A high-sensitivity near-infrared science combiner for MROI

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ABSTRACT

We report on the design and performance of a 6-way multi-wavelength beam combining instrument for the MRO Interferometer, allowing for fringe measurements at any of the J/H/K near-infrared bands at switchable spectral resolution with high sensitivity. Three preliminary designs for the instrument are presented and compared. The results of an ongoing evaluation performed on the performance, costs, and risks of each designs are analysed. Signal-to-noise analyses confirm in particular the utility of one of the design at magnitudes as faint as K=13.

Keywords: Interferometry, Beam combiner, MROI, Switchyard, Bulk optics

1. INTRODUCTION

The Magdalena Ridge Observatory Interferometer (MROI) is an interferometric array currently under construction on a 10,500 foot altitude plateau in the Magdalena mountains west of Socorro, NM. It will ultimately operate from 0.6-2.4 microns and exploit baselines from 7.5-340 meters, giving angular resolutions as fine as 0.3 milliarcseconds, i.e. a factor of 100 times better than any adaptive optics-supported telescope. The infrastructure will support as many as 10 movable 1.4m diameter telescopes, and will permit four Y-shaped array configurations. The main participating partners in this interferometer project are NMT and the Cambridge Optical Aperture Synthesis Telescope (COAST) group at the Cavendish Laboratory in the University of Cambridge.

The MROI array is intended to be optimised strictly for model-independent imaging. In the MROI phase A, only six telescopes will be built, and early instruments will allow science at low to medium spectral resolution in the infrared. The priority is to get a near-infrared science combiner in the J, K and K band, as the visible instrument will be built later. A wide variety of targets will be observed, which should include Active Galactic Nuclei, variable stars, planetary disks and Young Stellar Objects. The most demanding case in term of sensitivity, from which is derived a limiting magnitude $H = 14$, is the AGN science mission.

In a previous paper[1] we reported on the concept study that was launched to determine possible candidate layouts for the beam combiners of the fringe-tracker and the science combiner. As we will not discuss the fringe-tracker further here, the reader is invited to refer to the paper by Jurgenson et al. in these proceedings.

The specification that the science combiners are required to meet, described in section 2, are demanding and no existing beam combiner can currently reach them. In section 3 we briefly remind the reader the current beam combiner concepts for the science combiners. In section 4 we present the performance evaluation of the combiners. Their throughput and instrumental visibilities are analysed, and a realistic signal-to-noise ratio for a typical observation run is derived. Assessment of the instruments using other evaluation criteria such as the technical risks, the schedule risks and the hardware costs is detailed in section 5. Finally a summary of the whole evaluation results is presented and analysed in section 6.

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2. THE SCIENCE COMBINER REQUIREMENTS

2.1 Science missions

The MROI science mission is based on its unique capability for model-independent imaging of faint and complex targets. In particular, the MROI will be well suited to imaging any source that contains a compact, high-surface brightness region (ideal for "phasing up" the interferometer) but which otherwise can have any distribution of apparent flux. Three key science objectives can be distinguished:[2–4]

- The study of YSOs and planet formation through near-IR imaging of the hottest dust close to the star, and, at the highest angular resolution, by imaging emission line emitting material being accreted onto the stellar core via magnetic field lines.
- Detailed studies of convection, mass-loss, mass-transfer and duplicity in "single", evolved, active, multiple and pulsating stars. Imaging all of these processes requires moderate spectral resolution (e.g., R 200 for isolating different molecular features), a high dynamic range (i.e., at least 100:1) and an instrument capable of imaging complex time-variable phenomena on timescale of days and weeks. This type of rapid imaging capability underlies much of the MROI's overall architecture.
- The study of the environment of black holes in the hearts of nearby active galactic nuclei (AGN) to quantify and characterize the disposition and kinematics of dust and gas, to assess the validity of unification schemes and to possibly detect the optical counterparts of radio jets.

The AGN science case is the most demanding as it requires the greatest sensitivity of the array, and it has driven the design towards 1.4m diameter unit telescopes. To reach our goal of significantly extending the sample of AGN studied by existing arrays by at least a factor of 10, the science instrument needs to be particularly efficient in terms of throughput, imaging speed and instrumental visibility (see section 2.2.1 in particular).

2.2 Overview of the near-infrared science instrument

The light that travels along the "beam highway" in the inner Beam Combining Area of the MROI will encounter several optical tables in the following order: first the visible science instrument, then the near-infrared science instrument, then the fringe tracker, and finally the guest user science instrument. In a first phase, only the fringe tracker and the near-infrared science instrument will be present.

Fig. 1 present a block diagram of the science combiner's main functions. The science combiner will use light from either the J, H, and K band, as required by the science observation, while either the H or K band will be transmitted to the fringe tracker. We envisage two scientific modes of operation, using different dichroics to reflect into the science combiner and transmit to the fringe-tracker (1) reflecting the J and H photometric bands, using K band for fringe tracking and (2) reflecting the K photometric band, using H band for fringe tracking. We have developed initial designs for these dichroics that are much more efficient than off-the-shelf components, with integrated losses over the full bandpasses of $< 0.5\%$; test versions of these coatings are currently being manufactured.

The paths of the science combiners and the fringe trackers, which are affected by inter-band dispersion and internal drifts, have to be matched. Consequently the dichroics should not introduce more that 13 nm rms static wavefront error and more than 20 nm piston jitter into the beam transmitted to the fringe tracker.

Note that the same combining optics will be used in the science combiner for all wavebands. The science combiner will allow switchable low and medium spectral resolution mode, respectively R=30 and R=300. A high resolution mode R¿1000 is also in study and the combiners were studied to allow this possibility of upgrade.

The science combiner will provide suitable fringe encoding and support calibration procedures so that the calibrated square visibilities, the closures phases, and optionally the triple amplitudes can be derived by the off-line software from the raw detector frames.

The instrument shall allow all of the baselines (for V^2 measurements) and all independent closure triangles (for closure phases) provided by up to six available telescopes to be measured. However a certain level of

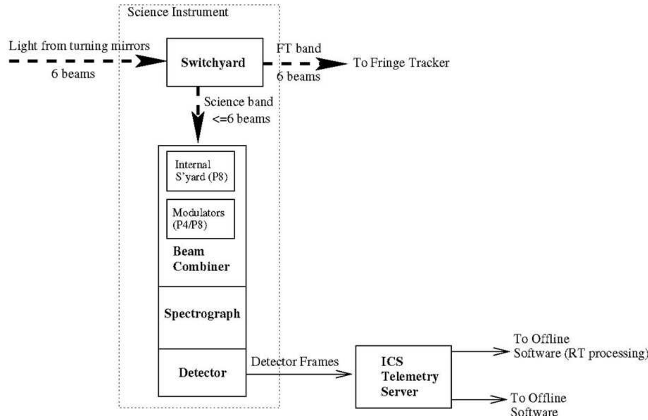

Figure 1. Block diagram of the near-infrared science instrument.

redundancy may be needed as a sanity check. Consequently the instrument shall also allow at least some of the non-independent closure phases to be measured. Similarly it will allow some of the baselines to be encoded at more than one spatial or temporal frequency, and to be measured using more than one set of routes through the beam combining optics (it should be noted that the potential reconfigurations required for this redundancy will not need personnel access to the BCA).

For bright sources, the instrument will permit calibration of V^2 measurements to 2% rms, and closure phases to 0.8° rms without exceeding the total overhead described further

Interface with the fringe-tracker is defined to limit the OPD drifts. Those low frequency changes in the OPD for any baseline, which are not common to the science and fringe-tracker instruments, must not cause visibility losses exceeding 0.7% in the science instrument. This corresponds to a maximum of 2.4 μm. As the calibration procedures needed to meet these OPD drifts requirements may have to be performed once per hour, the question of the overheads in our science combiner is a critical one.

The science combiner candidates were designed to reduce the total overheads to between 5 and 20 minutes for the typical observation with all baselines. This includes the time for photometric and detector calibration, the OPD drift recalibration we have just mentioned, as well as switchyard reconfiguration and the consequent realignment. The time spent acquiring and integrating the fringes is excluded of that calculation excepted when it is part of an additional visit to a calibrator star necessitated by a switchyard reconfiguration. The overheads also include night-time switching between spectral resolutions or operating wavebands: typically in that case the diffraction element of dichroics will be on a wheel and only the focal plane array may need refocusing. Another overhead is linked to photometry measurements, for which simple shutters shall be used to mask out the beams.

Finally the maximum absolute error in visibility amplitude due to leakage from other polarization states will be less than 2%, meaning the science combiner will be a polarization-fidelity instrument.

2.2.1 Limiting sensitivity

The most demanding science case for the science combiner will be the ability to observe more than 100 AGN targets. This requires a sensitivity enabling the acquisition of useful data on magnitude H=14 and K=13 targets in a reasonable time. This level of performance out of reach of current science instruments in similar facilities.

To compare the sensitivity of our science combiner candidates, we define here the sensitivity performance as the signal-to-noise ratio obtained in 300 seconds of incoherent integration case for:

- a squared visibility measurement for a K=12 unresolved source;
- in the central spectral channel of the K band assumed to be a top-hat bandpass centred on 2.20 μm with a width of 0.073 μm (i.e. at low spectral resolution R=30);

- with all six unit telescopes in use in a bootstrapping configuration, using switchyards for the combiners that require them;
- using only a single detector of effective read noise $5e^-/\sqrt{21}$ and a quantum efficiency of 65%;
- while performing group-delay tracking on the source in H (with the subsequent group delay errors);
- under good seeing conditions, defined as $r_0 = 14$ cm and $t_0 = 4.4$ ms at $\lambda = 500$ nm.

Under those conditions, our simulations show that a minimum signal-to-noise ratio of 2 allow to achieve all our science goals. If we wish to image the source, that minimum SNR should apply to the baseline on which the target is most resolved, as the other baselines measured contemporaneously will give higher SNR in the same time. We do not consider here the more complex scenario where a fixed total integration time is apportioned between any switchyard reconfigurations needed to access all 15 baselines. The visibility we expect for an AGN as a function of baseline length cannot be predicted accurately : this is why even low SNR results will be scientifically interesting. Here we assume that the object visibility in the science band is 0.9 on the shortest, nearest-neighbour baselines. In a six-telescope bootstraping configuration the ratio of maximum to minimum baseline length will be around 2.5:1, so if we make the worst-case assumption of a uniform disc visibility function, the visibility on the longest of the 15 baselines will be 17. If the target was larger than that with respect to the angular resolution of the array, thus giving smaller visibilities, visibility measurement would not be possible on all baselines, but the shorter baselines would yield a measurement of the angular size in preparation for a follow-up observation with a more appropriate array configuration.

The typical dynamic ranges of the images produced by this instrument will be 100:1 or greater, it will in many cases be possible to image resolved components of the target (for example nebulosity and disks around stars). Observations of targets as bright as $J = -3$, or $H/K = -4$ will be possible.

3. CANDIDATE SCIENCE COMBINERS

In the following we briefly describe the combiners before analysing their performance. For a more detailed presentation of the combiners the reader may refer to our previous paper.[1]

3.1 Presentation of the concepts

Three candidate science combiners have been selected:

- a 4-way pupil plane fed by a fast switchyard (**P4S**). The fast switchyard selects 4 of the 6 input beams to be sent to the science combiner.
- a 4-way image plane fed by a fast switchyard (**I4S**). As for the combiner P4S, the switchyard is 6-way-in 4-way-out.
- a 6-way image plane (**I6**).

3.2 The fast switchyard

The first element of the science instruments P4S and I4S is the fast switchyard depicted in Fig. 2.

The basic design utilizes a set of dichroic beam splitters and mirrors mounted on orthogonally-oriented mechanical slides. The geometric layout allows for any set of 4 input beams out of the 6 input beams to be delivered to the instrument while allowing the light transmitted by the dichroics to continue on to the fringe-tracking subsystem.

The use of a switchyard selecting only 4 of the input beams may seem unusual, but in fact is optimized for the specific science goal of the MROI, i.e. faint-source imaging. For these faintest targets, the MROI fringe tracker will be operating in a coherencing mode, and so incoherent averaging of multiple short-exposure data will be necessary. Under these conditions, the optimum number of beams to combine so as to maximize the signal-to-noise ratio of the interferometric measurements is fewer than six, and hence by selecting four we will both optimize the signal-to-noise ratio of the data and maintain good efficiency in sampling the baselines available.

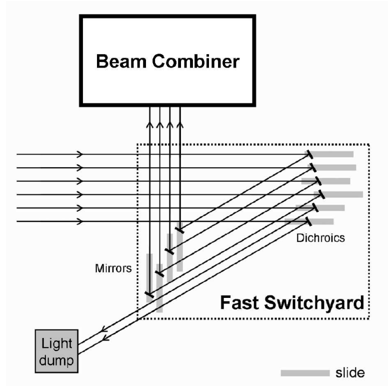

Figure 2. Schematic layout of the fast switchyard design. The 6 input beams enter horizontally from the left, while the 4 selected beams exit vertically. The beams transmitted by the dichroics exit to the right. The footprints of the mechanical slides are shown as gray rectangles.

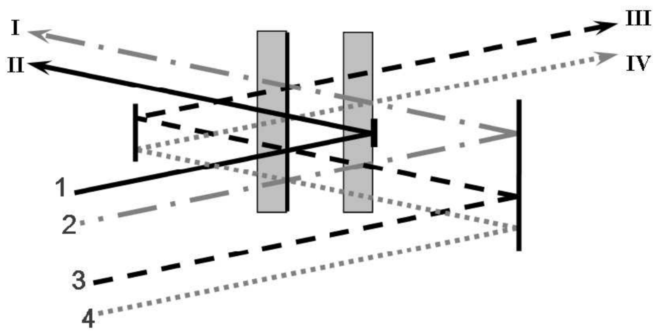

Figure 3. The pupil plane beam combiner P4. In this all-on-one scheme, the incoming beams (1 to 4) are recombined into the (I-IV) output beams which contains all interference between pairs.

The reconfigurations of the switchyard will be automated. To measure the visibilities on all the 15 available baselines only three reconfigurations are necessary, or five to access in addition all independent closure phases. We expect each reconfigurations to take a few tens of seconds, and so will be able to sample the full set of baselines in only a few minutes.

3.3 The pupil plane combiner P4S

The pupil plane science combiner P4S is composed of four subsystems: the fast switchyards described previously, the modulators, the beam combiner itself, and the spectrograph.

The modulators add a time modulated optical path delay to the beams coming from the beam relays, so that the fringes are encoded temporally. The visibility for each pair of input beams and the closure phases for each group of three input beams can be straightforwardly derived from the measured time variation of the output beam intensities.

The beam combiner itself combines the modulated beams using 50:50 beam splitter made of coated glass slabs. The beam combination is illustrated on Fig. 3. It is of the type all-on-one, the interference between all pairs of beams selected by the switchyard is present in every outputs. Such bulk optic combiner has already been built and tested at COAST,[5] though only for 5 mm beams.

A key element of this design is the optimisation of the anti-reflection coatings on the surface of the glass slabs. Without those, parasite reflections would form and significantly decrease the performance of the combiner. To reduce the visibility losses the size of the combiner would then have to be a lot larger. Using optimised coatings allows both to reduce the overall footprint of the combiner down to 45×25 cm^2 and to avoid those visibility losses.

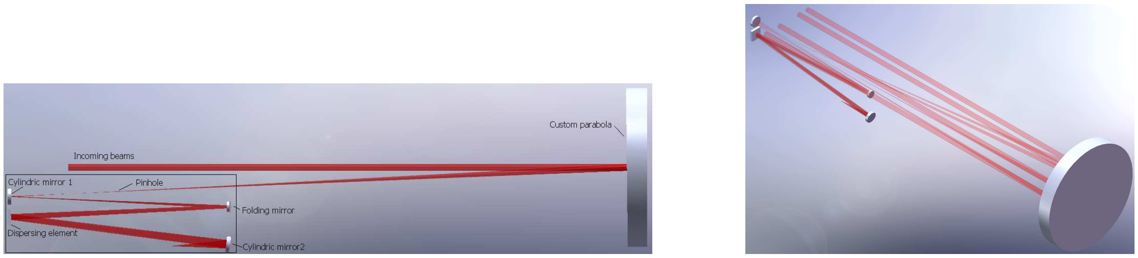

Figure 4. 3D views of the I4S design: from a plane perpendicular to the input beam configuration (left) and from the side (right).

3.4 The image plane combiners I4S and I6

The optical design of the image plane combiners uses only reflective components, in order to minimize chromatic aberrations. The beam combiner and spectrometer subsystem forms spatial fringes while dispersing the light so that fringes can be recorded in multiple wavelength channels simultaneously.

Fig. 4 presents the layout of the combiner components. Fringes are formed by imaging a linear non-redundant arrangement of the four or six incoming 13mm beams onto the array detector. Anamorphic optics are used to "squash" the fringe pattern for one wavelength channel into a single row of pixels. Spectral dispersion is used in the low-magnification direction, perpendicular to the fringes.

The beam combiner/spectrograph incorporates a cold pinhole to limit the thermal background signal. A side effect of the pinhole is to provide some spatial filtering of the atmospherically-induced wavefront errors, which helps meet our visibility calibration requirements. The anamorphosis is implemented using only three powered mirrors (a warm parabola and two cold cylindrical mirrors), which is a compromise between minimizing the dewar size and increasing the optical complexity. The beam path inside the dewar is folded using flat mirrors and a reflective dispersing element to further reduce the cooled volume required to $45 \times 14 \times 4$ cm^3 for the I4S and $50 \times 17 \times 4$ cm^3 for the I6. Note that the design offers multiple locations for installing background-suppressing stops even though there is not a true pupil plane inside the dewar.

4. PERFORMANCE ASSESSMENT OF THE CURRENT CANDIDATE COMBINERS

This section presents the results of the budget and tolerancing studies carried on the science combiners. All throughput and visibilities under this section are given $\pm 0.1\%$. For each combiner, the signal-to-noise ratio obtainable with the (currently) planned hardware is computed.

4.1 Throughput of the science combiner

Photon losses in the image plane beam combiners arise from :

- the fast switchyard for the I4S, which has 91% throughput (three reflections on silver-coated mirrors).
- the imperfect reflections on internal elements, the 4 mirrors ($\simeq 99\%$) plus the dispersing element and the dewar window throughput. About 8% of the flux is lost this way;
- the cold stops to limit background flux;
- the diffraction by the dispersing element (higher orders). The absolute efficiency of a custom made diffractive element can reach about 95% for the central wavelength, and is around 90% elsewhere in the band. Several diffractive elements are being investigated to determine the best suited in terms of efficiency for each band and spectral resolution (volume phase grating, gold plated and blazed grating, grism);
- the diffraction losses, i.e. the flux lost due to the fringe pattern being wider than the detector. The total loss depends on the beam configuration and waveband, ranging from about 2% (I4) to 5% (I6).
- the average positioning errors, which have been evaluated using Zemax, and amount to less than 2% loss.

Overall this translates into a throughput of 68% for the I4S (including the switchyard) and 65% for the I6, without spatial filtering.

The throughput of the P4S is determined by:

- the fast switchyard (91% throughput);
- the beam combiner itself, containing coated slabs (97.5%, including losses due to ghost beams), the infrasil slabs (99% four times) and in the worst case 2 reflections on silver mirrors (97% twice), for a total of 87%.
- the spectrograph, total 90% (two silver-coated mirrors plus the dispersing element).

If all outputs are used, the final total throughput of the P4S is 71%.

Finally if spatial filtering is done as currently planned, using a pinhole radius of 0.74 λ/D to 1.20 λ/D, the calculated throughput should hover between 60 and 70%.

4.2 Instrumental visibilities

The switchyard has been optimized to reduce the visibility losses, and less than 0.5% loss.

Due to the transmissive nature of the pupil plane combiner, the visibility losses are well contained in this design, the slabs plus coatings loosing 6% at worse. The P4S spectrograph is also efficient, with only a small crosstalk between spectral channels (0.2%) and minor other visibility losses are due to aberrations (0.1%).

In the image plane design the losses are larger. They partially due to the optical aberrations of the mirrors, 1% for the I4 and 7% for the I6. To those numbers we have to add the losses related to the positioning errors, and the tolerancing studies show that the expected precision of 0.02° on the component angles and 0.1 mm rms on their positions insures that visibility losses will stay inferior to 2%. The truncation of the fringe pattern by the detector window is also a major contributor around 5%. Visibility losses incurred by spatial filtering are less than 0.8%.

In the worse case, the total visibility losses may reach 9% for the I4S (including the switchyard contribution), and 15% for the I6, while they remains under 7% for the P4S.

4.3 Detector and imaging characteristics

Only one detector The initial detector will be a 256 $\times$ 256 pixels Teledyne PICNIC array, used in conjunction with controller electronics from Astronomical Research Cameras, Inc. We expect to upgrade the detector in a few years, and the 40m pixel size of the PICNIC is compatible with that of the next-generation active-pixel device we expect to be able to procure and so will allow a straightforward upgrade path. All calculations in this paper utilize the PICNIC array performance, with an assumed quantum efficiency of 65% and an effective read-noise $5e^-$.

Each combiner requires a different optimal number of pixels. For the I4S this number ranges from 96 to 128 pixels and for the I6 between 128 to 192 pixels, depending on the waveband. The P4S needs 48 pixels per output, and the most adjacent output beams can be straightforwardly multiplexed on the same detector. Unfortunately, due to the spectrograph layout, it currently does not seem feasible to multiplex all four outputs on the sole PICNIC array and only two outputs may be multiplexed. In fact the P4S is doubly penalized by the current detector: only half the light would be used, and the read-noise is not low enough to significantly favour the pupil plane design over the image plane ones, as this is conventionally the case (our image plane combiners use a moderate number of pixels).

Finally, when a better infrared array becomes available, we expect to upgrade this part of our science combiner ultimately achieving a read-noise of $1.5e^-$.

Candidate	P4S	I4S	I6
Total throughput	71%	68%	70%
Instrumental visibility	93%	90 %	86 %
SNR (4 way)	3.4 to 6.0	5.4 to 6.6	3.7 to 5.5
SNR (6 way)	2.4 to 4.3	3.8 to 4.7	2.6 to 4.3

Table 1. Performance of the candidate designs: throughput, instrumental visibilites and SNR in the 4 way and 6 way scenario.

4.4 Realistic signal-to-noise evaluation

We derived the signal-to-noise ratio for the measurement described in section 2.2.1, where six telescopes are available ("6-way" scenario). As the science instrument is likely to be used for several years with no more than four beams, we also studied a "4-way" scenario, where the science instrument (designed for six beams) is used with only four beams.

In the 6-way scenario we assumed that 50% of the time was spent off-source due to the switchyard reconfigurations of the I4S and P4S. In the 4-way scenario no switchyard is being used and consequently this overhead does not exist.

To compute the signal-to-noise (see section 2.2.1), we took into account :

- the total throughput (about 13%). This includes the MROI optics (52%: the reflection and transmissions losses, the obscurations, the diffraction losses) as well as the contributions linked to the atmosphere (seeing, residual tip/tilt, infrastructure high orders).
- the system visibility, ranging from 30% in H to 45% in K. This includes the visibility losses due to the resolution, the integration, the instrumental piston jitter, the differential shear, the differential polarisation, the unequal beam intensities and the differential dispersion (60% in total). The atmospheric terms are also included, such as the visibility losses due to the piston jitter, the uncorrected tilt and the high order wavefront errors.
- the fringe-tracking errors, namely the quasi-static group delay errors and the dynamic group delay errors.
- the background sky luminosity, respectively 15.5, 14.0 and 12.6 mag.arcsec^{-2} in the J, H, and K bands.
- finally the performance of each candidate combiner, as detailed in the previous sections (the throughputs, the instrumental visibilities and the imaging characteristics).

Table 1 presents the lowest and highest SNR achieved, the SNR being typically lower in the J band than in the H or K band. All our candidates meet the specifications and therefore are susceptible to be used. They are surprisingly close in terms of performance, though the I4S and P4S are clearly ahead of the I6. in the 4-way scenario, the I4S design is clearly better suited than the I6. In the 6-way scenario, the larger number of pixels needed by the I6 overcomes all the advantage given by the lack of switchyard.

For all candidates, the SNR values computed in the 4-way scenario are 40% higher than in the 6-way one. There is a definite trade-off between the *uv* coverage and the SNR.

Note however that the numbers given here correspond to the use of a full complement of detectors. With our current PICNIC array at our disposal, it is not currently possible to multiplex more than two beams out of the four of the P4S. A larger detector or several detectors are required to fully utilize P4S. Without a detector upgrade the actual numbers for the P4S signal-to-noise will be divided by two, and the I4S becomes the obvious choice for performance.

Thus, the detector choice will determinant for the downselect of the candidate designs. Should an upgrade be done, it will be oriented toward a reduction of the read-noise: our calculation show a read-noise of $1.5e^-$ lead to factors of $4 - 6$ in improvement of the signal-to-noise ratio, corresponding to an increase of sensitivity of one magnitude.

5. OTHER EVALUATION CRITERIA

5.1 Costs

In this section we try to compare the approximative costs for each design. These costs can be divided into labour costs and hardware costs, but the labour costs are likely to be similar for all designs: the P4S and I4S both require the testing and installation of the fast switchyard, but the I6 may be more difficult to align.

The major hardware costs common to all designs are:

- the optical table and stand (around 60 k$).
- the detector (the PICNIC array) and the detector controller (160 k$ total);
- the Dewar enclosing the cold optics (around 60 k$). Its cost scales with the size or the volume to cool, thus being more expensive for I4S than for the P4S, and even more expensive for the I6.
- the control system (consisting of CPUs, racks, timing cards, etc.) which cost is minor ($<$ 15 k$).
- most of the cold optics (dispersing element, filter and dispersing wheels, pinholes, off-the-shelf mirrors, actuators and motor controllers for alignment), around 25 k$.

The remaining costs are particular to each design. For the switchyard in the I4S and P4S design, the main costs are the 10 slides and the coatings for the dichroics, then the optical table (for prototyping) and finally the control system, totalling around 150 k$. However this cost should be mitigated by the possibility of upgrade offered by the switchyard when 10 telescopes will be on site (phase B of MROI).

For the P4S, the slides and coatings of the beam combiner are here again the most expensive (100-150 k$). The other costs for the fringe modulators, the warm optical mirrors and their coatings, do not exceed 30 k$. The warm optics of the I4S is of similar price, the main expense arising from the custom parabola and the mirror coatings, and slightly more expensive for the I6 (50k$) due to the larger optics needed.

Overall, comparing only the differential costs, P4S and I6 are of equivalent cost, and the I4S is the less expensive design.

5.2 Technical risks

The technical risks, derived from the tolerancing studies, were shown to be moderate. They are mainly related to the movable parts of our designs (the switchyards and the modulators).

The tests on the modulators for the P4S are currently underway. For the switchyard, the opto-mechanical tolerancing of our design has shown that the repeatability and stability requirements for the individual component linear motions ($\simeq$ 2 microns) are easily met with commercial slides. Changes in the angular orientation of the components on switching are more critical ($\simeq$ 0.5 arcseconds), and will necessitate the use of custom optical mounts with tip-tilt actuators and pre-calibration of the slide configurations. Tests of candidate commercial slides at NMT show promising initial results.

The only other technical risk is the difficulty to build image plane combiners for a high number of beams. Tolerancing studies have shown that the allowed positioning errors in the I4S and I6 should reach the precision of 0.02° and 0.1 mm rms, well within reach of the mounts and actuators we plan on using. The image plane designs also include more elements inside the Dewar than the P4S, which could be quite difficult to align.

Criterion	Weight	N# beams	P4S	I4S	I6
Hardware Costs	3	4 way	3	1	3
		6 way	4	2	3
SNR	5	4 way	4.0	1.2	2.7
		6 way	5.0	2.2	3.5
Timescale	4	4 way	1	1	2
		6 way	2	2	2
Risk	5	4 way	2	2	3.5
		6 way	3	3	3.5
Weighted sum		4 way	43	23	48
		6 way	60	40	52

Table 2. Summary of the combiner evaluation.

5.3 Schedule risks

The schedule risks are linked to the procurement of the optical components and the time needed to test them properly.

For all combiners, the dispersing elements will have to be custom made. Volume phase grating is the currently favored option. For the pupil plane combiner in particular, the slides have to be cut from one bloc of glass, then the corresponding coatings have to be applied. While this process is long, the testing procedure is straightforward.

For the image plane combiner, good-quality parabolas may be difficult to procure (especially the 40 cm one for the I6). The cylindric mirrors however will not be an issue has they have been designed with that problem in mind and can be bought off-the-shelf. The critical time aspect will be in the implementation and testing of the image plane combiner. We assess that the I6 is to be the most difficult to test (6 beams, off-axis aberrations, large components to align precisely).

6. GLOBAL COMPARISON OF THE COMBINERS

Table 2 presents the summary of our evaluation of the three designs. Four criteria (hardware costs, SNR, timescale/effort, technical risk) have been attributed a weight in our selection process. The SNR and the technical risks are the most important criteria, followed by the timescale and finally the hardware costs.

Scores ranges from 1 to 5, 5 being the worst. During this final assessment we assumed that only two outputs out of four were used in the P4S (and multiplexed onto the PICNIC detector), hence the bad scores for the P4S performance.

We decided to give zero weight to the upgradability from 6 to 8 beams, as the decision to upgrade each design is likely to depend on the availability of better detectors or new material and money (all of which are difficult to predict).

The bottom line is that the I6 is too risky technically and susceptible to delays due to this complexity. The P4S is not competitive in terms of performance without an additional detector or another multiplexing scheme.

The I4S is the design that offers the best performance/price/risk ratio, and thus our clear favourite for the moment.

7. CONCLUSION

The level of performance required of the MROI near-infrared instrument by the science mission is very demanding. We expect its scientific sensitivity to be matched to the fringe-tracking sensitivity of the array, allowing images to be made of targets which are many magnitudes fainter than are accessible to any existing interferometric instrument.

Three candidate science combiners have been designed: a pupil plane with contacted optics using an all-on-one combination of four beams, and two image plane combiners using non-redundant beam configurations of four and six beams and optical anamorphoses to encode the fringes.

A detailed comparison of those concepts has now been completed. This has concluded that they all meet the expected performance requirements. However the actual choice of combiner ultimately depends on other factors, such as the technical risks and the availability of detectors. With the current hardware, the image plane design (I4S) presented here has significant advantages over the other designs in terms of cost, signal-to-noise at shorter wavelengths, and lower cross-talk between baselines.

This evaluation is ongoing as the final downselect of the science combiner will be completed in winter 2008, with a possible integration of the instrument during spring 2009. As the first light at MROI is due fall 2009 and the first fringe fall 2010, the science combiner shall be able to operate from 2011.

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REFERENCES

[1] Baron, F., Buscher, D. F., Coyne, J., Creech-Eakman, M. J., Haniff, C. A., Jurgenson, C. A., and Young, J. S., "Beam combiner studies for the Magdalena Ridge Observatory Interferometer," in [*Advances in Stellar Interferometry. Edited by Monnier, John D.; Schöller, Markus; Danchi, William C.. Proceedings of the SPIE, Volume 6268, pp. 62681R (2006).*], *Presented at the Society of Photo-Optical Instrumentation Engineers (SPIE) Conference* **6268** (July 2006).

[2] Creech-Eakman, M. J. and Magdalena Ridge Observatory Interferometer Team, "Magdalena Ridge Observatory Interferometer Science Mission and Design Requirements," *American Astronomical Society Meeting Abstracts* **207**, 14 (Dec. 2005).

[3] Creech-Eakman, M. J., Buscher, D. F., Haniff, C. A., and Romero, V. D., "The Magdalena Ridge Observatory Interferometer: a fully optimized aperture synthesis array for imaging," in [*New Frontiers in Stellar Interferometry, Proceedings of SPIE Volume 5491. Edited by Wesley A. Traub. Bellingham, WA: The International Society for Optical Engineering, 2004., p.405*], Traub, W. A., ed., 405 (Oct. 2004).

[4] Creech-Eakman, M. J., Buscher, D., Chang, M., Haniff, C., Howell, P., Jorgensen, A., Laubscher, B., Loos, G., Romero, V., Sirota, M., Teare, S., Voelz, D., and Westpfahl, D., "The Magdalena Ridge Optical Interferometer and its Science Drivers," *American Astronomical Society Meeting Abstracts* **203**, 03 (Dec. 2003).

[5] Haniff, C. A., Baldwin, J. E., Basden, A. G., Bharmal, N. A., Boysen, R. C., Buscher, D. F., Keen, J. W., Mackay, C. D., O'Donovan, B., Seneta, E. B., Thorsteinsson, H., Thureau, N. D., Tubbs, R. N., Warner, P. J., Wilson, D. M., and Young, J. S., "COAST: recent technology and developments," in [*New Frontiers in Stellar Interferometry, Proceedings of SPIE Volume 5491. Edited by Wesley A. Traub. Bellingham, WA: The International Society for Optical Engineering, 2004., p.511*], Traub, W. A., ed., 511 (Oct. 2004).