Options for a Commissioning Instrument for MROI

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Objective

To provide a basis for discussion of options for a "first fringes" beam combining instrument at MROI.

Scope

In its current form, this document aims to form the basis for discussions about the functionality required for a commissioning beam combining instrument, and ways of delivering as much of this functionality as possible, while minimising the cost and schedule impact on the MROI project.

The document is in several parts:

- Roles and Timelines for a comissioning instrument (Sec. 1)
- Functionality required (Sec. 2)
- Functionality delivered by various classes of beam combiner (Sec. 3)
- Possible locations for a comissioning instrument within MROI (Sec. 4)
- Suggestions for instruments that Cambridge might be able to deliver (Sec. 5)
- Suggestions for instruments that might be available from potential partner institutions (Sec. 6)

This document has been revised (as of rev 0.4) to include (a) information on which of the functions from Sec. 2 might realistically be provided by the science-phase beam combiners, and (b) a suggested prioritisation of the functional requirements for commissioning activities that take place *after* an initial 2-year commissioning phase.

We note that the final report on the evaluation of the science-phase beam combiner options will include an assessment of how straightforwardly the preliminary combiner designs can be adapted to use an existing detector device (such as the Rockwell HAWAII-1), as suggested in Sec. 5.1.3.

This version of the document *does not contain* a detailed evaluation of the extent to which the procurement options outlined in Sec. 5 and Sec. 6 would meet the functional requirements. We suggest that this disconnect could be addressed once the option space has been narrowed down, perhaps by means of discussions with potential collaborators.

Table 1: Low-cost/low-leadtime options for a commissioning instrument for MROI.

Source	Name	Type	Wavebands	Available	Needs
COAST	Visible Combiner	4-way pupil plane	RI	Yes?	Modulators
COAST	Infrared Combiner	4-way pupil plane	JHK	Yes?	Modulators
Cam	Miniature Comb. Mk2	Contacted 4-way pupil plane	JHK	Yes	Compressors, modulators
Cam/MRO	Cut-down Sci. Comb.	TBD	JHK	?	Commissioning back-end
IOTA	IONIC3	3-way integrated optics	H(K)	?	Injection optics

Table 2: Summary of the commissioning-specific functionality delivered by each of the instrument options from Table 1. Refer to Sec. 2 for more details.

		Can measure			
Source	Name	Tip-tilt	Shear	Unfil. throughput	Phase at 500 Hz
COAST	Visible Combiner	Yes	No	Yes	Dep. on modulator/detector
COAST	Infrared Combiner	Yes	No	Yes	Dep. on modulator/detector
Cam	Miniature Comb. Mk2	Yes	No	Yes	Dep. on modulator/detector
Cam/MRO	Cut-down Sci. Comb.	Yes?	No	Yes	Yes?
IOTA	IONIC3	No	No	No	Dep. on modulator/detector

Summary

The options for procuring a commissioning instrument with minimal cost and schedule impact on the project are summarised in Table 1. In all cases, some part of the instrument is already available (or will be available on the required timescale), but some part(s), listed in the "Needs" column, will need to be developed specifically for this application.

All of the options could potentially be used with either the HAWAII-1 camera being developed in Cambridge (Sec. 5.2) or the IOTA PICNIC camera (Sec. 6.2).

Table 2 summarises how well the options from Table 1 deliver the infrastructure-debugging functionality identified in Sec. 2.

In conclusion, we suggest that the option space should be narrowed down before investigating the remaining instrument options in more detail. Possible routes to reducing the number of options are:

- Decide which roles the instrument should perform (Sec. 1)
- Decide which debugging functionality should be provided by the instrument (Sec. 2): may need refinement of e.g. Alignment System
- Open discussions with partners who could provide a commissioning instrument
- Decide how the final Science and Fringe Tracking beam combiners will be procured

1 Introduction

The possibility of installing a "commissioning beam combiner" at MROI has been raised due to concerns that the Infrared Science and Fringe Tracking beam combiners intended for "First Science" and subsequent scientific operations would not be ready in time for "First Fringes" (and perhaps not "First Closure Phase").

In this document, we assume the following approximate milestone dates:

- (First telescope delivered: August 2007)
- (Second telescope delivered: March 2008)
- First Fringes: summer 2008

Some possible roles for such a "commissioning instrument" are as follows. It may be possible for an instrument to fulfill several or even all of these roles:

1. Provide facilities for debugging the interferometer "infrastructure" (Unit Telescopes, tip-tilt correction, beam relay, delay lines, beam compressors)
2. Provide facilities for debugging either or both of the IR Science/Fringe Tracking combiners, including any fast switchyards and path modulators
3. Deliver "First Fringes" (measure squared visibility on any star)
4. Deliver "First Closure Phase" (measure closure phase on any star)
5. Deliver fringe measurement on a faint ($H > 10$?) target
6. Provide some initial visible-wavelength science capability (given that there is no visible science capability in MROI Phase 1)
7. Provide facilities for debugging the interferometer infrastructure beyond the commissioning phase (=2 years?)
8. Provide facilities for debugging either or both IR Science/Fringe Tracking combiners beyond the commissioning phase
9. Provide some initial infrared science capability (to do science for publicity purposes)

As some of this functionality may require an instrument that does more than just interfere the beams to form a fringe pattern, we refer to the commissioning combiner as a "commissioning instrument" in this document. Different parts of such an instrument may need to be installed in different places in the BCA.

Providing more of this functionality is likely to complicate the design of the commissioning instrument, which may mean it cannot be delivered in time for "First Fringes." However, at least items 1 through 3 *are likely to be required* to successfully achieve first fringes.

We note that role 5 will be difficult to fulfill on the same timescale as "First Fringes" (although a brighter "faint" magnitude might be achievable). Fringe tracking capability would be needed, whereas we anticipate installing the science combiner before the fringe tracking combiner. It is likely that the new infrared detectors being developed by Rockwell would also be required. This role is not considered further in this document.

1.1 Design Approaches

There are two possible approaches to selecting a commissioning instrument concept:

Functionality-driven In this approach, we would state the purpose(s) of the instrument and hence derive a list of functional requirements. Finally we would choose the simplest instrument concept that can deliver that functionality. We might consider altering the date for first fringes based on the time required to deliver a suitable instrument.

Technology-driven In this approach, we would list all possible simple beam combiner concepts and their functionality (perhaps concentrating on those Cambridge or potential partners in MRO have experience of), then select a concept that provides sufficient capability and can be delivered in time for first fringes.

A variation on this approach would be to only consider concepts for which designs and/or actual hardware are (or will be) available.

The reader should note that the debugging functionality listed above may not be provided by *any* "traditional" type of beam combiner alone (we elaborate on this point in Sec. 3), hence a technology-driven downselect might, by itself, lead to design choices that result in a longer commissioning period.

These two approaches are complementary. In this document we adopt both approaches. Sections 2 and 3 follow the functionality-driven approach, while Sections 5 and 6 follow a technology-driven methodology.

2 Functional Requirements

The functional requirements that may be placed on a beam combining instrument during the commissioning phase of MROI are considered in this section. These encompass all of the potential roles listed in Sec. 1, except role 5 (fringe measurement on a faint target).

2.1 Scoring System

We adopt a scoring system based on that described in the Controls Requirements Document, INT-409-ENG-0001, to prioritise the functionality:

Priority 1 Essential. Must be present to get *first fringes*, or will make commissioning significantly faster.

Priority 2 Highly desirable. Will improve commissioning, but may be jettisoned if it proves expensive ($>$ \$50k?).

Priority 3 Desirable but gives no significant advantage for commissioning activities.

Priority 4 Not required. Do not implement — having this feature, even at zero cost, will cause more trouble than it is worth.

In all cases, priorities refer only to the commissioning instrument. For example, it is imperative that MROI measures closure phase, but measuring closure phase with the commissioning instrument is listed as priority 3. In assigning this priority, we assumed that we are only concerned with debugging the interferometer, rather than generating publicity. In other words, we have *de-prioritised* the roles in Sec. 1 that have no debugging element.

2.2 Definitions

The following definitions apply to terms used in Table 3.

Quasi-static No significant variation over the timescale of a calibrated fringe measurement (which may take up to an hour in the early stages of operation).

Dynamic Significant variation on shorter timescales. Dynamic effects may be caused by e.g. atmospheric turbulence, or vibrations within the interferometer.

Differential The difference of some measurable parameter (e.g. optical path delay) between beams from two different telescopes

Internal Measured using an artificial light source rather than a star. We envisage needing both white light (WLS) and laser (LS) sources. The artificial source will probably be propagated from a beam combiner output to either (a) a set of temporary retroreflecting mirrors in the BCA, (b) the telescope tertiary mirrors, or (c) the telescope secondary mirrors, in all cases being retroreflected then retracing its path though the system, back to the combiner.

2.3 Prioritised Functions

A list of suggested functional requirements for the commissioning instrument is presented in Table 3. Priorities have been assigned according to the scoring system outlined above. We list separate priorities for the initial 2-year commissioning phase and for commissioning activities taking place later (e.g. addition of further unit telescopes).

In Table 3, where applicable, we give approximate sample rates required for the measurements to be useful. "At COAST" means that the capability was available at COAST while the interferometer was being commissioned.

The table also contains an assessment of whether the functionality will be delivered by either of the science-phase combiners, in the "Provided by Sci/FT?" column. Where the answer is given as "Possibly" this indicates that the requirement would impact the design of the combiner and/or the associated detector(s).

2.4 Differences from Science Combiner Requirements

The instrument capabilities needed to make the *priority 1* measurements from Table 3 differ from those envisaged for the MROI science combiner in the following respects:

- Require field-of-view > Airy disk (i.e. no spatial filter)
- Require fringe phase measurement at up to 500 Hz (using laser source)
- Require quasi-static shear measurement on star
- Require measurement of low-order aberrations
- Spectral dispersion not required
- Relaxed sensitivity requirements
- Relaxed calibration requirements(?)

We have not identified a priority 1 need to install test instrumentation behind the switchyard (beyond that needed to calibrate the switchyard for normal operations) or path modulators of either the Science or Fringe Tracking combiners.

Table 3: Functional requirements, with priorities assigned according to the scoring system in Sec. 2.1. Some terms used in the table are defined in Sec. 2.2.

Measurement	Using	Rate /Hz	Priority (First 2yr)	Priority (Later)	At COAST?	Provided by Sci/FT?	Note
Squared Visibility	Star		1	1	Yes	Yes(either)	
Closure Phase	Star		3	2–3	Yes	Yes(Sci)	
Initial visible science capability	Star		3	3	(Yes)	No	
Internal Squared Visibility	WLS		1	1	Yes	Yes(either)	Infer wavefront errors
Internal Closure Phase	WLS		3	2–3	Yes	Yes(Sci)	
After infrastructure (UTs, tip-tilt, relay, delay lines, compressors):							
Quasi-static tip-tilt	any		1	1	Yes	Possibly	Must tie Alignment Sys. to BC.
Dynamic tip-tilt	Star	$\sim$100	1	1	Yes	Possibly	Test tip-tilt corr'n
Dynamic tip-tilt	WLS/LS	$\sim$2	1	3	Yes	Possibly	Internal seeing
Quasi-static low-order aberrations	any		1	1	No	No	Tel./compressor collimation errors Provided by WFS?
Dynamic low-order aberrations	any	$\sim$2	3	3	No	No	Dynamic collimation errors?
Quasi-static shear	Star		1	3	No	No	Check alignment on star
Dynamic shear	Star	$\sim$2	3	3	No	No	
Quasi-static differential OPD	Star		1	1	Yes	Yes(either)	Determine baselines
Dynamic differential OPD (2 beams)	LS	$\sim$500	1	2	Yes	Possibly	Test of OPD jitter
Dynamic differential OPD (2 beams)	Star	$\sim$50	2–3	3	Yes	Yes(either)	Test of UT mount & site
Dynamic differential OPD (3 beams)	WLS		4	4	Yes	Yes(Sci)	Test internal C.P. stability. In-combiner effects only
Quasi-static photon throughput	Star		1	1	Yes	Possibly	Without spatial filter
Dynamic photon throughput	Star	$\sim$500	1	2	Yes	Possibly	Without spatial filter
After switchyard (of Science/FT Combiner):							
Quasi-static tip-tilt	WLS/LS		1	1	n/a	Possibly	Daytime test/calib. of s'yard
Quasi-static shear	WLS/LS		1	1	n/a	No	Daytime test/calib. of s'yard
Quasi-static differential OPD	WLS		1	1	n/a	Yes	Daytime test/calib. of s'yard
Dynamic tip-tilt	Star	$\sim$2	3	3	n/a	Possibly	Probably none due to s'yard
Dynamic shear	Star	$\sim$2	3	3	n/a	No	Probably none due to s'yard
Dynamic differential OPD (2 beams)	LS	$\sim$500	3	3	Yes	Possibly	Probably none due to s'yard
Dynamic differential OPD (2 beams)	Star	$\sim$50	3	3	Yes	Yes(either)	Probably none due to s'yard
Dynamic differential OPD (3 beams)	WLS		4	4	Yes	Yes(Sci)	In-combiner effects only
After modulators (of Science/FT Combiner):							
Monitor/infer OPD modulation	Star		3	3	Yes	No	Independent of other OPD var'ns

3 Functionality of classes of Beam Combiner

We now consider how much of the priority 1 functionality identified in Sec. 2 is provided by various generic types of beam combiner. The classes of beam combiner considered here are defined in Appendix A.

We will consider image plane and pupil plane "free-space" combiners, as well as integrated optics combiners. We include integrated optics because one of the IOTA combiners that may be available is the IONIC integrated optics 3-way combiner (see Sec. 6).

The commissioning combiner will not require a dedicated fast switchyard, but may be installed behind the switchyard of either the Fringe Tracking or IR Science Combiner (see Sec. 4).

3.1 Tip-tilt

In principle, image plane combiners automatically measure tip-tilt. However (a) the images from different beams overlap (preventing simultaneous tip-tilt measurements of several beams), and (b) often their field-of-view is small (not much larger than an Airy disk — this may be limited by both the combiner optics and the size of the detector).

However, an image plane system combining two or three beams need only spread the Airy disk across a small number of detector pixels in order to adequately sample the fringes. Hence the extent of available detectors need not limit the field-of-view. It will still be necessary to consider the field-of-view of the combiner optics when designing the instrument.

Pupil plane combiners can measure tip-tilt using a dedicated camera (with appropriate pixel scale) at one of the beam combiner outputs. Again, the images from different beams overlap. So, a pupil-plane combiner and a custom-designed few-way image combiner are probably equally suitable for measuring tip-tilt.

For either class of combiner, no spatial filter should be installed when tip-tilt errors are being measured (this only applies to one of the combiner outputs in the pupil plane case).

Integrated optics combiners cannot measure tip-tilt: they are fed by single-mode optical fibres with a narrow range of acceptance angle (about an Airy disk diameter).

3.2 Shear

No standard combiner measures shear directly. However, recording a defocused image might give a sufficient indication of the shear.

3.3 Low-order aberrations

No standard combiner measures low-order aberrations (defocus, coma, astigmatism etc.) directly.

3.4 OPD

All beam combiners measure quasi-static and dynamic differential OPD (both internal and on-sky).

Pupil plane and integrated optics combiners generally require modulators to form fringes and hence measure OPD. Modulators can introduce unwanted dynamic OPD variation, which could be difficult to distinguish from effects due to the interferometer infrastructure unless e.g. a dedicated laser interferometer were installed to measure the modulator motion.

Alternatives to path modulation in a pupil plane or integrated optics combiner are:

- Use sidereal fringe motion to generate slow temporal fringes (i.e. change the delay line velocity). Note that this will not meet the priority 1 requirement to measure fringe phase at 500 Hz (using a laser source).
- Fixed achromatic $n\lambda/4$ delays at different combiner outputs.
- Use of spectral dispersion to obtain channelled fringes on an array detector (e.g. Lawson et al., 1998).

Monitoring of the modulators of a *different* combiner (the Science or Fringe Tracking combiner; this measurement is priority 3) could be accomplished *indirectly*, by recording fringes in that combiner and the commissioning instrument simultaneously (provided there are no non-common dynamic OPD effects due to the switchyards or static combiner optics, or to any modulators in the commissioning instrument).

3.5 Throughput

All combiners measure quasi-static and dynamic photon throughput, but we are interested in the throughput *without spatial filtering*. This presents a problem for integrated optics combiners – light is fed in via single-mode fibres which act as very good spatial filters.

4 Location(s) of the Comissioning Instrument

As mentioned earlier, if the functionality of the commissioning instrument is comprehensive, different parts of it may need to be installed in various places, as discussed below.

The order of the four instrument tables, starting from the beam compressors, is:

- Visible Science
- Infrared Science
- Fringe Tracker
- User Science

4.1 On the “User Science” Table

This location is appropriate for testing the interferometer infrastructure, and has the advantage that the commissioning instrument can usefully remain in place while the Science and FT Combiners are commissioned (subject to availability of suitable dichroics).

4.2 On the “Visible Science” Table

This location is also appropriate for testing the interferometer infrastructure, and has the same advantage that the instrument can remain in place. If the commissioning instrument uses visible light, the final dichroics can be used to feed all of the combiners.

4.3 On the “Fringe Tracking” and/or “Infrared Science” Tables

These locations are appropriate for testing both the interferometer infrastructure and all or part of the Fringe Tracking or IR Science Combiner respectively. However, there may be insufficient space to install two complete instruments on one table. The design of the commissioning instrument will also depend strongly on the design of the combiner(s) it must cohabit with, which may hamper early delivery of the commissioning instrument.

It may be that neither of the FT/Science combiners contains a fast switchyard, or any path modulators. In this case we would likely choose to test the infrastructure only.

5 Options from Cambridge

5.1 Combiner Optics

5.1.1 Original COAST 4-way Combiners

One of the beam combiners installed at COAST (or a copy) could potentially be installed at MROI. There are both visible-wavelength (0.65–1.0 μm, Baldwin et al., 1994) and infrared (1.0–2.4 μm, Young, 1999) combiners, which are 4-way pupil plane designs with discrete beamsplitters and mirrors on custom tip-tilt-adjustable mounts.

The beam combination scheme is conceptually the same as that shown in Figure 4. The instrument could trivially be cut down to a 2-way combiner, by removing three of the four beamsplitters.

Pros

- Performance demonstrated on sky
- Handle beam sizes up to 25 mm

Cons

- Require $\sim$weekly re-alignment; re-engineering would be needed to integrate with MROI alignment system
- Require development of path modulators

5.1.2 Prototype Contacted Optics Combiner (Mark 2)

This is the second-generation Cambridge contacted optics 4-way pupil plane combiner. The combiner was designed for 2.5 mm beams, but will cope with beam sizes up to XX mm. The existing combiner has coatings suitable for near-infrared operation (1.0–2.4 μm).

Pros

- Performance demonstrated in lab

Cons

- Would need second stage beam compressors
- Require development of path modulators

5.1.3 Cut-down Version of Selected MROI Science Combiner

One possibility for a commissioning instrument would be the selected MROI Science Combiner, re-engineered to use an existing infrared camera.

It seems likely that the longest-lead item required for the MROI Science Combiner will be the detector FPA device. We would be concerned about proceeding with detailed design of a science spectrograph to use devices still under development, as the fallback option would be to use a HAWAII-1 array with a different pixel size (18μm versus 40μm).

However, the design of the beam combining optics can (to a greater or lesser extent, depending upon which candidate combiner is selected) be decoupled from the spectrograph design. This opens the possibility of using the beam combining optics from the final science combiner with an interim back-end during the commissioning phase.

The interim back-end can be:

- For image plane combiner candidates: based on an available FPA (HAWAII-1), with the combiner optics outside the dewar (perhaps handling only 2 or 3 beams)
- For the pupil plane combiner candidates: an existing camera-in-dewar (see Sec. 5.2 and Sec. 6.2)
- Tailored to the commissioning role: no spatial filter, large field-of-view etc.
- Simplified as much as possible: no spectral dispersion, no reconfiguration to handle different spectral bands

A further temporary descope of the science combiner is possible. Whichever candidate combiner is selected, it will be possible to measure all baselines/triangles available from 4 telescopes using a static switchyard (note that I6 has no fast switchyard anyway).

We expect that a combination of these descopes would allow Cambridge to deliver a test combiner in time to achieve "First Fringes" in summer 2008, provided that sufficient resources are made available.

Possible initial (commissioning) versions of the four science combiner concepts might be as follows:

Candidate	Final instrument	Commissioning instrument
P4S	4-way w/fast switchyard	4-way w/static switchyard
I4S	4-way w/fast switchyard	2/3-way, warm combiner optics, static switchyard
P8	8-way inc. 2-config. internal fast switchyard	8-way inc. static internal switchyard
I6	6-way	2/3-way, warm combiner optics

5.2 Detectors

The HAWAII-1 camera under development at Cambridge (Neill and Young, 2004, 2005) could potentially be used with any of the commissioning combiner options. The earlier COAST infrared camera (Young, 1999) is also available.

If the COAST 4-way visible-wavelength combiner is used at MROI, it could potentially be used to feed the latest version of the Cambridge EMCCD spectrograph (version 1 is described by Basden, 2004; Basden et al., 2004). Alternative EMCCD cameras are available off-the-shelf.

6 Options from Potential Partner Institutions

Obtaining "free" instrumentation from a third party is a potentially attractive option. However, we would like to emphasise that this *must* come with adequate support. Ideally a team from the supplying institution would have hands-on involvement in commissioning.

In the absence of any specific offers, we describe the beam combiner options that might be available from IOTA. IOTA is due to be closed down, and its owners CfA have expressed an interest in collaborating on MROI.

6.1 Combiner Optics

The current IOTA beam combiners were described by Traub et al. (2003). The various beam combiners available to observers at IOTA are now:

- The 3-beam integrated optics combiner IONIC (Berger et al., 2003), developed by Grenoble (works best in H band)
- John Monnier's 2-beam asymmetric combiner (visible wavelengths)
- A 3-beam free-space (pupil plane) combiner (0.5–2.5 μm)

Of these, probably only IONIC has been in regular use at IOTA. In the absence of information about what might be available, we will concentrate on the mature option, IONIC. However, it may "belong" to Grenoble rather than CfA...

Two "guest" beam combiners have also been used at IOTA: FLUOR (moved to CHARA in 2002) and the JHK spectrophotometric image-plane combiner from MPI Heidelberg (Weigelt et al., 2003).

The compressed beam size at IOTA is 45 mm.

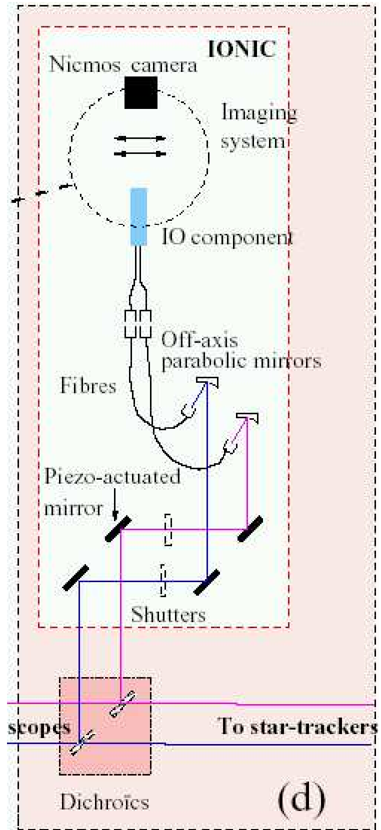

Figure 1: Schematic of the initial two-beam version of the IONIC combiner at IOTA.

6.1.1 IONIC

The initial two-beam version of IONIC and its installation at IOTA is described by Berger et al. (2001) (see Figure 1). A 3-beam derivative (Berger et al., 2003) is now used at IOTA together with the PICNIC fringe-detecting camera mentioned in the next section. This combination has reached a limiting magnitude $H = 7$.

The off-axis parabolic mirrors used to feed starlight into the IONIC input fibres would need to be changed, as they are designed for the IOTA beam size of 45 mm. The piezo-based path modulators could probably be re-used at MROI.

IONIC Pros

- Stability

IONIC Cons

- Initial polarization setup probably tricky

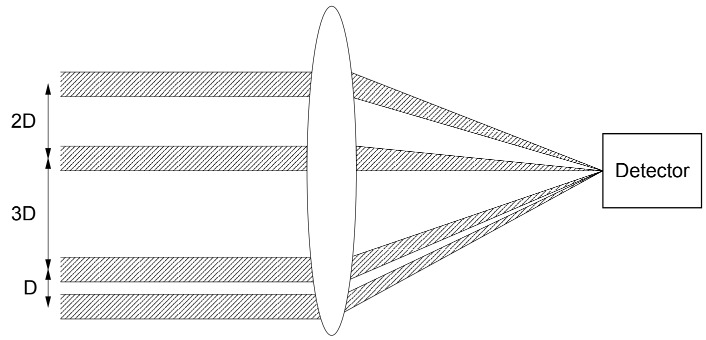

Figure 2: Simple scheme for making an image plane fringe pattern. Four path-compensated beams are arranged in a line with non-redundant spacings, and focused onto an array detector by a lens.

6.2 Detectors

The IOTA fringe-detecting camera is described by Pedretti et al. (2004). It is based on a Rockwell PICNIC array.

IOTA PICNIC Pros

- Good performance (3e readout noise using multiple reads)
- Existing capability to synchronise with IOTA path modulators

IOTA PICNIC Cons

- Requires reprogramming CPLD to change readout mode

A Beam Combination Techniques

Various beam combination technologies are outlined below.

A.1 Image plane combination

The beams are simply imaged together e.g. by a lens, to form a spatial fringe pattern on an array detector (Figure 2). The resulting image will be an Airy pattern crossed by fringes. A unique spatial frequency for each baseline can be obtained by arranging the input beams in a line with non-redundant spacings, as in Figure 2, or by using a non-redundant two-dimensional arrangement.

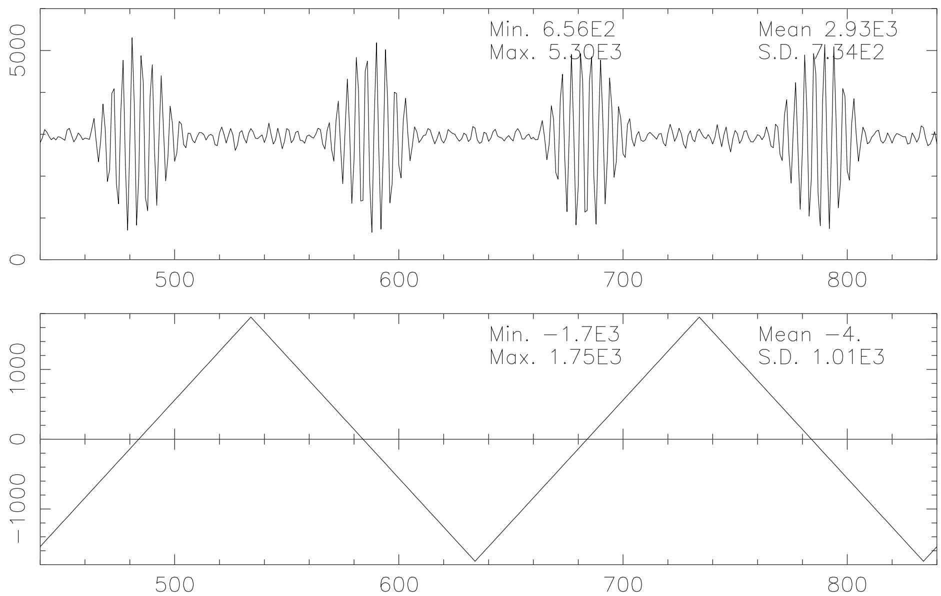

Figure 3: Example of a temporal fringe pattern. The upper plot shows fringes from the COAST IR system, obtained using an internal light source. The horizontal axis is time in milliseconds, and the vertical axis is proportional to the number of photons detected in each one millisecond integration. In the time interval plotted, the path delay (shown in the lower graph with the same time axis) was swept through the white-light fringe position four times. As the path delay exceeds the coherence length of the light, the fringes disappear.

A.2 Pupil plane combination

Two beams are superposed by matching their positions and directions. The optical path of one beam is changed, in order to scan through the white-light fringe position. The resulting fringe pattern is the intensity of a combined beam plotted against time (Figure 3). More beams can be superposed in the same way, and if their paths are scanned at suitable rates, the extra sets of fringes will have different temporal frequencies.

In practice, beam-splitters (partially reflective mirrors) are used to superpose the light beams. A schematic of a pupil plane beam combiner is shown in Figure 4. This beam combiner accepts four input beams, one from each of four telescopes, and gives four output beams. Each output beam contains equal amounts of light from the four telescopes. The system combines beams in pairs: beam 1 is combined with beam 2 at one beam-splitter, beam 3 is mixed with beam 4 at a second beam-splitter, then the mixture of beams 1 and 2 is combined with the mixture of beams 3 and 4 at each of two further beam-splitters. This scheme is readily extended to larger numbers of beams.

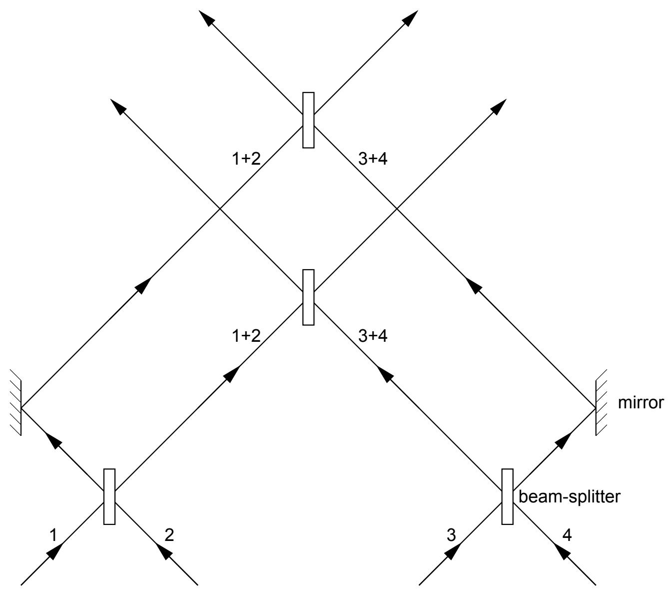

Figure 4: Pupil plane beam combiner. The combiner takes in four input beams (labelled 1–4), at the bottom of the diagram, and produces four output beams at the top. Each output beam contains equal amounts of the four input beams. The small rectangles are mirrors with 50% reflectivity.

A.3 Integrated Optics combination

In an integrated optics combiner, interference takes place inside a waveguide rather than in free space. As with a free-space pupil plane combiner, the OPD of one of the input beams can be modulated to generate temporal fringes. A schematic of the initial 2-beam version of the IONIC combiner is shown in Figure 1.

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