The optical beam diameter within the Beam Combining Area of the MRO Interferometer

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1 Objective

To determine the beam compression factor and clear aperture diameters that should be used within the Beam Combining Area (BCA) of the MROI.

2 Summary

A bimodal set of solutions exist, with either 12mm or 18mm beam combiner clear apertures being optimal depending on the risk/cost approach adopted.

3 Introduction

The optical beams exiting from the Unit Telescopes of the MRO interferometer have an initial diameter of 95mm. They propagate through the beam relay systems and the delay lines and then pass through a set of beam compressors which serve to convert the beam to smaller-diameter beams which propagate through the rest of the optics in the Beam Combining Area (BCA). The beam compression factor sets the size of optics used throughout the rest of the BCA, including the alignment optics, the beam turning optics, the beam switchyards and the beam combiners, as well as defining the design of the beam compressors themselves.

Ideally, one would set the beam size within the BCA to be as small as possible, in order to minimize the size of the downstream optics. However, there is a limit to how small a beam can be propagated within the BCA: as the beam propagates it will expand due to Fresnel diffraction effects and this will lead to a number of deleterious consequences, the most obvious being that the beam is no longer as small as it initially was and so the optics need to be made bigger than might be expected from simple geometrical optics theory.

Here we consider the choice of beam size, taking into account diffraction effects but also various other factors which affect the overall cost and performance of the interferometer.

4 Model

We assume that the collimated beam exiting the telescope has a diameter 95mm and it is uniformly illuminated over the aperture, i.e. we ignore the secondary obscuration etc. We further do all calculations for a wavelength of 2.2 microns. At shorter wavelengths the effects of diffraction will typically be less severe. We assume a seeing such that D/r0 is 1.7 at this wavelength, corresponding approximately to 0.7 arcsec seeing for 1.4m telescopes.

The beam propagates for a distance of approximately 400m where it encounters and aperture stop 125mm in diameter: this represents the delay line aperture. Following this aperture, the beam travels a further 200m to the beam compressor which is assumed to have a diameter which is large compared to the size of the diffracted beam. This means that the model does not have an aperture stop at this point. The beam is compressed by a demagnification factor M. The "nominal" beam diameter, that is the beam diameter in the absence of any diffraction effects, is then d_1=95mm/M.

This compressed beam then travels a further distance z to a stop on the beam combiner table diameter d_2. This stop represents the clear aperture of the beam combiner and is the minimum size of all the optics in the beam combiner and switchyard. Typically, because the beam has diffracted to a larger diameter, a choice of $d_2>d_1$ is appropriate. The distance z was chosen to be 20m, which corresponds approximately to a beam propagating from the beam reducing telescopes to a stop in the middle of the IR science combiner table (this stop could, for example, be at the lenses feeding light into the detector dewar). Beams traveling to other tables will travel a few meters more or less than this, but the results are only weakly dependent (approximately a square root dependence) on the actual distance traveled.

The beams from two identical optical trains (but with different random phase perturbations from the atmosphere) are combined to form fringes. In other words both beams are assumed to have traveled the same distance from the telescope to the beam compressor and the beam compressors are assumed to be equidistant from the beam combination point.

The light throughput of the optical system and the signal-to-noise ratio (SNR) of the resulting fringe power spectrum are calculated and averaged over a large number (>5000) realizations of the atmospheric phase perturbations.

The propagation of the beams was modeled using the beam propagation code used in Horton et al. (2001), modified to include multiple aperture stops within the propagation path.

5 Results

Figure 1 shows the results computed from the beam propagation simulations for the fringe power spectrum SNRs as a function of the "nominal beam diameter" (d_1) and of the "beam combiner clear aperture" (d_2). Different curves are plotted for ratios of the beam diameters d_2/d_1=1.4 to 2.2.

Figure 2 shows the fractional light throughput through the final stop. Though the fractional light throughput is mostly useful as a component of the SNR calculation, it is useful by itself as a means of understanding what fraction of the wavefront has been discarded by the stops in the system.

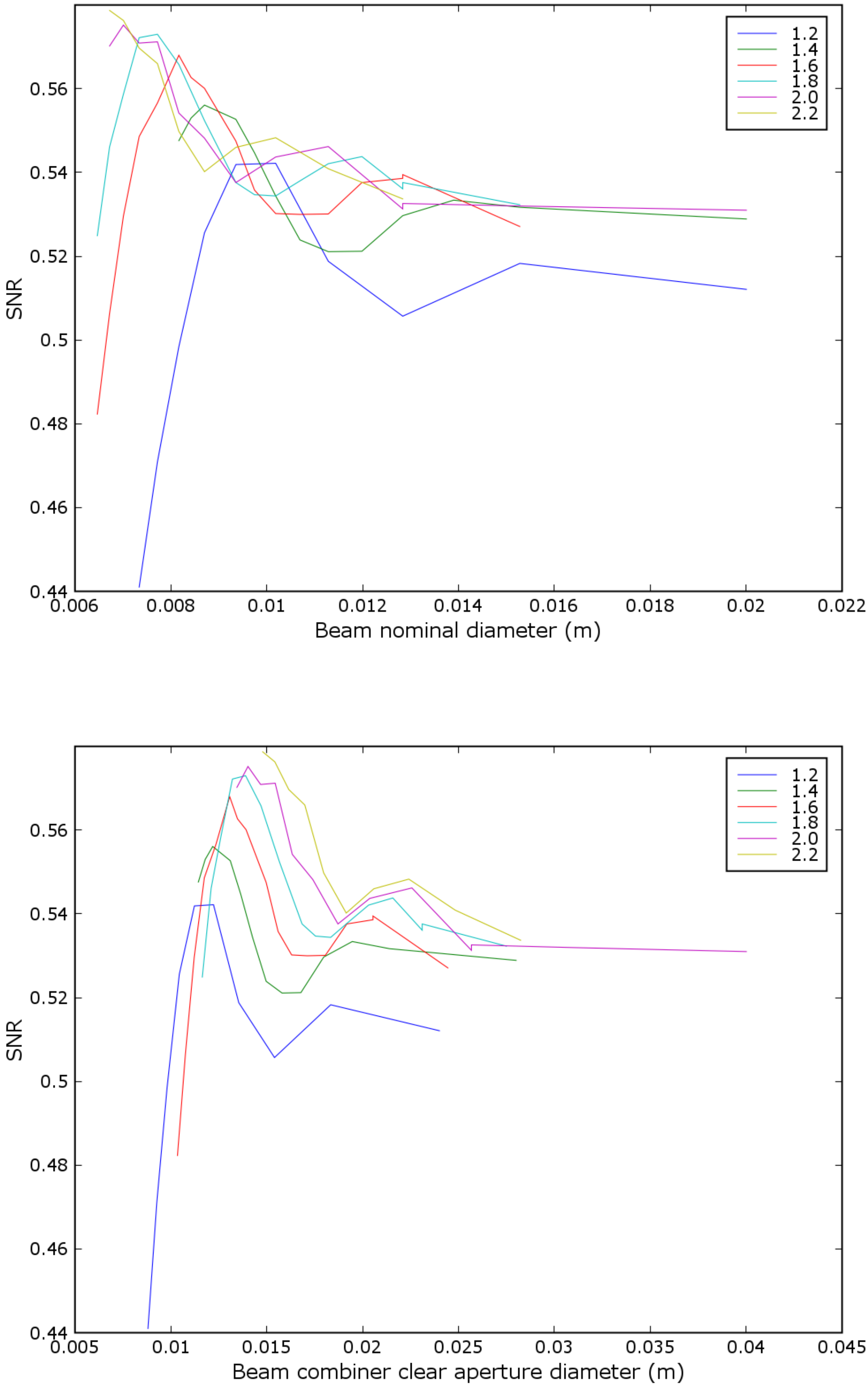
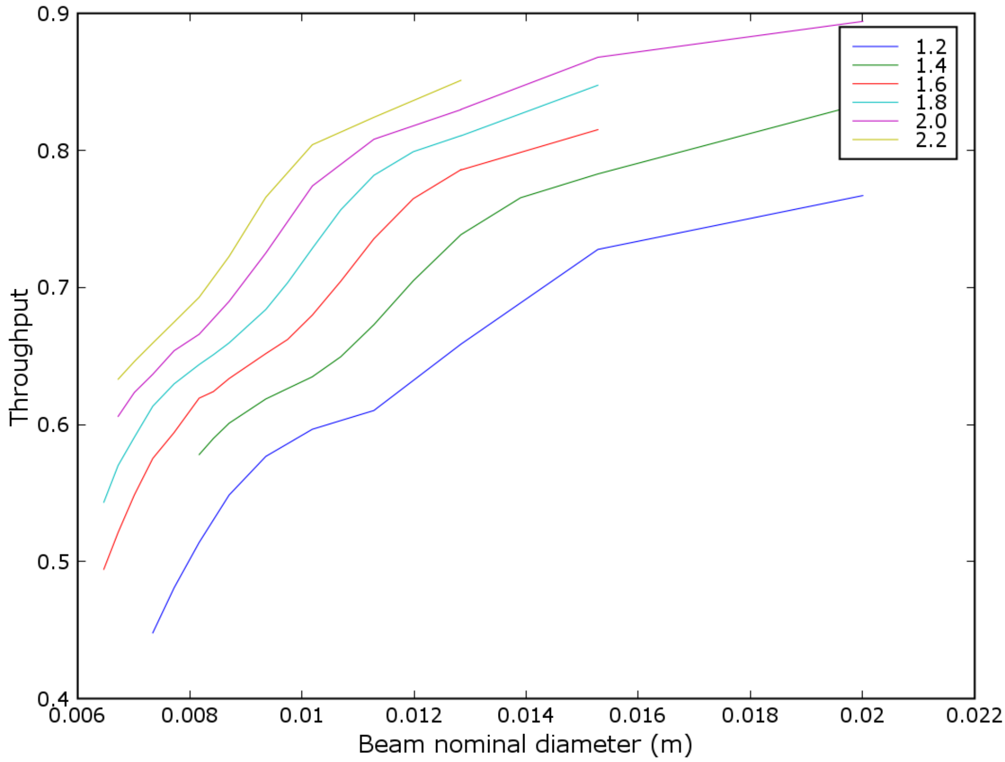


Figure 1: Signal-to-noise ratio as a function of beam nominal diameter (d1, above) and beam combiner clear aperture (d2, below). The different lines are for different d2/d1 ratios.



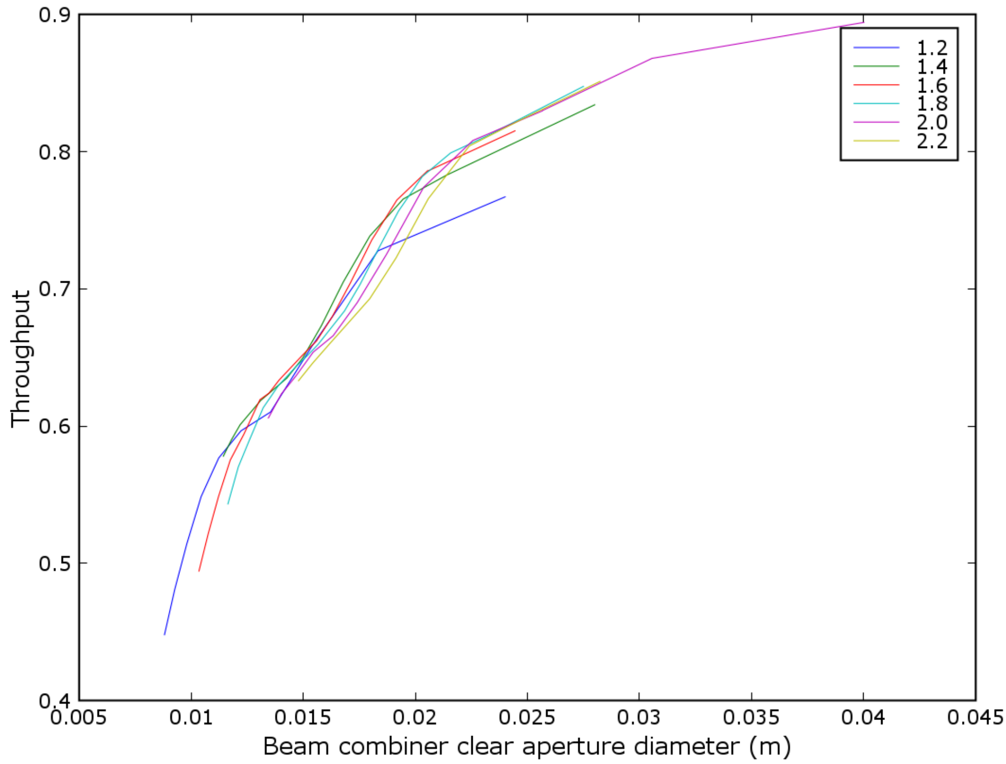


Figure 2: Mean light throughput as a function of nominal beam diameter (d1, above) and the beam combiner clear aperture (d2, below). The different lines are for different values of the ratio d2/d1.

6 Discussion

It can be seen from Figure 1 that, perhaps surprisingly, quite small beam diameters give the best SNR performance. The optimal beam diameters correspond to the nominal beam diameters being approximately equal to the Fresnel zone size for the beam propagation distance $\sqrt{(\lambda z)}$=6.6mm. A Gaussian beam of this size will expand in diameter by a factor of $\sqrt{2}$ over 20m of propagation distance, and initially uniform beams will look more like an Airy pattern than a sharp-edged disk. It is the fact that the beam is nearly in an image plane which causes the high SNR: truncation by an aperture is approximately equivalent to spatial filtering with a pinhole.

There are a number of reasons to be wary of choosing such beam sizes, mostly related to the fact that effects of diffraction cannot be neglected anywhere within the system, i.e. many of the assumptions from geometric optics will be invalid because the beams are neither in an image plane nor a pupil plane. We enumerate the potential problems of choosing these small beam sizes below.

1. Reverse propagation: beams traveling from the beam combiners to the telescopes, e.g. white-light test sources projected back through the system and used for alignment, do not identically retrace the volume sampled by the beams traveling from the beam compressors to the beam combiners, e.g. starlight. A beam of a given size propagated from a beam combiner will be larger when it reaches the beam compressor, whereas a starlight beam propagating from the beam compressor will be larger at the beam combiner. If an initially flat beam is propagated from the beam combiners, through the interferometer and reflected back into the beam combiners (a normal procedure for calibrating the system OPD), the returning wavefront will not only be much larger than the beam sent out, it will also have approximately a wave of curvature on it.
2. Thermal emissivity of the system: it is conventional to assume that all the mirrors in the system are approximately in a pupil plane, so that the thermal radiation arriving from the 100% emissive regions around the mirrors can be masked using a cold mask situated close to a pupil plane. When there is significant diffraction occurring between different optical elements, a pupil mask is less effective at removing radiation leaking from the edges of mirrors. As a rule of thumb, if a pupil mask twice the nominal size of the beam is needed to catch enough starlight, then approximately 4 times the amount of stray thermal radiation will be allowed in.
3. Poorer performance at other wavelengths: the simulations were done for the K band, but can be used at other wavelengths and propagation distances by making a transformation which keeps $d^2/\lambda z$ constant i.e. using a shorter wavelength or optical tables closer to the beam compressors corresponds to using larger aperture diameters. If one were to use an aperture optimized for 2.2 microns (K) at a wavelength of 1.65 microns (H), and a table which is 30% closer to the beam compressor (a worst-case estimate for the relative positions of the fringe tracker

table and the science combiner table), this corresponds to using apertures larger by a factor of 30%. For example, looking at Figure 1, we can see that a system with a ratio of 1.8 between the nominal beam diameter and the beam combiner clear diameter, the nominal beam diameter which optimizes the SNR at K is approximately 8mm. The effective diameter at H (and 30% closer to the beam compressors) would be 10mm, approximately in the "dip" of the SNR curve. In this case, the SNR at H is typically comparable to the SNR available with a much larger beam, but is some 15% worse than could be obtained by optimising at H. Optimising at H would give even worse results at K because the SNR curve is steeper on the left than on the right.

4. Little further SNR increase from spatial filtering: SNR increases afforded by small beam sizes can equally well be achieved by conventional spatial filtering after the beam combiner, so that if a comparison were made between the achieved SNRs for the different beam sizes which included a spatial filter, there might be little to choose between them. Including a spatial filter in the simulations would be possible but would require significant extra code development and testing. A measure of how effective a spatial filter would be can be derived from the system throughput curves shown in Figure 2: if most of the "bad light" has already been thrown away, then little light is left which can be profitably discarded by a filter.

None of these disadvantages of smaller beam sizes are "killer" reasons, but are reasons for caution. There are thus two possible approaches: an aggressive approach which strives to minimize the beam size and hence the optics cost, or a conservative approach which is easier to analyze (because geometric optics approximations are a better guide to design approaches: a big advantage is that most results are relatively wavelength-independent) and is this likely to have fewer surprises associated with it. We discuss these two approaches below.

6.1 Aggressive approach

In this approach we attempt to minimize the beam combiner clear aperture diameter (because this minimizes the total system cost), while trying to not to have the worst of the disadvantages mentioned above. Thus we limit the ratio d_2/d_1 to a moderate amount, say 1.6, so as to allow some level of thermal masking, and we require that the worst-case SNR is greater than 0.53 (the SNR attainable for the largest aperture), when allowing a ±30% variation in the wavelength/distance product $\sqrt{(\lambda z)}$. This gives us a beam combiner clear aperture of approximately 12mm for a d_2/d_1 ratio of 1.6, i.e. a nominal beam diameter of 7.5mm. The mean throughput of the system is a little over 60% indicating there may be some margin for further improving the SNR through further spatial filtering.

6.2 Conservative approach

Here we attempt to get closer to a geometric optics regime without sacrificing too much in the way of SNR or clear aperture requirement. We set a minimum throughput of 70%, which constrains the beam combiner clear aperture diameter to >16mm. A beam combiner clear aperture of about 18mm and a d_2/d_1 ratio of 1.4 appears optimal in this case (i.e. a nominal beam diameter of 12.9mm). It so happens that the VLTI beam diameter is 18mm and so this would enhance the commonality of designs for the MROI and VLTI. The nominal beam diameter is approximately 2 Fresnel zones in diameter, meaning that a test beam propagated out from the beam combiner through the optical train to the telescopes and retroreflected back to the beam combiner would still be in the near field.

7 Conclusions

It can be seen that neither of the above answers is definitively the right one. The main decision concerns the level of risk versus the level of expense needs to be made. It should be noticed that a "compromise" solution does not exist, as the results are essentially bimodal.