Options for LN after Lean-MCAO: Wide Field MCAO, Fizeau Interferometry, or Both

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1 Introduction

At their March 2015 meeting in Minneapolis the LBT Board charged "the LN project leadership, the LBTO director and the LBT STC, to work out and evaluate the costs, time, risks and scientific benefits of:

(a) an extended MCAO field-of-view, or

(b) (small-field) interferometric imaging"

and that this evaluation should "form the basis for future Board decisions whether to pursue option a), option b), both, or neither."

A proposal for implementing option (a) has been provided separately (Herbst, 2015d). Here we place that report in the context of a broader analysis that would keep the door open to interferometry, should funding and the necessary resources be found for that longer term goal. Clearly a wide field MCAO capability, where wide could be as great as $82'' \times 164''$, has the potential to be a workhorse for cutting edge science at LBT. At the same time, LN is being delivered with the hardware needed to test, in an on-axis configuration, 23-meter resolution Fizeau interferometry.

If near the end of 2018, we find ourselves with an MCAO workhorse and, at the same time, have developed and tested software for Fizeau interferometry, then another upgrade could well be considered. In particular, stakeholders might well be ready to consider an upgrade to hardware for Fizeau interferometry that covers most of the sky and provides correction over a $30''$ field; and yet in no way compromises already proven MCAO wide-field performance. But the prerequisites, an MCAO scientific workhorse and a tested Fizeau software system, must come first.

Here we determine whether it is possible to keep the door open to this improved interferometric mode, without sacrificing the fast and affordable track to wide field MCAO science given in (Herbst, 2015d), by making a few key strategic decisions in the near term.

In table 1 we provide the capabilities and costs for two scenarios to achieve option (a), neither of which closes the door to the third scenario: Fizeau interferometry with high sky coverage and a moderate field of view; together with MCAO (i.e., "both (a) and (b)"). In figure 1 we provide a schedule for realizing these scenarios. Both the table and the schedule, along with the text that follows, are taken from recent discussions at MPIA between LBT representative and members of the LN team leadership.

Table 1: A summary of the 3 possible futures considered in this document, with the capabilities and costs for each. The cost values for options (a) and (a') are taken directly from section 7 of (Herbst, 2015d). The €150K cost for a second cryostat is included in each (since modifying the existing cryostat would effectively close the door to future interferometry). Similarly, the option to use two H2 detectors is not considered here. We consider only the option to retain the delivered LN H2 in the existing cryostat, and either re-use the LUCI-1 H2, or acquire one or two new H4, for the second cryostat. The costs and capabilities for Fizeau Interferometry shown here are based on a novel new approach for fringe tracking, *on-chip* fringe tracking, which is described in greater detail in the text. (*) - The two-H4 configuration for option (a') provides both the *overlap* and *adjacent* modes shown in figure 15 on page 24 of (Herbst, 2015d)). The latter could provide an 82" × 164" MCAO mode, but this possibility is still under discussion.

(a) Wide field MCAO Detector: H2	Capability:	**FoV:**	41" × 41"
		Sky Coverage:	99% / 48%
		Resolution:	~0.053" @K (see fig. 2)
	Cost:	**FTE:**	4.6
		Hardware:	640K €
(a') Wide field MCAO Detector(s): 1 or 2 H4	Capability:	**FoV:**	82" × 82" or 82" × 120"(*)
		Sky Coverage:	99% / 48%
		Resolution:	~0.053" @K (see fig. 2)
	Cost:	**FTE:**	4.6
		Hardware:	€1.54M or €2.44M
(b) Interferometry Detector: H4	Capability:	**FoV:**	~30" radius
		Sky Coverage:	99% / 48%
		Resolution:	~0.02" @K (along baseline)
	Cost:	**FTE:**	9.0
		Hardware:	€1.5M

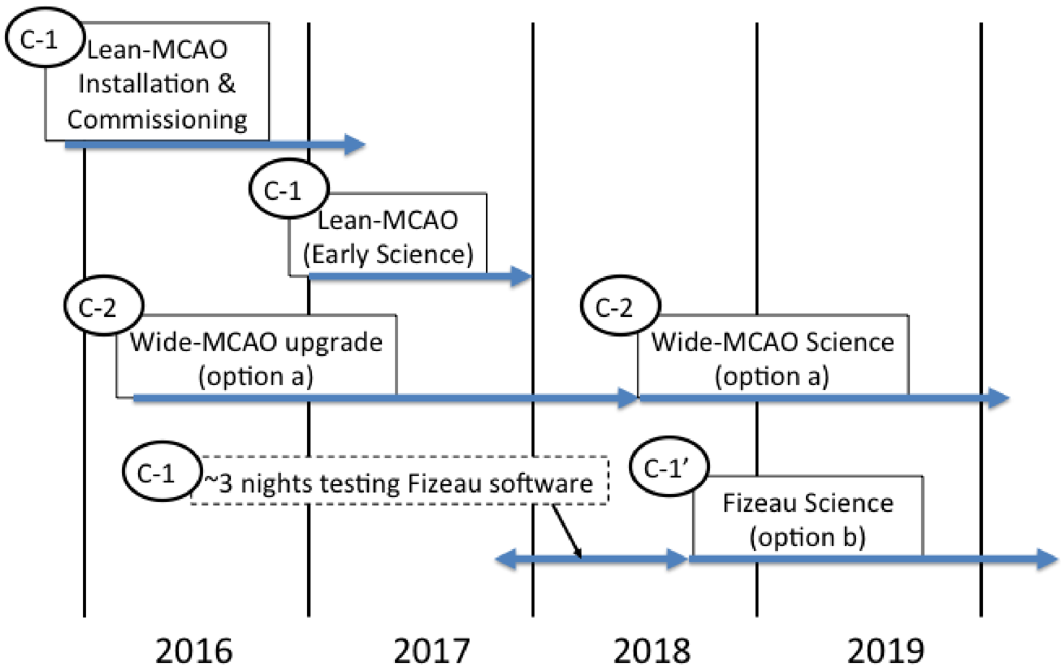

Figure 1: Schedule showing begin and end dates for four future phases, two scheduled and two under consideration: Installation and Commissioning (scheduled), Lean-MCAO Science (scheduled), Wide Field MCAO Science (under consideration), and Fizeau Science (under consideration). These date ranges are taken from (Herbst, 2015d) for Installation, Commissioning, and Lean-MCAO Science, from personal communication for the WF-MCAO upgrade, and from the analysis given in section 3.3 for Fizeau Science. The cryostat strategy is indicated by labels that appear in the black circles which accompany each phase. The three configurations are: the as-delivered cryostat (C-1); a new cryostat optimized for MCAO using either a single H2, one H4, or two H4 (C-2); and the C-1 cryostat modified to accommodate on-chip fringe tracking with an H4 (C-1').

2 Basis for the Hardware Costs Given in Table 1

2.1 (a) Wide Field MCAO (H2)

The hardware cost estimate is taken directly from section 7 of (Herbst, 2015d), with the €150K for a second cryostat included.

2.2 (a') Wide Field MCAO (one or two H4)

The hardware cost estimate is taken directly from section 7 of (Herbst, 2015d), with the €150K for a second cryostat included. The two hardware costs given in the table are derived by combining the total cost for option (a) with the cost of either one or two H4, respectively.

2.3 (b) Fizeau Interferometry

LN will be delivered to LBT with the fringe tracker system (FTS) provided to MPIA by MPIfRA and U. of Cologne in April, 2015 and installed into the LN cryostat after PAE. We estimate €50K will be required for additional test equipment and spares. The total hardware cost to (following on-sky software tests) replace this system with an on-chip, H4 fringe tracker, depends on which of three hardware configurations is used:

1. **Two H4 detectors, one per mode** - In this mode, two cryostats would be used in regular operation; each with its own detector or detectors. The new, wide-field, MCAO cryostat would host either one H2, one H4, or two H4; while the IF cryostat would use its own H4 for on-chip fringe tracking. Both the IF and MCAO cryostats could then be designed around optics specifically developed for the respective modes; no compromises.

2. **Motorized fold mirror** - In this mode, the second cryostat developed for wide-field MCAO would be designed to accommodate a later upgrade for hosting an additional, independent optical system for Fizeau interferometry in the same dewar. LN could be used for either MCAO or Fizeau on the same night by selecting the optical path with a motorized fold mirror, and these two systems would share an H4 detector.

3. **Compromise the MCAO plate scale** - In this mode, a new optical system would be developed that produced a single plate scale usable for both MCAO and IF. For example, 8 mas pixels would be

usable for IF and would yield an over-sampled MCAO field of 32" with the H4RG.

For this analysis, we rule out option 3 since it compromises performance of both modes. The first two options are optimal for both modes, but both require a plate scale changer. Of these two, option 1, although the most expensive hardware-wise, poses the least risk, minimizes the required FTE, and maximizes the scientific return. We consider only option 1 for the cost estimates given here. The cost figure given in table 1, which includes costs for an H4 detector, filters, optics, and cryostat modifications, is preliminary and based only on discussions that took place during a recent LBT visit to MPIA.

3 Basis for the FTE Costs Given in Table 1

3.1 (a) Wide Field MCAO (H2)

The FTE cost estimate is taken directly from (Herbst, 2015d), section 7.

3.2 (a') Wide Field MCAO (one or two H4)

The FTE cost estimate is taken directly from (Herbst, 2015d), section 7 (i.e., no appreciable FTE difference for one or two H4, from that required for a single H2).

3.3 (b) Fizeau Interferometry

The effort required for Fizeau Interferometry with the performance values given in table 1 (high sky coverage and radius = 30" FoV) requires both a software effort and a hardware effort. The software effort can be broken into four components (see also table 2):

1. The telescope control system (TCS) upgrade required for this mode is commonly referred to as "*TCS Gen Two.*" The approach for this effort, specific to the needs of LN, is outlined in (Bertram, et al., 2012).

2. The heart of the FTS (i.e., the software to acquire and fit fringes, and then control the piston mirror in accordance with those fits) is

Table 2: Software effort required to realize LN Fizeau Interferometry

#	Component	FTE
1.	TCS Gen Two	2.0
2.	Heart of FTS	1.0
3.	TwiceAsNice	1.0
4.	Operable	1.0
	Total:	5.0

already existing to first order. However, considerable testing and revision of this code is likely required.[1]

3. As described in (2) above, the FTS software exists to first order. However, to be integrated into the overall LN software framework, a considerable re-factoring effort is required. Although the underlying language (C) is OK as is, significant modification is required to bring the code into compliance with the LN framework, typically referred to as either "*the common software*" or "*TwiceAsNice*."

4. Lastly, some effort will be required to bring FTS to an operable level for early science.

For the design and fabrication of the hardware required for on-chip fringe tracking with an H4, we estimate 4.0 FTE. In terms of figure 1, these are the hardware changes required to go from the C-1 cryostat to the C-1' cryostat. Combined with the 5.0 FTE required for software, we arrive at the 9.0 value that appears in table 1. For the schedule shown in figure 1, we assume that the 5.0 FTE software effort is accomplished by a team of two or three between now and the demonstration in early 2017. The 4.0 FTE hardware effort is accomplished by one or two persons and takes place both before and after this test, with cryostat modifications necessarily taking place after.

[1] Some of this software is coming from an effort to improve the Observatory Vibration Monitoring System (Pott, et al., 2015). Although this upgrade, called *OVMS+*, will be first utilized by LBTI, some portions will eventually be reused for the LN FTS system.

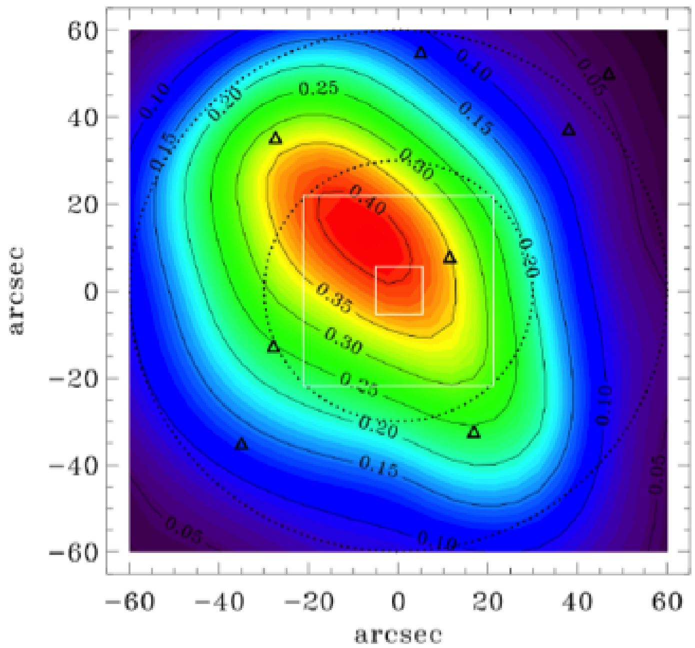

Figure 2: The Strehl map figure taken directly from (Herbst and Arcidiacono, 2015), page 2.

4 Basis for FoV and Sky Coverage Values Given in Table 1

4.1 (a or a') Wide Field MCAO (H2 or 2 H4)

The FoV values in the table are taken directly from (Herbst, 2015b), page 4. The two sky coverage values, 99% and 48%, refer to the galactic plane vs the North Galactic Pole, respectively.

4.2 (b) Fizeau Interferometry

The FoV value of radius = 30" is from (Bertram, 2007). The sky coverage value assumes the ability to fringe track on a star as faint as 14th Vmag.

5 Basis for the Resolution Value Given in Table 1

5.1 (a or a') Wide Field MCAO (H2 or 2 H4)

The resolution value in the table is taken directly from (Herbst, 2015b), page 4. Greater detail is provided in that table (e.g., image size for other wavelength bands). For Strehl, the reader is referred to the Strehl map given in fig. 2 (for MCAO a single number Strehl value is mis-leading, since the benefit from this mode is homogenous Strehl over a wide area).

5.2 (b) Fizeau Interferometry

The resolution value is taken directly from (Herbst, 2015b), page 4.

6 Conclusion

We have presented cost and benefit for three scenarios, two for wide-field MCAO, neither of which closes the door to the third scenario: Fizeau interferometry with high sky coverage and a moderate field of view; realized without sacrificing or compromising the wide-field MCAO capability. The two wide-field MCAO scenarios are taken from options given in section 7 of (Herbst, 2015d); they both include the second cryostat and exclude re-use of the LN H2 detector. These two restrictions on the choices given in (Herbst, 2015d) keep the door open for interferometry which, as shown above, could yield an instrument with significant scientific capability in the pre-ELT era, should sufficient resources be identified after the successful testing of Fizeau with existing hardware ***and*** demonstration of a workhorse wide-field MCAO system.

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