

# Ultra-lightweight, Deployable 1m-Class Optical Telescope for SSA Applications

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## 1. ABSTRACT

Deployable Optical/IR telescopes must be lightweight and rugged enough to withstand being placed from one location to another, in mostly adverse environments. This requires unique materials that are light, stiff and dimensionally stable in most any environment including a space environment. Continuous fiber reinforced polymer (CFRP) composite materials have been used to produce ultra-lightweight optical telescopes. Their thermal/mechanical properties offer advantages over conventional materials in terms of thermal expansion, stiffness and strength. The anisotropic nature of the material allows for weight and stiffness-optimized designs of dimensionally stable structures, ideal for telescopes. Optical mirrors can be produced from CFRP composites as well; yielding 1m diameter rigid primary mirrors weighing 12 kg. Presented will be unique telescope and mirror fabrication leading to extremely lightweight OTA systems up to 1.4m for the Navy Prototype Optical Interferometer, NPOI. The 1.4m NPOI Telescope, being produced by CMA, is required to be deployable along the baselines of the interferometer. We present the design of this system and how it evolved from various deployable concepts for optical telescopes.

## 2. CFRP MATERIAL ADVANTAGES

Carbon Fiber Reinforced Polymer (CFRP) composite materials offer many of the same advantages of SiC and Beryllium and certainly greater advantages over more conventional telescope materials. Unidirectional laminates are appropriate for low CTE structures such as strut tubes. Multi-angle laminates are used to produce plate elements with “quasi-isotropic behavior. CFRP material allows for tailoring properties of structures and mirrors. See figure X for graphic representation of ply-orientations. The following are advantages for using CFRP materials to produce lightweight, deployable optical systems.

- **Low Mass**

Density of CFRP materials is 1.6 gm/cc, which is roughly half of that of aluminum. Low mass produces low inertial problems that can result in high deflections of the optics during transportation and deployment. Obviously, low mass results in low energy requirements and fewer inertial problems affecting fast tracking and slewing.

- **Low Thermal Expansion**

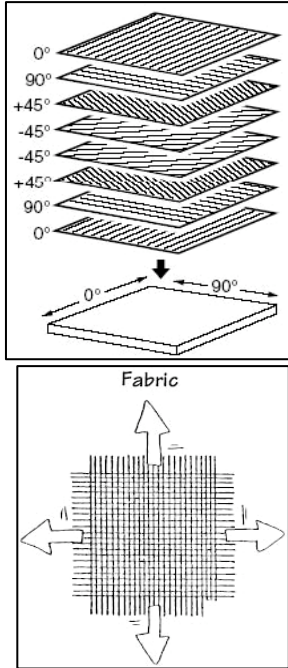
CFRP materials exhibit low coefficient of thermal expansion (CTE), lower than invar. CFRP telescopes and optics are produced from the same materials eliminating CTE mismatch resulting in simple telescope designs. Eliminating CTE mismatch can eliminate the need for costly and complex flexure and mirror cell designs. Low CTE designs such as unidirectional oriented laminates (unidirectional strut tubes or plates) along the optical axis will minimize the need for focus change across the operating temperature range of the system.

- **Anisotropic Design Flexibility**

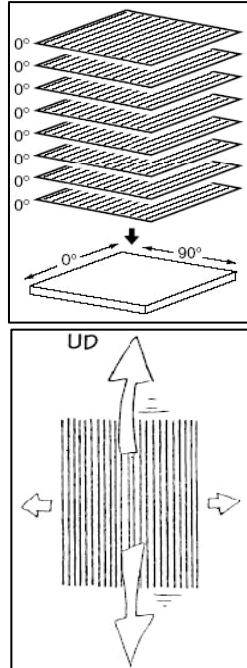
The unidirectional properties of CFRP material enables biasing of mechanical and thermal properties radially in plane. This means that ideal properties can be applied in specific directions in-plane, offering design flexibility while minimizing mass in directions on the structure where it is not needed. See figure 1a,b. Sandwich panels as shown in figure 2 offer lightweight and stiff structures, a great example of design flexibility.

- **High Stiffness/Strength-to-Weight Ratio**

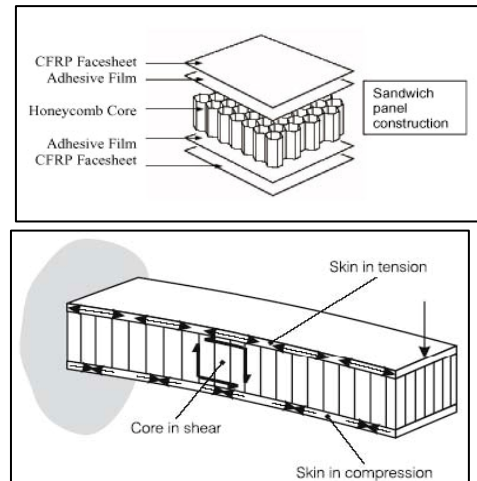
CFRP materials typically have stiffness-to-weight ratio 4 times greater than Aluminum, Cr Steel and Titanium. This makes CFRP materials ideal for stiff lightweight telescope structures, especially deployable systems that rely on the stiffness to hold alignment of the optics during deployability and under operating conditions at various elevation angles. See figure 3.



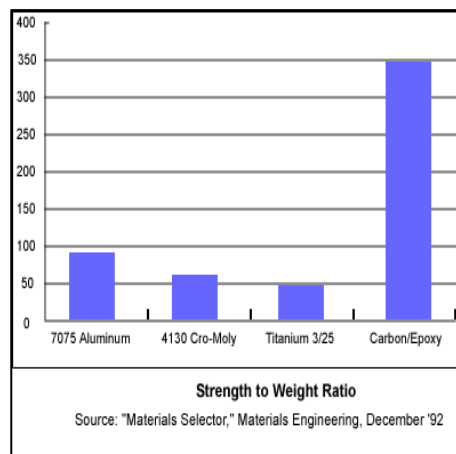
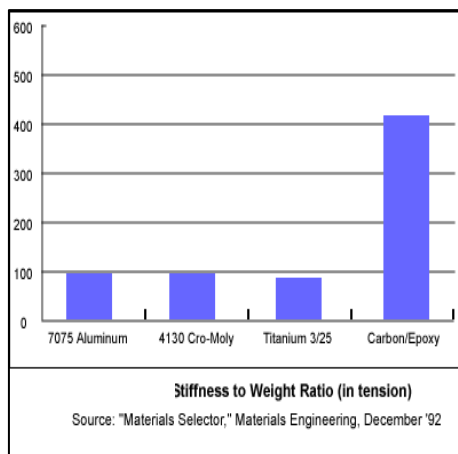
**Figure 1a**  
Multi-Angle  
Plies



**Figure 1b**  
Unidirectional  
Plies



**Figure 2** Honeycomb  
Sandwich Construction



**Figure 3**  
Stiffness/strength-to-  
weight ratios of  
CFRP composites  
compared to other

### 3. CFRP MIRRORS

#### 3.1 Composite Mirror History

CFRP composites have a history mixed history of success across a wide range of applications. JPL's Precision Segmented Reflector (PSR) program involved using carbon fiber/polymer matrix composite materials to produce image quality optics for use at submillimeter and into IR wavelengths down to 10.6 $\mu$ m, with a long term goal into visible wavelengths. The program was concluded with mixed results. In fact, no visible wavelength mirrors were produced under PSR due to complexity of processing and immaturity of high performance, dimensionally stable composite materials.

The PSR program, however, did yield vast amounts of material property data relating to composite materials, carbon fibers and various polymers such as epoxies and cyanate esters. Thermal performance data was also obtained for these materials suggesting their possible use for space telescope applications. CTE studies of the composites were measured to determine preferred ply-orientations, which could yield low stress and low out of plane deflections in the composite mirror substrates during processing. In addition, Sandia National Labs had performed studies relating internal stresses and resulting out-of-plane deflections of laminated composites due to ply-orientation errors [1]. This effort was important for verifying the use of cfrp composites for lightweight mirror substrates, but more work was required to produce specular mirrors. The key issues remaining were producing a highly polished surface quality and releasing the mirror from the mandrel. CMA has progressed to yield near diffraction-limited optical performance at 10X reductions in Mass.

#### 3.2 CFRP Mirror Fabrication

CFRP mirrors are produced via replication, which follows the path in figure 4 below. One must begin the replication process with a mold or "mandrel" exhibiting the identical optical prescription and accuracy of the desired final CFRP mirror. Bear in mind, the resulting CFRP mirror will only be as accurate as the mandrel unless some active figure control is applied to the mirror. The CFRP material is laid-up in a specific ply-orientation on the mandrel and the entire system is processed under heat and pressure. The result is a finished mirror requiring no grinding or polishing, ready for optical coating, again, as shown in figure 4.



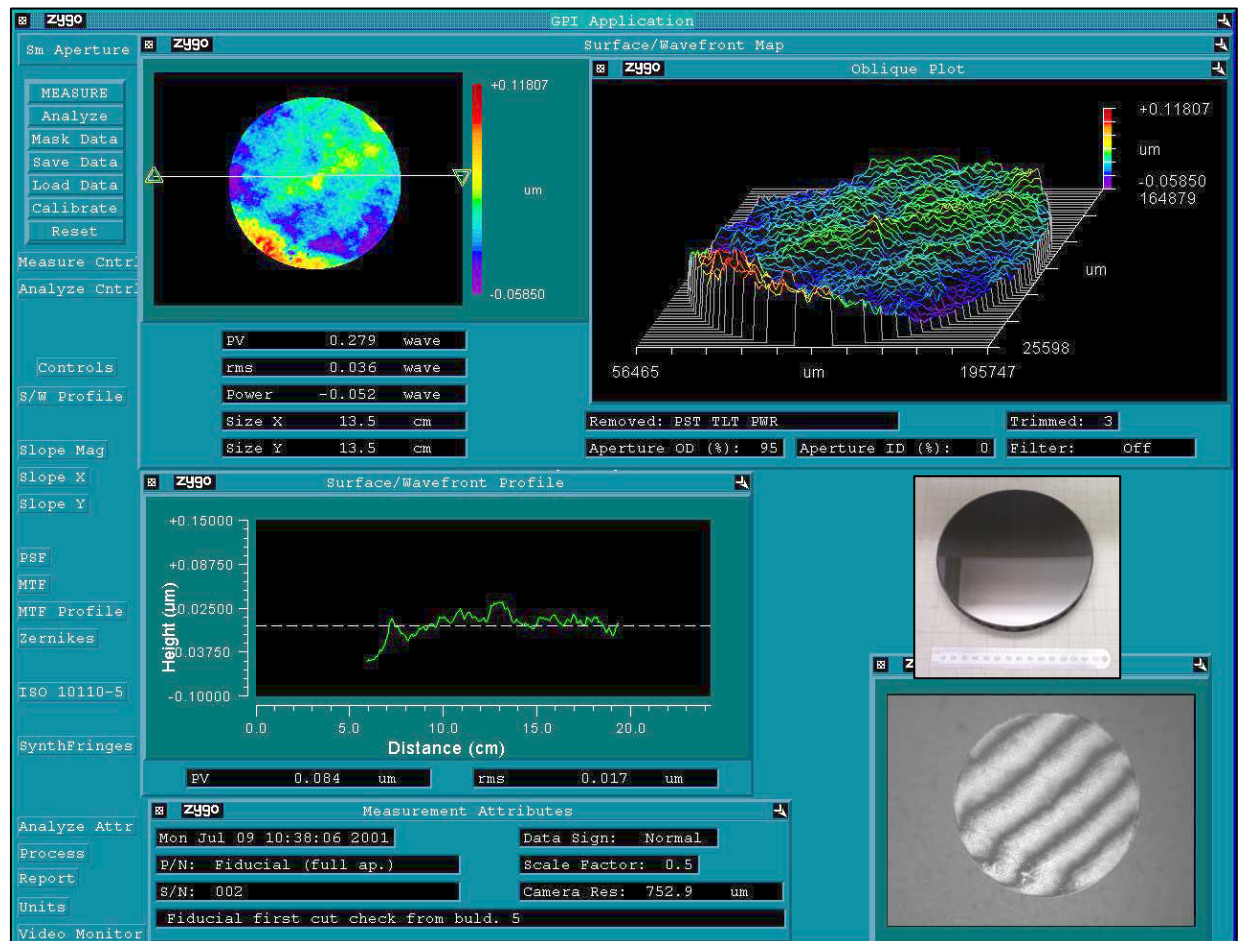
**Figure 4** CFRP fabrication sequence from left to right, processing the glass mandrel, CFRP prepreg material, lay-up of prepreg over the glass mandrel, processing and release CFRP mirror from the mandrel, ready for coating.

#### 3.3 CFRP Mirror Optical Performance

Currently, composite mirrors can be produced to near diffraction-limited optical performance at visible wavelengths. CMA is continuing development of the optical performance of CFRP mirrors under contract with the NRL supporting the Navy Optical Prototype interferometer (NPOI) program. In particular, CMA is producing a 1.4m prototype deployable telescope that includes CFRP primary and secondary mirrors. Smaller optics, 0.4m aspheric, were used as test "coupons" to establish procedures and materials for producing the 1.4m passive, f/2.0 parabolic primary mirror for the NPOI system.

The images below show interferograms and data reduction indicating imaging quality optics produced for test articles. The surfaces were achieved without grinding or polishing. Figure 5 shows ZYGO results of early work on a 150mm spherical mirror, indicating near diffraction-limited performance. The mandrel accuracy used for this mirror was  $\lambda/4$  p-v ( $\lambda = 633$  nm) on the wavefront. Figure 6 shows optical data relating to the 0.4m test mirrors. The mirrors in this case are limited by the wavefront quality of the mandrel [2], which measures to 0.5 $\lambda$  p-v. A 0.4m

Cassegrain primary is shown in figure 7. This mirror was produced for the NRL and the 0.4m prototype telescope described in section 4.1.

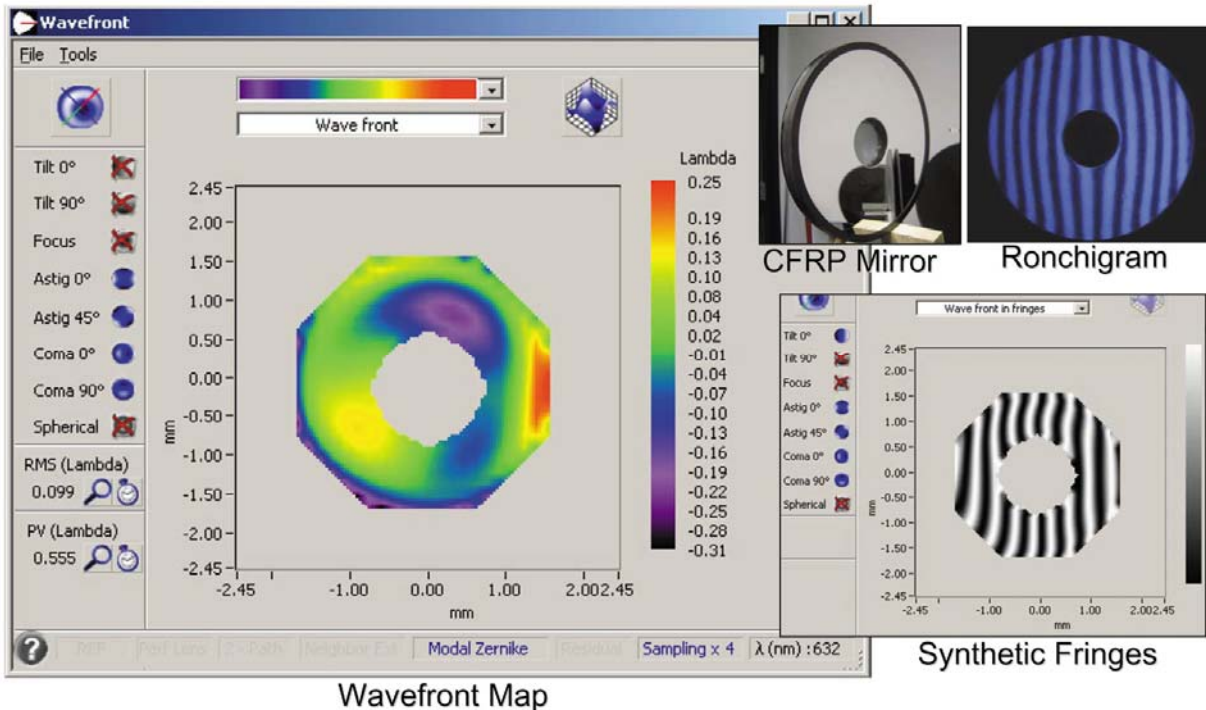


**Figure 5** ZYGO interferograms on a 150mm f/6.2 spherical mirror, mirror photo shown inset. Wavefront measures  $0.28\lambda$  p-v. Mirror was produced in 2001 and indicates decent optical performance.



**Figure 6** (Left) 0.4m parabolic CFRP mirror with aluminum coating, (Center) interference fringes for the mirror, (Right) 50lines/inch Ronchigram for mirror. Note turn-up edge [3] and central divot, indicating mandrel features.





**Figure 7** Shack-Hartmann Wavefront sensor data for a 0.4m parabolic CFRP mirror. The mirror and 50 lines/inch Ronchigram are shown inset upper right. Synthetic fringes are shown inset lower right. The wavefront map is shown with tip, tilt, piston and spherical aberration removed, indicating  $0.55\lambda$  p-v wavefront at  $\lambda = 632\text{nm}$ .

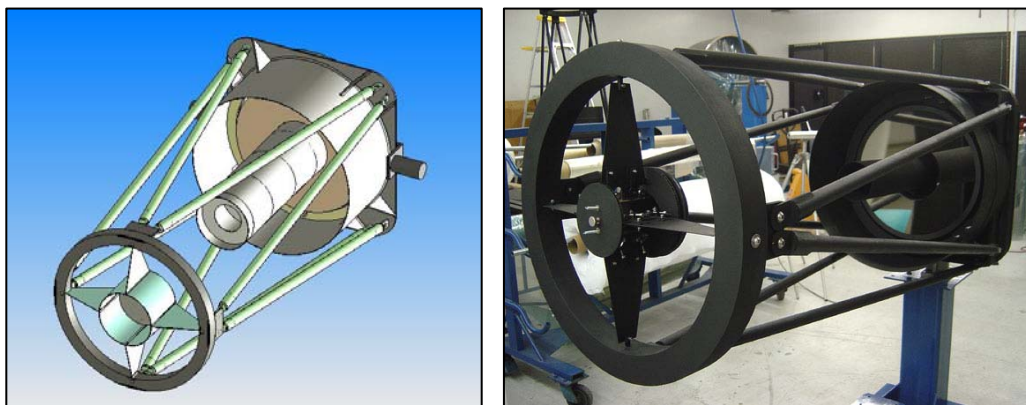
#### 4. OPTICAL TUBE ASSEMBLY DESIGN

The compatibility of the CFRP composite materials for use in deployable structures and CFRP mirrors has been defined above. The design of optical tube assemblies (OTA) from CFRP materials requires an understanding of how to produce the desired properties in the proper locations on the OTA. This means an understanding of when to adopt and when not to adopt unidirectional ply-orientation laminates. Conversely, it may be simpler to produce CFRP parts from quasi-isotropic ply orientations to avoid non-uniform thermal/mechanical properties but a weight penalty is paid as well as producing greater-than-zero CTE structures. An intelligent CFRP OTA design will incorporate both types of laminates as shown in figures 1a and 1b.

Deployable systems are not only concerned with dimensional stability and low mass, they must also be designed to withstand the load cases applied during stowage, transportation, deployment and redeployment. This requires the proper material selection capable of the strength and toughness required to meet all loading conditions. Fabrication methods will also be a key factor for survivability of deployable OTA systems. The proper methods of joining components, gluing or post curing of many parts to produce a single part will be essential to a proper design. Reduced part count is desired but difficult to achieve in a high performance part. A thorough knowledge of the conditions under which the OTA will exist is an essential beginning in a deployable OTA design. For the sake of this paper, ground-based conditions are assumed. Obviously, aerospace environments require different, yet doable, design considerations.

The following are deployable OTA designs that were also produced in CFRP. A brief description follows each.

#### 4.1 NRL 0.4m Cassegrain Telescope



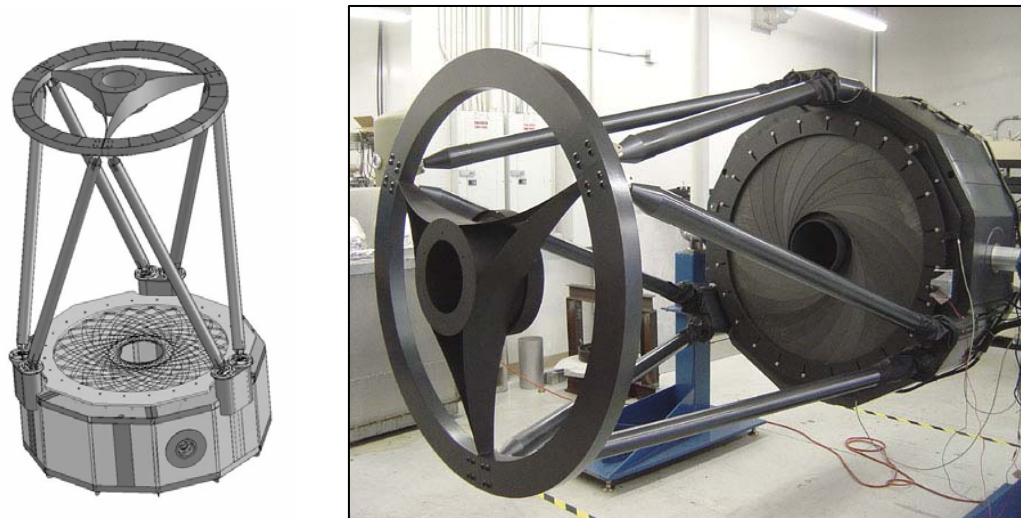
**Figure 8** (Left) 0.4m Cassegrain Telescope, 3-D design, (Right) 0.4m CFRP Cassegrain Telescope

The 0.4m system was produced as a deployable working prototype, incorporating all CFRP construction. The base was produced from CFRP/aluminum core sandwich composite shown in figure 2 and low modulus, high strength carbon fiber. The strut tubes were produced in high modulus carbon with a low moisture uptake cyanate ester resin system. The optics, both primary and secondary are made from the same high modulus/cyanate material but using a CFRP core structure instead of aluminum. This yields no CTE mismatch between facesheets with extremely high stiffness in the optics. The OTA was later integrated to a CFRP Az-El mount as shown in the images below. The system is 2-person deployable as noted by the handles on the side view. The mount is produced from CFRP and because of the lightweight characteristics of the OTA and yoke, utilizes piezo drive motors for high accuracy, high rate tracking capabilities. This system is currently being tested by NRL, Albuquerque.



**Figure 9** (Left) 0.4m Telescope front view, (Right) 0.4m Telescope, side view

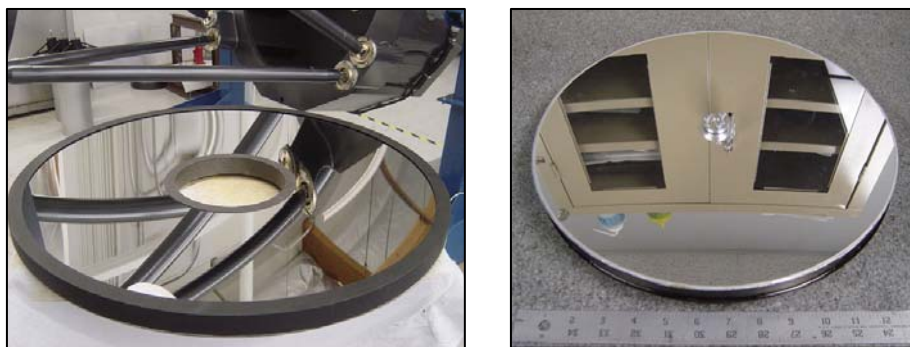
## 4.2 NSF 1m ULTRA Cassegrain Telescope



**Figure 10** (Left) 1m ULTRA Cassegrain Telescope, 3-D design, (Right) completed 1m ULTRA CFRP Cassegrain Telescope

Figure 10 shows the Ultra Lightweight Telescope for Research in Astronomy (ULTRA). This system, although is not currently deployable, it displays the tenets of a deployable OTA and serves as the prototype for the 1.4m NPOI upgrade telescope described in section 3.3. The complete OTA without instrument weighs 80 kg, which is nearly 2 orders of magnitude lighter than conventional “steel-and-glass” systems.

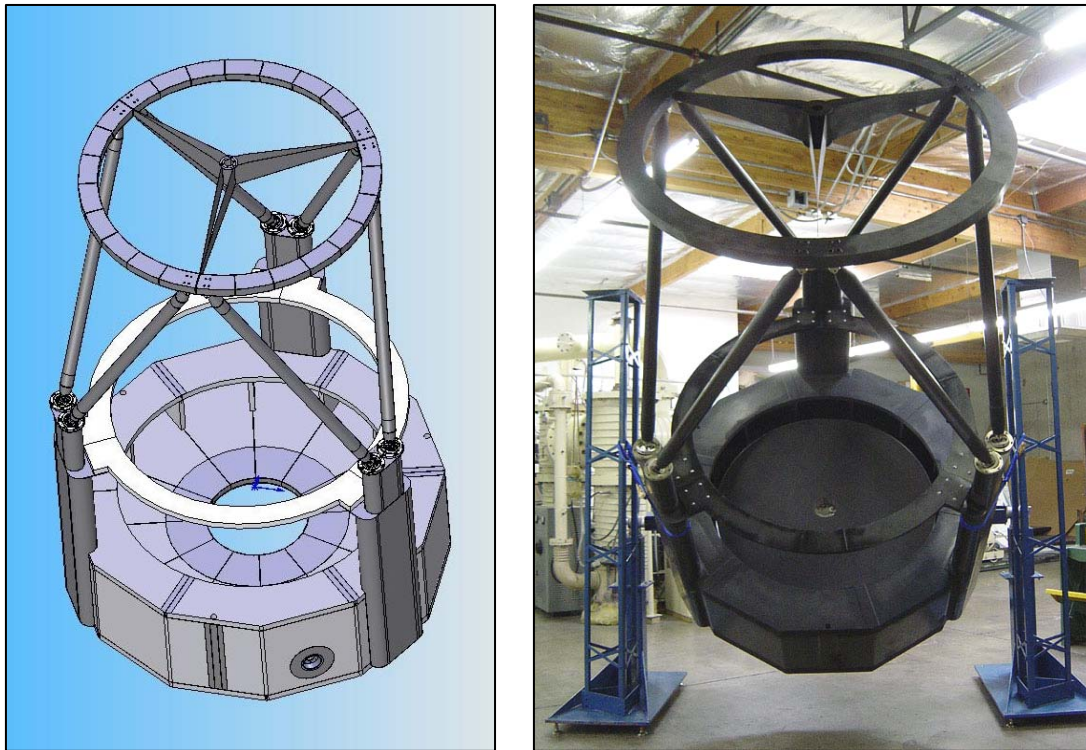
The base is produced from CFRP/aluminum core sandwich and produced with a set of sub sized parts adhered using a sophisticated bonding system. The primary mirror cell is actually the highly stiffened and reinforced base of the OTA. This was possible because no CTE mismatch exists between the primary mirror and OTA base. The strut tubes are produced as mostly unidirectional CFRP tubing, yielding near-zero thermal expansion and thus stable in focus across the operational temperatures. The secondary mirror is adjusted through a simple piezo driven hexapod, allowing for full 6-DOF on M2. Figure 11 shows the CFRP primary and secondary mirrors for this telescope. The primary mirror weight is 12 kg with the secondary mirror weight of 1.5 kg.



**Figure 11** (Left) 1m coated ULTRA parabolic primary mirror, 12 kg, f/3.0, (Right) coated hyperbolic secondary mirror for ULTRA. For testing hexapod alignment of the optics, a laser is located in the center of the mirror

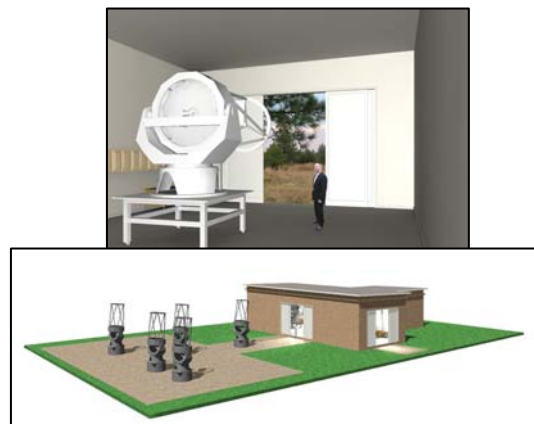
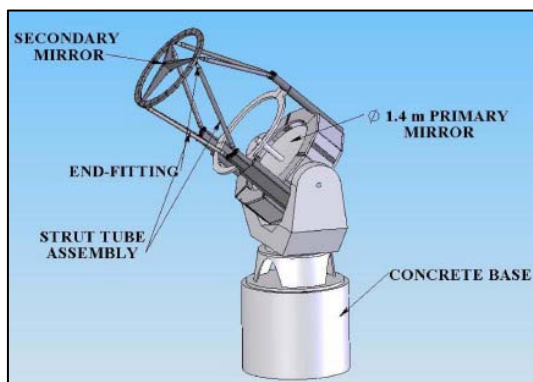


## 4.2 NRL 1.4m Cassegrain Telescope for NPOI Upgrade



**Figure 12** (Left) 3-D design of the NPOI 1.4m Cassegrain telescope (Right) Assembled NPOI Telescope shown in assembly structure at CMA. Complete OTA weight is 115 kg. The telescope is being painted and optics will be completed the end of 2007.

CMA is involved with the Navy Optical Prototype Interferometer (NPOI). Two programs are currently underway to support NPOI, the 0.5m CFRP mount and the 1.4m optical telescope. Figure 12 above shows the NPOI telescope. The CFRP mount is designed to be Az-El mount produced almost entirely out of CFRP materials. It will incorporate piezo drives for both axes and will support the NRL AO system. The mount was designed and is under construction at CMA, Tucson and shown in figure 13.



**Figure 13** (Left) 3-D design of the NPOI 1.4m Cassegrain telescope and mount (Upper Right) Stowage concept for the 1.4m telescopes inside the enclosure. (Lower Right) Deployed state for 1.4m telescopes outside the enclosure.



The NPOI prototype telescope is designed to be deployed (shown in figure 13) on a frequent basis at the site on Anderson Mesa, near Flagstaff, AZ. The telescope, initially, will be housed in an enclosure and rolled out in the evenings for operation. The scope will be transported on a special cart system and placed onto a concrete pier using a specially designed mounting system, capable of tip and tilt adjustments for each of the telescopes in the array. This requires the telescope to be accurately positioned, aligned and calibrated on a nightly basis. This is an ideal deployability scheme for a light weight telescope system. The telescope can easily be transported as it will weigh less than 600 lbs including the Az-El mount and AO system. The NPOI prototype is an ideal testbed for the deployability aspects of a lightweight telescope system. Six 1.4m telescopes are planned for NPOI after a successful prototype demonstration.

## 5. NEXT GENERATION DEPLOYABLE CONCEPT

### Deployable Observatory for Optical Reconnaissance, DOOR

The DOOR concept is one envisioned to employ ultra-lightweight carbon fiber reinforced polymer, CFRP, composite materials. DOOR is conceived be a multi purpose instrument, capable of a wide variety of deployment methods. The system is a 1m-class optical telescope, which is 3 to 4-person deployable and redeployable on a 24-hour basis. This includes hard mounting to various ground conditions, rocky to sandy conditions using a special mount-to-ground attachment system. The ground attachment can be done through unique techniques due to low telescope mass. Figure 14 below shows an example concept of what DOOR might resemble.



**Figure 14** Deployable Observatory for Optical Reconnaissance, DOOR, Advanced Deployability Concept

The DOOR concept involves the following features.

- Light-weight Optics**
  - Composite Mirrors
  - Composite Mount Structures
- Dynamic Optics**
  - Membrane Mirrors
  - Flexible Large Optics
- Optical Techniques**
  - Adaptive Optics
  - Non-Mechanical Zoom and Real-time Spot Size Optimization
  - Real-time Filter Modulation
- Domeless Weather Tight Telescopes**

## **6. CONCLUSIONS**

CFRP composites are ideal candidate materials for deployable optical telescope applications. Producing optical quality mirrors has been demonstrated on a medium scale and being produced and tested at the 1m and 1.4m size. The properties of the material are advantageous from many points of view, including thermal stability, rigidity and lightweight. The use of CFRP composites for precision optical telescopes requires knowledge of the nature of the material in order to gain every advantage possible in terms of a weight-to-performance ratio. CFRP OTAs have been successfully designed and produced, yielding lightweight systems exhibiting the essential structural features for SSA applications. Advanced deployable telescope concepts using CFRP materials can be pursued from the structures point of view based on the work presented. Further results of existing CFRP systems will add insights to applying CFRP to high performance optical imaging systems.

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2. Robert C. Romeo, Robert N. Martin, Bruce Twarog, Paul Etzel, "Final assembly of the ULTRA 1-m carbon fiber optical telescope", SPIE Symposium on Optical Engineering & Applications, San Diego Convention Center, San Diego, CA. 2007.
3. D. J. Malacara, "Optical Shop Testing", Second Edition, Wiley-Interscience, 1992.