Compact Telescope for Free Space Communications

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ABSTRACT

Several types of telescopes are used for free space telecommunications. The most common are Cassegrain and Gregorian telescopes. The main difference between Cassegrain and Gregorian optical systems is that Gregorian telescopes employ a concave secondary mirror located beyond the focus of the primary mirror. This results in longer tube lengths, as the distance between mirrors is slightly more than the sum of their focal lengths, which is the reason Cassegrain systems are the most common. In addition, Gregorian telescopes produce an upright image, while Cassegrain telescopes produce an inverted image.

FSONA is presenting a new compact optical system, which can be described as a modified Gregorian telescope. This telescope is ideally suited for free space optical communications but also has many other applications. The compact telescope is created from a standard Gregorian system by flipping the secondary mirror over a folding mirror installed approximately in the middle of the optical path between primary and secondary mirrors. In this manner, the primary mirror is constructed with a concentric "double curved" geometry, and a central obscuring folding mirror which matches the diameter of the smaller curve of the primary is mounted a short distance in front. This "double curved" geometry is easily produced using diamond turning technology, and the result is a compact telescope approximately 1/2 the length of a regular Gregorian telescope and roughly 2/3 the length of a Cassegrain telescope.

There are several advantages to using this type of telescope:

1. The system is very compact. Telescope can be as short as 1/7 of the focal length of the system.
2. For Cassegrain and Gregorian systems it is very critical to keep tight tolerances on the centration between primary and secondary mirrors. The modified Gregorian telescope will always have perfect centration because both curved surfaces are machined at the same time on a diamond turning lathe. The folding mirror is flat so no centration is required.
3. The modified Gregorian system is inexpensive. Instead of two curved mirrors, there is one mirror with two curves, and one inexpensive flat folding mirror.
4. The folding mirror can be used as a steering mirror for a tracking system.
5. If the modified Gregorian telescope is constructed out of one material (ie. aluminum), it is completely a-thermal and insensitive to changes in temperature.

Keywords: compact, modified, Gregorian, telescope, free-space, communications, diamond-turned, double-curved, mirror

1. INTRODUCTION

fSONA Communications Corp, a manufacturer of Free Space Optical communications products, developed a mirror telescope (patent-pending) for use in a high-speed optical transceiver. The design required that the telescope have a large receive aperture, be mass producible, compact in size, relatively inexpensive, and insensitive to thermal changes. The system also required positioning of the focal plain behind the primary mirror, and diffraction limited performance.

Two standard types of telescopes were considered for this application: Cassegrain and Gregorian. Unfortunately, while each of these systems has its own advantages, they also have several disadvantages for fSONA's application. The biggest disadvantages were the complex alignment between primary and secondary mirrors, plus the need to machine two curved mirrors. These designs were also sensitive to temperature changes, and not compact enough.

For classical Cassegrain telescopes, the primary mirror is parabolic and the secondary is hyperbolic, whereas for Gregorian telescopes, both mirrors are ellipsoidal. For aplanatic Cassegrain systems both mirrors are hyperbolical (so called Ritchey-Chretien telescope), while for Gregorian telescopes both mirrors remain ellipsoidal. Considering optical aberrations Gregorian telescopes perform slightly better than Cassegrain designs. Gregorian telescopes were popular in the 18th century because they produce an upright image, and so can be viewed without additional inverting optics. Sketches of simple Cassegrain and Gregorian telescopes are presented in Figure 1. One point of interest here is that the Gregorian telescope has an intermediate focal plain located between its two mirrors. This makes the Gregorian system much longer than the Cassegrain system.

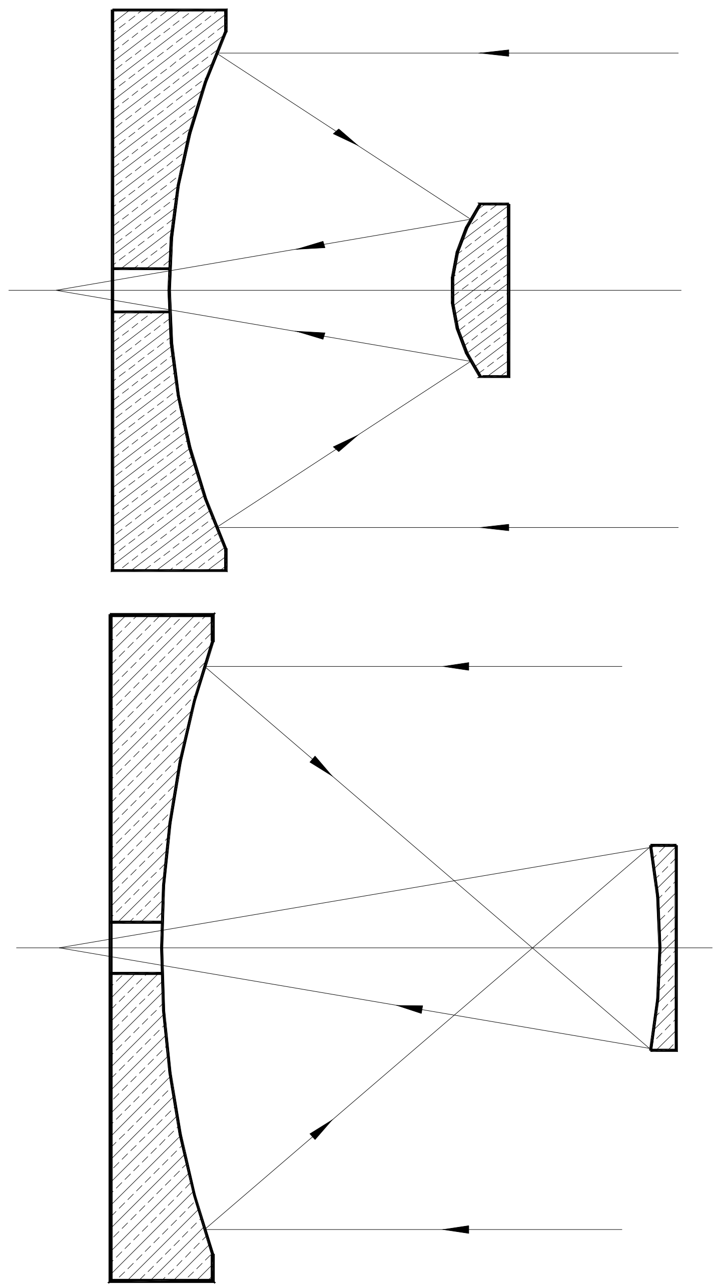

Figure 1. Cassegrain telescope (above), Gregorian telescope (below)

2. NEW TELESCOPE SYSTEM

By placing a folding mirror approximately mid-way between the primary and secondary mirrors, a Gregorian telescope can be constructed with roughly half its original length. A sketch of this modified Gregorian design is shown in Figure 2. This new design lends itself to diamond turning technology, where both the primary and secondary mirrors are turned in the same setup, thereby guaranteeing near perfect concentricity. The folding mirror is simply spaced out from the primary / secondary combination, and there is no additional geometric requirement other than controlling the tilt.

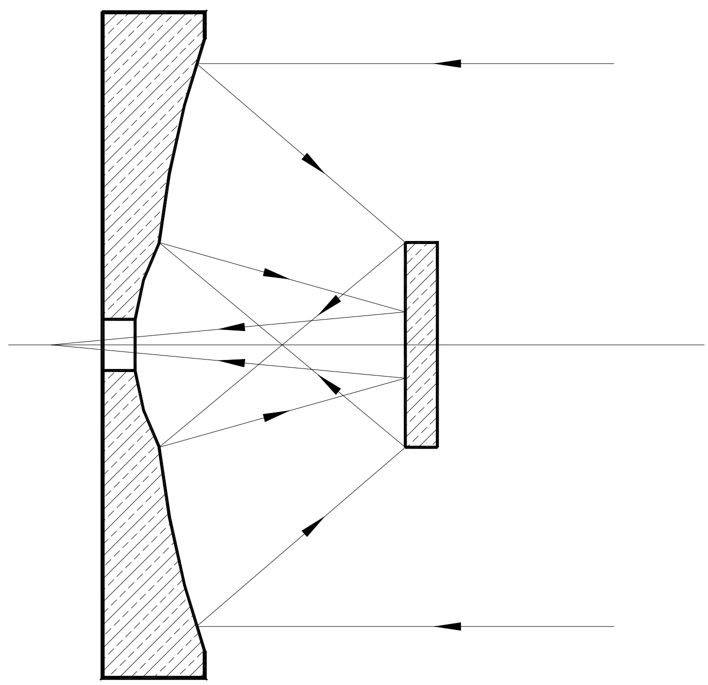

Figure 2. Modified Gregorian telescope

In commercial telescopes, typically both mirrors are made from glass. This limits mirror geometry to simple shapes that can be produced through the grinding and polishing processes. For the modified Gregorian design, fSONA specified diamond turned aluminum mirrors. This process gives full freedom for optical design and at the same time is very cost effective for a wide range of quantities. Light scattering in the focal plane, that is typical for diamond turned mirrors, is not critical for fSONA's application, where the receiver acts like a light bucket. The modified Gregorian telescope design produces a very small diffraction limited spot, which is critical for the small diameter high sensitivity detectors used in telecommunications.

Another advantage of metal mirror technology is that structurally sound mirrors can be produced with less mass than glass mirrors. Large solid sections can be hollowed out with supporting ribs or honeycomb structure. Also, mounting features such as tapped holes and alignment pins can be integrated into the mirror substrate, without the additional cost separate mounts. Since the telescope structure is most commonly made from lightweight materials such as aluminum, this also guarantees little to no differential thermal expansion between mirror and housing. In fact, the modified Gregorian telescope can be designed to be completely a-thermal, eliminating any thermally induced aberrations, or focal shifts.

One additional design option that can be considered with a modified Gregorian telescope is to replace the front folding mirror with a fast steering mirror. For systems requiring active tracking or beam steering, this approach offers some definite advantages.

3. PARAMETERS OF THE TELESCOPE

Geometric layout of the modified Gregorian telescope is derived from a standard Gregorian architecture. In order to achieve minimum obscuration, the secondary mirror diameter must match the folding mirror diameter, which is exactly 1/3 of the diameter of the primary mirror. The optical layout of a Gregorian telescope is shown in Figure 3, with the optimum location of a front folding mirror indicated.

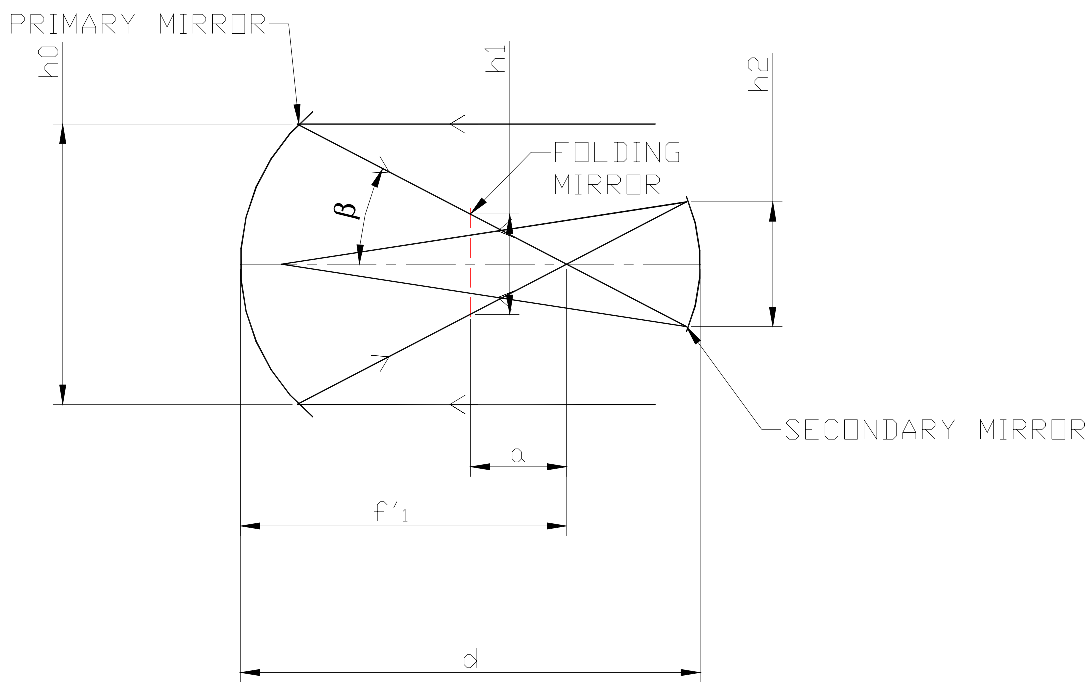

Figure 3. Gregorian telescope optical layout

Where:

d	Length of Gregorian telescope.
h0	Diameter of primary mirror.
h1	Diameter of the beam halfway between primary and secondary mirror. This is the folding mirror position for the modified Gregorian telescope.
h2	Diameter of secondary mirror. For minimum obscuration, h1 = h2 = h0 / 3 .
f'1	Focal length of the primary mirror. f'1 = r1 / 2, where r1 is radius of the primary mirror.
a	Distance from preliminary focus to folding mirror
β	Beam angle after primary mirror

For a modified Gregorian design, a few other parameters need to be factored into the final layout.

1) Focal length of the telescope.
2) Diameter of the primary mirror.
3) Back focal distance.
4) System must be corrected for spherical aberration and coma.

Referring to Figure 3, the following additional equations are derived.

$$f'1 = r1 / 2 \qquad (1)$$

$$a = f'1 - d / 2 \qquad (2)$$

$$\tan \beta = h0 * f'1 / 2 \qquad (3)$$

$$h1 = 2 * \tan \beta * a = a * h0 / f'1 \qquad (4)$$

$$h2 = 2 * (d - f'1) * \tan \beta = h0 * (d - f'1) / f'1 \qquad (5)$$

Using these equations and typical methodology, a modified Gregorian telescope system can be easily optimized. One example telescopes has a focal distance f = 700 mm and F/# = 3.3. After optimization, the total length of the telescope is shown to be close to 1/7 of its focal distance. Spot diagrams for this telescope through a field of view of 4 mRad is shown in Figure 4.

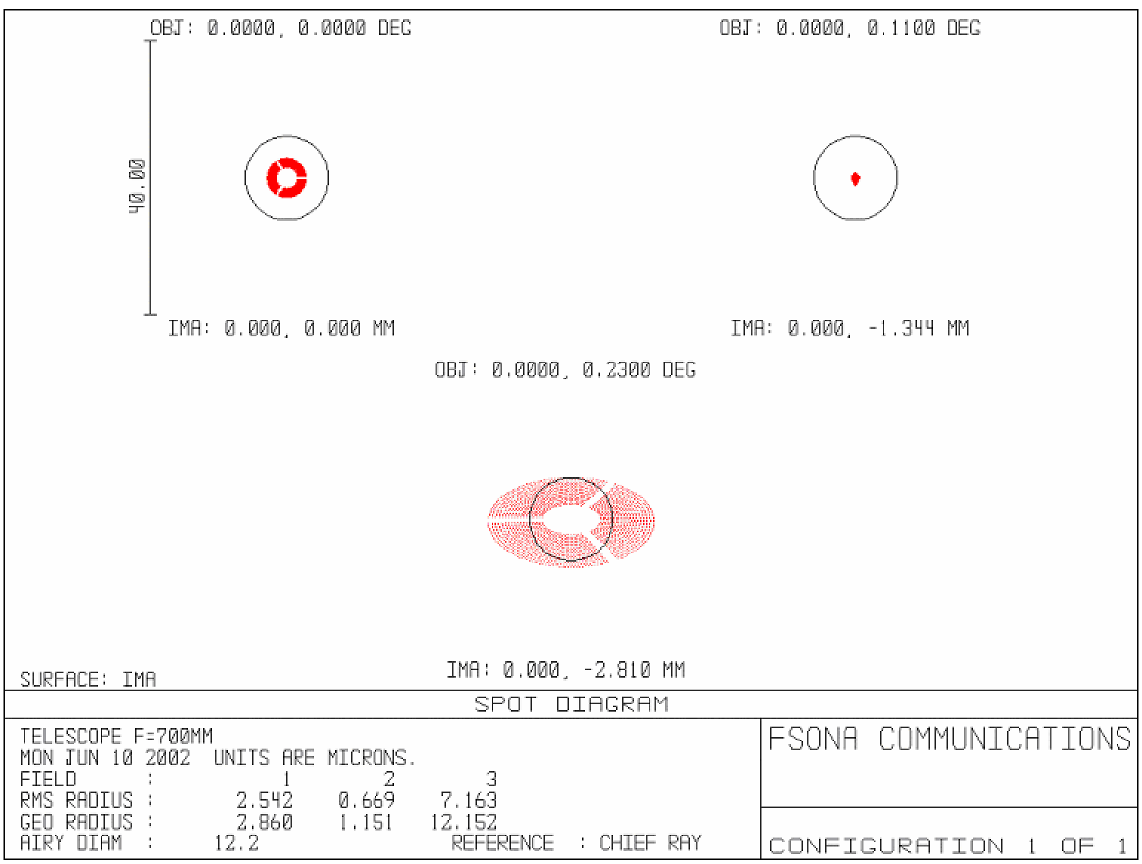

Figure 4. Spot diagram of modified Gregorian telescope

In Figure 4, the thin circles represent the size of the Airy disk. As can be seen, the modified Gregorian telescope is well corrected for spherical aberration and coma. The curved field of view is typical for Gregorian telescopes and cannot be corrected without additional optics. For the designed field of view, the telescope remains diffraction limited.

5) MECHANICAL DESIGN

Mechanical design of the modified Gregorian telescope required attention to the following details:

- Low mass – for potential aeronautic and space applications
- High natural frequency – immune to forced vibration
- Common material usage – avoid differential thermal expansion issues
- Minimal clamping and bolting stresses – avoid mirror distortion
- Simple machining, fabrication and alignment – for low cost and mass producibilty

Considering these criteria, an all aluminum design was proposed. For diamond turning, aluminum alloy 6061-T6 is recommended. Since this material is also commonly available, it was chosen for both the primary / secondary mirror and folding mirror. A spider was also designed from aluminum to position the folding mirror on axis. Since the spider was somewhat more complicated to machine, it was designed to be investment cast or die-cast out of 356 aluminum, which closely matches the thermal behavior of 6061. For critical applications, however, spiders can be machined from the same 6061 stock as the primary / secondary mirror.

Finite element analysis was performed on the mirror assembly to reduce the overall weight, while maintaining strength. Particular attention was given to reducing stresses that could be induced during diamond turning, or at the time of assembly. Mounting screws have the potential to deform the mirror surface, if not properly isolated. For this reason, tapped holes were strategically placed on rib sections or flanges where undercuts could be used to minimize the stress flow to the mirror surfaces.

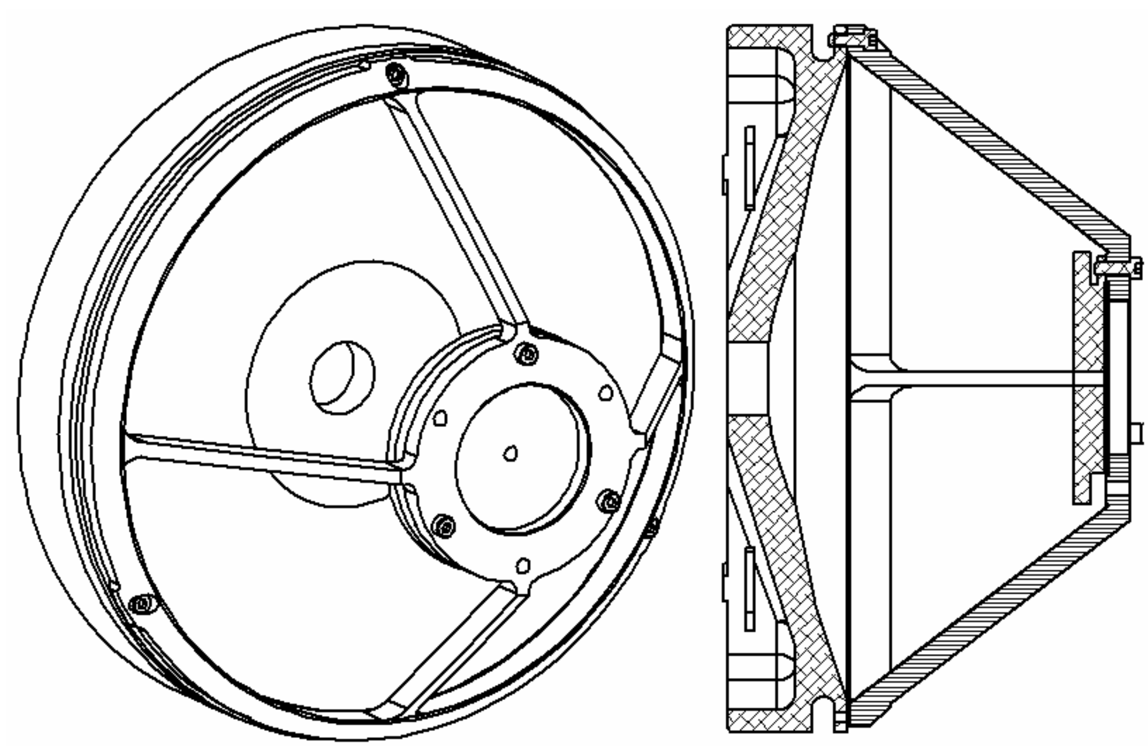

Figure 5. Modified Gregorian telescope

A modified Gregorian telescope design is shown in Figure 5. This particular design shows a four-leg spider supporting a diamond turned folding mirror. Undercuts around the outside diameter of both mirrors prohibit bolting stresses from propagating to the mirror surfaces. Both mirrors are mounted to the spider at three points. The mounting surfaces on the spider are diamond turned to ensure precise spacing between mirror surfaces and guarantee parallelism. Precision turned through holes in both the primary / secondary mirror and folding mirror can be used for optical alignment purposes.

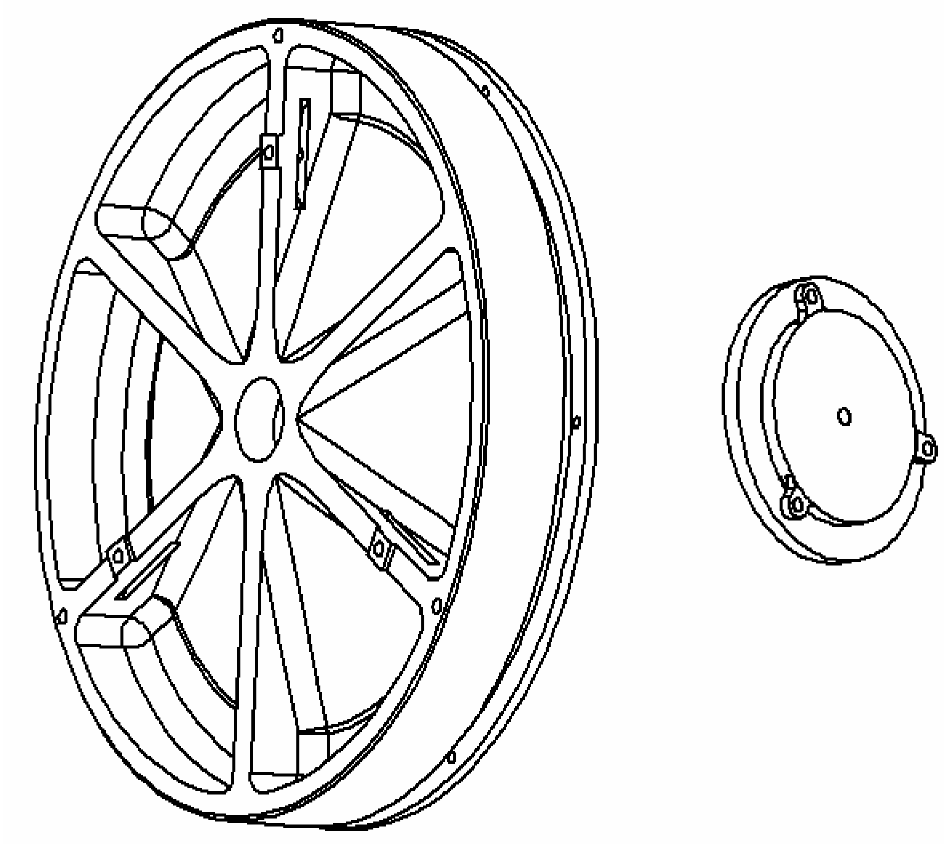

Figure 6. Mirror substrates

The primary / secondary mirror substrate is hollowed out in the back to reduce weight. There are three mounting bosses on three ribs, with slots cut through the ribs. These slots reduce the stress concentrations, which would otherwise form on the front mirror surface during the diamond turning process and subsequent mounting in the final system. The folding mirror is supported by three little legs, which again minimize the stresses on the front mirror surface.

6) CONCLUSION

The modified Gregorian telescope is extremely compact and can be as short as 1/7 of the focal length of the telescope. By constructing the telescope and supporting spider out of the same material, the telescope is completely insensitive to temperature changes. Such telescopes are also easy to manufacture and align, and can be designed to be very lightweight. Because of these inherent advantages, the modified Gregorian telescope has many applications in military, space, telecommunications, and other industries. The design is patent pending by fSONA Communications Corp.

7) REFERENCES

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