CHARA TECHNICAL REPORT

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Plan for Alignment of CHARA Optical Path Length Equalizer Supports and Shafts

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1. INTRODUCTION

The CHARA optical delay lines are called OPLE's, for Optical Path Length Equalizer. The optical delay is provided in two parts, with selectable, fixed segments of optical delay, in vacuum, and with continuously variable delay, provided by catseye retroreflectors which run in air along a rail system of circular steel shafts.

The catseyes have an advantage for optical alignment that, ideally, the aberrations in the retroreflected beams are fairly independent of mechanical translations of the catseye. This eases the requirements on the catseye drive and support system. However, the interferometric operation of the Array is not independent of alignment errors. At the grossest level, the beam overlap (visualized in the pupil plane) will be reduced if one catseye is translated, since this causes a (doubled amplitude) translation in the return beam. There are also additional, lower order effects, as the catseyes may not have ideal optical properties (particularly, imperfect focus).

The goal for OPLE alignment will be 0.1 mm over short distances, and 1 mm over the full length.

2. REFERENCE LINE

Any alignment scheme will depend on a reference line, which should be level or nearly so, and closely aligned to the line of the OPLE supports, which by construction is almost exactly east-west. The reference lines for the OPLE lines should be approximately parallel.

It should be possible to reinstall the reference line, preferably without reference to the components which are to be aligned, and preferably with some kind of consistency or stability check which is again independent of the components to be aligned. An example of an independent reference installation would be to position a pier on an inertial block east of the eastern-most OPLE support, with a precision machined vee block for mounting of a cylindrical barrel alignment telescope. An example of a consistency check would be an on-axis mark on a second pier mounted on the western inertial block beyond the end of the last OPLE unit.

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The reference line can be real or virtual. For example, the axis of an alignment telescope defines a virtual line. A projected laser beam provides a real line (at least in the sense intended here). Both an optical axis and a laser beam depend on the properties of the atmosphere. Both may be deviated due to thermal stratification in the air of the laboratory, which may very diurnally, seasonally, or according to disturbance by human presence.

2.1. Optical

The general idea of optical alignment is to define an axis with either an optical instrument (telescope) or an optical beam (laser) and mechanically adjust the shafts to be parallel to this axis.

2.2. Laser Beam

An ideal laser beam (single mode) will have a Gaussian profile. This is about the worst possible profile for alignment, since the Gaussian has very weak derivatives and no well marked features. In practice, the laser beam will show time varying distortion due to turbulence. This may be moderated by protecting the path, ultimately be even placing tubing sections to reduce airflow. The slow evolution of typical laboratory turbulence, and related scintillation, is very poorly suited to rapid determination of alignment. A somewhat improved scheme would employ a centroiding detector to integrate over the laser beam and determine a time average center of gravity for the flux distribution.

In the case of a laser beam, the beam will vary in size with distance, and laser speckle, mode structure (possibly variable), and coherence effects in the diffraction and scattering from irregularities in the beam may be troublesome. Extracting the centroid of the beam may be difficult. Local turbulence will be a problem.

2.3. Telescopes

We assume that a telescope will be used to sight on a target which is positioned with respect to the shafts, and moved to different distances, giving an x-y position error at each distance. An axis defined by a telescope will be limited by several effects. It will be necessary to refocus the telescope with distance, so the stability of the axis with distance will depend on the mechanical and optical properties of the telescope and may not be known. Reading coordinates from the telescope for a target at a distance will have an ultimate accuracy which varies inversely as the distance. The accuracy of the measurement will possibly depend on the skill of the observer.

An optical alignment instrument (transit, theodolite or bore-sight scope) can be expected to have an alignment error in the vicinity of 2 arcsec ($\pm$). Over the length of the CHARA OPLE's, 50 m, this corresponds to a transverse error of about 0.4 mm. If realized as a fluctuation of this order over short shaft lengths, this would probably be intolerable. It appears that the alignment telescope alone will not provide a sufficient reference line. At the least, some additional scheme would be needed to smooth out local bends in the alignment.

2.4. Transit

The classical surveyor's solution for the shaft alignment is the transit telescope, which is equipped to be positioned in 5 dimensions in order to select the desired axis. This very flexibility is also a weakness, since there is no simple procedure to return the transit telescope to the position used for alignment on a previous occasion, and the alignment of the telescope must be backed out of the current state of alignment of the shafts.

2.5. Alignment Telescope

The alignment telescope is a classical laboratory solution for optical alignment. The telescope is installed in a metal tube with an external cylindrical wall, whose axis is defined to be the reference axis. The optical alignment of the telescope at assembly is constrained to be consistent with the external wall. In use, a kinematic support should be provided for the telescope barrel. Often a vee block is used, although this is not a true kinematic mount. In the laboratory, the support can be installed as a permanent part of the instrument setup. The telescope can then be removed and returned to the reference position freely.

2.6. Stretched Wire

A stretched wire defines a real line, but not the precise one desired. A stretched wire may ideally define a straight line in the horizontal plane, but due to sag from self weight, the vertical position will follow a catenary due to gravity. A correction for this sag can be used to compute a (virtual) reference line which is ideally straight.

A stretched wire with computed correction for sag may provide a straight reference for alignment of the shafts. But since the optical beam through the delay line will suffer the same kind of refractive deviation as an optical reference beam, it appears that the true straight line alignment may not be optimum under all circumstances. This is a disadvantage of having the OPLE in air instead of in vacuum.

Fogale Nanotech[2] offers precision alignment equipment and services, including a stretched wire system which has been used for precision alignment over more than 50 meters. The stretched wire is a low CTE graphite-epoxy fiber. The stretching mechanism is carefully designed to produce a constant stretch force. The wire sags. The sag is calibrated with a secondary measurement system which uses water in connected reservoirs to determine a local level reference. Capacitative, non-contact sensors are used to determine the position of the fiber compared to the sensor reference surfaces. Although the water level may seem crude, it is in fact accurate to better than $1\,\mu$m over 50 m (although with a fairly low bandwidth). These devices easily measure earth tides in the terrestrial bedrock. The setup of the reference wire and the associated equipment is a relatively sophisticated process. However, once the equipment is installed, the readout of the shaft positions is a straightforward electronic measurement which doesn't entail special skills.

This method has been shown accurate to of order $1\,\mu$m over 50 m — an accuracy considerably better than required for CHARA. The method is also relatively expensive, though we do not have a fixed price at this time. The equipment can be rented - an advantage for initial cost, but a disadvantage for subsequent realignments.

3. THE MECHANICAL SYSTEM

The rails (circular OPLE cart shafts and rectangular OPLE drive rails) are supported on support brackets. There is no vertical adjustment in these brackets, and to function

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properly, they must all lie on a plane surface. They are then adjusted horizontally by sliding on that surface.

The hypothetical plane horizontal surface does not actually exist, but it is to be simulated by horizontal rectangular bars (here called sleepers, in analogy with the construction of railroad tracks). The sleepers are supported in turn on horizontal rectangular tubes, called simply crosspieces.

The crosspieces are installed at construction time. They are to be aligned by a combination of design, measurement, custom drilling and welding. The retaining bolts will then be grouted, precluding further adjustment, but adding rigidity. This initial alignment is required to be accurate to $\pm 1/4$ inch.

The sleepers are mounted on the crosspieces with two through bolts, by clamping each sleeper between nuts. Spherical washers on each side allow for tipping of the sleepers for leveling. Ideally, all of these sleepers will be adjusted so that their top (flat) surfaces lie in a common plane.

4. ALIGNMENT PROCEDURES

This discussion will be based on the assumption that a metrology scheme is available which allows determination of horizontal and vertical position errors for the OPLE shaft at any position along its length (sequentially, not concurrently).

5. SLEEPER ALIGNMENT STRATEGY

The following description applies to each OPLE platform (with capacity for two OPLE's).

An alignment line should be located in the (approximate) vertical plan of one of the mounting bolts of the sleepers (eg, the southern line of bolts). At each sleeper, a level is placed along the length of the sleeper.

- The vertical position of the southern bolt is adjusted to bring the sleeper into the correct height in the vertical plane of the alignment reference line.
- The northern sleeper bolt is then adjusted to bring the sleeper up to horizontal according to the level along the sleeper's length.
- The level (or perhaps more conveniently a second, shorter, level) is then turned east-west to monitor the sleeper level in that direction.
- The sleeper is then tilted to level it in the east-west direction.
- The top sleeper bolts are tightened lightly, while monitoring the levels and the sleeper height, pausing to iterate if necessary.
- The sleeper top nuts are tightened to the specified torque, partially compressing the spring washers. Initially, the required torque is estimated to be 25 inch-pounds, pending some practical experience.

The goal, of course, is to achieve a sufficiently tight condition on the sleeper bolts while maintaining the alignment. Only experience will show how difficult or easy this will be.

Variations in the level over short distances will be more important than slow drifts over tens of meters. Therefore, it may be useful to suspend a level between the sleeper under adjustment and the last adjacent adjusted sleeper to use the level between the two surfaces as a check and guard against steps in height. This may be more sensitive than the reference to the alignment reference line. Use of this cross-check must be established from experience.

6. OPLE GUIDE RAIL INSTALLATION STRATEGY

Following the guidelines in the previous section, it will now be assumed that the sleepers define a plane. The installation of the shafts will follow a simple procedure.

During the handling of the shaft, it is critical that the shafts are never bent beyond the elastic limit. Since we are concerned with precise alignment, we really don't know what this limit is. Therefore, each shaft section should be handled by at least two people and supported at approximately the optimum support points for minimum self-weight induced deflection: approximately 0.22 times the length from each end (3.5 foot or 1 m) (It is OK to pick one end up while the other is resting on a support.)

First, coat all sleeper surfaces where the shaft supports will rest with a lubricating agent (to be selected). The shaft will initially be assembled with an offset of about 2.5 inches, then shifted into place. This requires pulling on it firmly, but avoids bending maneuvers.

7. OPLE GUIDE RAIL PRELIMINARY ALIGNMENT STRATEGY

Experience has shown that the shafts are very smart and know what straight is. The best alignment allows them the maximum freedom to do their own thing.

The proposed scheme is to align only the shaft joints, and to initially let the intermediate portions of the shaft float. Optimally, the joints should be constrained in the correct north-south position without imposing torques on the shaft . This might be accomplished by placing narrow (even vee-shaped) blocks to constrain the north-south position. The spring force of the shafts will tend to restore them to their naturally straight condition. The shaft joint supports will ensure continuity of straightness between shaft sections. Floating of the shaft into position can be encouraged by lifting the center of each the shaft slightly (to remove friction) with minimum transverse constraint. A fabricated fixture may facilitate this. The straight thus defined can be secured with shaft support clamps as required.

Strangely, the naked eye is extremely sensitive to straightness of the shafts. This sensitivity can be enhanced by providing a small light source at one end of the shaft string (eg a few feet above) and sighting from the other end. The variability of the reflection of the light from the circular top of the shaft is very sensitive to small changes in the shaft angle. The eye should pick up deviations from straightness of order 0.1 mm. This can be an efficient way to check if the shafts have relaxed into their straight configuration.

8. RECOMMENDED OPLE FINAL ALIGNMENT

Fine adjustment of each shaft section by "brute force", that is, by tweaking each support point along each shaft, is much more difficult, as the induced torques may propagate position errors to more distant locations, making the alignment process tedious and perhaps non-converging.

The stretched wire technique appears to have many advantages. The major disadvantage of the commercial system is that it provides greater accuracy than CHARA can use, and at a relatively high price. The recommended solution is for CHARA to develop the stretched wire technique, but only to the level required for the OPLE alignment. Rather than the elaborate electronic systems used in the commercial implementation, the CHARA implementation will use optical readout, combining microscopes and CCD imagers, and cross hairs to measure with respect to the wire.

For the horizontal adjustment, this is relatively straight forward, and is just a matter of centering the microscope. For vertical adjustment, the measurement process must take into account the sag of the wire. A model, based on the known parameters of the wire, can be used. The maximum depth of sag will thus be predicted. The prediction can be checked optically with the theodolite, which also serves to set the two end of the wire at the same relative altitude. The accuracy of this calibration will be optimized if the theodolite is installed near the midpoint of the OPLE. Then the accuracy from center to end should be about 0.5-1 mm.

This arrangement is well suited to the CHARA alignment goals. The accuracy over the full length of the OPLEs will be within the 1 mm intended, and the stretched wire should provide a very smooth interpolation, giving an extremely good local approximation to straight line alignment.

By way of further preparation of this scheme, it will be necessary to identify a source of wire and determine its properties, model the wire's shape, devise a means of mounting and adjusting the wire, devise an optical system and stage for performing the measurement. A calculation could be done to confirm the magnitude of the local deviation from straight due to an error of the expected magnitude in the calibration of the sag, but it is likely to be extremely small.