More telescopes than photons: beam multiplexing in imaging interferometers

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ABSTRACT

Imaging with interferometers is dramatically improved with increasing numbers of telescopes, because the number of baselines sampled increases quadratically with the number of telescopes. The Magdalena Ridge Observatory Interferometer (MROI) is designed so that it is possible in theory to combine the beams from all 10 telescopes simultaneously with one another to form fringes on 45 different baselines.

All-in-one combination with this large number of beams is problematic for both technical and fundamental physical reasons. We propose instead to use a number of smaller beam combiners, each of which combines a subset of telescopes together at any given time. This requires an "optical switchyard" which is able to switch permutations of beams between different combiners while maintaining alignment in the tilts and pistons of the beams.

We describe here the design for the switchyard for MROI. The design has a low-angle-of-incidence geometry which allows high optical throughput and polarisation fidelity. We describe the criteria driving the design at both the geometric and mechanical level and explain how these are met using our proposed implementation.

Keywords: Beam combiners, interferometric signal-to-noise ratio, kinematic couplings

1. INTRODUCTION

It is clear from the experience at millimetre wavelengths, exemplified in the recent spectacular ALMA images of the rings of material around the young star HL Tau,[1] that (a) high-fidelity model-independent imaging is a key science enabler for interferometers and (b) that producing such images is strongly dependent on having more than the handful of telescopes available in earlier generations of interferometer. Thus optimising the use of large numbers of telescopes in visible/infrared (referred to hereafter as "optical") interferometers is a key question for the design of the next generation of arrays.

The Magdalena Ridge Observatory Interferometer (MROI) project[2] has been a pioneer at addressing the design of many-element optical arrays for model-independent imaging. From the start, the array infrastructure has been designed to allow the simultaneous operation of up to 10 telescopes, while the top-level requirement of fringe-tracking on a magnitude $H = 14$ source tensions the imaging requirement against the requirement to access critical science targets such as Active Galactic Nuclei.

One problem to be addressed in many-element arrays is the best way to effect beam combination. Combination of the beams from all telescopes simultaneously in an "all-in-one" combiner maximises the baseline and bispectrum coverage of the array, but presents a number of problems, both technical and fundamental (where the term "fundamental" is used in the sense that improvements in technology will have no effect on the underlying limitation).

In the following sections we explain these limitations for many-element arrays and how they can be overcome using beam multiplexing to allow for the operation of multiple parallel beam combiners. The implementation of this multiplexing in the MROI is described, both in the overall geometric design to meet the polarisation fidelity goals of MROI and the mechanical implementation which meets our stringent optical wavefront requirements.

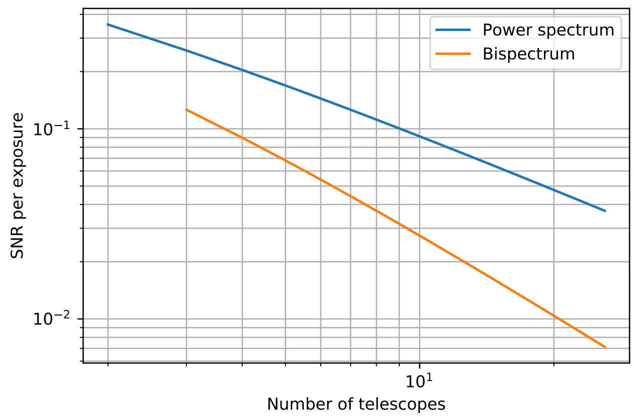

Figure 1. Signal-to-noise ratios for the power spectrum and bispectrum estimators as a function of number of telescopes with an all-in-one beam combiner for a photon rate of 1 photon per exposure per telescope. The calculation assumes a unit source visibility on all baselines and no instrumental imperfections causing a degradation to the fringe contrast.

2. THE NEED FOR MULTIPLEXING

To maximise the instantaneous Fourier plane coverage of an array of M telescopes, the best beam combining architecture combines the beams of all the telescopes simultaneously, giving measurements at all $M(M-1)/2$ baselines in one go. There are a number of problems in implementing this when M becomes large, especially for faint sources.

The first category of problems are technical challenges related to the large number of baselines which need to be measured simultaneously. A number of factors in the beam combiners scale with the number of baselines, which means that they scale quadratically with M and therefore become rapidly worse with increasing numbers of telescopes.

The most critical of these scaling factors in technology terms is the scaling of detector size. Independent of whether a free-space or guided-optics beam combiner is used, the information from which the $M(M-1)/2$ complex visibilities is extracted is usually encoded spatially on a single detector. To allow for adequate sampling of the fringe and adequate "guard bands" to reduce cross-talk between fringes on different baselines, the number of detector pixels needed to sample the fringes at a single wavelength scales linearly with the number of baselines for most designs.

For observation of fringes over a wide wavelength range, which is usually desired for both sensitivity and scientific reasons, there are additional complications. The first of which is that, in many combiner designs, fringes need to be sampled over a range of delays which is proportional to the number of baselines, usually for $N_{\rm bas}$ baselines the range of delay is of order $\pm N_{\rm bas}$ fringes. The fringes furthest from the zero-delay location will be "washed-out" by temporal coherence effects unless the fringes falling on any pixel are narrow bandwidth. The way to get around this is to spectrally disperse the fringes with a minimum resolving power R which scales linearly with the number of baselines.

In addition, for a beam combiner using a fixed set of diffraction-limited optics, the fringe pattern scales linearly with wavelength, which means that to work over an octave range of frequencies requires a detector which is twice the size in the fringe-encoding direction as one which works at only a single wavelength.

Both spectral effects can be ameliorated by including in the beam path an optical arrangement whose magnification varies inversely with wavelength,[3] but implementation of such a scheme to work well over a large wavelength range is technically challenging: no modern beam combiner incorporates this technology.

As a result, a realistic beam combiner combining all the beams from 10 telescopes needs of order 800 pixels in the fringe-encoding direction, and perhaps 800 pixels in the spectral-dispersion direction. While detectors of

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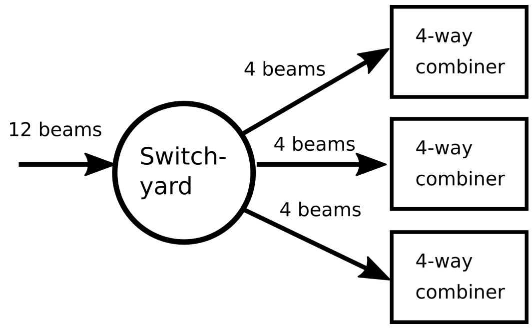

Figure 2. Diagram showing the function of a switchyard in distributing beams between parallel beam combiners.

such size are available, detectors with the high read rates and low noise needed for interferometry such as the Saphira[4] detector from Leonardo, are only currently available in much smaller formats.

A more fundamental downside to combining large numbers of arrays arises from the quantum noise limit of interferometers. For a photon-counting detector, the signal-to-noise ratio of a fringe measurement is proportional to $V\sqrt{\overline{N}_{\rm phot}})$ where V is the fringe contrast and $\overline{N}_{\rm phot}$ is the mean number of photons detected per "exposure" in the beam combiner. If we combine the beams from M telescopes in a single fringe pattern, the photon rate will increase as M but the visibility of the fringe on a given baseline will fall as $1/M$, so that the signal-to-noise ratio per exposure falls as $M^{-1/2}$.

At low signal-to-noise ratios, where coherent fringe tracking becomes problematic, we need to use the incoherent power spectrum and bispectrum estimators. The signal-to-noise ratios of these estimators are monotonic functions of the fringe signal-to-noise ratio, and at low light levels scale quadratically or as the cube of the fringe signal-to-noise ratio respectively.[5]

Figure 1 shows how the signal-to-noise ratio of these estimators scale with number of telescopes at the light level where there is one detected photon per exposure per telescope. It can be seen from the graph that for large number of telescopes the signal-to-noise ratio becomes so small that averaging for hundreds of thousands of exposures is necessary to achieve adequate precision on interferometric variables. For an exposure time of order 20 milliseconds, this may correspond to hours of on-source time; the time for Earth rotation to significantly change the baseline is of order 10-20 minutes so observations of this type become impractical.

To avoid this catastrophic loss of sensitivity with large numbers of telescopes we can instead use the beam combination architecture shown in Figure 2. Here the array of M telescopes is effectively converted into a parallel set of sub-arrays of smaller numbers of telescopes, each feeding a separate m-way combiner. These combiners will not sample all the baselines accessible from the M-telescope array, so after a sufficient length of observation in a given configuration, the beams fed to each combiner are interchanged, and this process is repeated until all the available baselines have been sampled. The subsystem responsible for changing which beams are fed into which combiner is call the "switchyard" as it functions analogously to a set of interconnected switchable railway tracks.

Clearly the instantaneous signal-to-noise ratio of the fringe measurements will be higher in this scheme by a factor $\sqrt{M/m}$, but the averaging time allowed will be lower because of the need for switching. To get an idea of the competition between these two factors, we can define a measure which we call "observing speed". The measure is inversely proportional to the total time taken to make an observation on a given number of baselines or bispectrum triples to reach a given mean-squared signal-to-noise ratio over all baselines or triples. If we assume that the time taken to switch between configurations is negligible, then if a set of beam combiners measures n_p power spectrum points and n_b bispectrum points with signal-to-noise ratios after averaging for unit time of $\{\gamma_k,\ k=1\ldots n_p\}$ and $\{\beta_k,\ k=1\ldots n_b\}$ respectively, our power spectrum observing speed will be defined as

$$\eta_p = \sum_{k=1}^{n_p} \gamma_k^2 \tag{1}$$

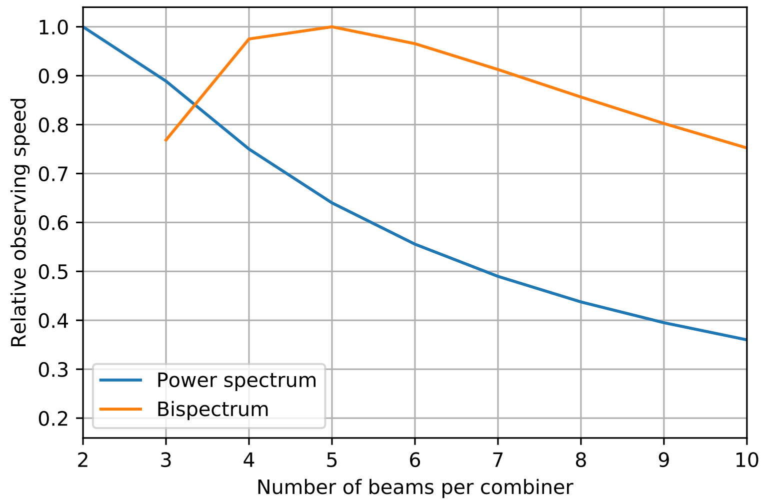

Figure 3. Relative speed to collect a specified number of power spectrum or bispectrum samples at a given signal-to-noise ratio as a function of the number of beams sent to each combiner in a parallel array of beam combiners. The calculation assumes that the number of telescopes is divisible by the number of beams going to the combiner and that the signal-to-noise ratio of a fringe measurement in a single exposure is much less than unity.

and bispectrum observing speed will be defined as

$$\eta_b = \sum_{k=1}^{n_b} \beta_k^2. \tag{2}$$

The question then arises as to what the most efficient use of M telescopes is — is it better to split them up into a large number of small combiners or a small number large combiners? If each combiner combines m beams then there will M/m combiners operating in parallel (assuming that M is divisible by m). Each combiner measures $m(m-1)/2$ power spectrum points and at low photon rates the signal-to-noise ratio for each point will scale as $1/m$, so the power spectrum observing speed will be

$$\eta_p \propto \frac{M}{m} \cdot \frac{m(m-1)}{2m^2}.$$

In the case of the bispectrum, each array will measure $m(m-1)(m-2)/6$ bispectrum points. At low photon rates, the noise on these points will be uncorrelated[5] and will scale as $m^{-3/2}$ so the bispectrum observing speed will be

$$\eta_b \propto \frac{M}{m} \cdot \frac{m(m-1)(m-2)}{6m^3}.$$

Figure 3 shows a plot of the relative observing speeds as a function of the number of beams per combiner m. This shows that the highest observing speed is obtained for small beam combiners: $m = 2$ is best if we are solely interested in measuring amplitudes (from the power spectrum) and $m = 5$ is best if we prioritise closure phases (from the bispectrum).

3. SWITCHYARD GEOMETRY

Introducing parallel combiners and a switchyard circumvents the technical problems of building large combiners and improves observing speed at low photon rates. However the switchyard needs to fulfil a number of functional and performance requirements in order not to degrade the performance of the interferometer. Briefly, the most important requirements are:

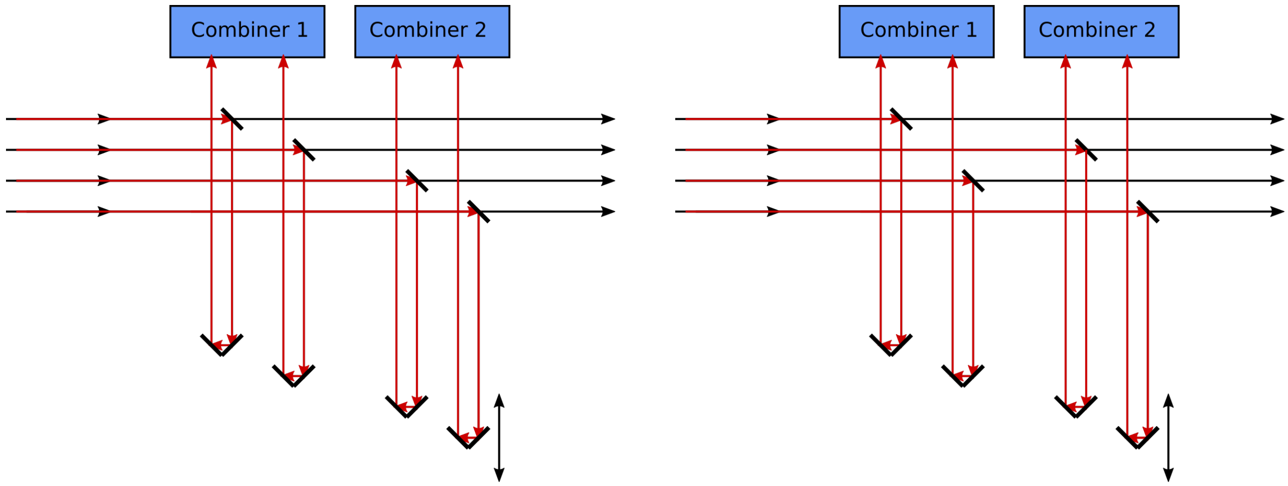

Figure 4. Basic concept for an optical switchyard arrangement. The optical beams first strike a dichroic and then a roof mirror. The left and right figures show two configurations of the switchyard which swap two beams. The adjustment of the roof mirror positions to maintain piston matching between the two configurations has not been shown.

1. The switchyard should serve to provide a quasi-static "wavefront impedance match" between its inputs and outputs. That is, it must take input beams from the telescopes and provide output beams going into the beam combiner with the correct tilt, beam shear and "piston" (optical path delay) required for optimal fringe contrast. This function is not absolutely required if the downstream optics have the appropriate internal adjustments, but it is convenient to subsume this functionality as part of the beam-switching functionality, and can serve to reduce the total number of reflections in the system and hence improve throughput.

2. The switchyard must allow permutation of beams between multiple combiners, accessing sufficient permutations to cover all the required baselines. Ideally, it should also allow permutation of beams within one combiner as well, in order to calibrate systematic effects in the combiner.

3. The switchyard should have a low time overhead for switching between different beam permutations. For MROI, where the basic observation cadence for a single configuration is of order a minute, the goal is to switch between configurations in less than 10 seconds.

4. Once aligned for a given configuration at the beginning of the night, the switchyard should maintain the wavefront matching with high repeatability over multiple switches between configurations during the night. The wavefront alignment tolerances for MROI are of order 1 arcsecond in tilt, 100 μm in shear and 1 μm in piston.

5. For MROI, one science priority is maintaining high polarisation fidelity[6] (defined to mean the ability to accurately measure visibilities in the Stokes I polarisation in the presence of highly polarised targets). This leads to a derived requirement of angles of incidence of less than 15° on dichroics and less than 30° on silver-coated mirrors.

6. For MROI, it should be possible to operate switchyards for up to 4 beam combiners simultaneously in the beam combining area. This mostly translates to a requirement on switchyard footprint.

Figure 4 shows one idea of how an optical switchyard can be implemented. The switchyard consists of a dichroic for each beam which picks off light at the wavelength needed by the beam combiner and sends it to a roof-mirror "delay line" which feeds the beam combiner. Switching the positions of two of the dichroics as shown in the figure and adjusting the delays with the roof mirrors appropriately allows two beams to be swapped while maintaining piston matching.

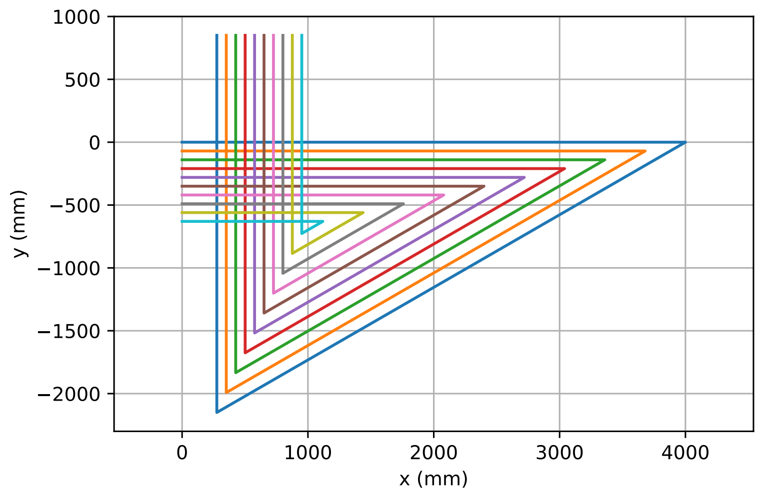

Figure 5. Initial two-mirror configuration with incidence angles of 15° on the dichroics and 30° on the mirrors. The mirror or dichroic at each reflection of the beam are not shown.

While this system is perhaps conceptually simplest, it suffers from a number of problems. The most severe impact is on the polarisation: the incidence angles of the beams on all reflecting surfaces is 45°, greater than allowed in the requirements. An alternative scheme is shown in Figure 5 which uses a smaller number of reflections (and hence has higher throughput) but also meets the angle of incidence requirements. Piston matching is achieved by translating both the mirror and dichroic while maintaining their respective tilts. An important consideration for polarisation matching is that the mirror and dichroic angles of incidence are matched at the sub-degree level between all beams — beam permutation by tilting the beams is not allowed.

This configuration was originally envisioned for use on MROI, but deeper investigation revealed a number of problems. One problem is that some permutations of the beams are not feasible because mirrors or dichroics would obstruct nearby beams. A more serious limitation is that the footprint of the switchyard along the direction of the input beams is about 4 metres. This means that there is no space remaining for a switchyard for the fourth beam combiner as shown in Figure 6

A layout which avoids both limitations is shown in Figure 7. The angle of incidence on the dichroic has been drastically reduced, while the space between beams has been increased. These alterations of the geometry allow the mirror for the second reflection to be placed between the incoming beams for all possible beam permutations, with no beam obstruction. In addition the footprint dimension along the initial beam direction is reduced by about 1.5 metres, allowing 4 switchyards to easily fit in the MROI beam combining area as shown in Figure 8. An additional benefit of this design is that the it allows more freedom in the dichroic coating design, because the polarisation requirements are less constraining at these low angles of incidence.

4. SWITCHYARD MECHANICS

A critical combination of requirements for the switchyard are the combination of fast switching between permutations and repeatability of the beam tilts and pistons at the arcsecond and micron level respectively. We have chosen to meet these criteria by using a mechanical concept which relies on kinematic couplings to allow accurate repeatability of mirror position, without requiring time-consuming realignment of the mirrors.

The most common type of kinematic coupling relies on using a set of three ball bearings coupling to a set of three v-grooves. Each v-groove allows one degree of freedom so that overall there is a unique constraint when the two halves of the joint are mated. We have inverted the traditional design to have the ball bearings on the bottom of the coupling and the grooves on the top. In addition we have mounted the ball bearings on motorised flexure mounts as shown in Figure 9 so that the position of the ball bearings to adjusted in a direction perpendicular to the direction of the v-grooves. By adjusting the positions of all three ball bearings, the mirror or dichroic sitting

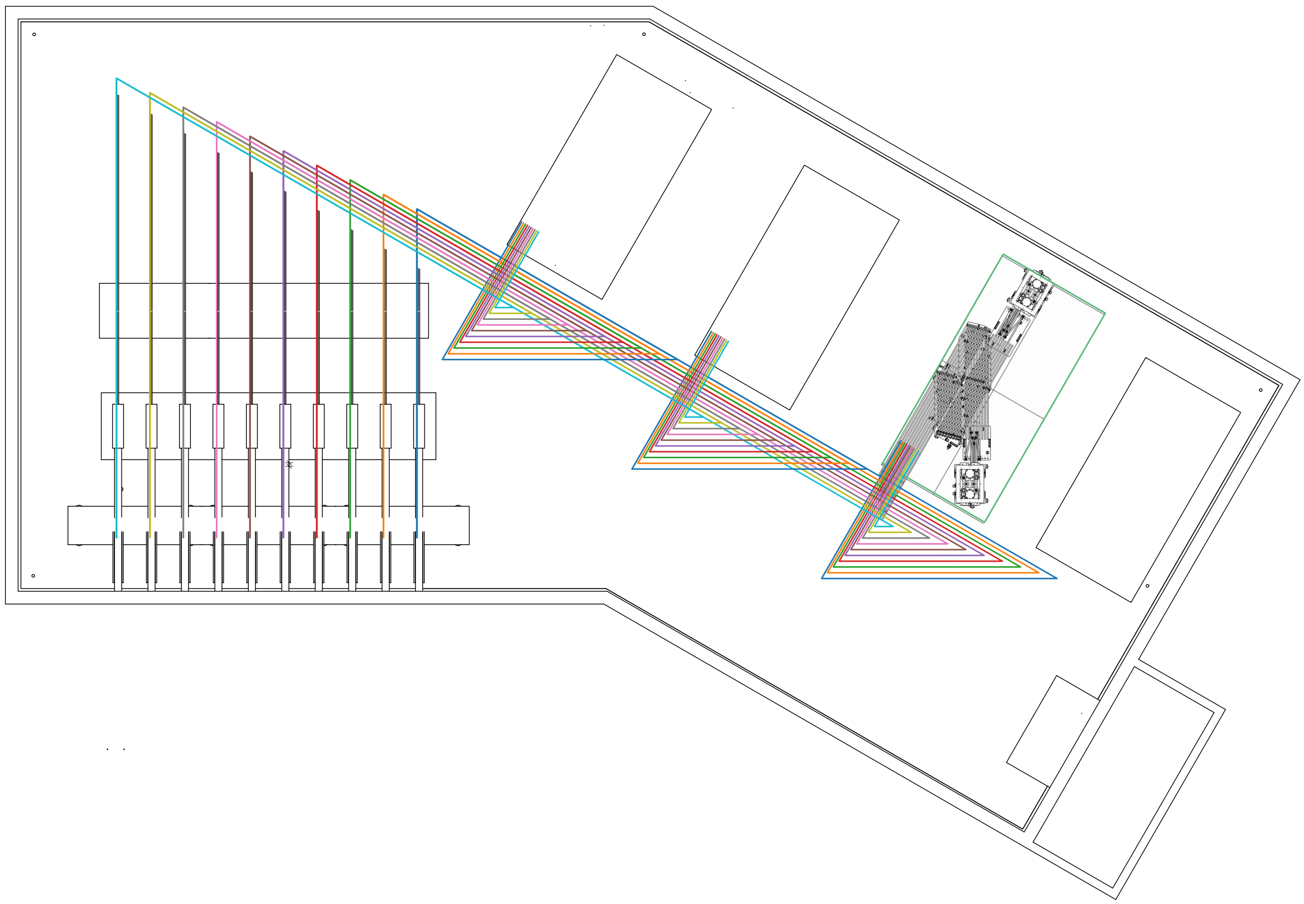

Figure 6. Layout of the MROI beam combining area using the initial switchyard design. The beams from 10 telescopes enter the beam combining area from the delay lines at the bottom left and are picked off the "beam highway" running past the four $2 \times 4\,\mathrm{m}$ MROI beam combining tables by three switchyards. The layout of the ICoNN fringe tracker on one of the beam combining tables is shown — note that ICoNN does not need a switchyard for rapid baseline swapping, but uses one to allow beam swapping if a telescope goes out of operation.

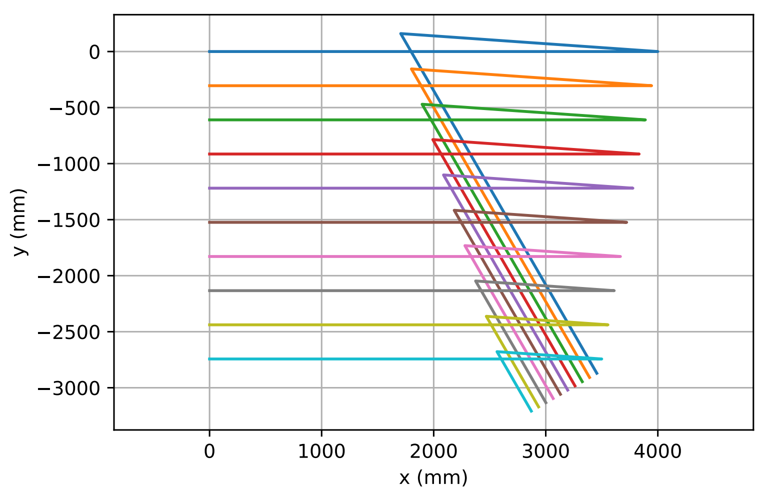

Figure 7. Revised two-mirror configuration with dichroic incidence angles of 2° and mirror incidence angles of 28°.

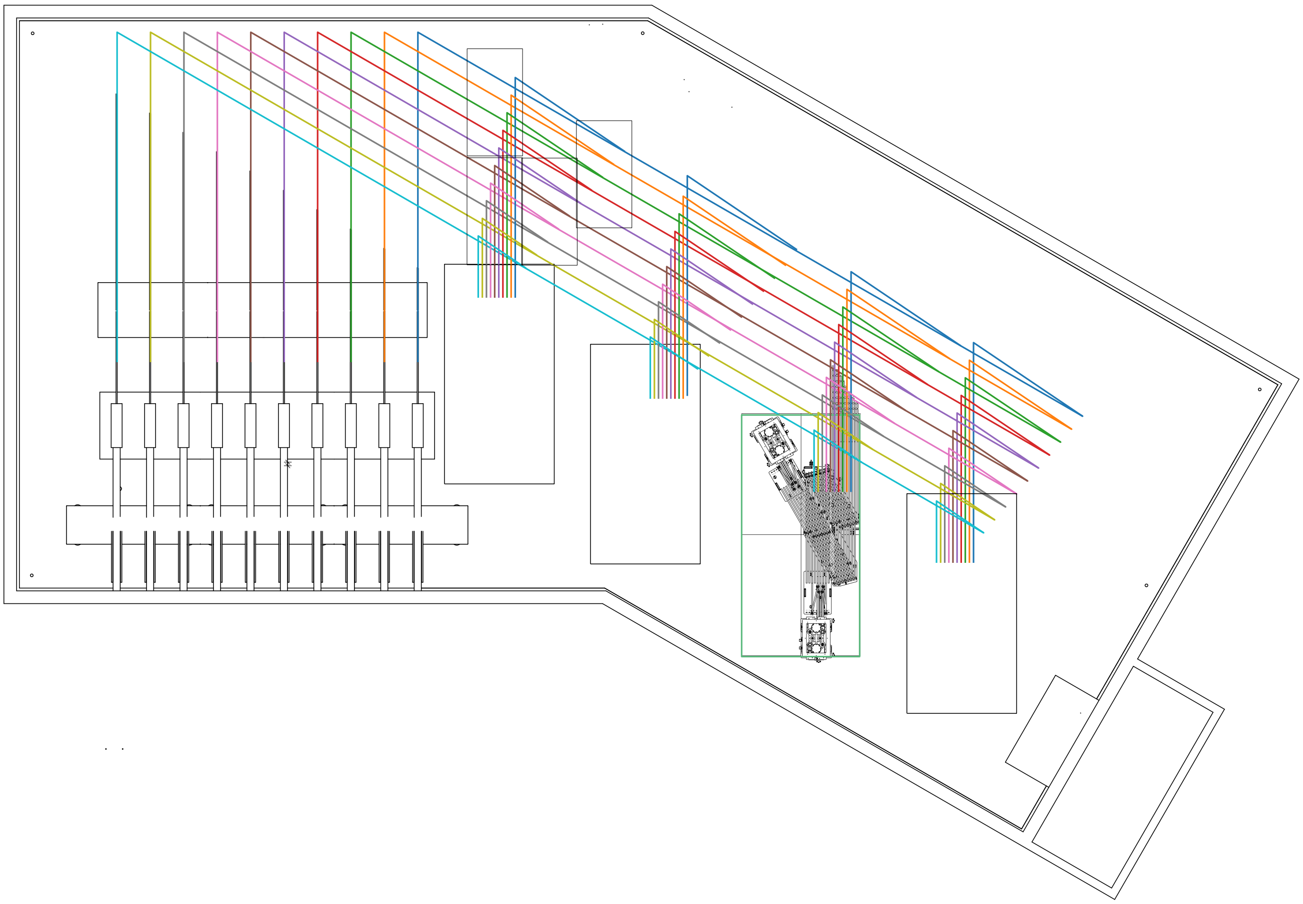

Figure 8. Layout of the beam combining area using the revised design. There is now room for switchyards on all 4 tables.

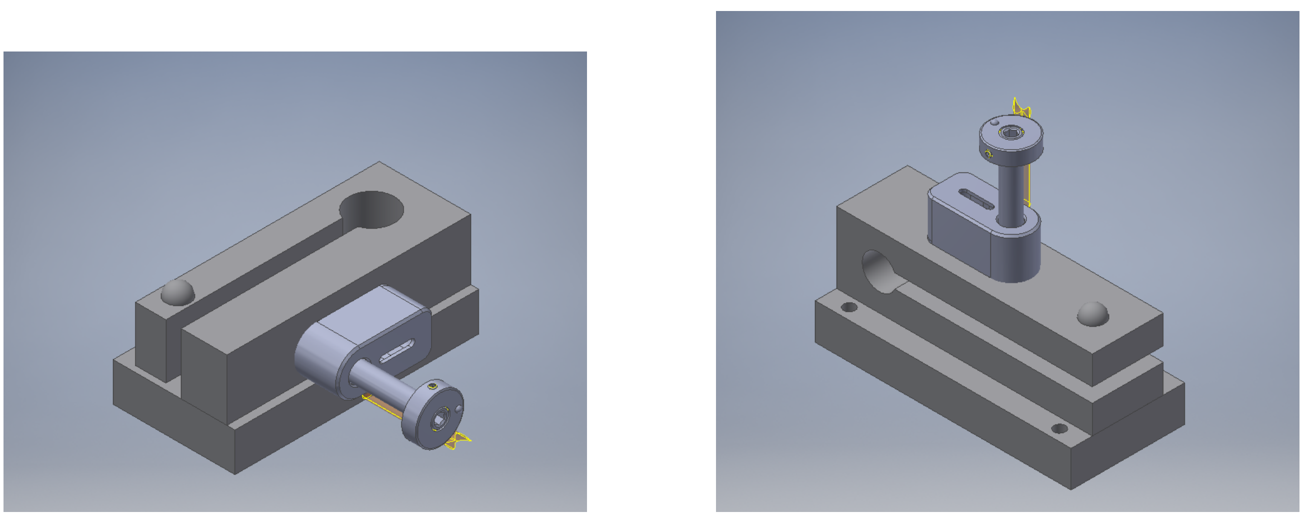

Figure 9. Designs for the kinematic ball-bearing mounts with adjustment in the horizontal axis (left) and vertical axis (right).

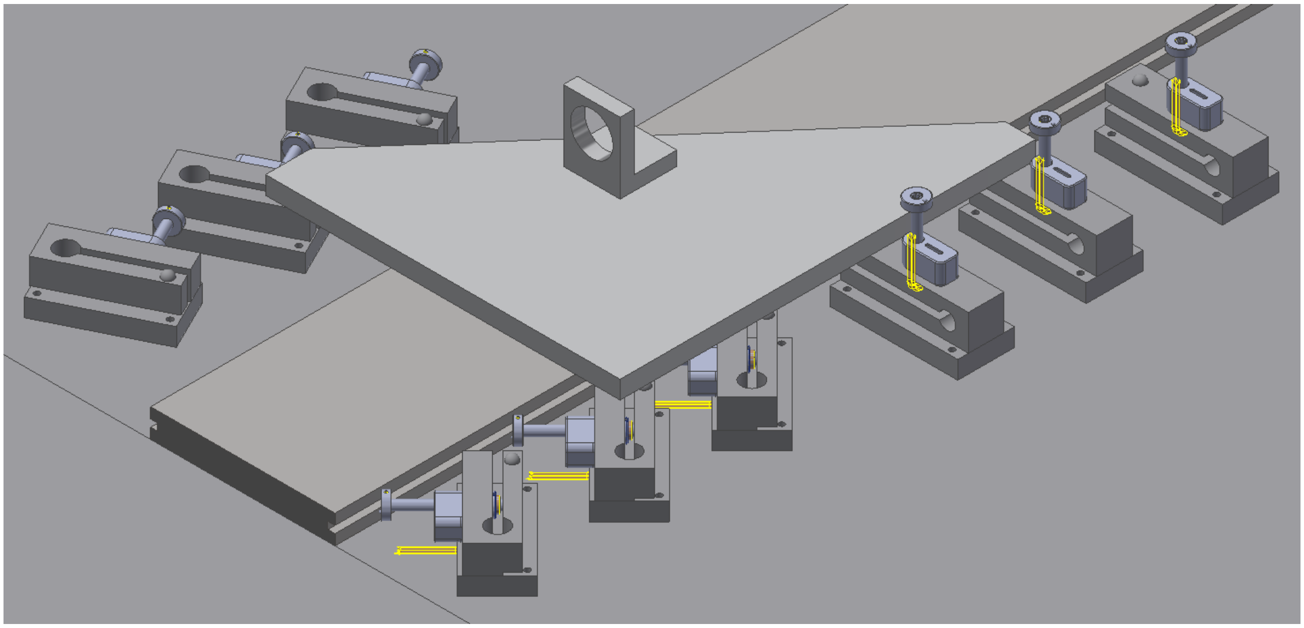

Figure 10. One mirror/dichroic mount of the switchyard shown kinematically mounted on a set of 3 ball bearings. A carriage underneath the mirror mount allows the mount to be lifted up, moved along the slide and lowered onto a different set of 3 ball bearings under computer control.

on top of the coupling can be precisely adjusted in tilt and piston at the start of the night for precise wavefront control.

For a typical repeatability of a ball-groove pair of order 0.5 μm, a distance between grooves of order 200 mm gives 1 arcsecond repeatability in the wavefront tilt. Figure 11 shows the locations of the mirrors and dichroics for an example set of beam permutations. It can be seen that the locations where a mirror or dichroic are required can be less than 100 mm apart in some cases. To keep the lever arm of the coupling large, we interleave the lower halves of the couplings as shown in Figure 10 and then move the top half of the coupling containing the mirror or dichroic between the lower halves using a slide.

Typical operation of the switchyard involves aligning the locations of the ball bearings at the beginning of the night to achieve wavefront matching with the dichroics placed at each of the possible positions. During the night, the end of each observation in a particular configuration, the top half of the kinematic pair is lifted off one set of ball bearings and onto a carriage on a slide. The carriage moves the mirror or dichroic over to a new set of ball bearings and the mirror is then lowered onto them. With this design the moving part has no adjustments on it and so it is possible to do without having to trail wires along with it. All 20 mirrors can move in parallel when changing configurations, so that a switch time of 10 seconds between any two desired configurations should be readily achievable.

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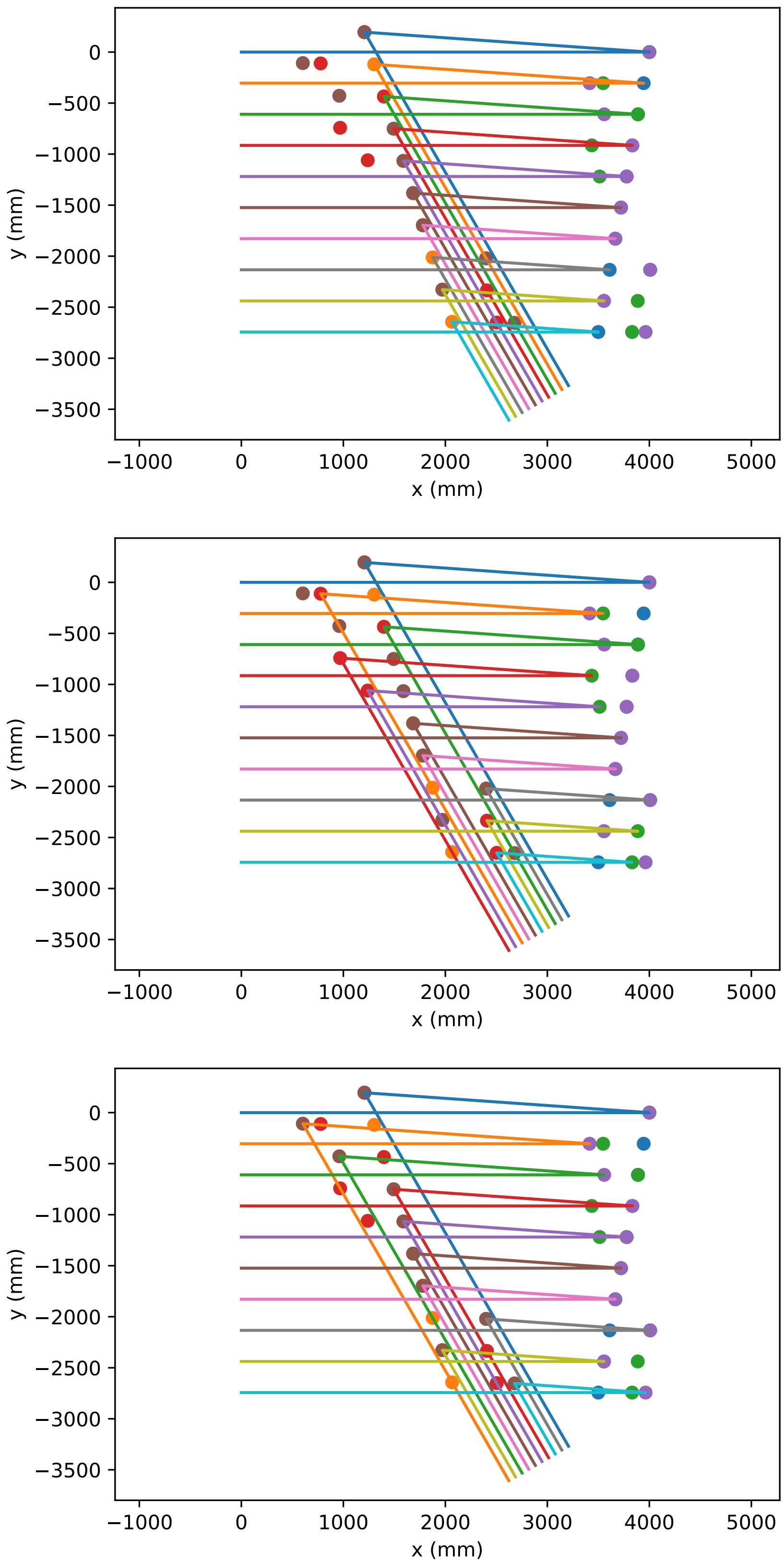

Figure 11. A set of example switchyard layouts demonstrating different mappings of input beams to output beams. Dots indicate possible locations for a mirror or dichroic.

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