National Aeronautics and Space Administration
Goddard Space Flight Center

Telescope technologies for solar sytems observations from near-Earth space

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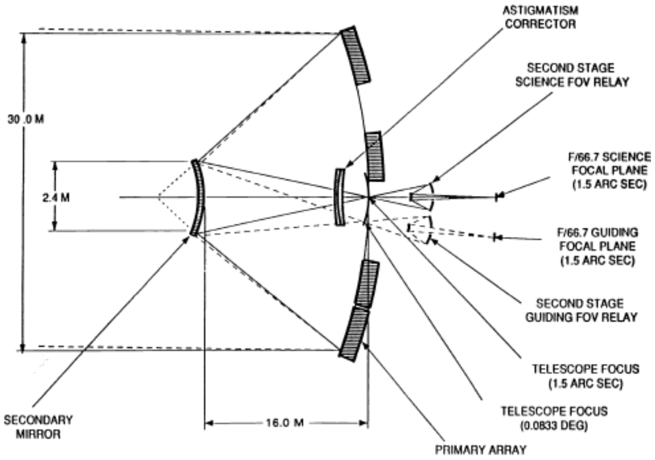
- Outline
  - Description of PDX from telescope design perspective
  - Telescope technology possibilites applicable to PDX or other planetary telescopes from near-Earth
    - Telescope design form
    - Primary mirror fabrication possibilities
  - Telescope complexity
    - Size, format, temperature, precision
  - Study of imaging quality vs pattern & fill factor
  - Suggestions for next steps

Ref: Wong et al. white paper: "**A DEDICATED SPACE OBSERVATORY FOR TIME-DOMAIN SOLAR SYSTEM SCIENCE**"

- 3m baseline, sparse aperture
- ~1 arcmin FOV (≥Jupiter at closest approach)
- UV, vis, IR (≤15um?) ultra-wide bandpass
  - Strongly suggests all reflective layout
    - AlMgF2 ("Hubble") coating implied
  - High precision for UV/vis diffraction limited performance
  - Only ~1m^2 of combined aperture required for sensitivity
    - Implied area filling fraction ~10%
  - Measurement timescales msec-years
    - Implied requirement – sufficient UV-plane coverage in each measurement sample (no spinning or other resampling to gain UV-coverage)
  - EELV launch vehicle likely required for Geo, L1/2
    - 4-5m fairing diameter means no deployment, can build & test as fixed array
    - Extreme lightweighting would NOT be required
    - Does not really push mirror technology for weight
    - Technical tall pole is beam combining and segment phasing

Possible PDX implementations: Telescope design form

- “Fizeau”
  - 1. segments of same primary mirror



S. Synott, SPIE 1494 (1991).

N vs Area of subapertures		
N	D (m)	
3	0.577	
4	0.500	
6	0.408	
9	0.333	

Aperture diameter vs. # of apertures

  - 2. multiple telescopes

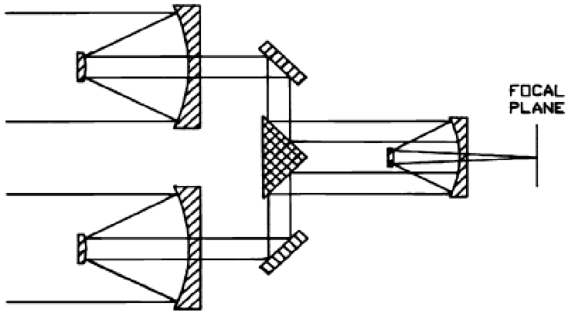


Fig. 1 A typical phased array telescope. Only two of the telescopes

Wide field performance of a phased array telescope, C. R. De Hainaut, D. C. Duneman, et al., Optical Engineering 34(3), 876-880 (March 1995).

- Using same PM preferred for maintaining UV throughput

Space telescope mirror design considerations

- Ideal material properties
  - Zero thermal expansion at operating temperature for good thermal stability
  - High thermal conductivity
  - Robust against mechanical and acoustic loads
    - No real materials match all 3 at room temperature
      - SiC robust, high conductivity, high CTE
      - ULE fused silica, Zerodur are very low CTE, more fragile, low conductivity
- Ideal fabrication approach
  - Fast mirror blank fabrication approach
  - Replicated optical surface
  - → Lack of these at TRL6 for these two components is why current SOA is ~\$4M/m^2 (JWST)
    - However this cost may be tolerable for ~1m^2 area for

Lightweighting discussion

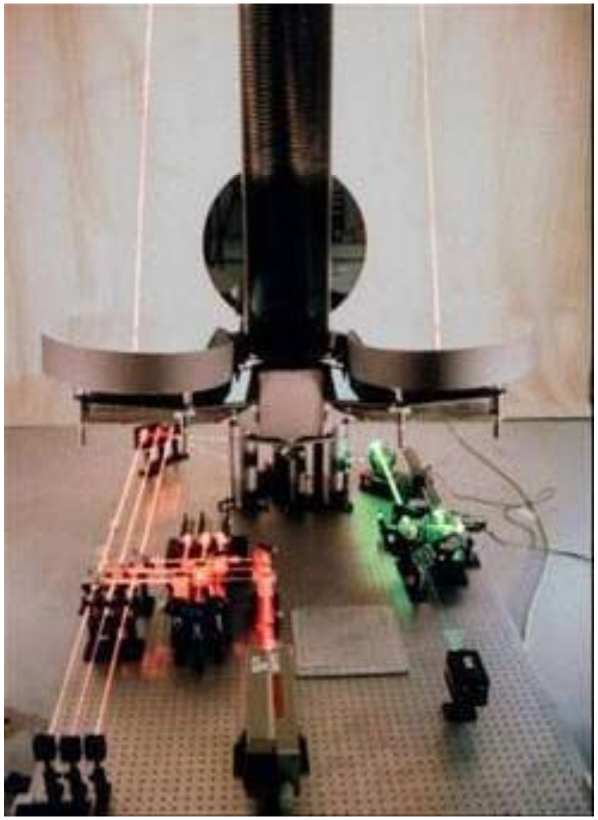
- JWST segments (~SOA) are ~25 kg/m^2 areal density
  - HST is 180 (1970's technology)
- Typical range for UV precision might be ~60 kg/m^2
- For 1 m^2 this is only 60kg
- Lightweighting is NOT the driver **– the system phasing and beam combination are the drivers; also telescope precision and temperature**

Telescope implementation possibilities

- Primary mirror fabrication possibilities:
  - Matched standalone mirrors (glass, SiC, etc.)
    - Many vendors and material sources, examples include
      - Zerodur (Schott),
      - ULE (Corning)
      - SiC (CoorsTek, Poco, SSG, Trex, Xinetics)
      - Be (used on JWST but not good roughness for visible λ's)
  - Segments cut out of parent
    - Guarantees radius matching
    - Inefficient for sparse apertures (fab & polish ~10x used area)
    - Cutouts complicate efficient lightweighting
  - Replication-like glass
    - Examples – HexTek borosilicate (but high CTE)
    - ITT "corrugated" borosilicate (see following)
  - Replicated SiC
    - Xinetics "nanolaminate"

Matched segments

- Fabrication challenge is very close radius matching
- Current cost & schedule paradigms would apply
  - Lightweighting and polishing all aperture directly



AFRL's Deployable Optics Telescope – 3 0.75m segments, ULE standalone segments

http://www.af.mil/news/story.asp?storyID=123014705

ITT corrugated glass

- Rapid fabrication of multiple segments
  - Made 5 (plano) 0.5 blanks in ~1 month
  - Process works by molding thin glass sheet into corrugated cores (1 macro, 1 top ‘micro’ layer) and back sheets (5 total)
  - Mirror face formed to near-final shape against a (convex) mandrel; some fine polishing and figure correction is required
  - Currently TRL5 using borosilicate glass; development needed for ULE glass

http://optics.nasa.gov/tech_days/tech_days_2006/docs/37

HexTek borosilicate glass

- Borosilicate glass tube sections & plates fused into a relatively stiff, inexpensive mirror blank
- Not SOA lightweighting (but enough for this)

- Thermal control much more difficult with high CTE (at room temp)

http://www.hextek.com/

Xinetics nanolaminate

- SiC substrate with back face actuators, thin film mirror facesheet
- Figure below from poster for 16m segmented aperture concept submitted to Astrophysics Decadal review {ATLAS-T 16m}
- Active controllability useful for relatively high CTE material; high conductivity helps with thermal uniformity
- Not yet demonstrated at UV wavefront precision

Controllable Primary Mirror Segments

♣ATLAST-16 will require lightweight, actively controlled optics such as Active Hybrid Mirrors (AHMs)

♣AHMs combine a cast SiC substrate with integrated ceramic actuators and a Nanolaminate facesheet

♣AHMs are fabricated by replication

♣AHM technologies are a joint development of Northrup Grumman Xinetics, LLNL and JPL

http://www.stsci.edu/institute/atlast/documents/Redding_16m_WFSC_aas2009.pdf

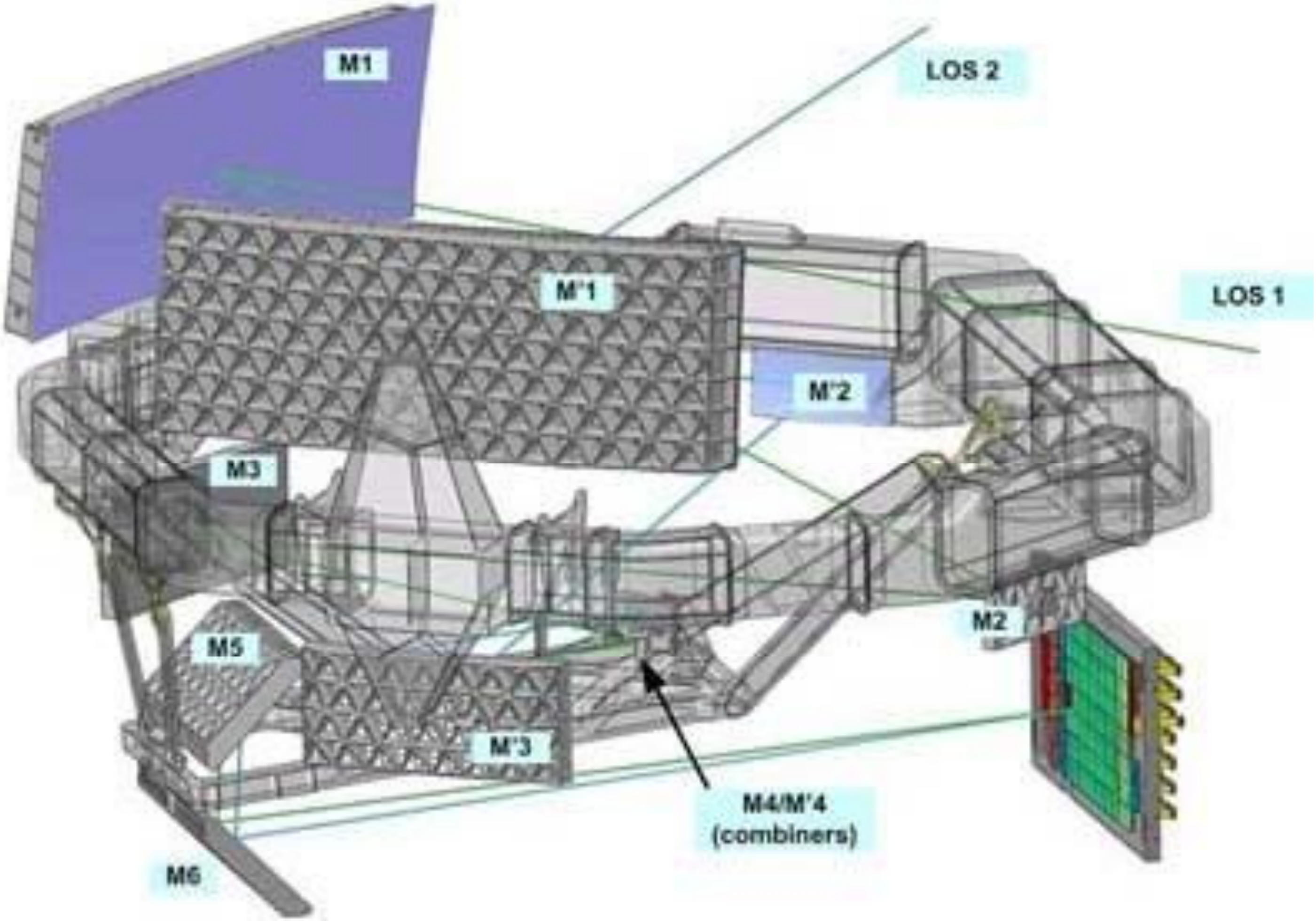
GAIA – astrometric, 2 telescope, all reflective Fizeau example

Ea. PM is ~1.5x0.5m;

All SiC optics & structure

6 reflections in each arm

In build for 2012 launch



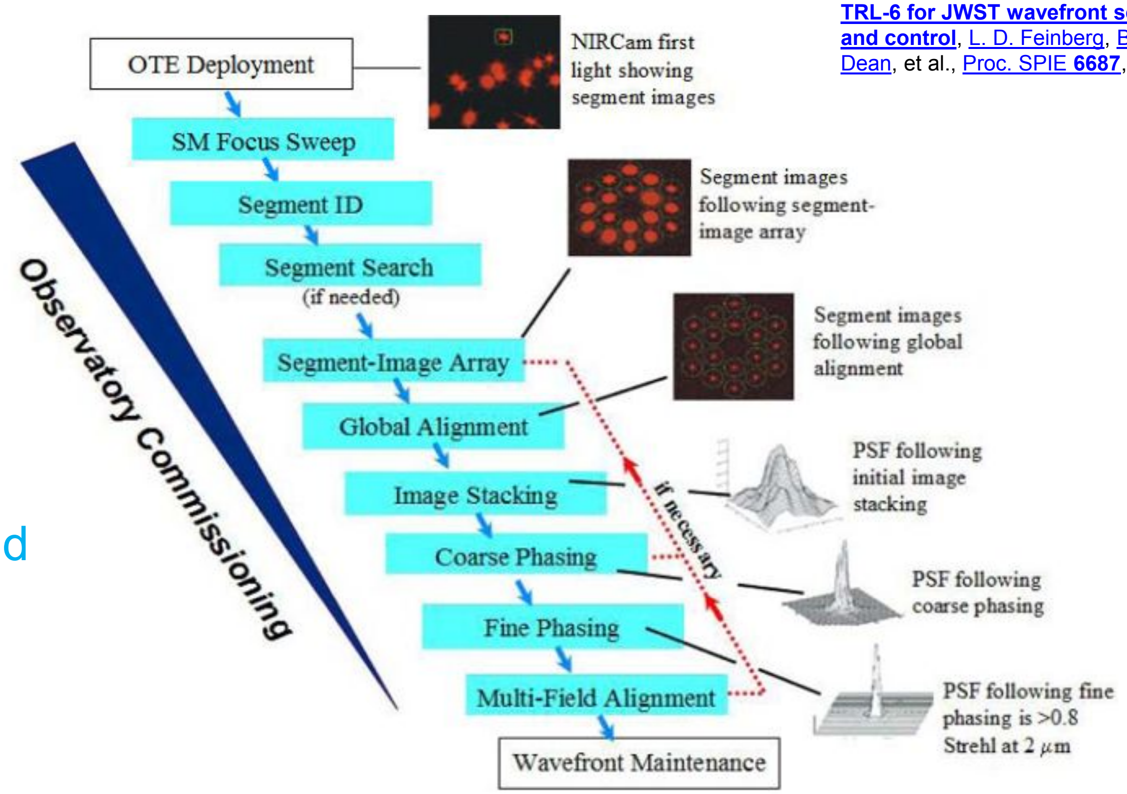
url: http://www.rssd.esa.int/index.php?project=GAIA&page=picture_of_the_week&pow=79

Segment phasing

- JWST segment is done using focus diversity on point sources
- This may well work for this applications
- Another possibility is phase diversity which can work using extended sources

Work on JWST has matured WFSC to the point where it should be engineered in from the start

For ~3m aperture, all but the last steps needed for JWST could be done before flight (no deployment necessary)



TRL-6 for JWST wavefront sensing and control, L. D. Feinberg, B. H. Dean, et al., Proc. SPIE 6687, (2007)

Telescope cost and complexity

- For ~3-4m a monolithic telescope may not be much more expensive than a many-aperture system
  - Rough consensus that at >4m it is easier to build a segmented telescope than a monolith
- There is a range from monolithic (eg HST), to nearly filled segments (JWST) to moderately sparse (cases looked at here) to highly sparse
- Clearly testing is easier at large filling fractions
- Not very much flight heritage yet for sparse apertures
- Compared to many concepts (e.g. Stellar Interferometer, SIM) this is not a large baseline system

Telescope temperature trade

- Most space telescopes (e.g. remote sensing) look down and so can operate at room temp.
- Even HST is room temp and is limited by its own thermal emissions to ~1.7μm
  - For 2 μm telescope should be cooled to ~-30C
  - For ~4 μm, need to get to ~100K (-173C)

- Cost increases some for any departure from RT
- Will increase more with increased dT

- Match materials to get minimum strain to operating temperature and good thermal stability at operating temperature

The hard parts are matching and phasing

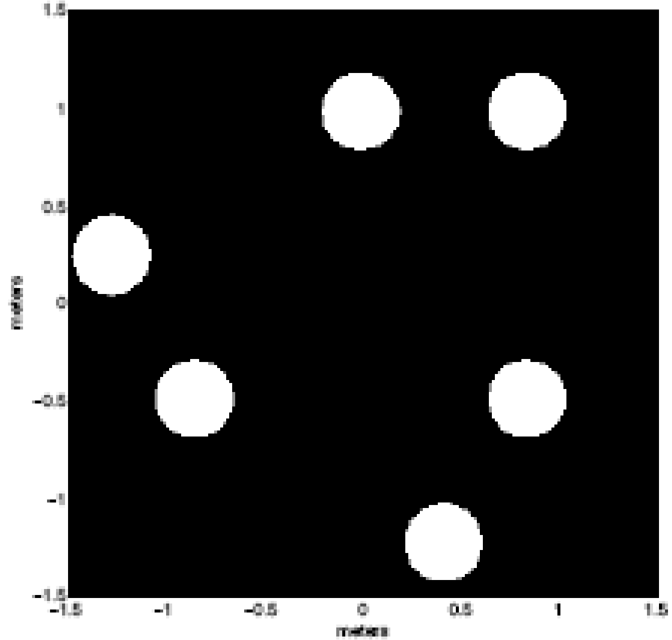
- From prior experience with groundbased telescopes and testbeds for flight telescopes, the technical challenges are
  - matching of the beam radii of curvature,
  - Wavefront quality for UV imaging/spectroscopy
  - Complexity of beam combination,
- *not the front end itself*
- However this is all ground testable so this risk can be retired through early demonstrations
- Implication is: you need to build a prototype early
  - Following slides are a quick look at image quality as a function of aperture filling configuration and area fraction

Simulation Parameters

- F/24 beam, *λ = 500 nm, EFL = 72 m*
  - Assumed oversampled (Q = 4) to show fine detail in PSF & MTF structure
- No aberrations - diffraction-limited system

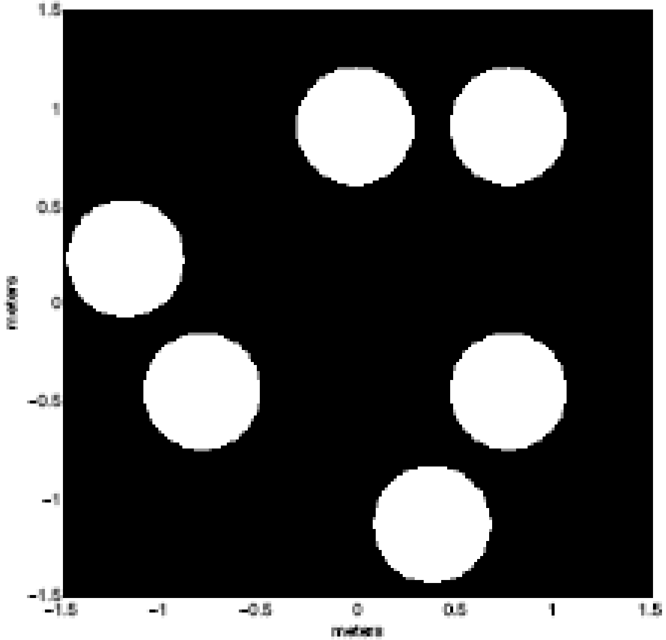
- Variations:
  - Ring-of-6 Sparse Aperture
  - **Golay-6 {shown, others in backup}**
  - Triarm 6,
  - 2 rings (3, 6) {similar to Lockheed STAR-9}
- All use ~3-meter baseline; unobscured sub-apertures with 0.4, 0.8 or 1 meter diameters as noted
- Results show modulation transfer function – if these exhibit zero MTF frequencies, unavoidable signal loss at some angular scales will occur

Golay-6 Sparse Aperture -- Pupil Function



0.4-meter
diameter sub-aps

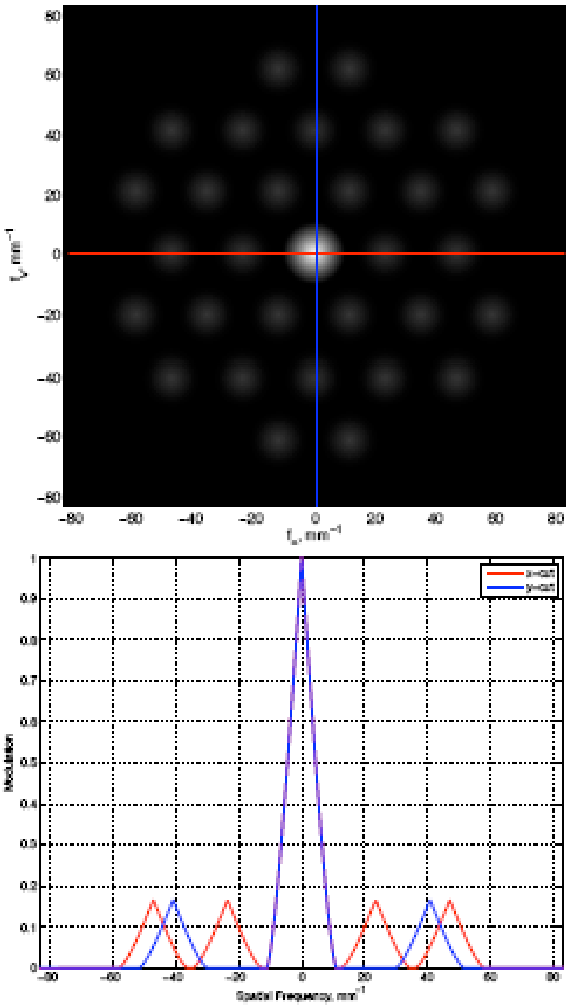
10.7% Fill Factor
by area



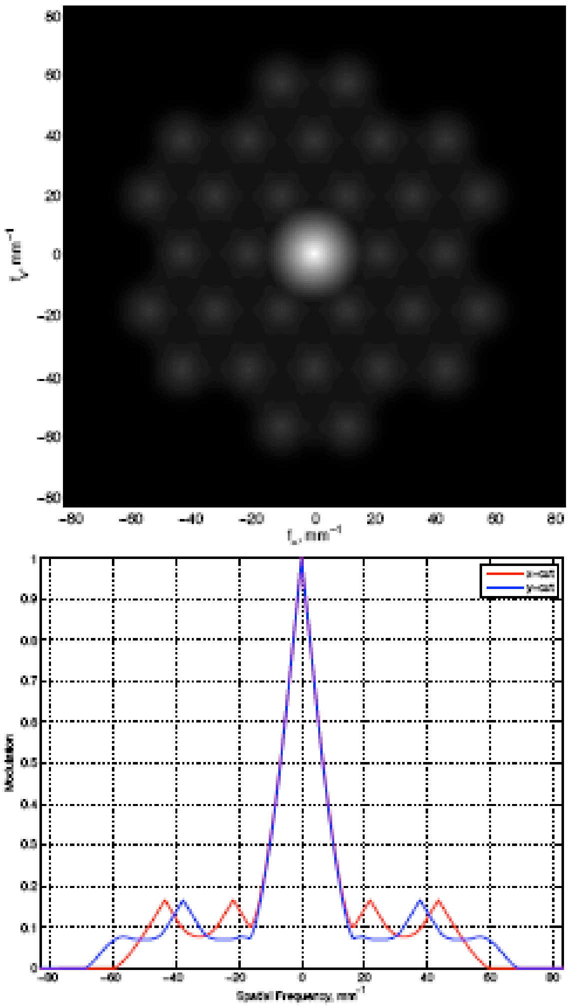
0.6-meter
diameter sub-aps

24% Fill Factor
by area

Golay-6 Sparse Aperture -- MTF



0.4-meter
diameter sub-aps



0.6-meter
diameter sub-aps

Tentative conclusions of aperture study

- 0.6m subapertures gives significantly better approximation of full aperture resolution than ≤0.5m
  - Also this size subaperture will give good UV imaging from ea. aperture
- 2 or more radial distances recommended (not 1 ring)
- >3 angular positions recommended

- Golay6 or 2-ring give better performance than triarm or single ring

Next steps

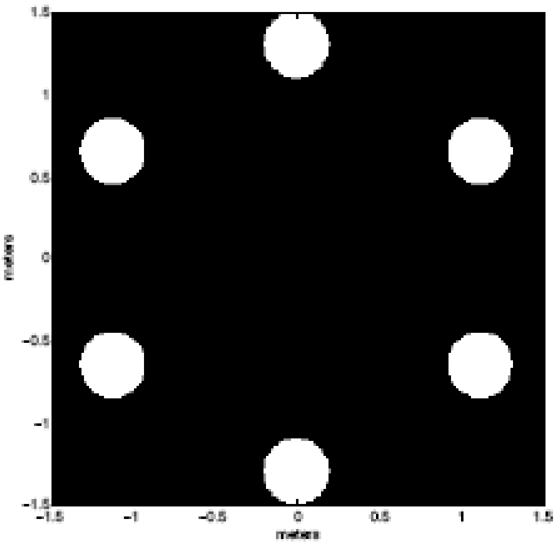
- GSFC has all the needed expertise to study, assess performance, design, build and test such a system:
  - Systems engineering, mirror technology, optical design, segmented telescope phasing, and I&T expertise
  - Goal is low risk, quick schedule for build, consistent with a medium-class mission

  - Thanks to Rick Lyon, Michael Amato, John Clarke for useful discussions

backup

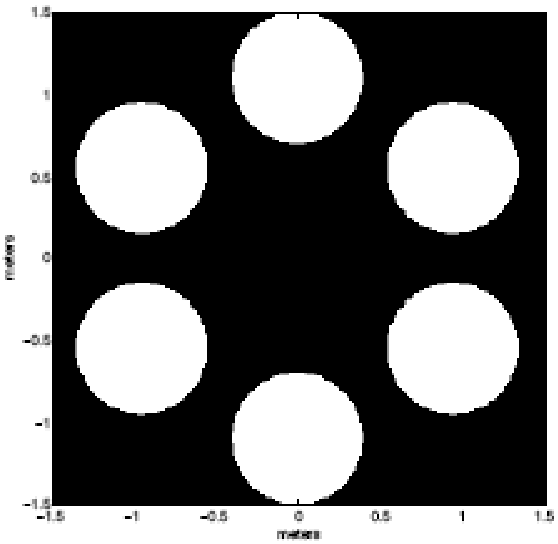
Pupil Function

Ring-of-6 Sparse Aperture



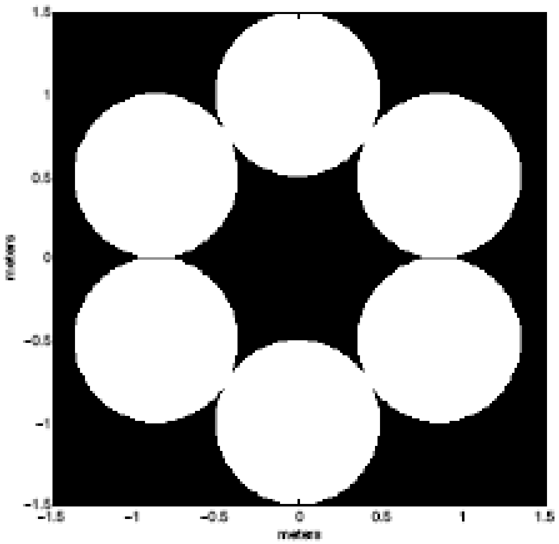
0.4-meter
diameter sub-aps

10.7% Fill Factor
by area



0.8-meter
diameter sub-aps

42.7% Fill Factor
by area

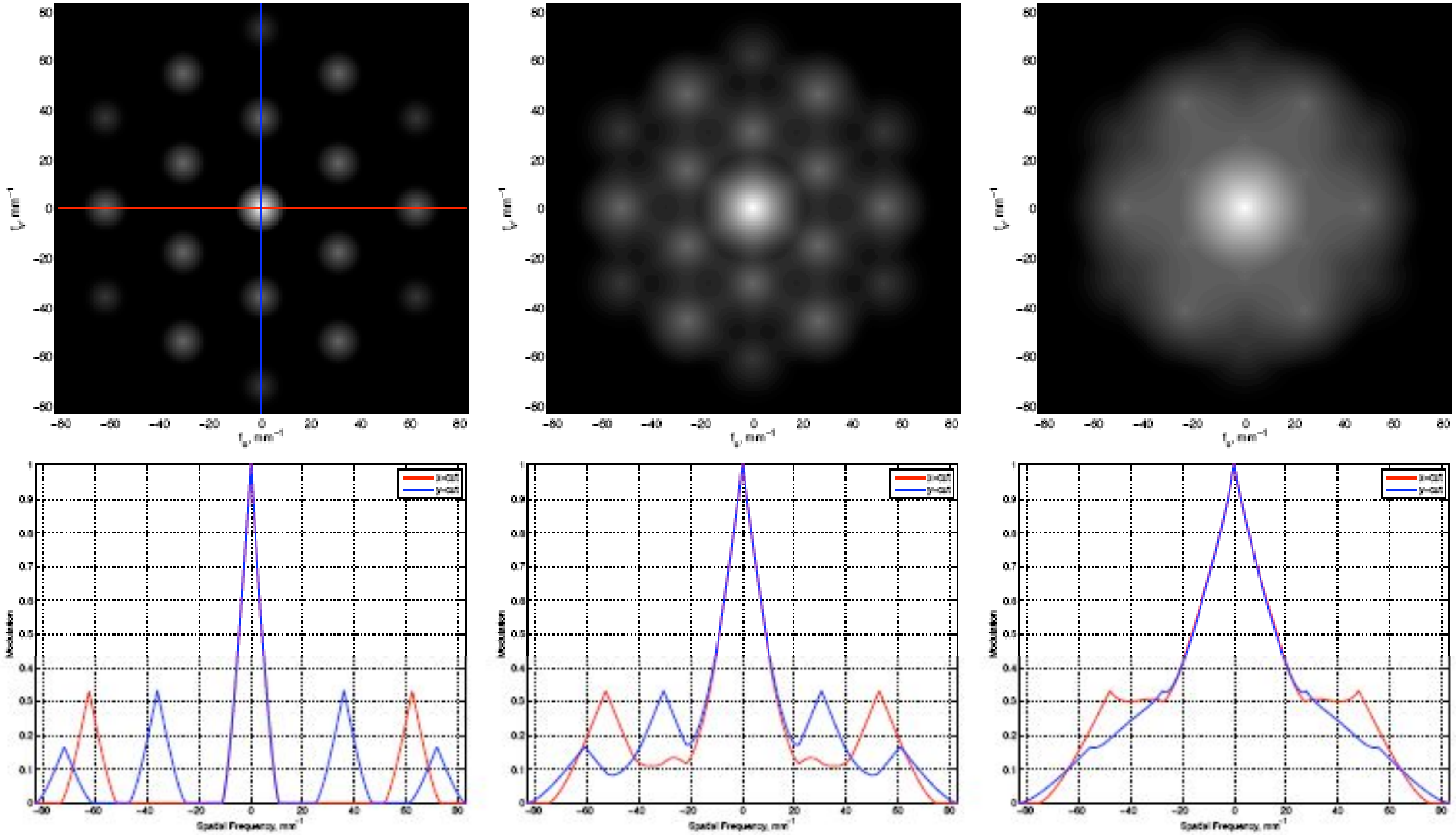


1.0-meter
diameter sub-aps

66.7% Fill Factor
by area

Modulation transfer function (MTF)

Ring-of-6 Sparse Aperture



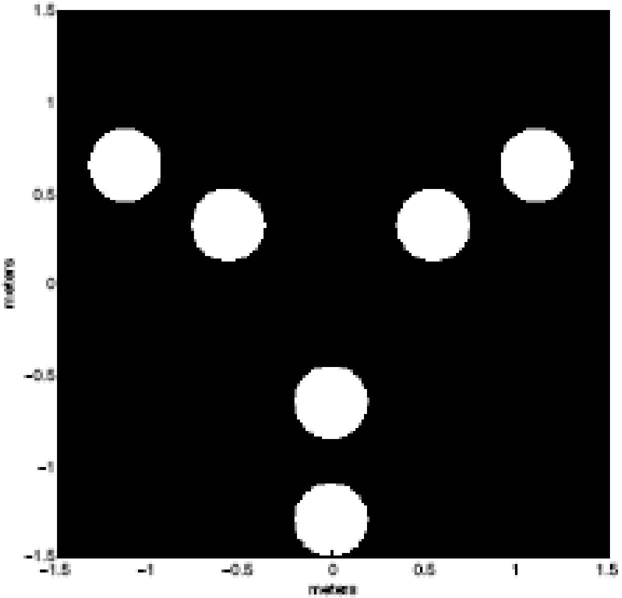
0.4-meter diameter sub-aps

0.8-meter diameter sub-aps

1.0-meter diameter sub-aps

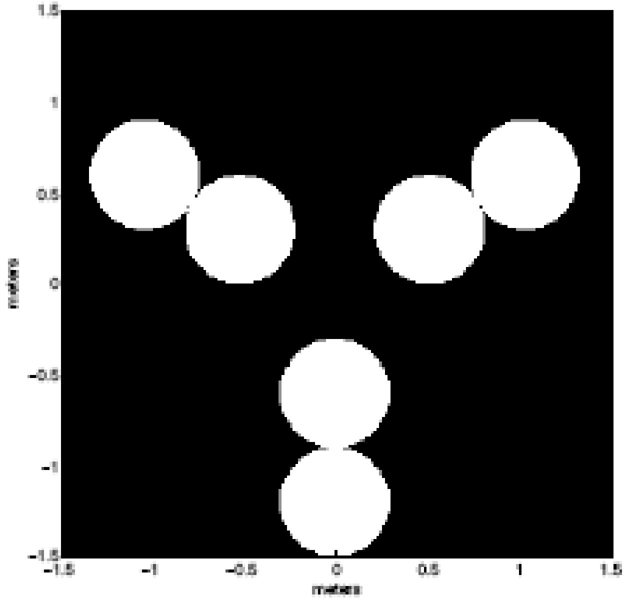
6

Triarm-6 Sparse Aperture (open center) – Pupil function



0.4-meter
diameter sub-aps

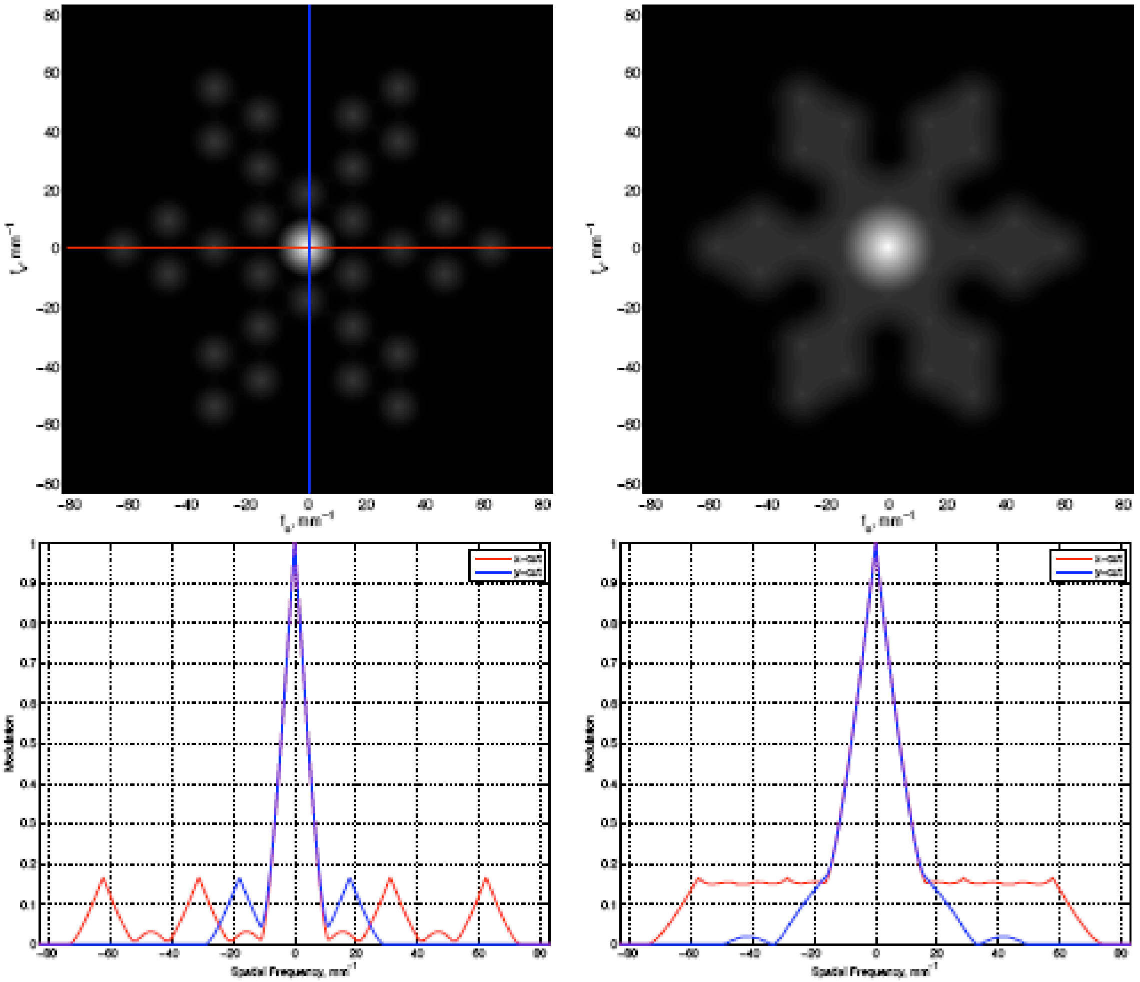
10.7% Fill Factor
by area



0.6-meter
diameter sub-aps

24% Fill Factor
by area

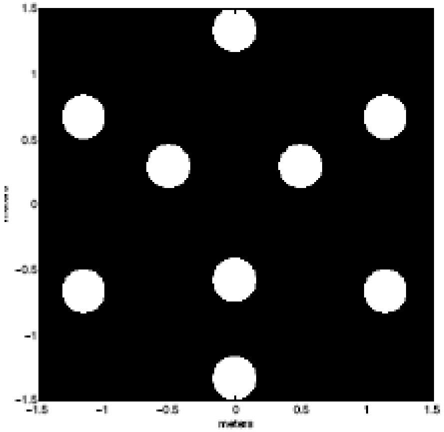
Triarm-6 Sparse Aperture (open center) --MTF



0.4-meter
diameter sub-aps

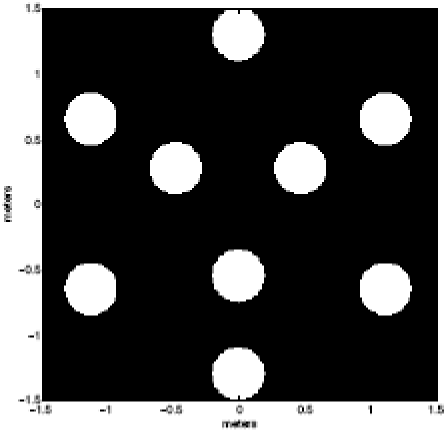
0.6-meter
diameter sub-aps

2 ring, 9 aperture – Pupil function



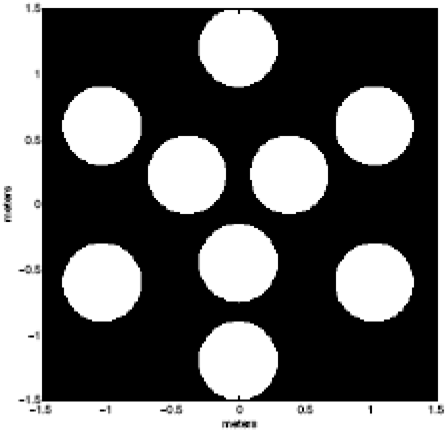
0.33-meter
diameter sub-aps

11% Fill Factor
by area



0.4-meter
diameter sub-aps

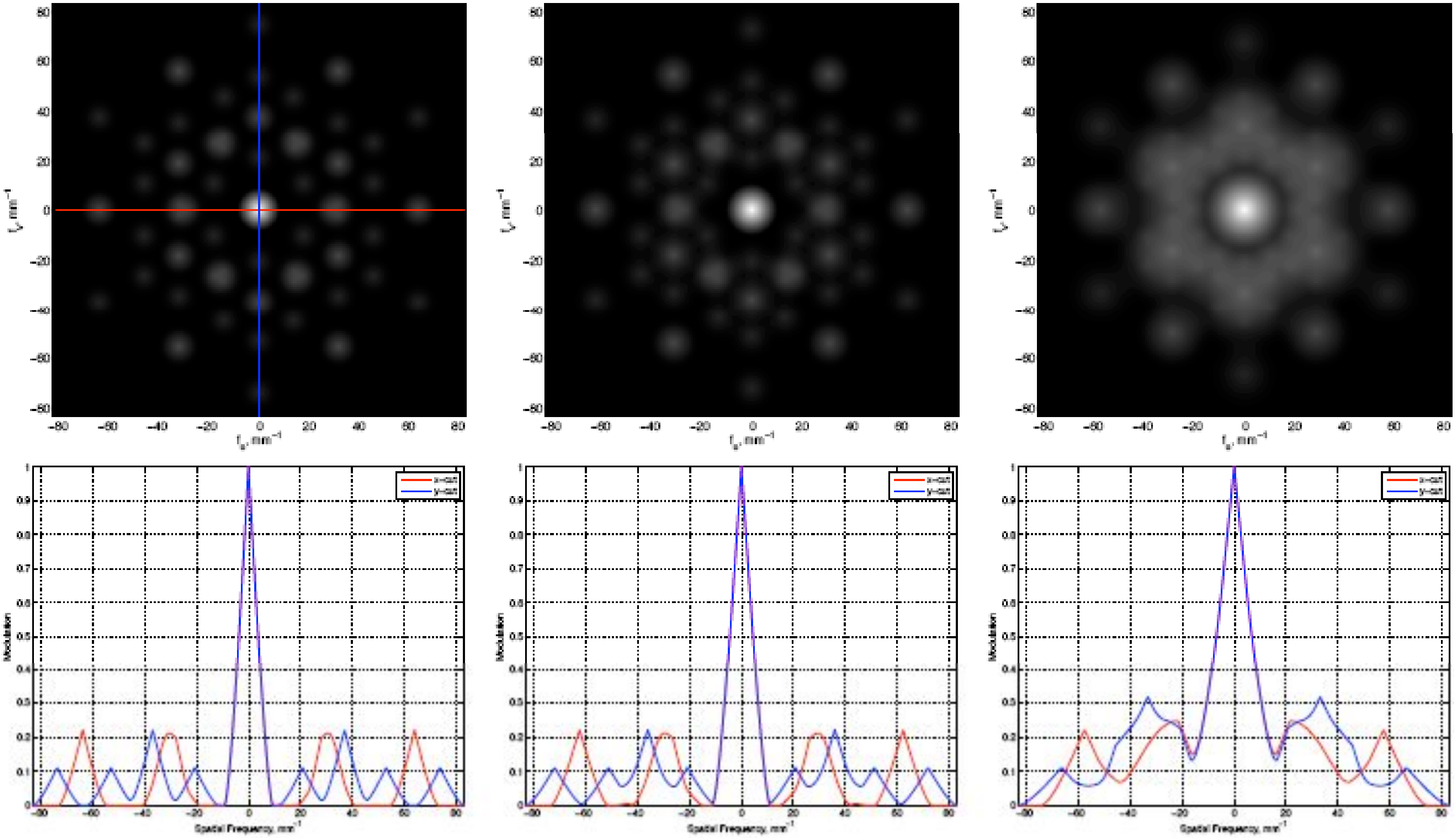
16% Fill Factor
by area



0.6-meter
diameter sub-aps

36% Fill Factor
by area

2 ring, 9 aperture – MTF



0.33-meter
diameter sub-aps

0.4-meter
diameter sub-aps

0.6-meter
diameter sub-aps

21