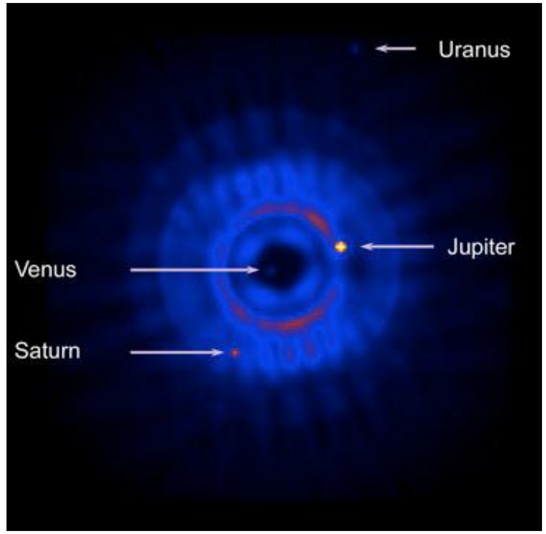

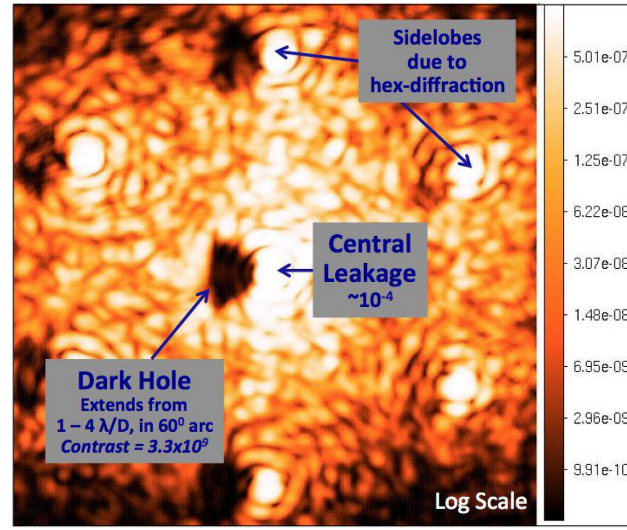

Affordable, Ultra-stable CVC SiC UVOIR Telescope for BENI Mission

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NASA Phase I SELECT SBIR Contract NNX13CM04C
NASA MSFC COTR: Ron Eng

Mirror Technology Days; October 2, 2013

Background on the SELECT SBIR Topic

- **Purpose: mature demonstrated component level technologies (TRL4), in this case Trex chemical vapor composite silicon carbide (CVC SiC™) mirrors and telescope structures, to demonstrated system level technologies (TRL6) by using them to manufacture complete telescope systems.**
- **Technology advances that are required in the near term (by mid-decade) are:**
  - Reduce the areal cost of telescopes by 2X such that larger collecting areas can be produced for the same cost or current collecting areas can be produced for half the cost.
  - Reduce the areal density of telescopes by 2X such that the same aperture telescopes have half the mass of current state of art telescope. Less mass enables longer duration flights.
  - Improve thermal/mechanical wavefront stability and/or pointing stability by 2X to 10X.
- **Potential solutions for the mirrors of the telescopes include but are not limited to direct precision machining, rapid optical fabrication, slumping or replication technologies to manufacture 1 to 2 meter (or larger) precision quality mirrors or mirror segments.**
- **The relevant Technology Taxonomy is:**
  - Spectral Measurement, Imaging & Analysis (including Telescopes – ultraviolet, visible, infrared);
  - Optical (mirrors, telescope arrays);
  - Materials and Compositions (ceramics);
  - Mechanical Systems (structures).
- **What's cool about it? You get to work with a NASA PI whom needs the technology!**

What is BENI?

- **NASA Exoplanet Exploration Program (ExEP) response to Astro 2010**
  - Develop technologies to detect and characterize the spectra of Earth-like exoplanets, measure their atmospheres for signatures of life as we know it.
  - Detect exoplanets up to 26 orders of magnitude fainter than their star
  - Contrast ability of 10^{-10} at visible wavelengths, 10^{-8} contrast level in LWIR
- **Balloon Exoplanet Nulling Interferometer (BENI)**
  - Telescope feeds into a visible nulling coronagraph (VNC) to suppress starlight and increase the contrast of the planet and dust/debris disk.
  - NASA PI: Rick Lyon (ExoPlanets and Stellar Astrophysics Lab/NASA GSFC)
  - Compact Achromatic Visible Nulling Coronagraph Technology Maturation effort (*see Lyon et.al.,"Visible nulling coronagraphy testbed development for exoplanet detection", Proc. SPIE 7731, 2010*).
  - Mr. Lyon funded via Technology Development for Exoplanet Missions (TDEM) component of the Strategic Astrophysics Technology (SAT) solicitation (*"Exoplanet Exploration Program Technology Plan Appendix: Fall 2011" Lawson et.al., JPL Document D-72279, 30 November 2011*)
  - VNC can be used with on-axis or sparse aperture telescopes
  - Instrument control bandwidth is independent of the state of the errors of the telescope plus the instrument. Relaxes telescope tolerances.
  - **For a Space Observatory maybe, But not for a High Altitude Balloon!**

Nuance of Balloon Experiments

- At 100-120kft, thermal excitation of the residual atmosphere (< 1%) within and around the telescope induces turbulence within the telescope tube.
- Significant constraint for coronagraphy from a balloon .
- Best solution is to measure the temperatures at various tube and PM and SM locations and add or remove power to these locations to minimize the air to telescope material temperatures.
- This implies materials that have low thermal inertia (e.g. SiC) are more desirable than glass (ULE® etc) due to the SiC's ability to quickly change temperature.

Objectives of Phase I

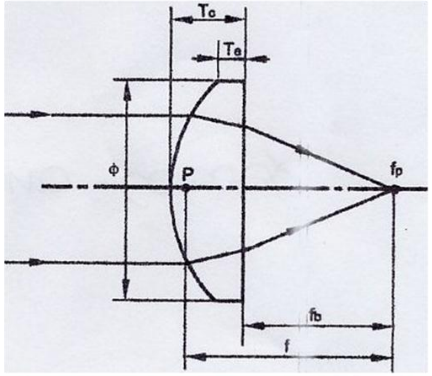
- **Demonstrate new replication process for rapidly and inexpensively producing large, high quality, lightweight silicon carbide mirrors**
  - Eliminates long lead, high cost rough and fine grinding procedures prior to polishing the mirror surface
- **Demonstrate meniscus PM mounted using suitable approach**
  - Obviates need for mirror mount hub (mushroom), lessens overall PM thickness, eliminates long lead time and & expensive isogrid lightweighting.
  - Explore tangent and edge mounts
- **Conceptualize, design and analyze a 1-meter aperture, ultra-stable, CVC SiC™ UVOIR telescope tailored to the specific mission requirements of BENI, with the quality of the mirrors being traceable to the goals of future UVOIR observatories such as ATLAST**
- **THERE IS A LARGER QUESTION:**
  - *What is the best mirror material to use for a future UVOIR observatory such as ATLAST: ULE® or SiC?*

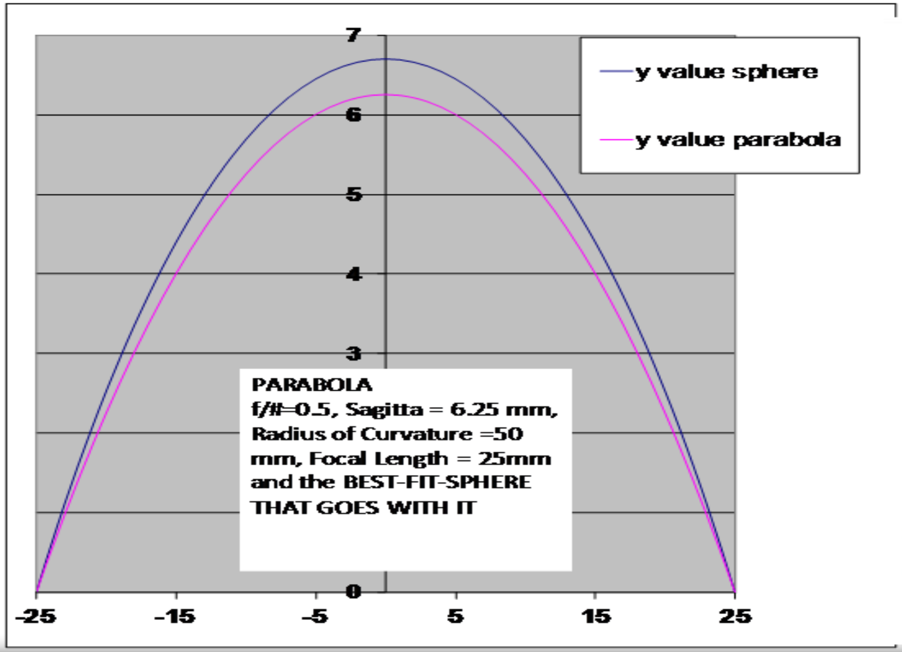
Phase I: Replication Experiments

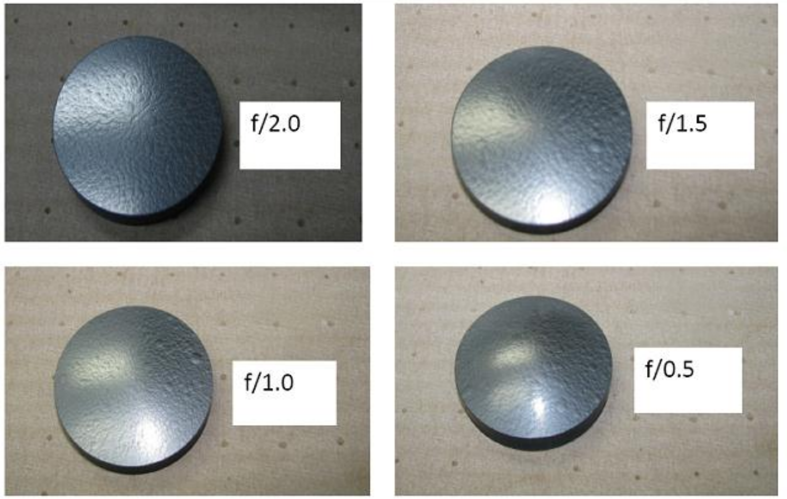
- **Trex attempting to produce concave, parabolic CVC SiC™ replicants with varying sagitta from polished PYROID® SN mandrels w/best-fit-sphere surfaces.**

Table 1. Parameters for desired CVC SiC™ Replicant and PYROID® SN Mandrel

CVC SIC™ Parabola				
f/#	0.5	1.0	1.5	2.0
Sagitta (mm)	6.25	3.125	2.083	1.5625
ROC (mm)	50	100	150	200
Focal Length (mm)	25	50	75	100
PYROID® SN MANDREL Sphere				
Sagitta (mm)	6.699	3.175	2.098	1.569



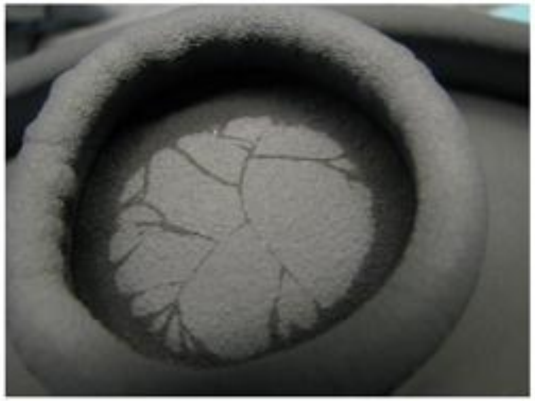




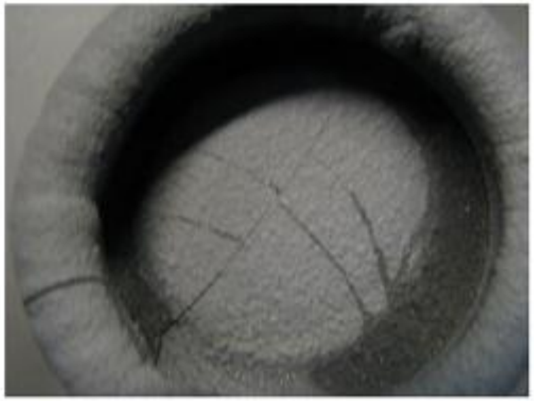
Four SN-PG coupons with f/# = 0.5, 1.0, 1.5 and 2.0

Surfaces are actually smooth, rather than the bumpy, granular "orange peel" appearance

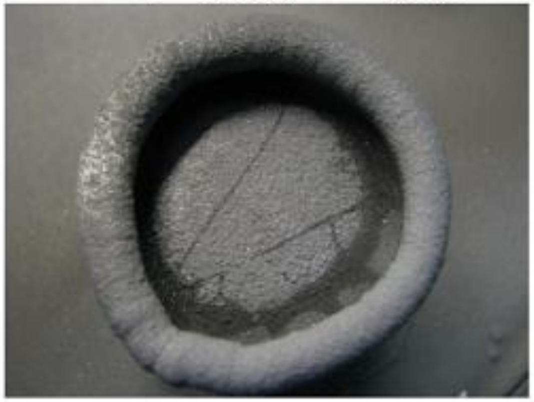
Run #1 Result



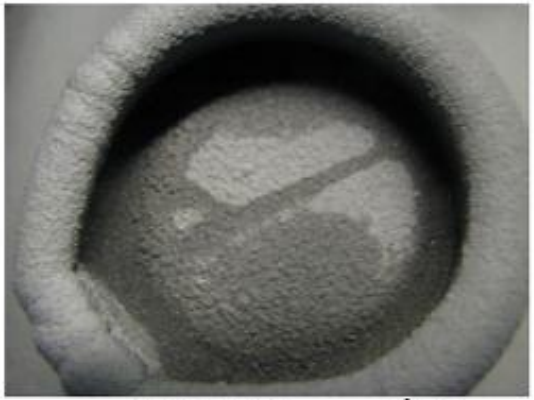
Y = 6.699; f/0.5



Y = 3.175; f/1.0



Y = 2.098; f/1.5



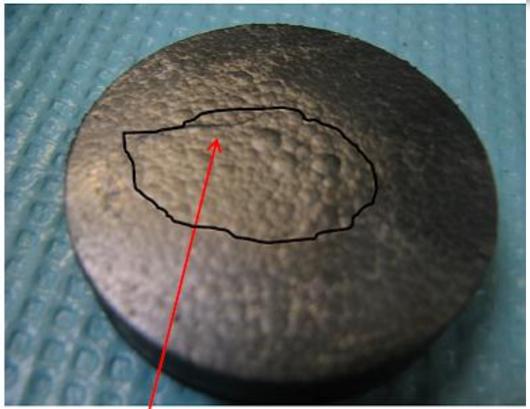
Y = 1.569; f/2.0

All four coupons showing crack lines out of the reactor. (wetted with alcohol to highlight lines)

NOTE: The faster the mandrel, the more the deposit cracked.

In the past no cracking occurred for a plano mandrel/deposit.

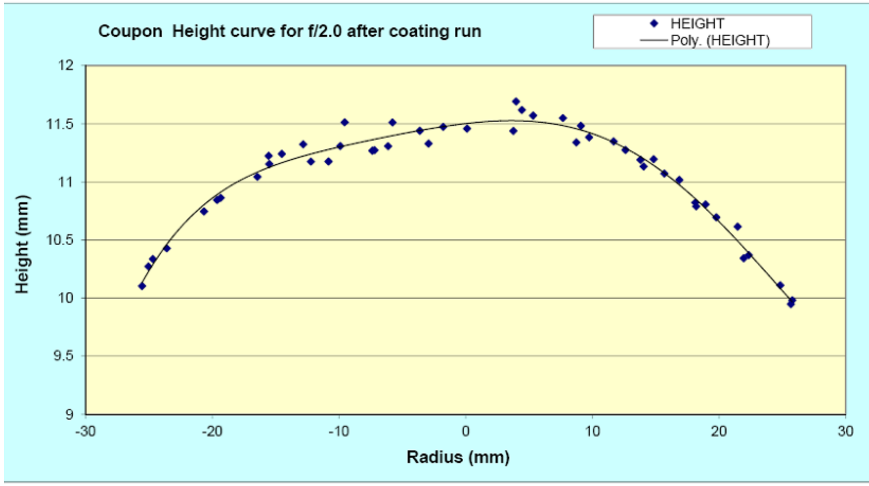
Example Post Run Inspection



Y = 2.098; f /1.5 Y = 1.569; f /2.0

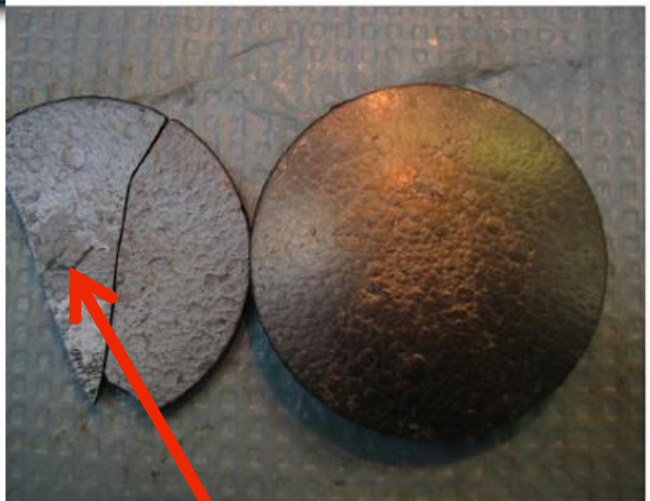
Coupon f /1.5 shows some separation and surface cracking. Coupon f/2.0 has crack line across surface. The *black outlined area* on f/2.0 encloses a collapsed or recessed area that is visible to the eye and is indicted in the CMM data collection for the R.O.C.

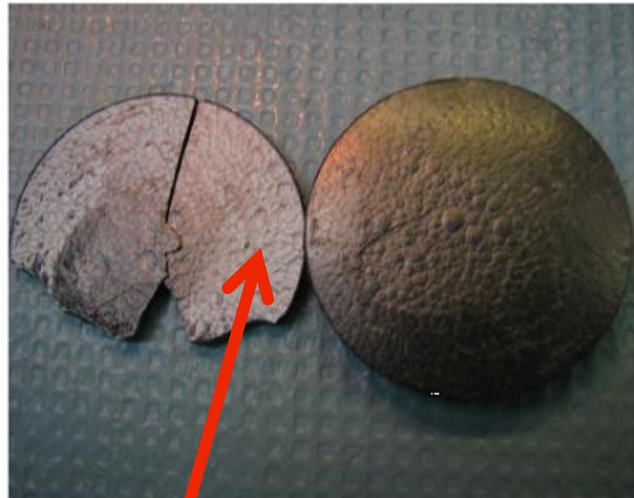
Coupons f/1.5 and f/2.0 after deposit removal



Major change in this surface curve for coupon f/2.0 after coating run

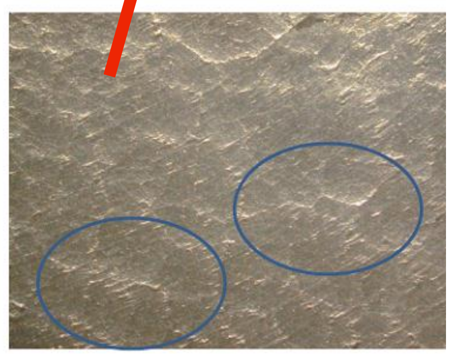
Optical illusion of bumpiness on the mandrel REPLICATED on the silicon carbide deposit





= 2.098; f 1.5

Y = 1.569; f 2.0

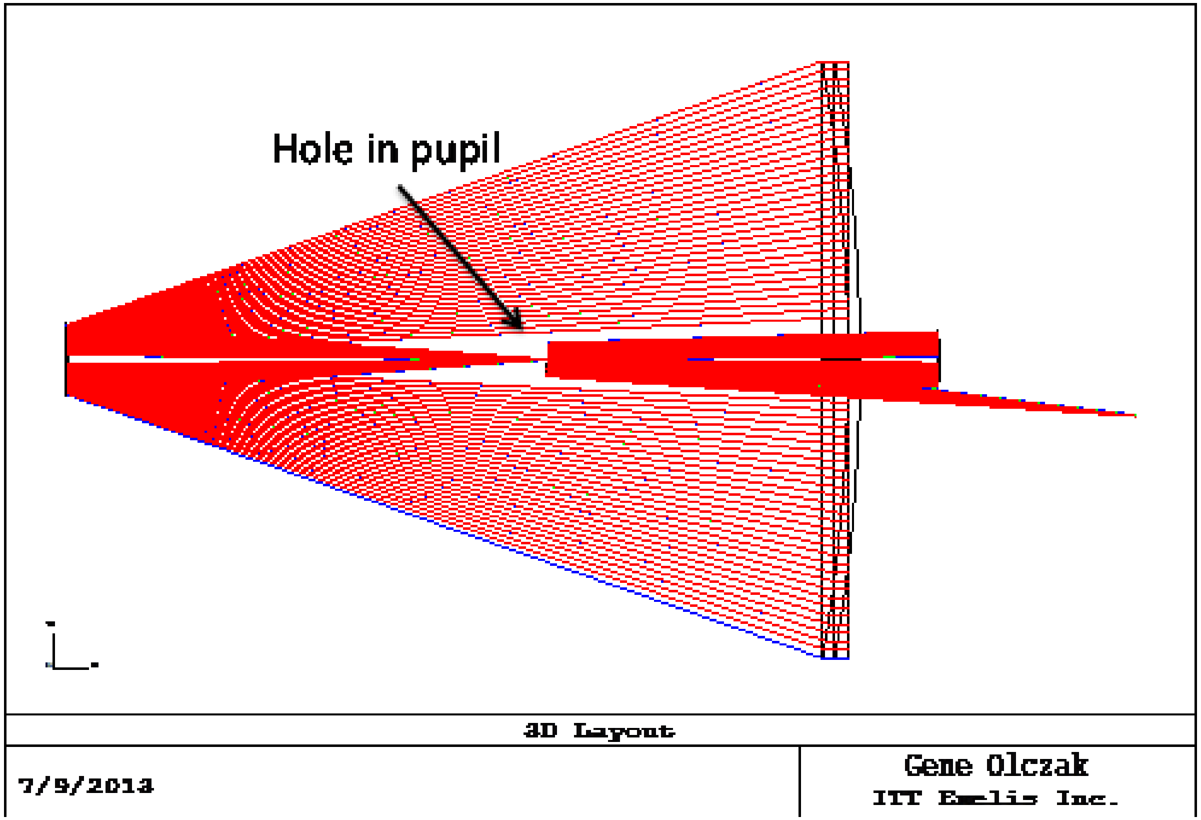


Sticking of the SiC Deposit
To the exposed basal planes
of the PG is believed to be the
problem.

10X Magnification shows transfer of PG mandrel to SiC on left for f/1.5 mandrel.

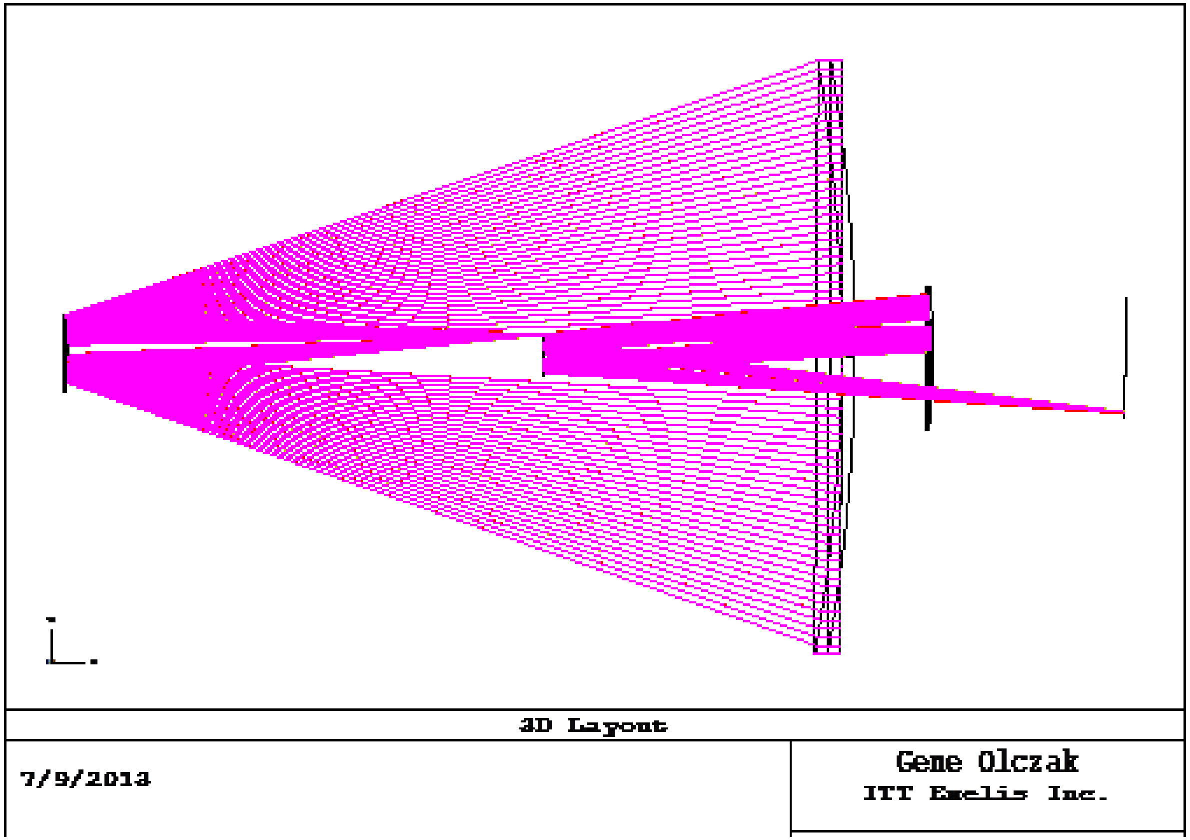
On right is shown excellent transfer of surface to f/2.0 SiC replicant. The "staircase" features of the graphite basal planes (right oval) and polishing marks (left oval) can be seen.

3 Telescope Designs Evaluated by ITT Exelis
Ted Mooney, Gene Olczak & Mark Allen



Three mirror telescope design with an annular fast steering mirror (FSM) and low obscuration ratio primary mirror (PM) which has all three mirrors along a common axis. On-axis components and an on-axis field. This is the design concept with the lowest SM alignment sensitivity. The field is constrained by the size of the hole in the FSM, and the required field is small.

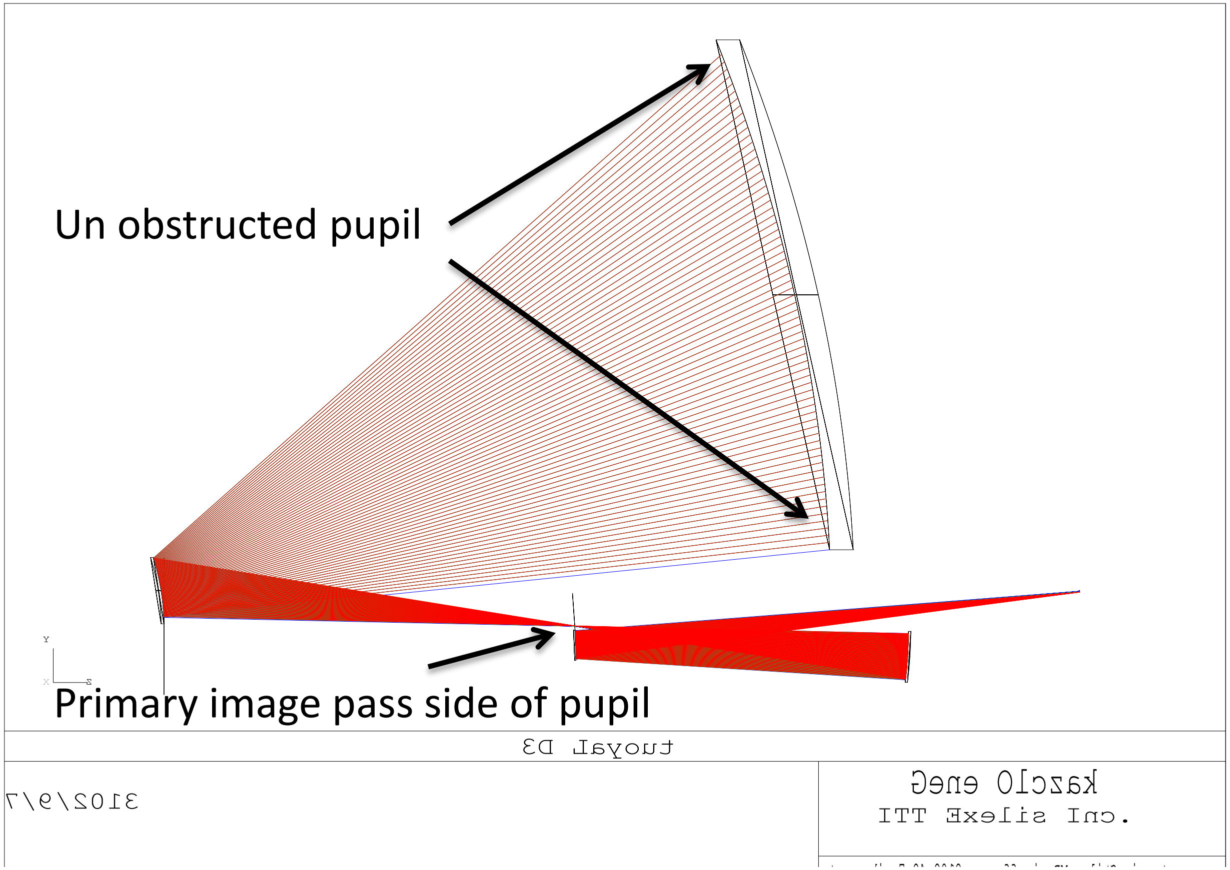
Telescope #2



Three mirror telescope design with an off-axis field, a solid FSM and a low obscuration PM . On-axis components and off-axis field. This design concept has slightly higher SM alignment sensitivity than the on-axis components, on-axis field TMA.

Unclassified

Telescope #3



This off-axis un-obscured TMA has similar packaging constraints as options 1 and 2. It is different from recent off-axis systems for nulling coronagraphs in that the PM is quite fast and the secondary is convex and does not form a real pupil (the off-axis systems use Gregorian designs with concave pupil image forming secondary mirrors). The design provides a rough apples-to-apples comparison of off-axis design and on-axis design for secondary mirror (SM) wavefront error (WFE) alignment sensitivity.

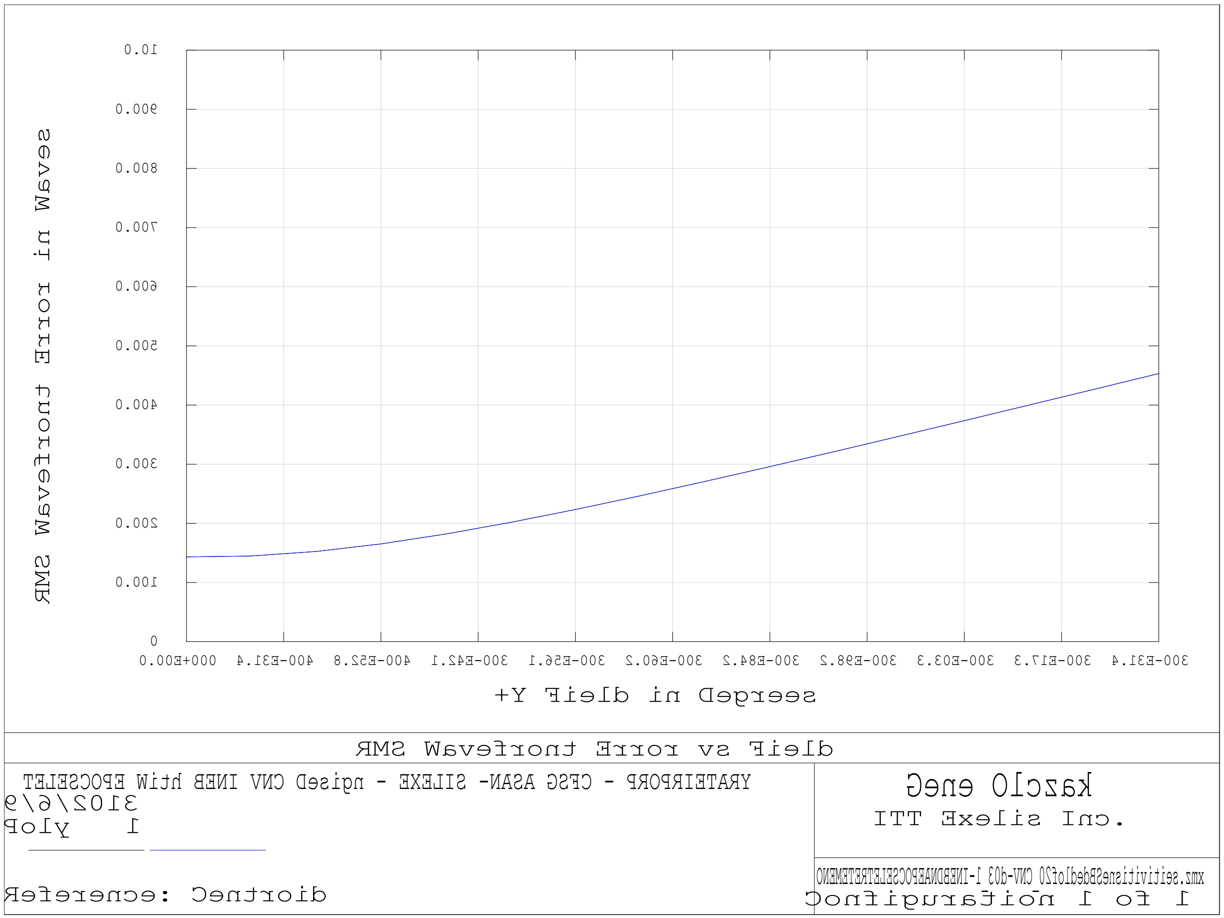
SM Sensitivity Analysis

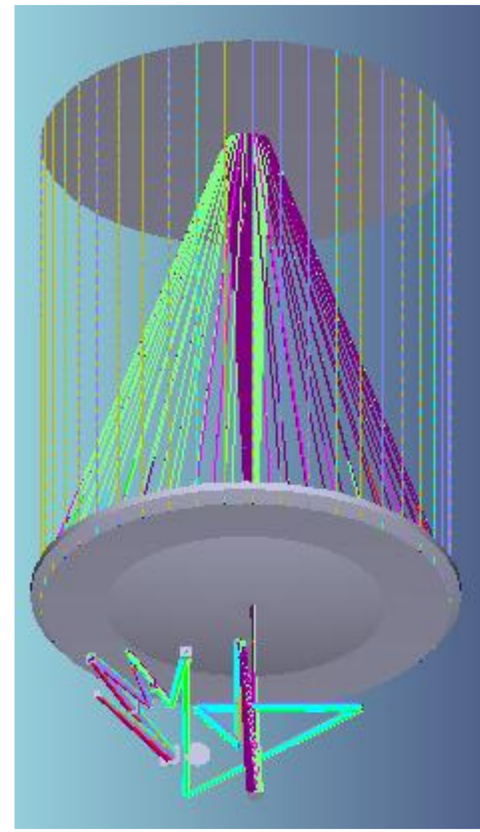
- **SM to PM alignment one of the major alignment/wavefront sensitivity drivers. Parameters included pupil & field w/fixed focal length, entrance pupil diameter, field size, exit pupil size & position.**
- **Fringe Zernike polynomials at 1-micron for the center of the field as a function of the SM position.**

Term	$Z(\rho,\varphi)$			Fringe Zernike cefficients at 1 um for center field as a function of SM position											
				Case 1: On axis design				Case 2: Off axis field				Case 3: Off axis unobscured			
				Nominal	dY [20 um]	Rotation about X [100 urad]	dZ [2 um]	Nominal	dY [20 um]	Rotation about X [100 urad]	dZ [2 um]	Nominal	dY [20 um]	Rotation about X [100 urad]	dZ [2 um]
1	1	Piston	1	-0.00118512	-0.00115967	-0.0012208	-0.06056689	-0.01757782	-0.02784404	-0.01248593	-0.07698106	-0.00001863	-0.2145634	-0.1874125	-0.04958153
2	$\rho\cos\varphi$	X-Tilt	2	0	0	0	0	0	0	0	0	0	0	0	0
3	$\rho\sin\varphi$	Y-Tilt	3	0	-5.48824476	-11.600663	0	2649.093789	2643.407708	2637.073413	2649.093596	0.00398748	-4.53074051	-10.7777098	0.30067735
4	$2\rho^2-1$	Defocus	4	-0.00058097	-0.00055566	-0.0006165	-0.05942318	-0.0172946	-0.02753335	-0.01220187	-0.07616061	-0.00027743	-0.2121376	-0.18541637	-0.04949259
5	$\rho^2\cos2\varphi$	Ast 0/90	5	0	-0.00000621	0.00005972	0	0.00230023	-0.00051802	-0.03094003	0.00230616	-0.00097409	0.20081889	0.17571431	-0.01026393
6	$\rho^2\sin2\varphi$	Ast 45	6	0	0	0	0	0	0	0	0	0	0	0	0
7	$(3\rho^2-2)$	X-Coma	7	0	0	0	0	0	0	0	0	0	0	0	0
8	$(3\rho^2-2)$	Y-Coma	8	0	-0.06274194	-0.0568029	0	0.00013133	-0.06220885	-0.05901448	0.00011206	-0.0002458	-0.03993535	-0.03541706	0.00424834
9	$6\rho^4-6\rho^2$	Sphere	9	0.00040326	0.00040312	0.00040341	0.00093822	0.00001006	0.00003729	0.00001072	0.00054274	-0.00026578	0.00239364	0.00196804	0.00007998
10	$\rho^3\cos3\varphi$	X-Tref	10	0	0	0	0	0	0	0	0	0	0	0	0
11	$\rho^3\sin3\varphi$	Y-Tref	11	0	0	0	0	-0.00154634	-0.00153529	-0.00152436	-0.00154636	0.00090001	-0.00627119	-0.00512266	0.00122623
12	$(4\rho^2-3)$	2-Ast 0	12	0	0.00000013	0.00000011	0	-0.00169987	-0.00169292	-0.00167917	-0.00169988	0.00050263	-0.00189292	-0.0015097	0.00068189
13	$(4\rho^2-3)$	2-Ast 45	13	0	0	0	0	0	0	0	0	0	0	0	0
14	$(10\rho^4-1$	2-X-Coma	14	0	0	0	0	0	0	0	0	0	0	0	0
15	$(10\rho^4-1$	2-Y-Coma	15	0	0.00054149	0.0004594	0	-0.00008147	0.00045489	0.00038008	-0.00008171	-0.00014296	0.000041	0.00001184	-0.00019187
16	$20\rho^6-30$	2-sphere	16	-0.00019917	-0.00019918	-0.0001992	-0.00020374	-0.00027087	-0.0002711	-0.00027104	-0.00027538	-0.00000697	-0.00003195	-0.00002791	-0.00000894

What Team BENI Selected

- Downselected to Case 2, slightly off-axis field. Moved primary focus location behind the PM to avoid the potential for a thermal load between the SM and PM. PM f/#=1.4507, sag=43.09 mm





Mass Budget and PM Modes

Subassembly	Weight Percentage (from average of 3 referenced telescopes)	Weight Allocation (kg)
PM	11%	33.5
PM Mounts	3%	8.0
Aft Telescope Structure	17%	52.5
Telescope Mounts	8%	23.0
Barrel	14%	42.1
Secondary Mirror Supports	4%	13.1
Alignment Drive & Sys	2%	4.9
SMA	3%	8.0
TMA	2%	6.2
Fold Mirror Assy	1%	3.1
FSM	0%	1.5
Cables & Brackets	8%	22.8
Closeouts/Baffles	5%	15.3
Thermal Control	6%	19.0
Mounting Brackets/Blocks	8%	22.9
Electronics	8%	24.4
Total Telescope	**100%**	**300**

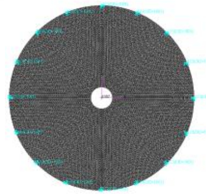
- PM Target ~34 kg (means <25.4 mm thick), SM Target ~4 kg
- Some items on list may belong to different budget

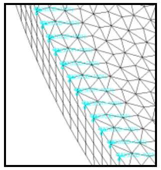
PM	25.4 (mm)	1/3 LightWeighting = 41.7kg	
Mode #	Frequency (Hz)		Shape
1 – 6	0	0	Rigid Body
7	305.2	189.5	Astigmatism
8	305.2	189.5	Astigmatism
9	708.8	469.7	Trefoil
10	708.8	469.7	Trefoil
11	784.7	649.1	Power

- PM Free-Free Modes
- Solid 1-inch versus 1/3 Lightweighted at same thickness
- Frequency values are good for LW

Mount Conditions, Gravity Sag (GS) and GS Correction

- **8, 16 & 24 Edge Mounts (3 DOF translations constrained)**
- **Tangent Mount (PM front surface at OD has constrained translations)**

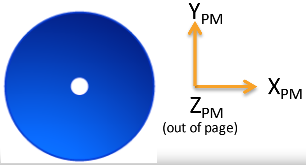




	Wavefront Error (nm RMS)								
	Input			BFP Removed			Power Removed		
	1gX	1gY	1gZ	1gX	1gY	1gZ	1gX	1gY	1gZ
8pt Edge Mount	25.6	25.6	706.8	25.6	25.6	706.8	25.6	25.6	48.4
16pt Edge Mount	27.5	27.5	560.3	27.5	27.5	560.3	27.5	27.5	14.3
16pt Edge Mount – LW	23.7	23.7	797.6	23.7	23.7	797.6	23.7	23.7	68.8
24pt Edge Mount	29.5	29.5	471.5	29.5	29.5	471.5	29.5	29.5	13.3
Tangent Mount	36.6	36.6	226.3	36.6	36.7	226.3	36.6	36.7	34.4

- **Sag w/Power Removed >20 nm rms Misalignment/Gravity residual WFE req't.**
- **BENI telescope operates between 25° to 65° from horizontal**
  - Gravity Loads relative to Mirror Coordinate System [X_{PM} Y_{PM} Z_{PM}]:
    - 25° Pointing: [-0.906 0.00 -0.423]g
    - 65°Pointing: [-0.423 0.00 -0.906]g
  - Can manufacture gravity effects in the X_{PM} and Z_{PM} directions into the mirror figure
  - Results in a "correction" of +0.664g in X_{PM} and +0.664g in Z_{PM}
  - The "corrected" gravity vectors become:
    - 25° Pointing: [-0.242 0.00 0.242]g
    - 65° Pointing: [0.242 0.00 -0.242]g

- **Perfect gravity correction is assumed**



Gravity Sag Assessment w/ Gravity Correction

	Wavefront Error (nm RMS) w/ Gravity Correction								
	Input			BFP Removed			Power Removed		
	25°	45°	65°	25°	45°	65°	25°	45°	65°
8pt Edge Mount	171.2	30.4	171.2	171.2	30.4	171.2	13.3	2.3	13.3
16pt Edge Mount	135.8	24.1	135.8	135.8	24.1	135.8	7.5	1.3	7.5
16pt Edge Mount – LW	193.1	34.3	193.1	193.1	34.3	193.1	17.6	2.3	17.6
24pt Edge Mount	114.3	20.3	114.3	114.3	20.3	114.3	7.8	1.4	7.8
Tangent Mount	55.5	9.9	55.5	55.5	9.9	55.5	12.2	2.2	12.2

- **Light-weighting the PM results in increased Wavefront Error**
- **The Simple 25.4 mm meniscus with no lightweighting, 16-point Edge Mounting, and corrected for Gravity Sag SHOWS PROMISE!**
- **Eliminating Isogrid Lightweighting Saves Many Months of Schedule, CVC SiC Deposition and Machining Costs, and Manufacturing Risks. Provides Enormous Heat Sink Capacity for Thermal Stability, and Eliminates Issue of Rib Print-Through.**
- **Trex recently machined 3 SM sized substrates to pre-polish condition in 2-weeks**
- **Once Replication dialed-in substrates should have IR quality off the mandrel.**

REQUIREMENTS: From "Slushy" to Firm

Requirement Name	Requirement	Prediction	Units	Comments/Rationale
Clear Aperture	100	100	cm	Minimum aperture
F-number	F/20 or greater		dimensionless	
Exit Pupil	Real Pupil			Needs real pupil after telescope to place FSM at
Full Field of View (FOV)	30.0		arcseconds	±15 arcseconds or 42.43 arcses along diagonal
Field of Regard (FOR)	25 - 65		Degrees	Elevation (axis thru mounting flanges)
Mirror Material (PM, SM)	CVC SiC™	CVC SiC™	N/A	Low CTE, Low Weight, High Stiffness, High Thermal Stability
Barrel	Composite		N/A	Lightweight, dimensionally stable
Structure Material	CVC SiC™		N/A	Athermal design; 220K Oper. Temp.
Lowest Resonant Frequency			Hz	
Telescope Wavefront Error	27.14		nm rms	Diffraction Limited @ λ = 380 nm
- Design residual	5		nm rms	At corners of 30 arcsec FOV (allocation)
- Misalignment/gravity residual	20		nm rms	After SM rcorrection (allocation)
- Dynamic /with SM control	18		nm rms	Drift per control step (allocation)
Wavefront error drift rate	18 nm / 30 sec			30 sec is control per time step
Secondary Mirror Adjustment Resolution	2 nm		LSB	Wavefront error (not mirror motion) per DOF
Secondary Mirror Adjustments	6 DOF			Rigid body motions (5 DOF may work)
Surface Roughness	10		Angstroms	UVOIR Diffraction limited
Scratch/Dig	40/20		microns/index	
PM Conic Constant	-1.002955		dimensionless	RC Cassegrain, Conics are design dependent, other designs possible.
SM Conic Constant	-1.367083		dimensionless	
PM to SM Spacing	≤ 170	130	cm	
Magnification	M = TBD		dimensionless	

Reqt's Cont.

Requirement Name	Requirement	Prediction	Units	Comments/Rationale
Alignment Repeatability to Host Gimbal Drives	Tilt: Disp:		μrad mm	
Optical Coating	Enhanced Al		N/A	Meets 350-2200 nm req'ts.
Operating Temperature Range	-40 C to +20 C		deg C	Based on STO temperature profiles
Temperature difference PM to SM	0.25		deg C	Set by induced thermal turbulence in tube.
Temperature slew rates	<0.25 C/ 8 minutes			Set by control system
Operating Vibration: X, Y, Z Tilts X, Y, Z Translations			 μrad, 1-σ mg, 1-σ	Telescope pointing error = 0.5 arcsec rms, without FSM control. With FSM control <0.1 arcsec rms
Handling/Transportation Shock Levels (all axes)	10 g of shock		g	Balloon launch / landing loads
Humidity during observation	12%		Relative humidity	During science observations
Humidity during shipping	<60%		Relative humidity	
Telescope Weight	<300		kg	Entire telescope budget
Telescope Moments of Inertia: Ixx/Iyy/Izz	TBD		lbm-in2 wrt CG	At center of rotation, depends on wheel size and slew rates