Optical Delay for OHANA

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ABSTRACT

The OHANA interferometric array will be implemented by linking existing Mauna Kea telescopes with optical fiber. No new facility construction on Mauna Kea is required or planned for OHANA. Fibers will be run through existing cableways. The maximum potential baselines are approximately 800 meters in length. Interferometric operation with good UV coverage will require within the instrument variable optical delay approaching 400 meters. It will be necessary to provide this length of delay within a modest amount of existing laboratory space. An obvious approach is the use of multiple passes within a short delay line space. This poster investigates possible multi-pass implementations and related issues of efficiency, cost, wavefront quality and diffraction. The required optical delay can be provided at reasonable efficiency and moderate cost. The simpler optical delay for OHANA Phase II, already under construction, is described.

Keywords: Interferometry

1. INTRODUCTION AND OVERVIEW

The OHANA Array, discussed elsewhere in this conference, will employ optical fibers to connect an *ad hoc* array of existing telescopes on Mauna Kea. OHANA will access the scientific opportunity offered by large AO equipped telescopes combined interferometrically with large baselines, giving a combination of high angular resolution and sensitivity. The connection of existing telescopes offers this unique science capability with an enormous savings in infrastructure and facilities investment over a comparable dedicated array. On the other hand, retrofitting telescopes and observatories for interferometric operation involves some complications. Much of OHANA Phase I has dealt with defining and resolving these issues.

In Phase II, OHANA will move to on-sky technical and science demonstrations, and at least a partial implementation of the full OHANA capability will be required. This includes, of course, an optical delay. Here, we will discuss approaches to a full OHANA Phase III optical delay capability, and then we will describe the optical delay provisions currently under development for OHANA Phase II.

2. OPTICAL DELAY REQUIREMENT

The dominant design driver for OHANA optical delay is fitting the delay into a modest existing laboratory space.

Stretched optical fibers may offer the ultimate in compact delay lines (Ref. 1). At present, however, stretched fiber delay lines produce an imbalance in dispersion over the extended bandpasses required for astronomical applications. Thus with current technology we are probably restricted to conventional optics. While it is generally best to keep the number of optical elements in an interferometer light path at a minimum, other factors can dominate a design. If it is required to provide large optical delay within a small space, some compromise may be necessary. This report examines the possibility of providing a compact delay line based on multiple reflections.

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The concept is, simply, to arrange multiple reflections of a beam over closely adjacent paths. The concept-specific issues which arise are: layout, light loss, wavefront quality, polarization, phase delay, alignment and metrology.

Consider two telescopes separated by N meters. Interferometric operation over the full sky will require N meters of variable optical delay. For optimum matching of dispersion, this delay should be in vacuum. In addition, the optical path in beam transport to the beam combination laboratory must be matched between telescopes - with matching vacuum, air or fiber paths. In OHANA this will be in fiber paths.

A common way of providing variable optical delay with large dynamic range is to cascade a unit which offers large delay with low control bandwidth, and a shorter delay unit which provides high bandwidth control. While part of the delay can be in switchable segments, it is desirable to carry out continuous observations for at least 30 minutes without reconfiguring the delay. For an east-west baseline of N meters, the total required delay horizon-to-horizon will be N, which must be available to apply to either beam, switching at transit. The delay differential optical path will vary by 0.26N meters/hour maximum (at zenith). We suggest that at least 0.15N of the optical delay should be in continuous delay, in order to offer reasonable operation time without reconfiguring the segmented delay.

With continuous delay available over 0.15N, an additional segmented delay is needed of at least 0.85N, with available increments of no greater than 0.15N. For reasonable flexibility in executing observations, an increment size 2X smaller will be preferred. For OHANA, these numbers correspond to 120 m of continuous delay, and 680 m of segmented delay.

3. OPTICAL DELAY OVERVIEW

This conceptual proposal for OHANA Phase III will provide both continuous and segmented delay lines, in series, in an optical arrangement that will be benign with respect to polarization effects, and reasonably efficient. It will be assumed that polarization will be maintained throughout the beam transport and combination process, and that different polarizations will be detected separately. (This allows us to admit concepts which introduce polarization dependent phase shifts.)

Figure 1 shows a generic layout for a complete OHANA III delay implementation.

4. A SCHEMATIC CONCEPT FOR SELECTABLE SEGMENT DELAY

When a large optical path is desired in the laboratory for absorption spectroscopy, there is a standard solution - the White cell (Ref. 2). A White cell provides multiple passes in an optical cavity between mirrors. By tilting the optics, the number of passes can be varied. It is common to provide path lengths of 100 meters or more within a physical envelope of 1 meter. A number of variants on the optical design are possible (eg, Ref. 3). A disadvantage of the classical White cell and its derivatives is that they employ powered optics in order to control beam expansion. With powered optics, the injection and extraction of the beam occurs near a focus, where the beam is small, and this is a substantial design convenience. However, in a many-pass optical system, cumulative aberrations are a potential severe problem for an interferometric application. In view of the well developed technology for fabrication of flat mirrors, it is interesting to consider flat optics. It is possible to do so because of the low divergence of a spatially-filtered and collimated beam.

Here we will consider an array of independently controlled flat mirrors to replace the fewer powered mirrors of the White cell. As long as we accept that the number of double passes will be only equal to the number of mirror pairs, it is easy to find interesting configurations.

Figure 2 shows a conceptual layout. The delay occurs within a cylindrical volume, which could well be within a vacuum vessel. Arrays of mirrors are placed, in complimentary locations, at opposite ends of the volume. Each mirror is sized appropriately (i.e. about 1.2$\times$ the nominal beam diameter).

There are a number of considerations in laying out the mirror placement. In order to avoid mixing of polarizations, all reflections should be in the horizontal or vertical planes - never at compound angles. Also, angles of incidence should be kept small to minimize differential phase shifts between polarizations and wavelength

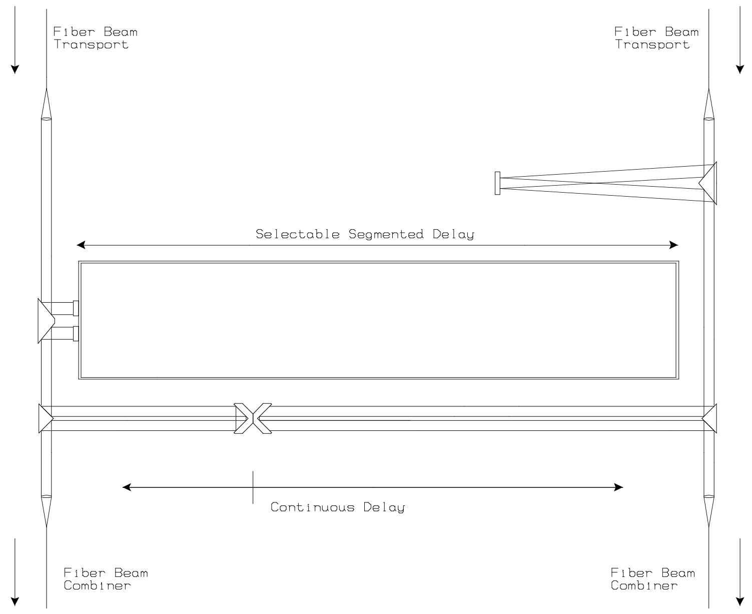

Figure 1. A generic layout for a complete optical delay implementation for OHANA Phase III. Two beams are shown entering at the top, transported via optical fibers. The beams are expanded and the optical delay is added with conventional macroscopic optics. The sketch shows a long delay, which is assumed to be implemented with a selectable segment delay line, and a shorter, continuous delay. Several beam folds are shown to preserve polarization matching between beams. The beams are reinjected into fibers for beam combination in a fiber coupler or integrated optical element.

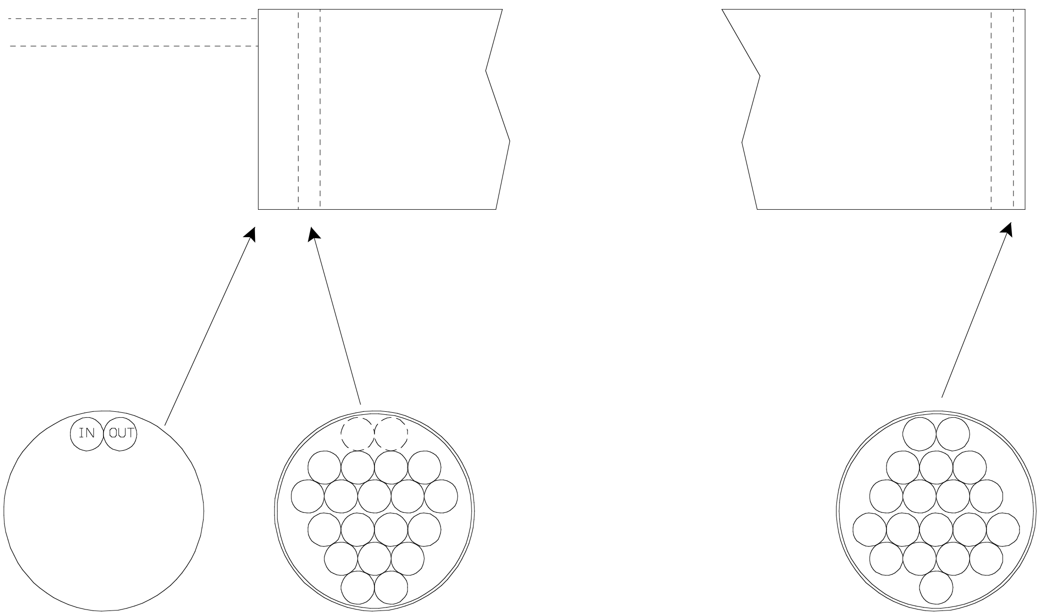

Figure 2. Above, an overview of the Selectable Segment Delay concept. Beam enters and exits at the left. Below, on the left, the entrance and exit windows. The delay is composed of multiple passes in the cylindrical volume. Complimentary mirrors arrays are shown which enable up to 19 double-passes, with benign polarization and good efficiency.

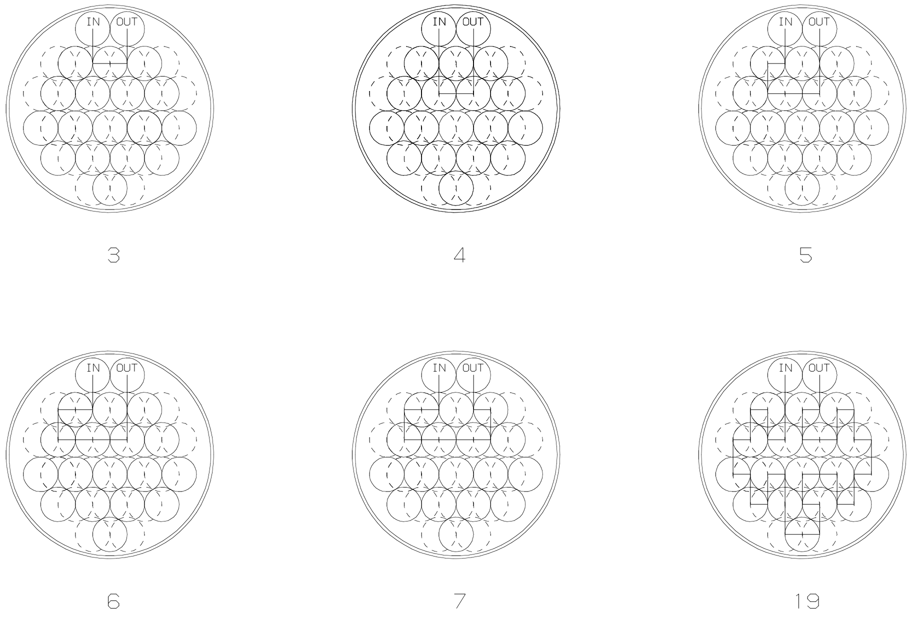

Figure 3. Examples of beam paths through the mirror array to compose various total delays. Examples of 3-7 passes are shown, and the maximum number, 19.

dependent phase shifts. (Both of these conditions may be violated provided polarization mixing tolerances are not exceded, but here we will assume that the goal is minimal mixing.)

Figure 3 shows for the example of Figure 2 the corresponding beam walk, in projection, to obtain the maximum 19 double passes with this optical arrangement. In this example, the 19 passes fit into a diameter $7\times$ larger than the single beam diameter. For a spatially filtered beam, vignetting and diffractive losses (for wavelengths less than 2.5 μm) can be held under 15% by expanding the beam to 8cm and using 10cm optics. Then the OHANA Selectable Segment Delay can be contained in a cylindrical diameter of about 70 cm. This can be provided in a vacuum chamber constructed from standard industrial grade (carbon) steel tubing at modest cost.

With 19 double passes, the desired total Selectable Segment Delay of 680 m can be achieved in a physical space of about 18 m.

5. CONTINUOUSLY ADJUSTABLE DELAY

Following the prescription recommended above, it would be desireable to have at least 120 m of continuous delay. In Fig. 1, the continuous delay is shown as, effectively, quadrupley passed, as in the concept implemented at the SUSI interferometer (Ref. 4). This could be easily doubled again, with a stationary retroreflector and doubled retroreflectors on the moving stage. Then, 120 m of continuous delay will fit within a space of order 15 m. There are available laboratory spaces among the consortium member facilities on Mauna Kea of suitable size to fulfill both segmented and continuous delay requirements for Phase III.

6. EFFICIENCY

Efficiency will obviously depend on reflectivity of the mirrors. Two cases should be considered: bare silver coatings, and enhanced silver coatings. Bare silver will have higher broadband reflectivity and lower polarization, but may deteriorate with exposure to the atmosphere.

Bare silver coatings can offer reflectivity in excess of 0.98 in the near- and mid-infrared. At a reflectivity of 0.98 per surface, an efficiency of nearly 0.5 will still be achieved with 38 reflections. Bare silver coatings can be considered, particularly since vacuum operation can ensure protection against corrosion. In-place evaporative coating of the optics could be a reasonable option.

For operation in the visible, bare silver is less satisfactory. A reflectivity of 0.96 per surface (near 500 nm) will give an efficiency of 0.21 for 38 reflections. For that reason, an enhanced silver coating might be considered for the visible (or in the infrared, for durability). A reflectivity of about 0.98 per surface is claimed in the visible by several manufacturers (though it appears that the best formulations for the visible compromise the infrared performance). But a drawback of enhanced silver is the possibility of accumulating wavelength dependent phase shifts (Ref. 5) discussed below.

7. WAVEFRONT QUALITY

Accumulating wavefront errors must be considered with a large number of reflections. However, currently operating optical interferometers have large numbers of optical surfaces, 20 being typical. Increasing the total by a factor of $2\times$ is not dramatic, especially since the added surfaces are small flats, production of which is one of the best developed areas of precision optical fabrication.

To assign some numbers to the discussion, surface quality of 1/20 visible wave PTV error on a reflected wavefront is readily obtained. By a common rule of thumb, the corresponding RMS wavefront error is 0.014 waves, or 0.09 radians. Cascading elements and assuming random errors, the RMS error following 38 reflections would be 0.57 radians. By the Maréchal criterion, this corresponds to a Strehl of 0.72. The implied loss of efficiency of order 25% is not negligible. However, this may probably be considered an upper limit or worst case. In high quality flats, the largest component of error is a small fraction of a wave of spherical power. In a delay line, employing the optics in near-normal incidence, this component can be approximately compensated by a small refocus prior to beam combination. For operation at longer wavelengths (OHANA will begin operation in the near IR) the wavefront quality will be significantly better.

8. POLARIZATION

Polarization must be controlled carefully in interferometry. Since orthogonal polarizations in general suffer different phase shifts on all but normal reflections, the situation can become quite complex. The best solution is to avoid mixing polarizations. A simple strategy is to ensure that all reflections are in the horizontal or vertical planes, and to avoid optically heterogeneous transmissive elements (except possibly for polarization preserving optical fibers, which employ heterogeneity to ensure the required isolation).

Once it is accepted that orthogonal polarizations should be treated independently, there is no need for great concern for differential phase shifts between polarizations. However, in near-normal reflections, these differential effects are small. For example, with bare silver, and an angle of incidence of 0.5 degrees, the differential phase shift is only 0.0028 waves at 500 nm (less in the red) which is virtually negligible.

For Newport Corporation's ER.2 enhanced silver coating, the corresponding shift is approximately 0.05 degrees. This is small, but possibly not negligible in careful phase measurements. The cumulative effect from 40 reflections is still far smaller than the corresponding value for a single 45 degree reflection (up to 1.5 degrees).

Consequently, large numbers of near-normal reflections do not appear to offer difficulties with polarization.

9. PHASE DELAY

Differential delay between polarizations can be troublesome, hence the preference to maintain the identity of the two polarizations and deal with them separately. Thus any wavelength-independent component of phase delay will be unimportant (not separable from optical path delay) on a per polarization basis. Of course, since a common delay line is probably used for both polarizations, a small OPD adjustment may be required in order to phase both polarizations simultaneously.

More troublesome may be wavelength-dependent phase delay, which will accrue for each polarization. This amounts to a longitudinal dispersion, as contrasted with the angular dispersion due to off-zenith passage through the atmosphere. If there is a substantial differential component between beams, combination will give a “chirped” interferogram, with the zero path difference occurring for slightly different delays at different wavelengths. (Other sources of longitudinal dispersion are differential air paths, differing thickness windows, or material variations between nominally identical materials.) Whatever the source, it must be controlled or reduced to the level that is appropriate to the beam combination and detection system (briefly, detection with increasing spectral resolution is more forgiving of this dispersion, owing to the increasing effective coherence length). The most convenient means of balancing dispersion is through the rigorous matching of optical paths and materials (Ref. 6).

For the example of the Newport ER.2 coating, the differential delay across the 500-1000 nm range is approximately 100 degrees per reflection (almost independent of angle of incidence). This is a very substantial value, and a different number of reflections in the beams will chirp the ZPD. Bare metal is much more favorable, and pure silver reflections are preferred reflectors (Ref. 5). In any configuration, residual phase shifts may be present. These can be reduced with compensation systems designed for phase correction.

10. ALIGNMENT

The scheme envisioned for alignment of the multi-pass segmented delay line is through the use of encoded motors on each mirror. For a required optical delay, a beam path would be chosen, and the required mirrors commanded to the required positions. Various schemes are available for control of cumulative error. For example, a coaxial laser beam (probably sharing solid angle but at a different wavelength) could be used to establish and verify the output angle. An alignment telescope, with variable focus to access each optical surface in succession, could be used to rapidly establish collimation.

11. IMPLEMENTATION PLAN

OHANA is currently in Phase I, demonstration of beam extraction from the AO-equipped telescopes. Preparation for Phase II, demonstration of interferometric operation, is currently underway. For Phase II, the optical delay requirement is significantly less than for Phase III. A slew and hold delay will provide coarse delay. In order to avoid a stringent requirement for alignment of the rail system to interferometric tolerances, the retroreflector element will include metrology and automated fine-adjustment, ensuring efficient beam injection into the fiber coupler.

For fine and continuous delay control, a commercial optical stage has been procured. It will be used in single pass. All of the delay will be in air, which is satisfactory in the H and K band region for OPD compensation of this magnitude.

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REFERENCES

1. P. Zhao, J. Mariotti, V. C. du Foresto, P. Léna, and G. Perrin, “Multistage fiber optic delay line for astronomical interferometry,” in *Fiber Optics in Astronomical Applications*, **2476**, pp. 108–119, SPIE Proceedings, 1995.
2. J. White *J.Opt.Soc.Am.* **38**, 1942.
3. J.-F. Doussin, R. Dominique, and C. Patrick *Apl.Opt.* **38**, 1999.
4. J. Davis, W. J. Tango, A. J. Booth, T. A. ten Brummelaar, R. A. Minard, and S. M. Owens *M.N.R.A.S.* **303**, 1999.
5. S. Ridgway and W. Bagnuolo, “Polarization revisited,” tech. rep., GSU, Atlanta, 1996.
6. W. Traub, “High-resolution imaging by interferometry,” in *ESO Conference and Workshop Proceedings*, F. Merkle, ed., **29**, 1988.

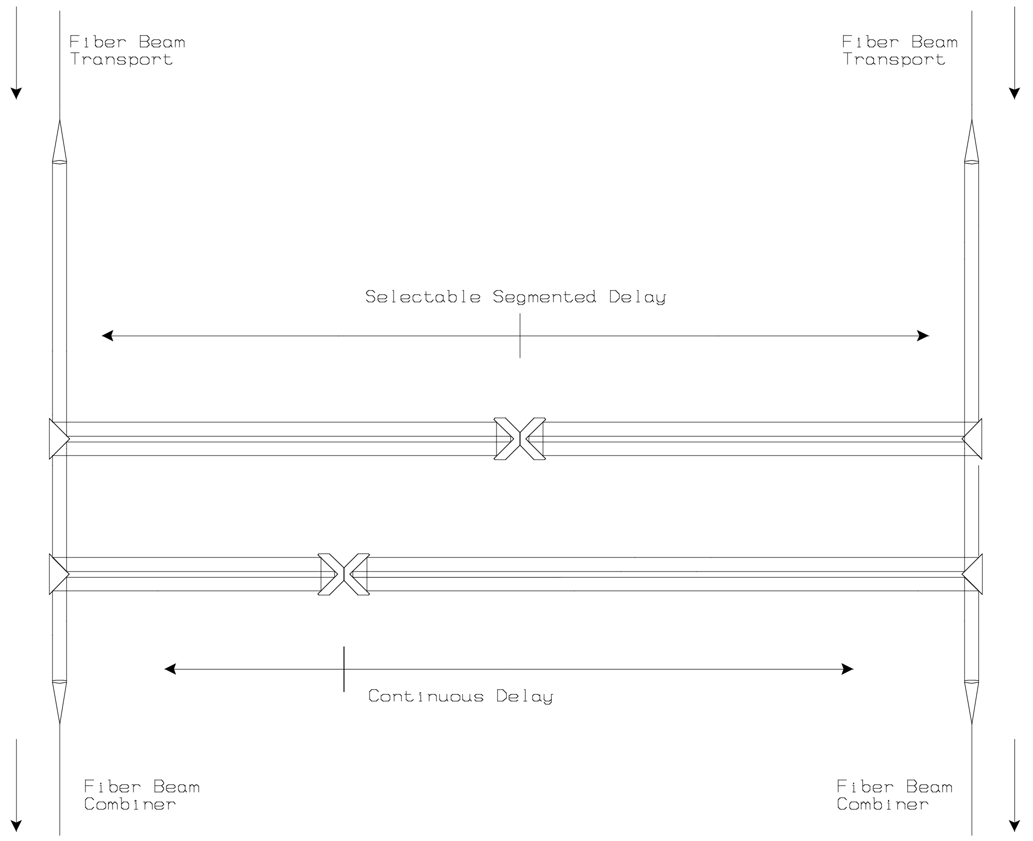

Figure 4. A simplified layout for the optical path delay planned for Phase II (in progress). The slew and hold delay will provide a long delay component, to which will be added a shorter continous delay. An interesting element of the slew and hold delay is the plan to use simple flat mirrors, with automated realignment after slewing. This promises optimum efficiency and low cost.