Thermal Control and Optical Tolerances

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ABSTRACT:

An examination of the optical and interferometric requirements for thermal stability indicates that the use of steel tables and support structures (preferably with the same CTE throughout) will suffice for optical components which are "upstream" of the tilt detection. However, for components after the tilt detection beamsplitter, low expansion materials are stongly advised, in spite of the great cost.

T.1. REQUIREMENTS FOR THE THERMAL CONTROL

Thermal drifts should not provoke changes in the optical alignment which excessively degrade geometrical alignment (with resultant vignetting) or reduce interferometric efficiency (by lowering measured visibilities). The mechanical structures should be sufficiently immune to thermal deformations that the temperature stability requirements are realistic.

T.2. THE NATURE OF THE PROBLEM

Beam alignment errors can result due to deformations or displacements of the optical tables and other optical support structures, and due to mechanical drift of optical mounts.

In order to minimize displacements, foundations must be installed at sufficient depth and with proper preparation of the excavation.

To control deformation of optical tables, the thermal characteristics of the materials and of the environment must be considered.

Typical values for the Coefficient of thermal expansion (CTE) per degree Centigrade are: stainless steel (17.3×10^{-6}), carbon steel (12.1×10^{-6}), aluminum (23×10^{-6}), and super invar (-0.2×10^{-7}).

T.3. OPTICAL TABLES

Two effects should be considered. One is the effect of thermal gradients in the table. The second is the effect of the use of incompatible materials.

If a table of thickness H with coefficient of thermal expansion α has a temperature gradient top to bottom of $\Delta T/\Delta x$, then the table will distort. The relative tilt of the table top per unit length across the table will be,

$$\phi = \alpha \frac{\Delta T}{\Delta x} H \tag{T.1}$$

If the top and bottom plates of a conventional honeycomb optical table have different CTE, then a change in lab temperature will cause a warp of the table.

For a CTE difference of $\Delta\alpha$, a table thickness of H, and a temperature change of ΔT, the The relative tilt of the table top per unit length across the table will be

$$\phi = \Delta\alpha \ \Delta T \ H \tag{T.2}$$

Note that the most popular optical tables have a stainless steel top plate and a carbon steel bottom plate. The CTE difference for these two materials is $\Delta\alpha \approx 5.2 \times 10^{-6}\ {}^{o}C^{-1}$.

T.4. FORMULATION OF THE REQUIREMENTS FOR THE BEAM COMBINING OPTICS

The requirements can be estimated by several approaches involving increasingly detailed assumptions about the optical and mechanical layout of the array and beam combination system.

When the interfering beams are combined at an angle there will be a loss of visibility. Assuming interfering plane waves, the visibility transfer function for tilted recombination is,

$$T_V = sinc(\frac{2\pi\phi b}{2\lambda}) \tag{T.3}$$

where ϕ is the relative beam angle, b is the width of the beams at recombination (eg on the beamsplitter), and λ is the wavelength. For $T_V \geq 0.99$ with $b = 2.5cm$ and $\lambda = 0.6$ microns, $\phi \leq 2$ microradians.

A similar calculation taking into account Kolmogoroff turbulence confirms this result.

If the tilt detection could take place at the interferometric detector, then all tilt errors could be approximately removed with an articulating element. However, the tilt detection and fringe detection will be implemented on opposite outputs of a beamsplitter or dichroic, so there is the possibility of relative tile motion, uncorrected by the tilt correction scheme.

Therefore, the relative tilt between tilt detection and fringe detection should be no greater than a 2 microradians. The equations above lead to stringent requirements. For a stainless steel (top and bottom) optical table, the temperature gradient between top and bottom surface must be less than $0.1^{o}C$. For a stainless steel top and carbon steel bottom, the temperature in the lab must not change by more than $0.4^{o}C$. Both of these requirements are very severe and not realistic for even moderately stable environments. With invar top and bottom, the temperature difference must be less than $1^{o}C$, and the change in temperature is unimportant. Thus invar tables are indicated for the beam combination area. Note that if the equipment is located on more than one table, the relative tilt of these tables is also critical. If the tables are mounted on steel legs, these legs should have invar metering rods to reduce varying tilts due to horizontal temperature gradient changes.

T.5. CONTROLLING THERMAL DRIFT

The four basic approaches to controlling thermal drifts are: to control the surrounding environment (eg the beam combination lab) through insulation and active systems; to control the thermal state of the structure by insulation (to prevent non-uniform heating or cooling); to minimize gradients by using construction techniques which maximize, or at least do not impede, thermal transfer across the structure; and to employ materials with a low thermal expansion coefficient.

Controlling the environment is costly but necessary. The structural design and insulation are relatively inexpensive. Thermally stable materials are rather costly. For example, Newport breadboard tables, 4'×8' and 4" thick costs $23,393, or 731$/square-foot, while their highest grade of stainless steel top breadboard in similar size costs $3809, or 119$/square-foot. This is one of the rare occasions where interferometry poses a really severe budget problem.