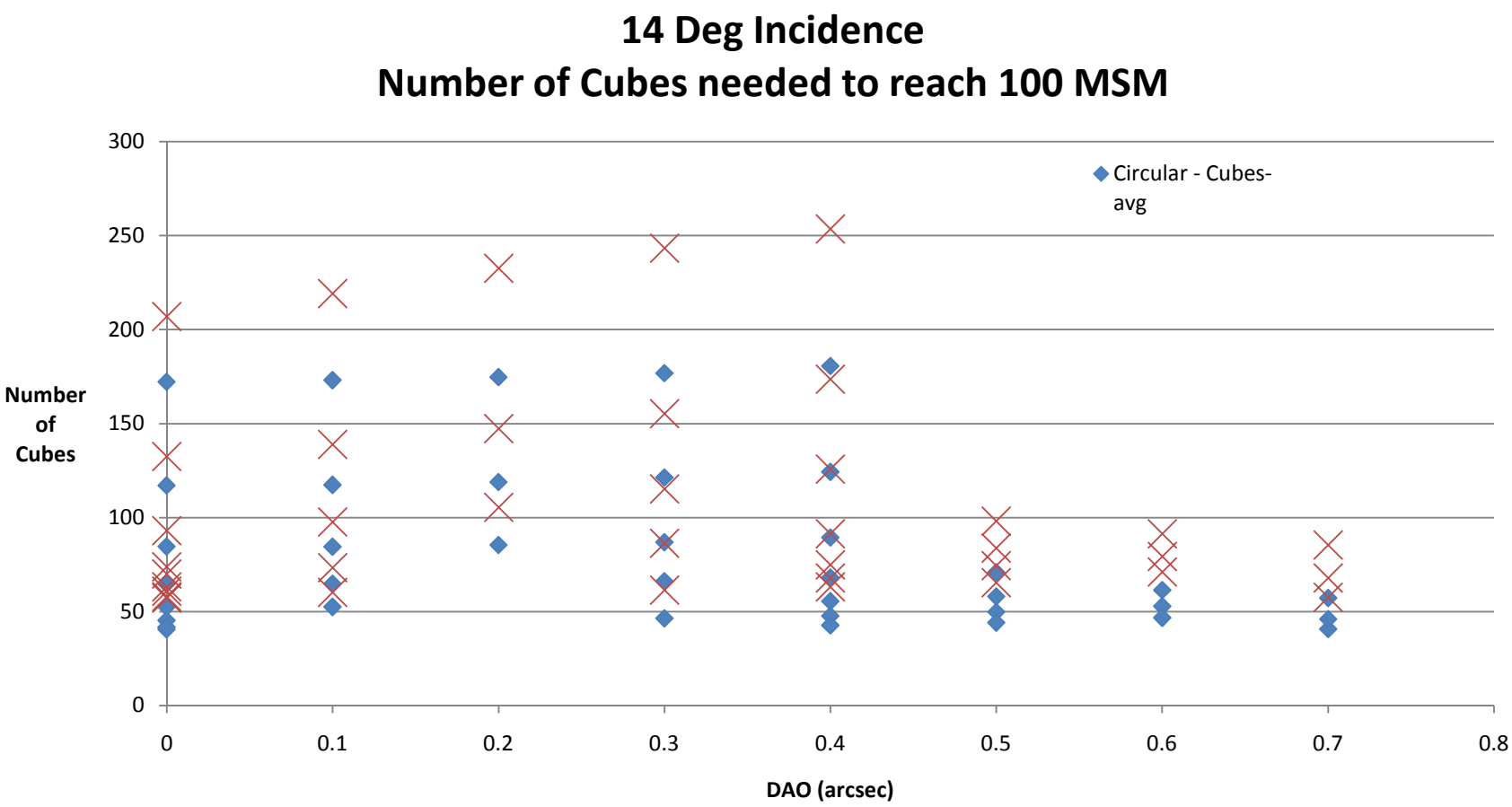
Minimum must exceed 100MSM

14 deg incident Pattern Smoothness
4 quad clocked cubes - Linear



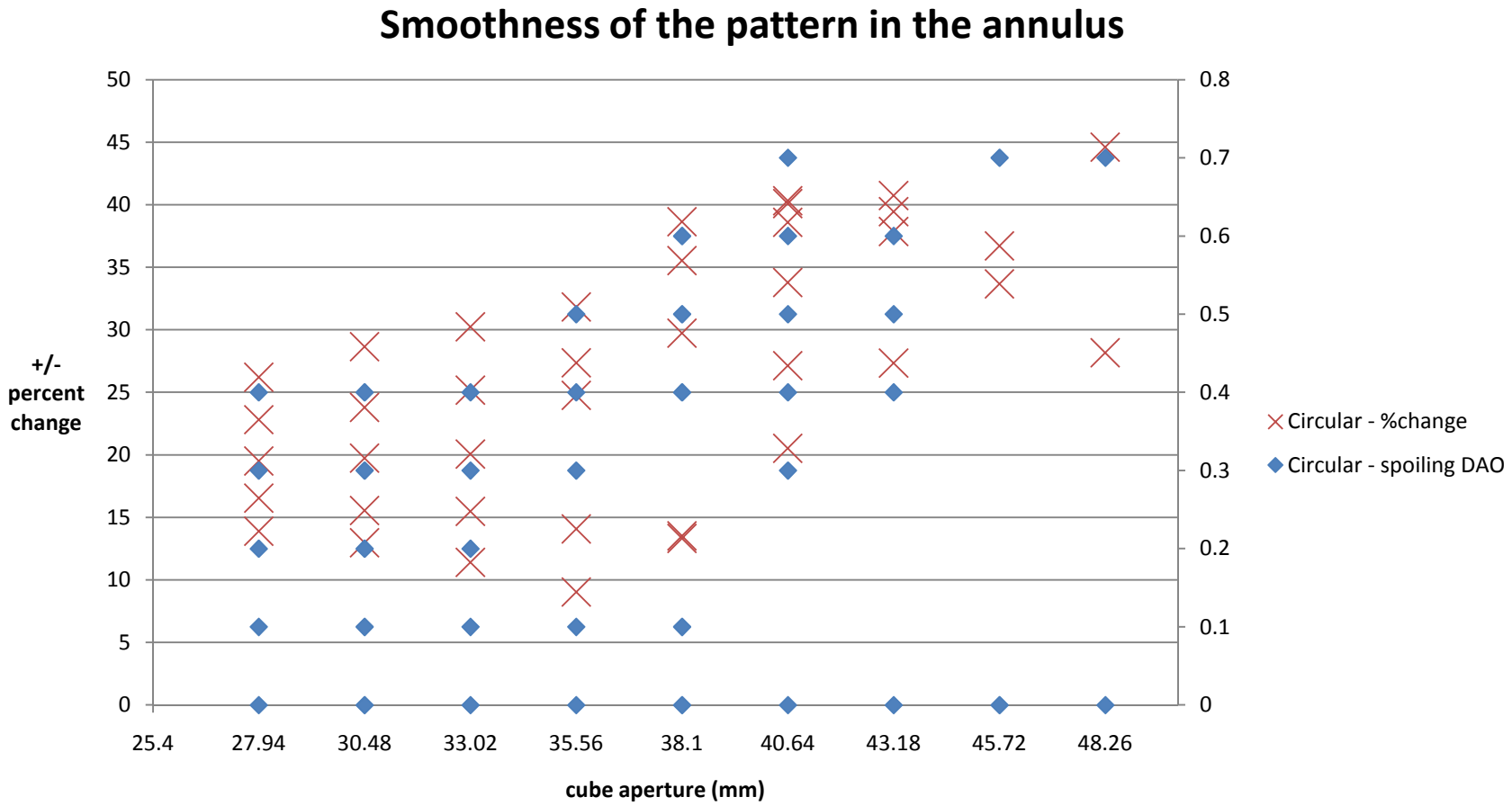
Minimum must exceed 100MSM

14 deg incident Angle Only



Minimum must exceed 100MSM

14 deg incident Pattern Smoothness
4 quad clocked cubes - Circular



Minimum must exceed 100MSM