An all-spheric unobstructed optical terminal for free-space quantum communication

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ABSTRACT

We design and built a novel optical terminal specifically designed for free-space communication operating at light levels at the quantum limit, such as in quantum communication. Our system is particularly well suited for this task, as it is based on an all-spheric catadioptric design, which allows for large and un-obstructed apertures. This design offers an easier and cheaper approach to building high-quality optical terminals with large apertures than schemes based on off-axis parabolic mirrors. We utilized an off-axis version of the original Schwarzschild concentric design, and correct the spherical aberration by substituting the original on-axis secondary spherical mirror with an off-axis catadioptric secondary mirror. A prototype of the optical terminal was realized and tested and it meet the expected performance.

Keywords: Quantum communication, optical vortex, telescope.

1. INTRODUCTION

There is quite a large number of different optical terminals that have been designed specifically for free-space optical and laser communications, realized with either refractive or reflective optics. Optical design of the terminals usually follow the classic scheme of astronomical telescopes, with minor modifications. A good review of existing configurations may be found in[1]. These telescopes are, in principle, all suitable as receivers for quantum communication. However, in order to achieve maximum photon collection efficiency it is necessary to realize a large and unobstructed aperture. In classical laser communication, the presence of a central obstruction does not pose a significant disadvantage, because the information resides in the modulation of a relatively bright signals. In quantum communication, instead, the information is encoded in single photons, and in certain encoding schemes the presence of even small obstructions can be a serious problem[2]. Moreover, in realizatons of Bell's inequality tests and quantum communication experiments, a high noise-limited fidelity of the optical terminals, and therefore reducing losses on the free-space channel, is the main priority. Bell's inequality experiments might use terminals at distances of several kilometers and telescope apertures on the order of at least 20-40 cm are necessary[3-5].

To minize the possible loss of single quanta, a clear logical step is to eliminate the central obstruction in the telescope. This even becomes crucial when transmitting and receiving either photons, or even a macroscopic signal of light, carrying orbital angular momentum (OAM)[6-9]. The presence of a central obstruction and of the mechanics holding the secondary mirror dramatically alters the spatial mode for both transmitted and received photons, leading to a distortion of the OAM state.

Refractive optics offer the advantage of having an un-obstructed design that avoids the loss of photons due to the presence of a central obstruction which is instead common in all the optical terminals based on a classical reflective design. However, because of the high costs for both the optical quality glasses required to realize the objective lens(es) and for realizing large apertures, all transmissive-optics-based terminals rarely exceed a diameter of 30 cm. Therefore large terminals are best based on reflective designs. Commonly, reflective optical terminals are based on a Cassegrain or a Gregorian configurations, extensively studied in astronomy. In both the configurations the primary mirror is parabolic,

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while in the first scheme a hyperbolic secondary mirror is used, and in the second scheme an elliptical secondary mirror. Aplanatic version of both configurations, corrected for the off-axis coma, are also widely used. The Cassegrain design is usually more compact than the Gregorian, but both configurations always have the central obstruction of the secondary mirror[1].

As a solution for the realization of large unobstructed aperture optical terminals we designed and built a novel optical setup in which the central obstruction is totally eliminated. The beauty of our design is that it is based only a spherical primary mirror and an off-axis, but also spherical, secondary mirror. In particular, the choice of an all-spheric design has key advantages over complex aspheric designs in respect of both the manufacturing of the optics and their final alignement.

2. OPTICAL TERMINAL DESIGN AND TEST

The optical terminal is an un-obstructed (off-axis) version of the classical finite-conjugate Schwarzschild all-spherical concentric design, which is built by using only two spherical mirrors. The optics of our terminal have been optimized for free-space optical communication at very long distances, by modifying the original finite-conjugate design to an infinite-finite-conjugated one. A sketch of our optical configuration is shown in figure 1.

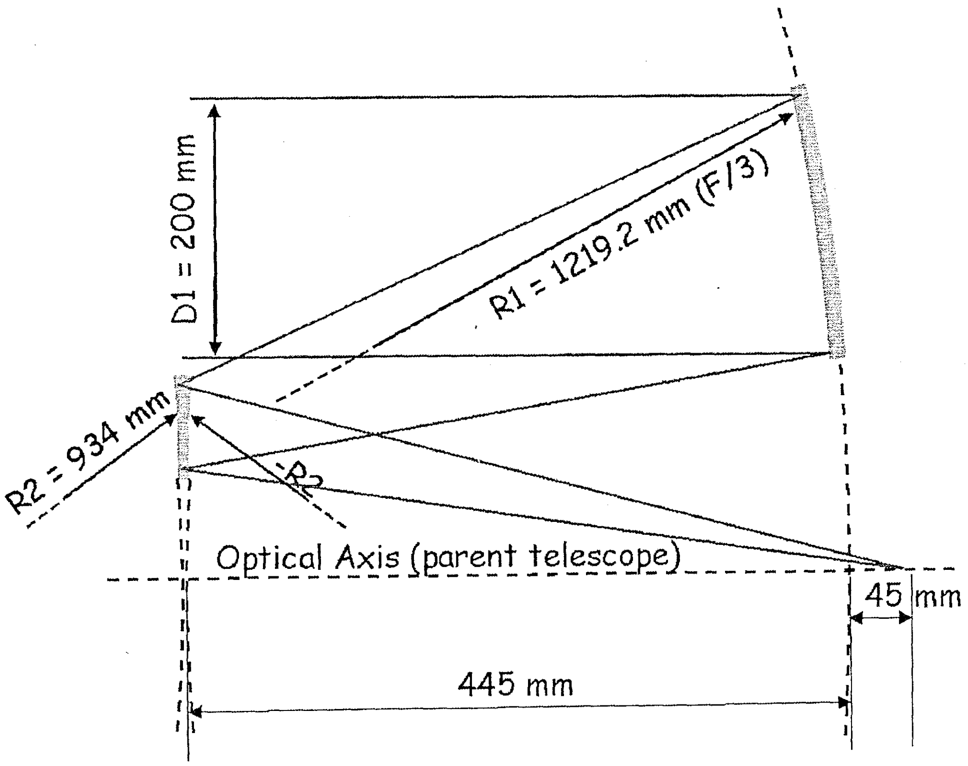

Figure 1. Ray-tracing sketch of the optical layout. Parameters are described in the text

The prototype we built is formed by a 200 mm spherical primary mirror, of 609.6 mm in focal length (f/3) and an all-spheric double-concave catadioptric secondary in which both the surfaces are spherical and have the same radius of curvature. More specifically, the secondary mirror has a diameter of 80 mm and a curvature radii of 934 mm (for both the front and back surfaces). The back surface is fully aluminized making the catadiopter act as a three-surface corrector, and is obtained from an high-quality UV-W76 Schott glass support. The primary mirror is tilted by 10° with respect to the direction of the incoming light beams. The secondary mirror is located at a distance of 445 mm from the primary as measured along the optical axis of the parent telescope. The back focal distance is of 45 mm.

The optical setup works at F/10 and has been designed to be diffraction limited for a field of view (FoV) of +/- 20 arcseconds at a working wavelength of 850 nm. More than the 90% of the photons collected by the terminal falls in the focal plane inside a region having a radius of 25 μm for a FoV of +/- 1 arcmin (see figure 2).

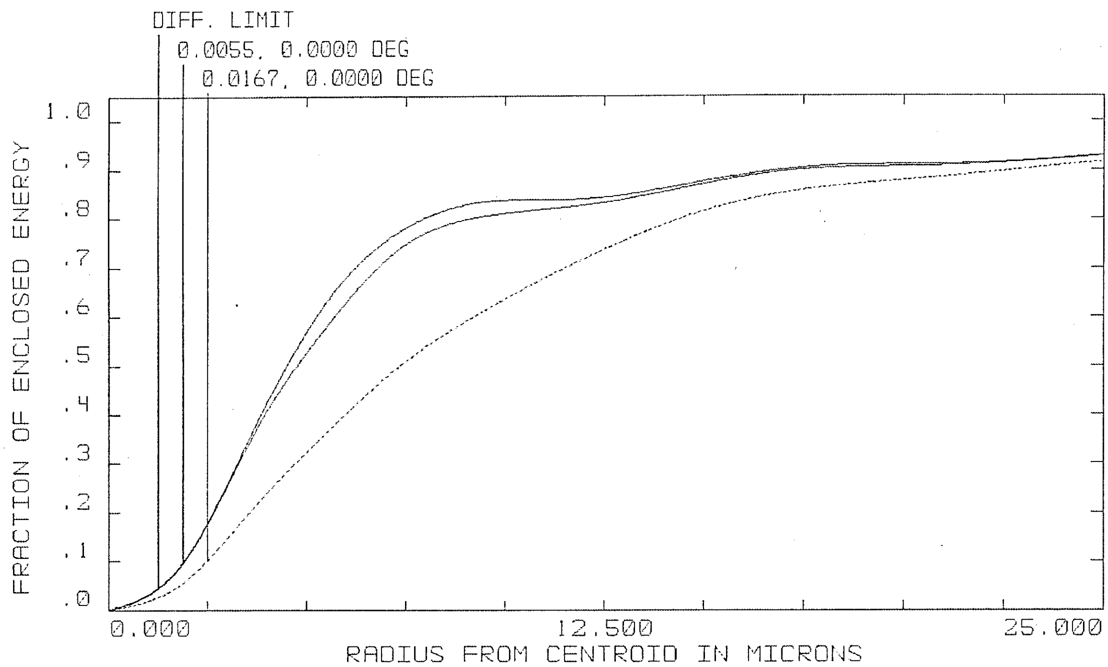

Figure 2. Probability for a photon to fall inside a given circular area in the focal plane for a +/- 1 arcmin FoV for the naked (F/10) telescope. More than 90% of the energy falls down an area of 25 μm in radius for the whole field.

In order to reduce the telescope aperture ratio, a commercial aspheric lens can be placed close to the focal plane. To be used as a quantum communication receiver, it is necessary that the photons are focused well within the typical 50-150 μm dimension of avalanche photon detectors[5]. This can be accomplished with a 11 mm aspheric singlet placed 40 mm back from the F/10 focal plane, hence giving F/2 operation of the telescope. Thereby 95% of the collected photons are focused within a FoV of +/- 1 arcmin, but inside a circular area with a radius of 8 μm, as reported in figure 3.

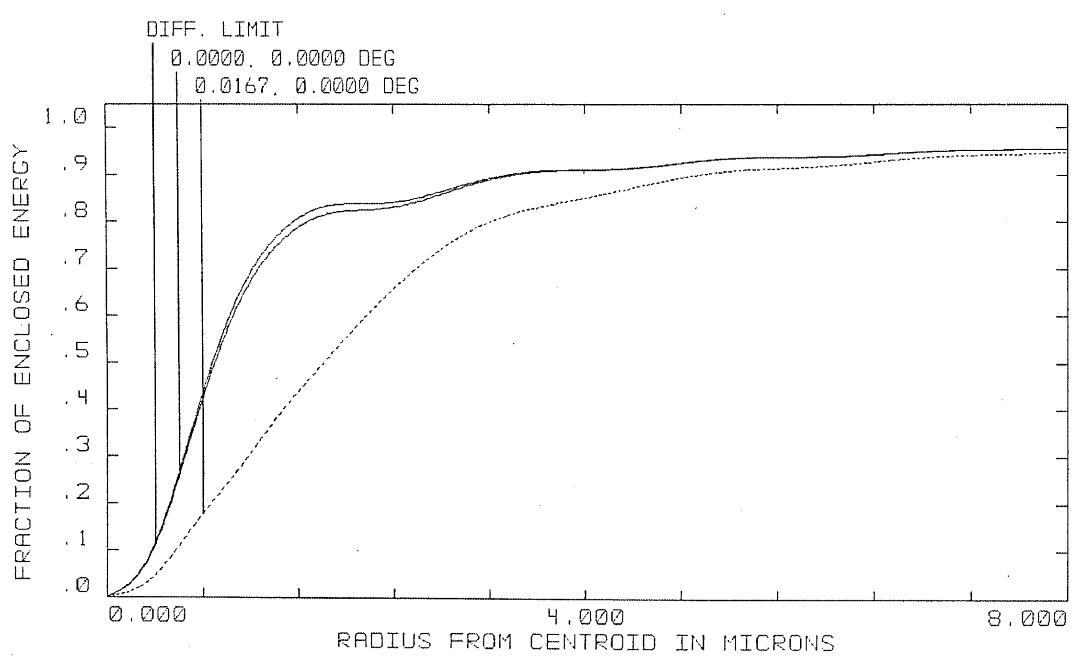

Figure 3. Probability for a photon to fall inside a given circular area in the focal plane for a +/- 1 arcmin field of view for the faster (F/2) telescope. More than 90% of energy falls down an area of 8 μm radius for the entire field.

As primary mirror we used a commercial spherical mirror, λ/4-corrected at λ=650 nm. The catadioptric secondary mirror was custom built according to our design. Both mirrors have been tested with interferometric methods before being mounted on the optical bench. The test on the catadioptric secondary was performed by using a Ronchi rulings classical approach. The measurement of the optical quality, that include both the two refractions and the reflection occurring in the secondary mirror, is shown in figure 4. From the fringe analysis one can estimate of the optical quality to be about λ/4.

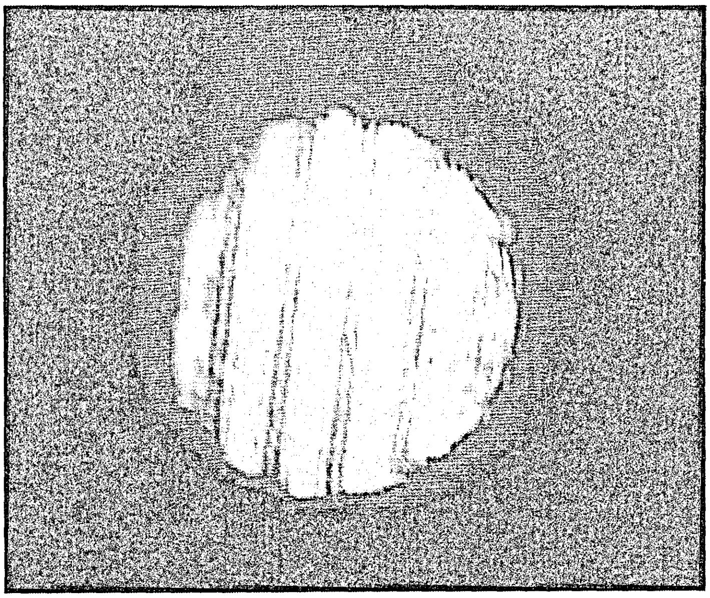

Figure 4. Optical quality for the catadioptric secondary. Fringes are obtained by using a Ronchi set-up.

Once mounted, the telescope has been roughly aligned in an auto-collimation set-up using a red laser. After collimation, the telescope was finely aligned and tested by a double pass Bath interferometer[10] using a green laser source (λ=550 nm). Two pictures taken during the alignment phase, with the terminal mounted in its proper optical bench, is shown in figure 5 and 6.

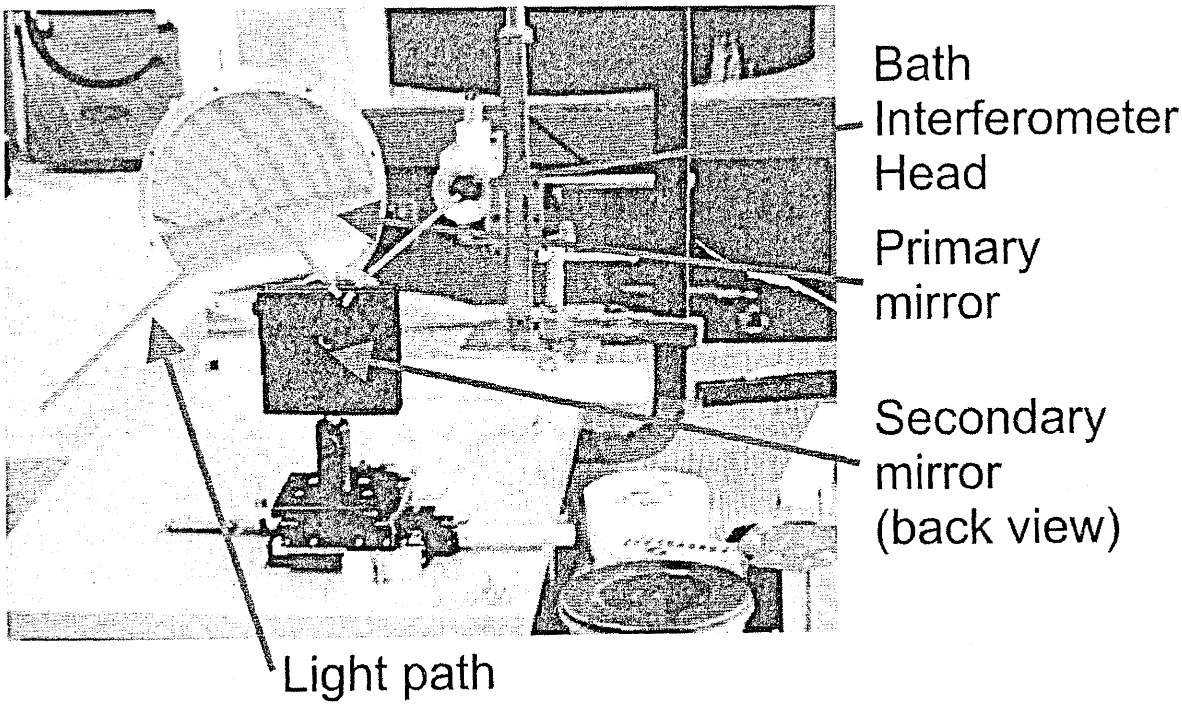

Figure 5. The Bath interferometer set-up during the fine alignment test.

Figure 6 shows the terminal see from the backside. The reference mirror for the autocollimation set-up is visible on the back. The Bath interferometer was been not yet mounted in this picture.

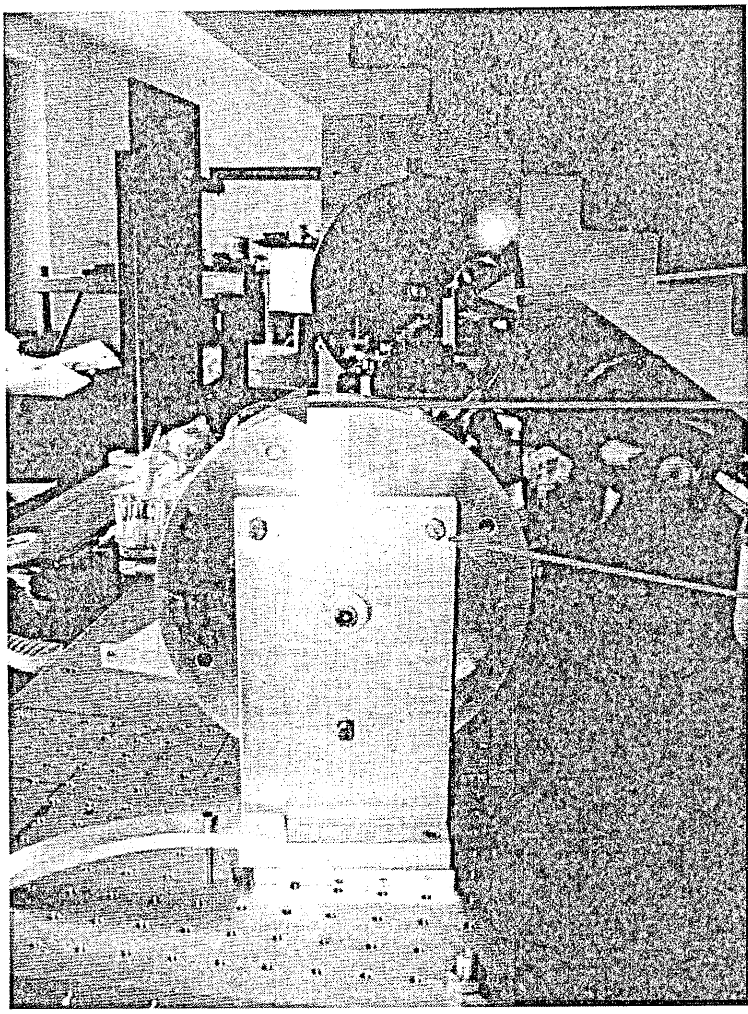

Figure 6. The telescope with the auto-collimation reference mirror visible on the back.

The interferogram was projected on a translucent screen and then recorded by means of a commercial camera. The fringes obtained are shown in figure 7 (next page). The fringe analysis, after correcting for the wavefront tilt and defocusing, gave a wavefront quality on the order of 0.6λ (peak-to-valley) and λ/10 (r.m.s.) when scaled at λ=850 nm. Most of the observed aberration was due to the presence of astigmatism (0.4λ), which is probably due to some residual misalignment. Removing this effect from the observed residual optical aberrations, the aberration coefficient of the telescope becomes λ/5 P.T.V. at 850 nm.

3. CONCLUSIONS

We demonstrated the design of an all-spherical reflective telescope, which is particularity well suited for applications where unobstructed apertures are needed, such as in quantum communication. As a proof of principle we set up with a 20 cm spherical primary mirror and a 8 cm spherical secondary mirror. The performed interferometric tests showed that the optical terminal reached the required performance. After careful alignment of the optical terminal its optical quality was on the order of λ/5 P.T.V. at 850 nm. The residual distortion can be mainly understood from spherical aberration. Besides the clear advantages offered by the elimination of the central obstruction and by the possibility of building large-aperture optical terminals, our all-spherical design is based on easily accessibly and cost-effective elements. The main remaining challenge of this design appears to be the alignment of the two mirrors, because of the off-axis design. Future improvements will therefore concentrate on the realization of a compact and easily alignable optomechanics. It is further conceivable to utilize our design even for very-large segmented apertures with several spherical mirrors.

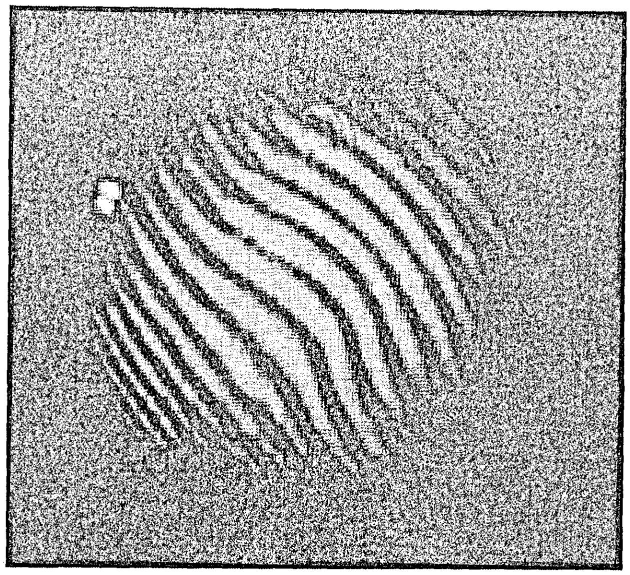

Figure 6. Final fringes measuring the wavefront quality obtained with a Bath interferometric set-up.

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