MRO Delay Line

Metrology laser choice

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The Cambridge Delay Line Team

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Change Record

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0.1	2008-01-27	CAH	First released version
0.2	2008-01-28	CAH	Included comments from JSY & MF
1.0	2008-01-28	JSY	Pruned list of acronyms
1.1	2008-01-30	CAH/JSY	Clarifications after feedback

Objective

The objective of this document is to describe the choices of metrology laser head currently being evaluated for use in the metrology system for the Magdalena Ridge Observatory Interferometer delay lines.

Scope

This document provides a description of the desired design features for the laser head associated with the MROI delay line metrology system, and the possible candidates currently under consideration. How well each candidate meets these needs is discussed.

Reference Documents

RD1 Results of the Risk Reduction Experiments – INT-406-VEN-0005

RD2 Top-level requirements – INT-406-TSP-0002

Applicable Documents

AD01 Metrology System and VME Hardware Design Description – INT-406-VEN-0113

AD02 MRO Delay Line Derived Requirements – INT-406-VEN-0107

Acronyms and Abbreviations

BCA	Beam Combining Area
BCF	Beam Combining Facility
DL	Delay Line
DLA	Delay Line Area
MROI	Magdalena Ridge Observatory Interferometer
OPD	Optical Path Delay
TBC	To be confirmed
TBD	To be determined

Contents

1 Introduction

A key component of the MROI delay line metrology system is the laser head used as the fundamental distance standard when measuring the location of the delay line carriages. The metrology design that has been proposed for the MROI utilises a Zygo 7712 water-cooled laser head. However, we are also evaluating two alternative laser heads, one another Zygo model (7702, air cooled) and the other an equivalently-functioning Agilent 5517D air-cooled head.

In this document we review the most important design features required for the MROI metrology laser head and report on how well each of these three possible laser heads meet these challenges. The key design features are presented in section 2, while section 3 assesses each laser head's performance.

The reader should note that although the laser heads under consideration are produced by different manufacturers, both Zygo and Agilent provide a range of metrology components (e.g. beam splitters, interferometer heads, counting cards etc) that are not only essentially identical in function, but also compatible in size and performance. Our design team in Cambridge has operated systems provided by both companies for many (i.e. >5) years, and can confirm that any change from one provider to the other would not involve any significant need for re-design of any of the proposed optical, mechanical or software sub-systems.

2 Key laser head features for the MROI system

Given the top level requirements for the MROI delay lines, in particular their long stroke single-pass design, the choice of a suitable metrology laser head will be governed in part by the following key performance criteria.

2.1 Beam size

In order to limit diffraction losses during propagation to and from a cat's-eye up to 200m away, the beam from the metrology laser will need to be expanded to of order 20mm (see, e.g., Sec 9.4.2. of RD1). A beam diameter of ~6mm will ensure that this can be accommodated straightforwardly using a beam expanding telescope with a moderate magnification of ×3.

2.2 System range

There are two aspects of the laser head (and its associated metrology components) that impact the maximum system range that can be accommodated:

2.2.1 Counter capacity

In any metrology system it is usual for the fringe-counting hardware and software modules to support only a limited maximum metrology range, beyond which the associated counter or register will overflow. This distance limit is typically of order 40m, and so it is important to establish that this overflow condition does not lead to a failure mode that stops metrology sensing. Suitable laser systems should signal the overflow, but otherwise allow metrology sensing to continue uninterrupted, allowing a software fix to "unwind" any wrap-around of counters.

2.2.2 Coherence length

A second limit to the maximum metrology range will be set by the coherence length of the laser head. For beam propagation paths longer than the coherence length, there will be an effective loss in signal, and it may be that the metrology system will fail. For example, for a Gaussian laser line profile, with a coherence length (FWHM) of 200m, the fringe visibility will be reduced to 50% for an OPD of 100m (i.e. a cat's eye distance of 50m from the metrology optics), and hence will mimic a loss in signal of 50%.

Given that the maximum OPD associated with the MROI delay lines will be ~ 2×190m = 380m, laser heads with coherence lengths in excess of 300m are to be preferred, unless significant fringe visibility losses can be accommodated.

2.3 Velocity limits

Because the MROI carriages will need to slew at speeds as fast as 0.7m/s the metrology laser head and counting boards must be able to handle velocities as fast as this.

2.4 Delivered optical power

Because the MROI will, in principle, be able to accommodate up to 10 delay lines, it will be advantageous if a single laser head can supply enough power to manage the monitoring of 10 linear axes simultaneously. The optical layout and components for the proposed MROI metrology system have, however, been designed to allow for two laser heads to be used, one located at each end of the metrology optical table.

The expected power losses for the metrology optical components in the proposed design are as follows:

Component	Number	Description	Unit throughput	Total throughput
Feed to beam expander	2	2 surfaces	$(0.97)^2$	0.885
Beam expander	2	4 surfaces, 2 glass paths	$(0.97)^4\times(0.99)^2$	0.753
System windows	2	2 surfaces, 1 glass path	$(0.97)^2\times(0.99)1$	0.868
Wedges	2	2 surfaces, 1 glass path	$(0.97)^2\times(0.99)^1$	0.868
Cat's-eye	1	3 surfaces	$(0.97)^3$	0.913
Diffraction	2	Long propagation path	$(0.99)^1$	0.980
Pickoff to shear sensor	1	1 surface	$(0.97)^1$	0.970
Total				0.436

Table 1: Losses in the metrology system optics.

Note we have assumed a 2% loss at any air/glass interface, a 98% efficiency for any reflective optics and a conservative additional 1% scattering loss at all surfaces.

The table above only includes the optics associated with launching and receiving the metrology beams to/from each delay line. The "beam splitter and fold mirror stage", which splits the laser output into multiple copies using a sequence of beam-splitters introduces a further loss of approximately 50% overall, so that for a 10 axis implementation each axis will only receive 1/20th (and not 1/10th) of the laser power. In addition a factor of typically 70%

must also be included to accommodate the internal efficiency of the metrology interferometer head.

The upshot of this calculation is that for a 10-axis implementation, the laser head power and receiver sensitivity should allow for:

- The intensity of the reference beam in any one of the axes being measured being only 4.6% of the laser head power and not 10%, as would be the case for lossless splitting .
- The intensity of the beam returned from the cat's-eye being close to a factor of two weaker (i.e. the reciprocal of 43.6%) in intensity than the reference beam.
- The metrology interferometer blocks having an internal efficiency of no more than 70%.
- Any visibility losses associated with imperfect optical surfaces and the laser coherence length.

2.5 Frequency stability

As described in RD1, the short term frequency stability required for the MROI metrology laser head for a 400m total optical path is summarised in the table below. For shorter optical paths, the frequency stability required will be reduced linearly, i.e. for 100m long delay lines short term stability a factor of two poorer will be adequate.

The reader should note that the most stable laser operation is only needed for optical observations, i.e. at the shortest wavelengths where the atmospheric coherence time will necessitate a 10 ms basic integration time.

Time interval	Corresponding wavelength	Fractional frequency stability
10 ms	600 nm (R-band science)	3.75×10^{-11}
35 ms	1650 nm (H-band science & fringe tracking)	1.10×10^{-10}
50ms	2200 nm (K-band science)	1.37×10^{-10}

Table 2: Frequency stability requirements for the metrology system laser head.

2.6 Pointing stability

As described elsewhere (see, e.g. INT-406-VEN-0107, Derived Requirements) there is a 0.32" error budget allocation for the single-axis pointing stability of the laser head so as to minimize shear errors in the return science beams. This must be maintained over the expected ±0.1°C diurnal temperature range expected in the inner BCA. This allocation is in addition to contributions associated with the angular stability of the feed and launch optics for the metrology beams.

2.7 Heat dissipation

The maximum thermal dissipation allowed in the inner BCA from the delay line metrology system is limited to 20W, with a goal of 10 W. The major contributor from the delay line metrology system will be the laser head, and to a much smaller degree the shear cameras (one per delay line). The typical dissipation of all the laser heads under consideration is a few tens of Watts. In all cases, then, we expect to enclose the laser head in a thermally insulated shell, with a chimney to allow free exhaust of hot air through ducts in the inner BCA ceiling.

2.8 Other special needs

Other needs that may need addressing include the following:

- Special interface requirements.
- Use of non-standard and/or high risk components.

3 Laser choices

The current lasers under evaluation are as follows:

3.1 Zygo ZMI 7702

This is the laser head that has been used for all of the tests and prototyping work undertaken to date in Cambridge. Its relevant features are summarised below:

Desired feature	Assessment	Additional notes
Beam size	OK – 6mm diameter	Consistent with design for current beam expanding telescopes and mounts.
Range – counting limit	OK	Current software includes work-around to accommodate counter overflow.
Range – coherence length	~300m (FWHM) according to manufacturers spec	Adequate for 100m stroke (V=29%). This is unlikely to be satisfactory for a 150m stroke (V=6%) given the power output of laser head and the need to monitor multiple axes. Inadequate for full 190m stroke.
Velocity limit	4.2 m/s	Satisfactory
Laser power	525 μW (min)	Adequate for 6 axes up to 100m stroke: delivered power ~20μW (5μW is required for V=100% when using the most sensitive receiver) Inadequate for 10 axes unless only a short stroke (~75m where V=50%) is required: delivered power ~12μW (5μW is required for V=100% when using the most sensitive receiver)
Frequency stability	Typically in range 3 to 4×10^{-11} over 10ms to 50ms. Based on actual data measured at NPL on relevant timescales	Marginal on 10ms timescales since results were variable between 3.6 and 9.2 $\times10^{-11}$ (requirement is 3.75×10^{-11}). We have been advised that "best case" is likely to be most representative. Easily adequate on 35 and 50ms timescales.
Pointing stability	<0.1"/°C	Meets requirement easily (3.2"/°C)
Heat dissipation	39 W	Requirement can be accommodated by using a thermally shielded enclosure with venting through the BCA ceiling.
Other needs	None	

3.2 Zygo ZMI 7712

This is an alternative water-cooled laser head produced by Zygo. Its relevant features are summarised below:

Desired feature	Assessment	Additional notes
Beam size	OK – 6mm diameter	Consistent with design for current beam expanding telescopes and mounts.
Range – counting limit	OK	Current software includes work-around to accommodate counter overflow.
Range – coherence length	~200m (FWHM) according to manufacturers spec	Adequate for 100m stroke (V=6%), but only if laser power per axis is kept high. Inadequate for 150m stroke (V=0.2%).
Velocity limit	4.2 m/s	Satisfactory
Laser power	1350 μW (min)	Adequate for 10 axes as long as stroke is <75m (V~20%): delivered power ~30μW (5μW is required for V=100% when using the most sensitive receiver)
Frequency stability	Typically in range 3 to 5×10^{-11} over 10ms to 50ms. Based on actual data measured at NPL on relevant timescales	Satisfactory on 10ms timescales (3.0×10^{-11} vs 3.75×10^{-11} requirement) Easily adequate on 35 and 50ms timescales.
Pointing stability	<0.1"/°C	Meets requirement easily (3.2"/°C)
Heat dissipation	<2 W	Meets requirement since this head has internal water cooling.
Other needs	Water cooling	Needed to maintain optical and thermal performance: a flow rate of 0.5 litres/minute is needed, in the range 20-25°C, and stabilised to ±0.1°C

3.3 Agilent 5517D

This is a similar laser head that has been used at COAST for many years. This particular model is suited to applications with slew rates as fast as 1m/s. Its relevant features are summarised below:

Desired feature	Assessment	Additional notes
Beam size	OK – 6mm diameter	Consistent with design for current beam expanding telescopes and mounts.
Range – counting limit	OK	Manufacturer has confirmed that a software work-around will accommodate counter overflow.
Range – coherence length	>1000m based on manufacturer’s information	Will be adequate for full 190m stroke (V>90%).
Velocity limit	1.0 m/s	Satisfactory
Laser power	180 μW (min)	Adequate for 10 axes: delivered power ~3μW (0.8μW is required per axis for V=100% in the worst case)
Frequency stability	Currently unknown on short timescales.	The short term frequency stability of this head is currently being measured for us by Agilent in Santa Clara.
Pointing stability	Currently unknown.	We are awaiting information from Agilent on this feature.
Heat dissipation	23 W	Requirement can be accommodated by using a thermally shielded enclosure with venting through the BCA ceiling.
Other needs	None	

3.4 Status of evaluation and recommendations

As will be clear from the previous sections, we are awaiting some final information from Agilent regarding the pointing and short-timescale frequency stability of their 5517D laser head. Should these be satisfactory, we would proceed with that head.

In the event of unsatisfactory performance, we recommend proceeding with the choice of the Zygo ZMI7702 laser head (rather than the water cooled 7712 model) with the following caveats:

- This should be adequate for a 6 delay line implementation, and with an additional laser head can manage a 10 delay line configuration. The only change in opto-mechanical design required from the baseline design presented in the FDR documents will be a change in the height of the laser head mount.
- The *guaranteed* coherence length of this head is only satisfactory for a 100m delay line stroke. However, we would intend to measure the metrology jitter induced by this head’s coherence length in-situ at the MROI, hence empirically determining the maximum delay line stroke that can be monitored. It may well be that the actual

coherence length of the 7702 laser head is longer than the manufacturer is willing to guarantee.

- We would use the time between now and the commissioning of the longest stroke modes of the delay lines – expected to be several years – to investigate alternative laser heads to retro-fit in due course.

We do not favour the ZMI7712 head at this moment in time because its shorter guaranteed coherence length, as compared to the ZMI7702, will have a much greater impact on the scientific productivity of the MROI (because of the concomitant restricted stroke of the delay lines) than the small additional frequency jitter of the ZMI7702. The reader should note that the information on the shorter coherence length of the ZMI7712 was only established well after the frequency stability of the heads was determined and the detailed design of the metrology opto-mechanics had been completed.

The typical lifetime for these Zygo and Agilent laser heads is in excess of 50,000 hours, i.e., greater than 5 years assuming continuous operation and hence consistent with a timescale for any potential upgrade path over, say, the next 5 years.