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Rationale and Procedures for Development of a NASA Primary Metrology Laboratory for Large Optics

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TABLE OF CONTENTS

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1 Introduction

Traceable optics metrology is not an expensive overhead. Rather it can improve NASA's procurement process and eliminate costly Hubble-like mistakes.

- **Improved procurement?** In deciding if a part meets specification, ISO Standard 14253, Part 1[1] requires that the vendor must subtract the measurement uncertainty from the tolerance, ensuring that the customer always gets a good part. This procedure is not common in the US optics industry. Indeed, we have heard of optics companies who effectively relax the tolerance by the size of the measurement uncertainty. This practice could lead to the shipment of questionable parts. By contrast, the rigorous approach described by the ISO standard increases the probability of shipping a part that meets or beats specification.

- **Elimination of mistakes?** Discrepant measurements were taken during the manufacture of the Hubble primary mirror.[2] If those measurements had been accompanied by rigorous uncertainty analyses, it would have been clear that the results disagreed by more than the estimated uncertainties - thus launching an investigation (rather than launching a flawed mirror).

It is therefore in NASA's best interests to develop traceable large optics metrology capabilities and with them the culture of rigorous statement of measurement results with associated uncertainty. This report provides a preliminary road map toward that end.

1.1 Motivation

Metrology is required to verify that manufactured products meet specifications and may be used to guide a manufacturer to make necessary changes in a product or manufacturing process. In order to fulfill its advanced observatory missions, NASA should establish a primary standards laboratory for dimensional metrology of large optics. This would enable NASA to verify the accuracy and quality of optics produced by NASA suppliers and would enhance the capabilities of its customers and suppliers in the nation's optical industry with whom NASA has a symbiotic relationship.

Such a facility must not only include advanced measurement tools but also an institutional culture that emphasizes rigorous measurement and analysis procedures demonstrating traceability to the SI unit of length.

Detailed reasons for NASA to develop a primary standards laboratory are as follows:

- **Efficiency:** Specialized large metrology facilities for testing large optics are very expensive. In the past, NASA has typically paid for the development of facilities and competence as needed for specific programs; when the programs are complete, the facilities may no longer be supported. Meinel and Meinel[3] observed many years ago that the cost of astronomical optics increases faster than the square of the aperture. Much of that cost is in facilitization (e.g., fabrication and test equipment). Larger optics will be a central part of NASA missions for the foreseeable future; centralized competence in their measurements will help minimize the cost.

- **Independent verification:** Even if optical fabrication contractors possess adequate metrology capabilities themselves, a high degree of independent measurement expertise by NASA will enable NASA to verify the claims made by contractors. Independent confirmation is extremely important in metrology, and an independent capability by NASA is especially important for NASA's and the country's long term interests.

- **Technology Transfer:** With an in-house measurement and standards laboratory for large optics, NASA will develop special capabilities, for example in self-calibration techniques, that it will be able to transfer to its contractors so that they might demonstrate traceability themselves.

- **Expertise:** Having a primary standards laboratory for large optics metrology will result in increased expertise that NASA can draw upon as it monitors the designs, optics fabrication, and measurement results of its contractors.

- **Measurement Support:** A permanent NASA-based facility in optics metrology will benefit optical contractors, who know how to manufacture components with optical quality surfaces but lack critical measurement expertise to establish the quality of their product.

- **Physical Standards:** With a primary metrology laboratory and with existing world-class facilities for certain fabrication processes, NASA will be able to fabricate and calibrate transfer artifacts such as flats, spheres, and mid-spatial wavelength specimens that can be used by suppliers and contractors to verify processes and calibrate products. Note that the preferred option is the transfer of competence in self-calibration. The use of transfer artifacts is a second choice.

- **Partnership with NIST:** A primary metrology laboratory at NASA's Marshall Space Flight Center (MSFC) optics facility will be complementary to NIST's optics calibration facilities, which are designed for optics up to about 300 mm.

Overall, the metrology facility will provide a needed measurement infrastructure for the optics fabrication community and particularly for the small but crucial large optics community. Furthermore, there will likely be a strong spillover of metrology expertise into the areas of optics fabrication at NASA.

1.2 Focus

NASA has a massive array of optics development projects. Each of them has specific needs in fabrication and metrology, and taken collectively, the projects have common needs. For a single metrology laboratory to demonstrate that all the optics in NASA's collection of missions meet all of the dimensional specifications to the last detail may not be necessary and is certainly not tractable. Therefore, NASA should focus its metrology development on the critical dimensional specifications in the higher risk, higher payoff projects. By this example, NASA can motivate contractors to improve the metrology for the remaining optics to be supplied across the board. We therefore focus much of the following discussion on optics and the required metrology for the Next Generation Space Telescope (NGST) and Constellation X missions.

1.3 Organization of Report

The remainder of this report is organized as follows. In Section 2, we give formal or working definitions of several concepts. In Section 3, we discuss metrology issues that are common to both NGST and Constellation X. In Sections 4 and 5, we discuss issues specific to NGST and Constellation X, respectively. In Section 6, we present road maps for achieving traceability with MSFC instruments for measurement of the key specifications of NGST and Constellation X.

2 Definitions

2.1 Large Optics

The term, *large optics*, is difficult to define. In general, we mean optical elements too large to be measured conveniently with an interferometer having a 300 mm aperture diameter. 300 mm is the aperture diameter for NIST's new **X**-ray Optics **Calib**ration **I**nterferomete**R (XCALIBIR)**. XCALIBIR can measure flats up to 300 mm diameter, concave optical elements somewhat larger than 300 mm, and convex elements that are smaller. There are also focal length limitations. To simplify the definition further for this report, we will assume that large optics have elements with their largest dimension greater than or equal to 600 mm.

2.2 Traceability

The definition of *traceability*[4] is:

"Property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties."

Another way of expressing it – with respect to testing optics - is that the measurement will be traceable if:

(a) the unit of length is realized in the measurement process, and
(b) a defensible uncertainty analysis of the measurement process is developed.

Genuinely traceable metrology requires a management culture that demands rigorous measurement procedures with uncertainty analyses compliant with the *Guide to the Expression of Uncertainty in Measurement* (GUM).[5] Use of the uncertainty analysis in GUM promotes rigor. The staff need to understand and practice it in order to transfer skill to prime contractors. Creating the right management culture for metrology would be aided by a policy promoting the use of rigorous uncertainty statements in conformity with the GUM.

Note that the definition makes no mention of an external authority such as NIST, although "the unbroken chain of comparisons all having stated uncertainties" may be achieved through a comparison of a calibrated artifact from such an authority.

In this report we recommend that artifacts be used for some measurements. For others we recommend that NASA MSFC realize the unit and use one of the well known "self-calibration" methods.

An important aspect of traceability is the validation of the "stated uncertainties". For those NASA MSFC measurements that do not depend on calibrated artifacts, this may be achieved by:

(a) documented and critically reviewed uncertainty analysis; and/or
(b) intercomparisons among independent measurement methods.

The world's national measurement institutions are currently involved in a number of key comparisons,[6] where carefully selected artifacts are measured at different institutions.

Confidence increases when measured values agree within stated uncertainties. For NASA MSFC large optics measurements, this approach has limitations; there are few institutions capable of measuring very large optics, and the costs involved would be substantial. An alternative, however, is to measure calibrated "check standards"; examples of this approach will be seen in the recommendations which follow.

2.3 Surface Finish

Surface finish or *surface roughness*[7] consists of the fine spatial wavelength surface deviations that produce scatter in reflected or transmitted light thus producing reduced signal and contrast in optical measurements and images[8]. If the light has wavelength λ, we consider that the scatter-producing surface deviations constituting optical surface roughness occupy a bandwidth[9] of spatial wavelengths between $\lambda/2$ and about 1200λ, depending on the angular resolution of the optical system being used as well as the angles of incidence and reflection. Surface finish is generally regarded as a statistical property of the surface topography and is measured by sampling the surface at different positions.

2.4 Figure

Figure, also known as surface form deviation,[10] is the overall departure from the nominal part shape that is localized in the spatial coordinates of the part. Deviation from perfect figure leads to aberrations in an optical image. The definition implies that figure is a deterministic property. To improve it, the optician must know the positions of the surface peaks and valleys. Therefore figure is not sampled in a statistical fashion as is roughness but is measured over the entire functional surface of the component if possible. Surface topography deviations are frequently described in simple amplitude terms or in terms of Zernike polynomials,[11] the lowest orders of which are directly related to well known aberrations in optical images, including spherical aberration and coma. Other descriptors such as power spectral density[12,13] are also used for some applications.

2.5 Mid-spatial Regime

There is often a gap between spatial wavelength regimes specified as roughness and figure. This intermediate regime is often called the *mid-spatial regime*. Here, topographic specifications may be developed in terms of slope deviations[14] because slope deviations on a surface are related to broadening of an image focal spot upon reflection from the surface or upon transmission through it.

3 Measurement Requirements in Common

In this section, we discuss measurement requirements for the surface finish and mid-spatial wavelengths of optical components. These metrology requirements are common to both NGST and Constellation X and to many other optics fabrication projects as well.

3.1 Surface Finish

Both NGST and Constellation X require similar, traceable surface finish (roughness) measurements. We considered above that the scatter-producing surface deviations constituting optical surface roughness occupy a bandwidth of spatial wavelengths between $\lambda/2$ and about 1200λ. For an optical system with, say, a HeNe laser illumination source having a wavelength λ of 633 nm, that means a spatial wavelength range from about 300 nm to about 1 mm. NGST will operate in the IR, so the spatial wavelengths that need to be measured will be longer than those for visible optics. We expect then that optical designers are going to specify surface roughness over a range inside the 300 nm to 2.5 mm spatial wavelength range and that the surface metrologist must be ready with instruments and procedures that cover this spatial wavelength range.

Measurements over that whole range and larger are readily achievable with a combination of three widely available surface measurement techniques. These are an atomic force microscope capable of measuring the spatial wavelength range of 10 nm to 50 µm, a stylus instrument covering the range, 200 nm to 2 mm, and an interferometric microscope covering the range, 600 nm to 5 mm.

Two aspects of the operation of these instruments are important. First is the noise resolution. All of these instruments have a noise resolution on the order of 0.1 nm, which is approximately the minimum level of roughness that needs to be measured on the highest quality optical surfaces. Considerable skill and effort are required to unfold the surface roughness deviations from the instrument noise and other instrument errors.

The second major issue is calibration. Calibration of the z-scale of the instrument is always important for measurement of amplitude parameters, but calibration of the x- and y-scales is also important for measurements of certain surface-finish statistical functions, such as the power spectral density or the autocorrelation function, which have the lateral spatial coordinate or the spatial wavelength as the independent variable.

3.2 Mid-spatial Regime

We consider that the outer limits of the mid-spatial wavelength regime for NASA large optics extend over two orders of magnitude from approximately 1 mm to 100 mm. At the bottom of that range (1 mm), the spatial wavelengths fit conveniently into a roughness formalism where the surface specification can be arrived at from a scattering description of the surface function. The long wavelength limit depends on the test used for *figure*; an interferometric test of a full 10 m optic with a conventional camera will be Nyquist limited to about 80 mm. For convenience, we will take the boundary as 100 mm. If the mid-spatial regime must be singled out by the optical designer, the specifications may be cast in terms of slope deviations as stated in Section 2.5.

This mid-spatial regime is measurable by specialized instruments. The principal instrument is the long trace profiler (LTP)[15] developed by Takacs et al.,[16,17] which directly measures surface slope profiles. For NASA to verify the accuracy of the LTP, completely independent methods are available. These include both figure measuring interferometers and three curvature measuring methods: the Bauer profiler developed by Glenn[18] and two methods developed by Weingärtner et al., the extended shear angle difference (ESAD) method,[19] and the large area curvature scanning (LACS) method.[20] Results from the curvature measuring instruments must be spatially integrated to produce slope deviation profiles, whereas results from figure measuring interferometers, to be discussed in Section 4.2, must be differentiated.

Mid-spatial wavelengths cause image broadening and have been found on grazing mirror components made with state-of-the-art techniques for synchrotron optics[21] and for the Chandra optics during production.[22] These optical elements are similar to those that will be produced for Constellation X.[23] The measurement of mid-spatial wavelengths on large optics is also important on the NGST.[24]

We anticipate that, if designers establish specifications for the mid-spatial regime of future NASA optics, the principal specification would be the root mean square (rms) slope deviation over a range of spatial wavelengths somewhere within the band between 1 mm and 100 mm. We should add that PSD specifications, including the 1 mm to 100 mm spatial wavelength regime, are also frequently given for synchrotron optics and were used for AXAF/Chandra. Hence, the metrologist must be ready to perform accurate measurements of surface slopes, which may also be integrated into surface amplitude profiles within that band using one of the specialized instruments. It may be beneficial that NASA possesses several instruments, operating on quite different physical principles, that can be used to make independent measurements of mid spatial wavelength slopes and can serve as independent checks. We will recommend in addition (Section 6), that a specialized set of check standards be developed to test the calibration and range of the instruments.

4 NGST Requirements

The Next Generation Space Telescope (NGST) is expected to be an (8-10) m aperture f/1.2 system. At the time of writing, final vendors – and hence final configuration – have not been selected. Thus it is not known if the primary mirror will be spherical or aspheric. In either case, the final configuration is likely to require the use of large flats and spheres in testing if not in application. Hence we focus here on developing the ability for NASA MSFC to make large-aperture, traceable-figure measurements of flats and spheres, which can then be used to make measurements of conics – paraboloids, ellipsoids, etc.

NGST will have a segmented primary and it will be important to match the radii of curvature of the base segments. We will briefly discuss radius measurements. In establishing alignments, NGST contractors must realize the subsidiary SI unit, the radian. Traceable measurements of angle will also be discussed.

4.1 Measurement of Large Flats with Profilers

There are two obvious approaches to measurement of large flats; use of large scale profilers or measuring machines and use of interferometric testing. The Cranfield Unit for Precision Engineering (CUPE)-built profiler[25] acquired by NASA MSFC and the horizontal long trace profiler (LTP) might be used to measure profiles on flats up to approximately 1 m aperture. Note, however, that the latter machine was designed for the measurement of aspherics – specifically grazing incidence synchrotron optics, where slope errors in a mid-spatial frequency range of about 1 mm to 10 mm are most significant. It was not specifically designed for measurements of flats with an uncertainty comparable to that being realized with interferometric tests.

4.1.1 The CUPE profiler

The operating principle of the CUPE profiler is that a vertical air-bearing probe contacts the surface under test. Displacement of the probe is measured using a HeNe distance measuring interferometer with respect to the bottom surface of a Zerodur straightedge supported at its Airy points. If the goal of the measurement is simply to report amplitude parameters describing the departure of the surface from nominal, key contributions to the uncertainty budget for this instrument will arise from the following:

- drift (which may be assessed with a drift test),
- dead path in the interferometers (which could be large),
- uncertainty in the correction of the form errors of the Zerodur straightedge,
- angular error motion of the slide,
- location of the measured profile on the part.

If spatial parameters are also required, then it is necessary to add components due to uncertainty in position in the lateral (X) direction.

We have one explicit recommendation based on visits to NASA MSFC. If this profilometer is to be used for rigorous metrology, it needs to be relocated to an environmentally controlled room. The profilometer is currently quite close to a roll-up door on a loading dock. There are likely large and variable temperature gradients in this environment. The substantial granite base of the machine has a large thermal inertia, but the columns and bridge will respond quickly to thermal changes. Hence, we believe that a drift test performed under normal conditions in the present space near the loading dock will show significant perturbations.

4.1.2 Horizontal LTP

The horizontal LTP has many features in common with the CUPE machine. Two major differences are:

(a) LTP measures surface slope,[26,27] not vertical amplitude, and integrates the slope measurements to produce an amplitude profile. This procedure introduces the issue of estimating the uncertainties arising from the integration process.

(b) Angular errors of the instrument are compensated in the design. Hence this uncertainty reduces to the uncertainty in the compensation.

A further difference is that the NASA MSFC LTP is in a location that appears to be significantly better than the location of their CUPE profilometer. However, a drift test will still provide an important contribution to the uncertainty budget. The recent paper by Takacs et al.[27] provides an excellent starting point for NASA to develop its uncertainty budget on this instrument.

4.1.3 Traceability for horizontal profilers

The unit of length (m) is realized in the CUPE profiler discussed above through the use of HeNe laser distance measuring interferometry. By contrast, calibration of the slope measuring LTP will likely be realized using calibrated surface slope artifacts such as sinusoidal waviness standards to be discussed in Section 6.2.

Once an uncertainty budget is derived, we recommend it be cross-checked through measurements of flats or very long radius spheres tested interferometrically. For example, the Laser Interferometric Gravitational Wave Observatory (LIGO) has extremely well characterized 250 mm diameter components with radii in the 6 km to 11.4 km range.

One of these was measured at NIST using a 150 mm aperture interferometer and at Argonne National Laboratory using the LTP.

LIGO optics (or similar artifacts up to 300 mm aperture) could be recalibrated using NIST's XCALIBIR and then used to check the vertical and horizontal LTPs. XCALIBIR could also be used to measure parts with systematic departures from either a flat or long radius sphere. Note, however, that change in the orientation or fixturing of the part introduces change in the part form and this would need to be considered carefully.

4.2 Interferometric Measurement of Flatness

It is much more likely that interferometric testing – rather than profilometry – will provide uncertainties at the levels required for astronomical instruments, for example, a maximum figure error of ($\lambda/12$) rms according to the Marechal criterion.

So-called "absolute testing" has been a staple of the optical testing literature for many decades. Unfortunately, we are aware of no procedure which makes no compromises. Typical limitations include relatively sparse coverage based on a series of profiles, fitting of measurements to an assumed function (e.g., Zernike polynomials) of the error, and insensitivity at some spatial wavelength, etc. To meet NGST needs, it is necessary to specify:

1. the test aperture;
2. the spatial wavelengths of interest, i.e. the bandwidth of measurements required;
3. the target uncertainty.

Given this, NASA MSFC can then select between three primary approaches:

4.2.1 Limited aperture

NASA MSFC has one of very few 800 mm (32 inch) aperture Fizeau interferometers. Within this test aperture limit, NASA MSFC may choose between a number of published algorithms[28-34] and generate an appropriate uncertainty budget. This approach requires – at minimum – two transmission flats for the instrument and one return flat. Also we suggest that the instrument be converted to wavelength shifting[35] and a new generation detector installed with 1000×1000 pixels or more. A critical requirement is that the interferometer be relocated; it is currently on the loading dock with the CUPE-built profilometer – except that it is even closer to the roll-up door (Fig. 1). In fact, the other form measuring instruments are located in relatively uncontrolled thermal environments as well. (See Fig. 2 for example.)

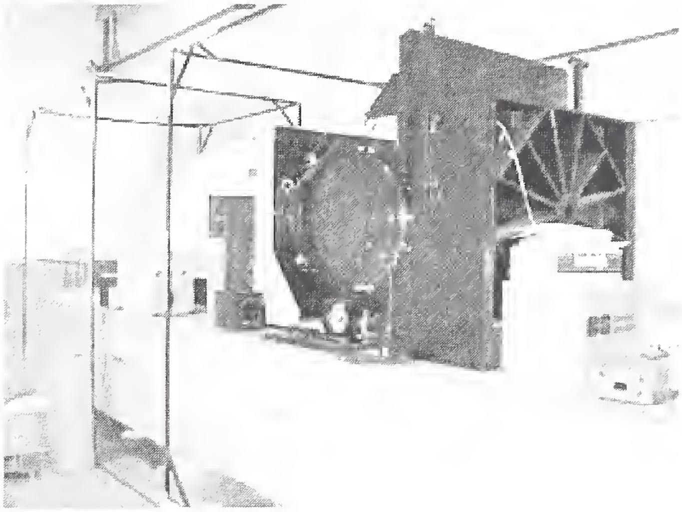

Fig. 1: Large Fizeau interferometer with 800 mm aperture transmission flat. The roll-up door to the outside is left of the field-of-view by about 6 m.

Fig. 2: Housing for the vertical Long Trace Profiler in an uncontrolled thermal environment approximately 15 m from an exit door.

In the case of a Fizeau interferometer operating with a HeNe laser, the unit of length is realized with a significantly smaller uncertainty than other components in the uncertainty analysis. If the HeNe laser produces a red light, it is operating at 633 nm to within a fractional error of 3×10^{-6} or better.[36] The theoretically possible but highly unlikely 612 nm and 640 nm radiations can easily be screened out using a narrow bandpass filter, which – if necessary – can be calibrated at NIST. The Fizeau interferometer measures OPD (optical path difference) which, for reasonable misalignments, will be less than

1 micrometer over the aperture of the part. Hence the uncertainty in wavelength will result in an uncertainty in flatness on the order of $10^{-5} \times 10^{-6}\,\mathrm{m} \cong 10^{-11}\,\mathrm{m}$.

Each of the many published approaches to "absolute testing" of flats will have a different uncertainty budget. Comparison between approaches to obtain agreement within stated uncertainties offers the chance to validate the uncertainty analyses.

Another approach is to measure a check standard, which could be calibrated by XCALIBIR. Such a 300 mm aperture artifact could be measured anywhere within the 800 mm aperture of the interferometer and – within the stated uncertainty – should give the same result for flatness.

4.2.2 Stitching interferometry

One approach to measuring large aperture flats is by "stitching".[37] A variety of different algorithms can be invoked to tie together sub-aperture measurements. Whichever algorithm is adopted, a rigorous uncertainty analysis will be required. Specifically we recommend that the procedure be tested on a small aperture system for which a full aperture measurement is also available. This will allow some estimate not only of the uncertainties arising from the algorithm, which could be derived from an appropriate simulation, but also from such issues as part translation, imperfect reference surface subtraction, etc. Simulations may also be used to evaluate algorithmic contributions to the uncertainty.[38]

Stitching may be applied in two different ways at NASA MSFC:

1. To bootstrap measurements of small flats so that the reference surface in the 800 mm Zygo may be tested; and
2. To use the 800 mm Zygo to test even larger flats.

4.2.3 Ritchey-Common test

In the late 19th century, Ritchey and Common demonstrated the measurement of flats in a diverging wavefront. This approach, as originally proposed, has a number of well documented disadvantages (ambiguity between power and astigmatism, and restriction to a single profile). For circular flats, recent work at NIST[39] (building on the contribution of Shu[40] in Arizona) has shown that, with the addition of two rotations, a full aperture map can be generated which does not suffer from the ambiguity over power in the flat.

This test is "self-calibrating", assuming that the wavelength of the light source is known, but requires an appropriate f/# return sphere with an aperture larger than the flat under test.

4.3 Sphere Testing

Assuming – for the moment – that the primary mirror for NGST is a segmented sphere, approximately 1 m diameter segments with a radius of curvature of the order of 10 m, will need to be tested. During our visits to NASA MSFC we did not see a 10 m test tower or similar facility. A further requirement is that for a fully operational test, the NGST optics must be measured in vacuum at a temperature of 35 K. We understand that tests may be performed either in the x-ray test facility[41] at MSFC or in test facilities at Arnold Engineering Development Center or Stennis Space Center.

Handling very large optics is expensive and risky. It is likely, therefore, that a commercially available phase measuring interferometer and appropriate reference (transmission sphere) will be calibrated using small optics and then used to measure the final part. If the interferometer used is a Fizeau, the needed refocusing will have only a second order effect on the measurement; the uncertainty introduced, however, must be estimated.

To perform such a specialized test, NASA MSFC may need to develop its own test facility with 10 m optical path length, cryogenic high vacuum system, ultra uniform vacuum window (thickness uniformity $\sim \lambda / 40$), and sufficient size capability. Much will be learned about the facility from observing the wavefront as the chamber is pumped and cooled.

4.4 Self-calibration Methods for Flats and Spheres

There are three major classes of self-calibration methods that are applicable to flats or spherical optics. Measurements using different approaches should agree within the uncertainties associated with each method. We do not advocate a particular method or set of methods; that choice is often determined by specific aspects of the measurement to be made.

4.4.1 Three flat (profile) tests

The well known three-flat test delivers departures from nominal for individual profiles. Procedures exist for tying together a number of such profiles to generate an area map.[32]

4.4.2 Rotational shearing methods

Rotationally varying contributions to the figure of a flat or sphere can be derived using one of a number of algorithms (e.g., Parks,[42] Fritz,[29] Evans and Kestner[30]). When appropriately combined with a "three-flat" type measurement to deduce the rotationally invariant component of the surface figure, these methods provide a full area (but bandwidth limited) map of the surface.

4.4.3 Averaging methods

An estimate of the errors in an interferometer can be obtained by averaging a number of uncorrelated measurements, [43,44] either of different apertures on a large part or a number of different parts. If the test apertures are truly uncorrelated, the uncertainty arising from using the average as an estimate of the instrument error decreases as the square root of the number of test apertures.

4.5 Radius of Curvature

The individual segments of the primary are relatively "slow". Their radius could be measured on a long radius bench. For a well designed and tooled radius bench, the limiting uncertainty is likely to be due to the displacement measuring interferometer (DMI) and specifically to the uncertainty in wavelength arising from uncertainty in temperature and pressure in the laser pathway.

We are currently developing a detailed uncertainty analysis for measuring radius up to 2 m using XCALIBIR. This analysis could be adapted to any optical radius-bench measurement developed for NASA MSFC. Other measurement schemes will need specific uncertainty analyses. As in Section 4.3, we note that radius needs to be measured in vacuum and cryogenically, requirements incompatible with a radius bench. One approach which should be investigated is to measure radius at ambient conditions, and then monitor changes as the mirror is enclosed in its housing, pumped down, and cooled.

4.6 Angle

Angle metrology is used in the alignment and setup of optical systems. Hence, traceable angle metrology will be required by NASA. Section 6.4 contains information concerning establishment of traceability of angle measurements.

5 Constellation X Requirements

Constellation X may be considered a replicated metal analog of AXAF/Chandra.[45] As such we assume for now that the HDOS-built metrology equipment[25,45] already used for Chandra will be installed in an appropriate facility at NASA MSFC and that it will provide most of the needed capabilities. However, the compatibility of the HDOS-built metrology equipment with the shape of Constellation X optical element designs will need to be reckoned and explicit uncertainty analyses for these measurements will be required. In particular, efforts should be made to remeasure the master straightedges, reference flats, and inside diameter reference bars of the HDOS equipment

On the original AXAF project, 200 mm diameter flats were used as check standards. These specimens could now be independently checked at NIST using XCALIBIR. Straightedges should be checked using straightedge self-calibration methods.[46] The vertical LTP will also provide useful information on the axial figure of Constellation X optics.

6 Achieving Traceability on MSFC Instruments – Example Road Maps

In this section we briefly describe road maps for measurement of surface finish and mid-spatial wavelengths, and for several types of figure measurements. These are only a subset of measurements that will be required for physical standards, which in turn will be only a subset of traceable measurements that could be performed to verify that manufactured optics meet all specifications. Just as NIST makes hard choices concerning which measurements it provides, NASA as well will have to emphasize a subset of required capabilities. NASA will not be able to tackle every optics dimensional measurement problem at once.

6.1 Surface Finish Metrology

We now describe a possible road map for establishment of a traceable calibration system for surface finish (roughness) in the large optics dimensional metrology laboratory. Overall, this process involves establishment of the accuracy of the scales of the system, establishment of the lateral resolution limit of the instrument, establishment of the lateral range of the instrument, and establishment of the vertical resolution of the instrument. The specific activities are:

- Acquisition of calibrated step height specimens.

- Acquisition of calibrated pitch specimens.

- Acquisition of calibrated roughness specimens and uniform roughness comparison specimens.

- Acquisition or development of software for instrument calibration.

- Acquisition or development of software for calculation of selected key surface parameters from surface profiles and/or topography maps. These parameters include step height, roughness average, rms roughness, and power spectral density function.[13,47,48]

- Testing of an entire system, hardware and software, for measurement of the selected surface parameters.

- Development of procedures for performing roughness measurements near the height resolution limits of the instruments.

- Development of procedures for determining the spatial wavelength limits of the roughness measuring instruments.

- Development of uncertainty budgets for the selected roughness parameters.

- Measurement comparisons with other laboratories to confirm the validity of the measurement procedures and uncertainty analyses.

We begin here with the acquisition of calibrated surface specimens for step height and pitch. We recommend this approach because it is relatively economical in comparison with the establishment of traceability from first principles with a HeNe laser performing interferometric measurements. This is in contrast with the approach suggested for figure measurement because, whereas the wavelength of the HeNe laser is a feature of a Fizeau interferometer, the high resolution sensors in roughness measuring instruments may be linear variable differential transformers (LVDTs), piezo-electric displacement devices, or interferometers with broad-band light sources. The unit of length is "on the table" for the Fizeau interferometers with laser light sources used for figure measurement but not for roughness measuring systems. This is not necessarily a significant drawback for roughness measurement tools. The uncertainty arising from the use of calibrated master steps as opposed to directly traceable measurements is not a major factor in the uncertainty budget for the low levels of surface roughness that need to be produced and measured on high quality optics. Vertical resolution and linearity, more than state-of-the-art scale calibration, are limiting factors for these instruments when measuring the roughness of optical surfaces.

The calibrated step heights and pitch standards serve as masters to calibrate the scales of the three types of instruments discussed earlier. For measurement of various types and grades of optics, we recommend step heights of approximately 7 nm, 30 nm, and 90 nm, and pitch standards of approximately 1 µm, 10 µm, 100 µm, and 1 mm. These specimens could be calibrated at NIST. With such specimens one can calibrate the scales of surface finish measuring instruments over the range of spatial wavelength discussed in Section 3.1 and over a sufficient range of surface heights. For surface height measurements significantly smaller than 7 nm, tests can be devised to check the linearity of the instruments in the vertical direction.

As time and budget allow, other specimens may be added to this set. Single atom step height standards on the lattice plane of Si(111) are 314 pm in height and may be useful for calibrating atomic force microscopes over atomic-scale height ranges.[49] Highly uniform, periodic roughness standards are also available down to 0.5 nm rms roughness levels. Tenth-nanometer-level random roughness standards also provide useful tests of instrument operation and calibration.

Once calibrated, these instruments may be used for several different types of measurements for NASA and its suppliers and customers. These are

- step height calibrations,
- rms roughness calibrations and tests,
- measurements of special functions, especially power spectral density, a function closely related to the scattering of light from smooth surfaces.

Capabilities in addition to scale calibration are important for providing and enabling traceable roughness measurements in industry. First is the capability to characterize the lateral resolution of the instrument. Second is the establishment of traceable software based on calculations of standard data sets using the algorithms present in the computer.

Examples of uncertainty statements for NIST surface roughness and step height calibrations and tests are shown in Appendix A. The description shown there is the most recent in a series dating from 1976.[50] New versions reflect changes in instrumentation and standards that have taken place and the continual acquisition of new data concerning the measurement systems. Another example of an uncertainty budget is shown in reference [51].

For x-ray optics, relevant spatial wavelengths for surface finish should range over a very wide regime of spatial wavelengths. The x-rays to be detected with Constellation X range in energy from 6 keV to 40 keV. 40 keV is equivalent to an x-ray wavelength of 0.03 nm. The highest grazing angle of incidence that will be used on Constellation X is 1°. At that energy and angle of incidence, the shortest spatial wavelength of the surface that affects x-ray scattering is

$$\frac{1}{2}\frac{\lambda}{\sin\theta} = \frac{0.03\ \mathrm{nm}}{2\cdot\sin 1^\circ} \sim 1\ \mathrm{nm}\ .$$

Therefore, it is important that surface finish measuring equipment have horizontal resolution of 1 nm or better in order to assess the quality of x-ray mirrors of Constellation X. That means that AFMs or x-ray scattering will be needed to assess the shortest spatial wavelengths of Constellation X optics. Even with AFMs, it is currently difficult to demonstrate 1 nm lateral resolution. It was implied in Section 3.1 that 10 nm lateral resolution is achievable. One way to improve the resolution beyond that may be the use of commercially available nanotubes[52] as AFM tips.

6.2 Mid-spatial Metrology

A possible road map for achieving traceability for the instruments that perform mid-spatial wavelength measurements is given below.

- Acquisition of sinusoidal specimens with calibrated slope amplitude and pitch.
- Acquisition of spherical artifacts with calibrated radius.
- Acquisition and/or development of software for instrument calibration and calculation of surface parameters from surface profiles. These parameters include rms waviness, rms slope, and power spectral density function.[13,47,48]
- Development of uncertainty budgets for rms waviness, rms slope, and power spectral density.
- Development of procedures for determining the short spatial wavelength limits of the mid-spatial instruments.
- Comparisons of the results of two instruments for measurement of the key surface parameters of rms waviness, rms slope, and power spectral density.
- Measurement comparisons with other laboratories to confirm the validity of the measurement procedures and uncertainty formulas.

The mid-spatial instruments can perform three types of measurements. First, they are specifically suited for measuring slope deviations over mid-spatial wavelength ranges. In Section 3.2, we estimated that the requirement for this type of measurement would be in the spatial wavelength range from 1 mm to 100 mm. Second, the slope measurements can be once integrated or the curvature measurements can be twice integrated to yield measurements of surface profile in the mid-spatial wavelength range. Third, if it were demonstrated that these instruments can produce accurate profile measurements over long spatial wavelength ranges, these instruments would provide independent profile measurements of figure to test the uncertainty budgets of the Fizeau interferometers. Moreover, LTPs were designed to provide axial profile measurements of grazing incidence optics. The configuration of LTPs is more suited to this task than that of Fizeau interferometers.

However, calibration of mid-spatial instruments is not as straightforward as calibration of surface roughness instruments. Standard surface specimens such as step heights or roughness specimens are not suitable because they usually have features with widths that are too narrow for testing the LTP, whose minimum point spacing is 1 mm. We therefore recommend the fabrication of sinusoidal specimens with surface height and wavelength designed to be measurable by the LTPs and the Bauer profiler near their limits of small spatial wavelength and maximum slope. For the LTP, possible choices are a spatial wavelength of 5 mm and a maximum slope of 10 mrad. For a sinusoidal specimen this implies a peak-valley amplitude of 15 µm. Such a specimen could be manufactured by diamond turning over an area of approximately 50 mm × 50 mm. This type of specimen could be used to test the LTP near its minimum spatial wavelength limit and its maximum measurable slope. To test linearity, a second specimen with longer wavelength and/or smaller amplitude could be developed. Similar limitations of the Bauer profiler would drive a requirement for slightly different specimens. A very good optical flat could be used to test the vertical resolution limit of both instruments. These specimens could be calibrated at NIST.

6.3 Figure Metrology - Flats and Spheres

Section 2 of this report defined traceability. From that definition, it should be clear that there is no single route to making a traceable measurement of a particular artifact. Rather there are a plethora of alternatives. The "best" approach depends on the equipment, resources, and skills available - as well as the target uncertainty. This is particularly true for figure measurements.

In the rest of this section, we suggest "road maps" that will enable NASA MSFC to provide *traceable* figure measurements of a variety of large optics. The recommendations are based on our understanding of current MSFC capabilities.

6.3.1 Flats up to 800 mm diameter

Flats may be measured at NASA MSFC using:

1. 100 mm aperture Zygo phase measuring interferometer
2. 450 mm aperture Zygo interferometer
3. 800 mm aperture Zygo interferometer
4. Horizontal and vertical Long Trace Profilers (LTP)
5. The CUPE profiler (1 m)

6.3.2 Flats up to 800 mm -- ideal

The ideal route for developing the capability to provide traceable measurements over the full area of large flats is to enhance the current 800 mm aperture interferometer by

1. Relocating the instrument to a state-of-the-art temperature controlled enclosure;
2. Converting from "fringe-center-finding" to "phase measuring", preferably through wavelength shifting of a laser diode;
3. Procuring at least one (preferably two) additional 800 mm diameter "transmission flats" with mounts and associated hardware that allow rotation of the "test" flat about the optical axis.

With these three changes, NASA MSFC could implement many of the self-calibration methods, just as is done at NIST and other national measurement institutions (NMIs). Intercomparison among the various methods (see Section 4.4) provides assurance that the uncertainty analyses include good models of the measurement process. Further, we recommend that a sub-aperture (300 mm) test artifact be measured at NIST; this artifact should then be measured at a variety of random positions in the 800 mm aperture. The measurements should be self-consistent within the stated uncertainty for the 800 mm aperture.

Note that converting the 800 mm Zygo to using a laser diode introduces a need to calibrate the output wavelength of the diode.

We note that NASA MSFC is working to increase its base of expertise in optics. The hiring of H. Philip Stahl as lead optical engineer and the experience of Holly Cagle in the Professional Intern Training Program are examples of this emphasis. We applaud this emphasis on hiring and training to develop a cadre of experienced optical test engineers who will be able to develop the measurement infrastructure and interact effectively with NASA optics vendors.

6.3.3 Flats up to 800 mm -- alternate approach

It has been indicated that NASA MSFC may not be able to make the needed investment (at least in the short term) to achieve traceability following the route outlined above.

As long as the target is measurements at 800 mm aperture, the key requirement is #1 in Section 6.3.2 that the instrument be housed in a state-of-the-art temperature controlled enclosure. Based on experience, we suggest that the limiting uncertainty in the performance of the 800 mm aperture Zygo in its current location will be thermally induced drift. We recommend that NASA MSFC initiate a long term drift check.

Assuming that drift of the 800 mm aperture system is reduced to acceptable levels, we think that NASA MSFC can achieve traceable measurements of flatness by "bootstrapping" measurements over smaller apertures using a stitching procedure. Here, the key will be calibration of a 300 mm aperture artifact at NIST. Assuming that NASA MSFC

1. has enough reference optics to perform self-calibration on their 100 mm aperture Zygo, and
2. has a working stitching procedure,

they should be able to stitch together multiple 100 mm aperture measurements on the 300 mm artifact and compare the resulting phase map to the NIST measurement. Any differences will give an indication of the uncertainties introduced by the stitching method adopted. Now, using the 300 mm calibrated artifact, NASA MSFC could stitch together a reference surface error map for the 800 mm system with stated uncertainties.

6.3.4 Flats larger than 800 mm

For flats larger than 800 mm, NASA MSFC must either stitch together 800 mm apertures or set up a Ritchey-Common test configuration. Ideally, they should do both and compare results.

6.3.5 Spherical optics

As noted earlier, we have not been able to inspect specific hardware to be used in the measurement of large spherical optics. Hence no specific road map is offered here. However, we assume that the test facilities will be based around a commercially available Fizeau interferometer. For this case, the following steps must be taken:

1. As with flats, the first step will be to determine the target uncertainty and the spatial wavelengths of interest.

2. Decide if one of the self-calibration procedures indicated in Section 4.4 will be used with the full-sized test part. Perform the test procedure. Derive an uncertainty statement as in the case of flat testing.

3. If Step 2 (which may be too expensive and difficult) is not followed, select a test procedure to implement with smaller artifacts to "master" the interferometer. Evaluate stability of that mastering process. Evaluate the effect on the apparent reference wavefront of changing zoom and/or focus, which are likely operations when changing from the mastering step to measurement of the final artifact. Cross-check the mastering procedure either through measurement of artifacts at NIST or elsewhere

or by implementation of multiple test methods. Derive an uncertainty statement as above.

6.4 Angle Measurement

The major requirements for angle measurements associated with next-generation space-based optical systems will most likely involve configuration and alignment metrology[53]. Many measurements of this type employ calibrated angle transfer standards such as optical polygons, alignment cubes, optical squares, angle gage blocks, indexing tables, and pentaprisms. Calibration algorithms for such artifacts are usually self-calibration designs that rely on a circle closure constraint to eliminate the need for separately calibrated reference artifacts. In a typical circle closure measurement, nominally equal macroscopic angles are compared. The differences between these angles are measured using a small-angle transducer. The most common comparator is an electronic autocollimator.

Traceability of a measurement result requires

- realization of the unit,
- a valid uncertainty budget.

In angular self-calibrations, the unit (for example, the microradian ≈ 0.2 arc-sec) is realized by a calibrated autocollimator. Such calibrations, over the full range of a modern autocollimator (±500 arc-sec) have traditionally been very difficult. The NIST AAMACS system[54] has the potential to provide such calibrations with an uncertainty of ±0.02 arc-sec (k=2).

We envisage NASA/MSFC performing angular measurements using NIST-calibrated autocollimators. NIST also can provide detailed guidance on the preparation of valid and technically reasonable uncertainty budgets associated with angular measurements.

6.5 HDOS/AXAF Equipment

At least some of the metrology equipment and procedures for Constellation X may be put into service without high expense. This is the equipment developed at Hughes Danbury Optical Systems (HDOS) for the Chandra Observatory. This equipment includes tools for measuring the roundness, axial figure, and surface finish of the AXAF (now Chandra) optical elements, which have a similar geometry to those anticipated for Constellation X. The instrument design and fabrication, the measurement procedures, and the measurement results are well documented.[45,55] Therefore, NASA's initial job will be to reinstall the metrology tools in a controlled environment and reproduce the procedures for those mirrors in Constellation X whose lengths and diameters are compatible with measurement by the AXAF equipment. This will be an excellent basis upon which NASA can revisit and improve the tools and procedures for the requirements of Constellation X. The AXAF metrology equipment was calibrated using self-calibration principles, and we recommend that the same procedures be applied as the equipment is reinstalled. The original consulting team, including R. Hocken, J. Bryan, and R. Parks, could be involved in this project.

6.6 Aspheres

Because many of the actual mission observatory optics will be aspheres, the ultimate goal of the dimensional metrology laboratory for large optics is the traceable measurement by both NASA and its contractors of aspheres with accuracies consistent with the mission requirements. However, the variety of aspherical optics makes impossible the development of a systematic procedure for measurement of aspheres. Hence, we have not provided one here. Methods of measuring aspheres range over the use of spherical references for mild aspheres, high resolution cameras to discriminate high density fringe patterns, the fabrication of aspherical references matched to the test optics, and computer-generated holograms providing reference wavefronts matched to the test optics. A chosen procedure and the associated uncertainty statement will be highly measurement specific.

7 Overall Recommendations

- NASA must establish a primary standards laboratory for dimensional metrology of large optics in order to fulfill its advanced observatory missions. Such a laboratory would enable NASA to verify the dimensional accuracy of optics produced by NASA suppliers, enhance the metrology capabilities of its customers and suppliers in the nation's optical industry and avoid costly mistakes related to metrology.

- NASA must foster an institutional culture that emphasizes rigorous measurement procedures demonstrating traceability to the SI unit of length.

- Traceable measurement systems must be developed for surface finish, mid-spatial, and figure measurement of optics.

- For surface finish measurement, a procedure for achieving traceability is outlined. Critical properties of the instruments for making surface finish measurements on optical surfaces include the lateral resolution, the vertical resolution, and the scale calibration.

- For mid-spatial wavelengths, a procedure is outlined for achieving traceability. This procedure includes the use of specially machined sinusoidal waviness specimens.

- For measurements of flats, procedures are outlined for establishing the uncertainty of measurements obtained with NASA MSFC's 800 mm aperture Fizeau interferometer.

- The entire collection of figure and mid-spatial instruments must be relocated to an environment with temperature controlled to probably ±0.1 °C or better and good vibration and humidity control in order to produce good stability in the measurements and accurate values of the dimensional parameters to be measured. Currently, the horizontal LTP is in a space controlled to ±0.5 °C, which is marginally acceptable, and the vertical LTP is in a space that probably varies by ±2 °C. The most critical instrument of all, the Zygo 800 mm aperture Fizeau interferometer seems to be in an even more variable thermal environment. As an example, data on the laboratory for NIST's XCALIBIR is shown in Appendix B. Features of the laboratory include separate rooms for the optical system and the control electronics, controlled access to the optical system room through the control room, which itself has ±0.5 °C temperature control, and an air handling system that provides a Class 1000 clean environment.

- The surface finish instruments will also require good vibration and humidity control and approximately ±0.5 °C temperature control. The environment currently housing several surface finish instruments at MSFC may prove to be adequate.

- Stitching of the measured surface topography results in order to increase the effective aperture of the 800 mm interferometer will require the use of self-calibration techniques .

- New techniques may need to be developed for measurement of large spherical optics in a cryogenic, vacuum environment similar to that of the orbiting mission .

- With the development of proper traceable measurement techniques NASA will be directly traceable to the SI unit of length for figure measurement and traceable to the SI unit length through NIST for finish and mid-spatial measurements.

8 Acknowledgments

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APPENDIX A

Measurement Conditions and Sources of Uncertainty for NIST Roughness and Step Height Calibration Reports

March 19, 2001

The property of surface roughness average *Ra*[*] in the range 75 µm and below and step heights in the range 75 µm and below are currently measured at the NIST by means of a computerized/stylus instrument. Under our standard operation, we use an interferometrically measured step to calibrate the instrument on each value of magnification employed during a measurement. Profiles of the calibrating step and the step or roughness sample under test are stored in a computer using up to a 16-bit analog to digital conversion, depending on the instrument used.

In measurement of roughness, surface profiles are taken with a lateral sampling interval of 1 µm over an evaluation length of 4 mm. *Ra* values are then calculated as described in an appendix of American National Standard ASME, B46.1-1995.[A1]

Two parameters of the instrumentation are important in the specification of roughness measurements. These are the stylus radius and the high pass electrical cutoff. Our standard stylus has a radius of (5 ± 1) µm as profiled by the razor blade trace method[A2-A4] and calculated by a procedure found in the ASME B46.1-1995 standard. The nominal cutoff length of the high-pass electrical filter is 0.8 mm. The filter transmission characteristics are in accordance with the 2RC filter described in ASME B46.1-1995.

The above measurement conditions of evaluation length, sampling interval, stylus radius, and electrical filtering are the customary conditions for our roughness measurements. Any unusual experimental parameters are given in the covering report.

In step height measurements, a straight line is fitted by the method of least squares to each side of the step transition, and the height is calculated from the relative position of these two lines extrapolated to the step edge. In the case of a double step, two different algorithms may be used. An algorithm developed at NIST is ordinarily used. For the NIST algorithm, the step height transition on each side of the step is measured independently and the two results are averaged (Fig. A1). Alternatively, a variation of

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[*] Note: The considerations here also apply to measurements of rms roughness *Rq* with minor increases in the values of several of the uncertainty components.

the ISO algorithm, described in ISO Draft International Standard 5436-1,[A5] may be used. If so, it is explicitly stated in the covering report. Our implementation of this algorithm is described in Fig. A2.

Uncertainty of *Ra* Measurements:

The quoted expanded uncertainty U is equal to the combined standard uncertainty u_c times a coverage factor k (=2). The combined standard uncertainty u_c is the quadratic sum of the instrument standard uncertainty $u(I)$ and the statistical variation of the measurements s. The statistical variation of the measurements is mainly derived from the uniformity of the specimen under test, but it also includes instrumental random variation during the measurement process. It is calculated as one standard deviation (1σ) of the set of measured values. The instrument standard uncertainty for *Ra* is the quadratic sum of six uncertainty components. These are derived from:

(1) Height uniformity and surface finish of the step-height master used to calibrate the instrument. This leads to an uncertainty in stylus measurements of the step-height master to obtain the calibration constant for the instrument.

(2) Variations in the calibration constant due to noise in the stylus instrument transducer, surface topography in the reference surface for the stylus instrument, sampling and digitizing processes in the controller, and round-off in the software computations.

(3) Variations in the measured *Ra* values due to nonlinearity in the instrument transducer.

(4) Uncertainty in the average height of the step-height master as determined from interferometric and stylus measurements.

(5) Uncertainty in the horizontal resolution of the instrument. This is most often due to uncertainty in the stylus width. However, for very fine styli with good horizontal resolution, the resolution of the instrument itself may be limited instead by the frequency response of the electronics. Uncertainty in either quantity causes uncertainty in *Ra*, which also depends on the roughness and form of the profile. Quoted uncertainties represent estimates of the difference obtained when a surface is traced with styli of different radii. Two different model surfaces were used to provide entries in Table A1.

(6) Instrumental noise. This component tends to increase the *Ra* value and depends on which instrument is being used. For the high resolution instrument in our laboratory, the noise is considerably lower than it is for the two instruments with moderate resolution. This component is negligible for surfaces with *Ra* greater than about 0.1 µm.

Table A1 shows the uncertainty budgets for *Ra* measurements, expressed in accordance with guidelines at NIST.[A6] The entries are rounded to two significant digits except for component 6, which only requires one significant digit. The components depend on the magnification of the instrument and hence on the step-height master *H* used to calibrate the instrument. The six uncertainty components are shown in Table A1 as standard uncertainties. Components 1-3 are type A uncertainties.[A6] That is, they are standard deviations calculated by statistical methods. Components 4-6 are type B uncertainties, which are evaluated by other means.[A6] These uncertainty components are 1σ estimates calculated from models that estimate biases in the measured *Ra* values based on the identified uncertainty sources. The expressions used for each component depend on the calibration step height *H* and the *Ra* value itself, and on whichever instrument in our laboratory is used for the measurement.

The six components are added quadratically to yield the formulas for calculation of instrument standard uncertainty $u(I)$.

Uncertainty of Step Height Measurements:

As with *Ra* measurements, the quoted expanded uncertainty U for step heights is equal to $2u_c$, and u_c is the quadratic sum of $u(I)$ and s. Instrument standard uncertainty $u(I)$ for step height arises from the same sources already described for roughness, with the exceptions that components 5 and 6 are eliminated and component 3 includes a contribution arising from the surface topography in the reference surface for the stylus instrument. Concerning components 5 and 6, neither the horizontal resolution nor the instrumental noise causes offsets in the step height measurements. Instrumental noise, however, contributes to the random variation of the measurement results s about the mean value. The formulas used to calculate the measurement uncertainty depend on the height of the measured step X and the height of the calibration step H and are given in Table A2.

The uncertainty reported by NIST represents only the estimated uncertainty in the NIST calibration of the customer's specimen. Additional uncertainties arising in the customer's use of the specimen (e.g., to transfer a calibration to another device) should be evaluated by the customer.

Additional information on the NIST surface measurement system is contained in the following references. References A2-A4 and A7-A11 may be obtained from us upon request.

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Table A1: Uncertainty Budgets for NIST Roughness Measurements

(R = measured *Ra* value, H = NIST step height master)

	Standard Uncertainty Components						Instrument Standard Uncertainty, $u(I)$ $= [(u^2(1) + ... + u^2(6)]^{1/2}$
H (μm)	1	2	3	4	5 (nm)	6 (nm)	
0.02937	0.014 R	0.0064 R	0.0018 R	0.0073 R	0.13	0.08	$[(0.017\ R)^2+(0.15\text{nm})^2]^{1/2}$
0.09065	0.0035 R	0.0030 R	0.0018 R	0.0024 R	0.13	0.08	$[(0.0055\ R)^2+(0.15\text{nm})^2]^{1/2}$
0.3024	0.00085 R	0.0015 R	0.0012 R	0.0041 R	3.5	0.08	$[(0.0046\ R)^2+(3.5\text{nm})^2]^{1/2}$
	1 and 2 Combined						
1.0157	0.0054 R		0.0012 R	0.0012 R	3.5		$[(0.0057\ R)^2+(3.5\text{nm})^2]^{1/2}$
2.587	0.0054 R		0.0012 R	0.0093 R	3.5		$[(0.011\ R)^2+(3.5\text{nm})^2]^{1/2}$
3.0289	0.0054 R		0.0012 R	0.0064 R	3.5		$[(0.0085\ R)^2+(3.5\text{nm})^2]^{1/2}$
12.668	0.0054 R		0.0020 R	0.0047 R	3.5		$[(0.0074\ R)^2+(3.5\text{nm})^2]^{1/2}$
22.90	0.0054 R		0.0020 R	0.00087 R	3.5		$[(0.0059\ R)^2+(3.5\text{nm})^2]^{1/2}$
152.37	0.0054 R		0.0020 R	0.00066 R	3.5		$[(0.0058\ R)^2+(3.5\text{nm})^2]^{1/2}$

Combined Standard Uncertainty, $u_c = [(u^2(I) + s^2]^{1/2}$

Expanded Uncertainty, $U = 2u_c$

Table A2: Uncertainty Budgets for NIST Step Height Measurements

(X = measured step height value, H = NIST step height master)

	Standard Uncertainty Components				Instrument Standard Uncertainty, $u(I)$ $= [(u^2(1) + ... + u^2(4)]^{1/2}$
H (μm)	1	2	3	4	
0.02937	0.014 X	0.0064 X	0.0018 X	0.0073 X	0.017 X
0.09065	0.0035 X	0.0030 X	0.0018 X	0.0024 X	0.0055 X
0.3024	0.00085 X	0.0015 X	0.0012 X	0.0041 X	0.0046 X
1.0157	0.0010 X	0.0015 X	0.0012 X	0.0012 X	0.0025 X
2.587	0.0013 X	0.0014 X	0.0012 X	0.0093 X	0.0096 X
3.0289	0.0010 X	0.0016 X	0.0012 X	0.0064 X	0.0068 X
12.668	0.00095 X	0.0012 X	$[(0.0020\ X)^2+(8.7\text{nm})^2]^{1/2}$	0.0047 X	$[(0.0053\ X)^2+(8.7\text{nm})^2]^{1/2}$
22.90	0.0013 X	0.00079 X	$[(0.0020\ X)^2+(8.7\text{nm})^2]^{1/2}$	0.00087 X	$[(0.0027\ X)^2+(8.7\text{nm})^2]^{1/2}$
152.37	0.00073 X	0.00053 X	$[(0.0020\ X)^2+(8.7\text{nm})^2]^{1/2}$	0.00066 X	$[(0.0023\ X)^2+(8.7\text{nm})^2]^{1/2}$

Combined Standard Uncertainty, $u_c = [(u^2(I) + s^2]^{1/2}$

Expanded Uncertainty, $U = 2u_c$

Step Height Algorithm Diagrams

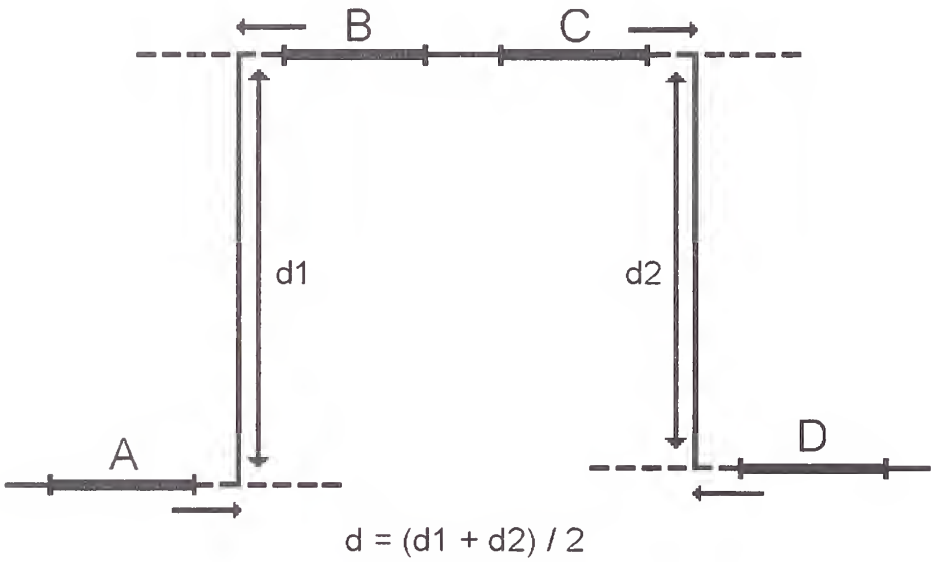

Fig. A1: NIST algorithm for step height measurement.
The fitted straight lines, A, B, C, and D, are extrapolated to the step edges to produce edge values d1 and d2, which are then averaged.

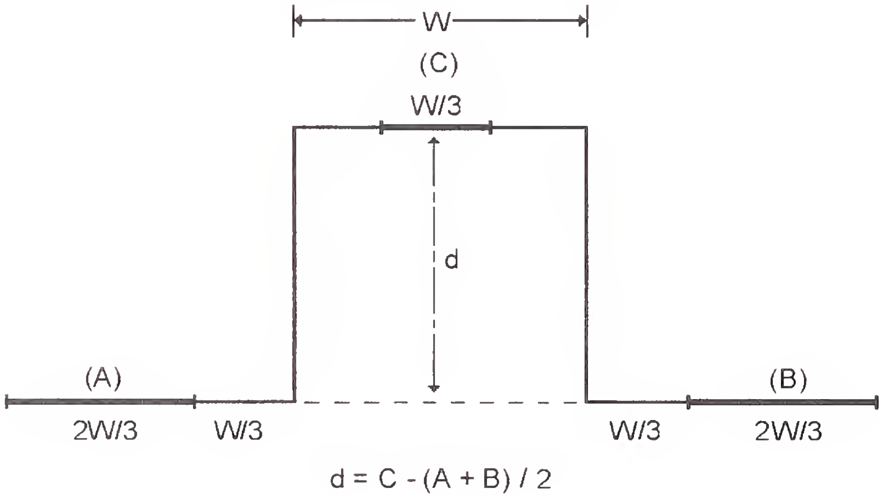

Fig. A2: ISO algorithm.

APPENDIX B

Environmental Control for Metrology Laboratories

Metrologists constantly have to deal with the effects of environmental fluctuations on both the measuring instrument and the part being tested. Naturally, no general rules can be given since the sensitivities depend on the response of the specific instrument and the part; a number of basic concepts are defined, however, in ANSI B.89.6.2 *Temperature and Humidity Environment for Dimensional Measurement*. In addition to temperature, pressure and humidity variations, precision measurements of optics can also be affected by vibration, electrical noise, and variations in the refractive index of air caused by trace hydrocarbons and other compositional variations.

A general procedure for defining the needed environmental control for any one of NASA MSFC's current metrology instruments would be first to estimate the response (and response time) of the instrument to various environmental changes. Next, perform a drift test while monitoring those environmental variables. The results can be used (see ISO Draft Technical Report 16015) as input to generate the appropriate uncertainty component as well as to indicate what improvements are needed.

Note that an economic trade-off is involved in specifying the environment. For many optical measurements, less than optimal environmental control can be mitigated by such strategies as massive averaging of data taken throughout the range of environmental variation experienced, or taking data at more stable periods (late at night, for example). Such approaches cannot be adopted without careful analysis and can add significantly to the cost of individual measurements. The uncertainties arising from environmental issues often dominate the uncertainty budget.

For new instruments, more engineering judgement is required. For example, experience with precision interferometry guided the specification of the environment built for XCALIBIR before we could test the instrument response. Figure B1 shows the physical layout and ducting design. Figure B2 shows the operating principle of the air temperature control system, the set-up for performance testing, and the mean temperature stability achieved. Figure B3 is an instrument overview that orientates the reader to understand the temperature gradient plots shown in Figure B4; these emphasize the importance of controlling not just average temperature but of localized heat sources.

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Figure B1: Physical Layout and Ducting Design of XCALIBIR Laboratory

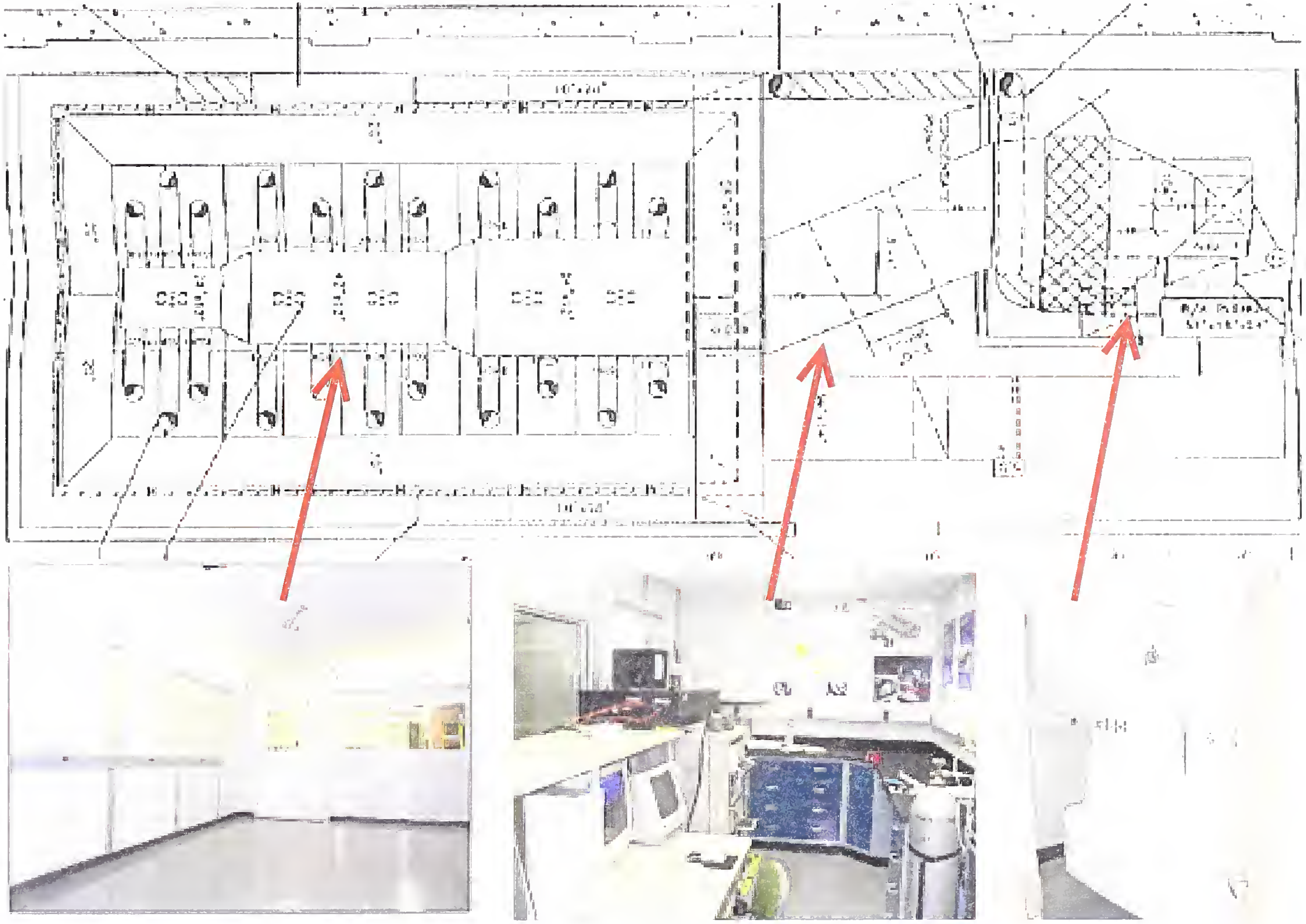
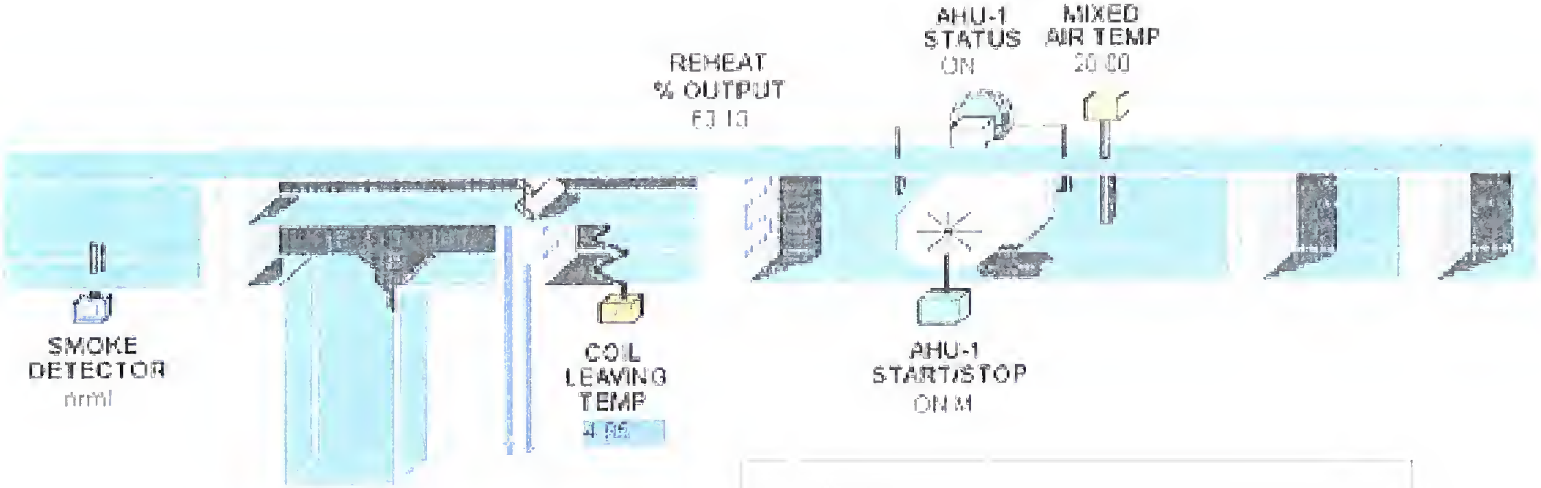
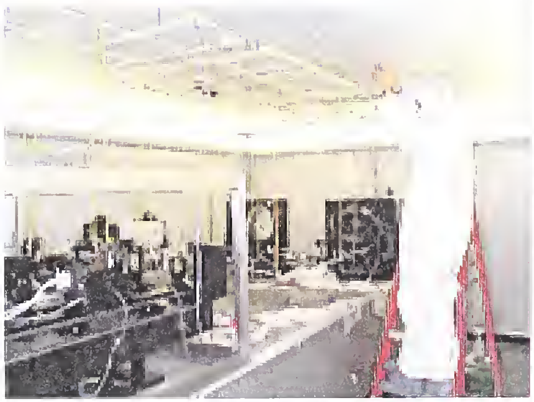
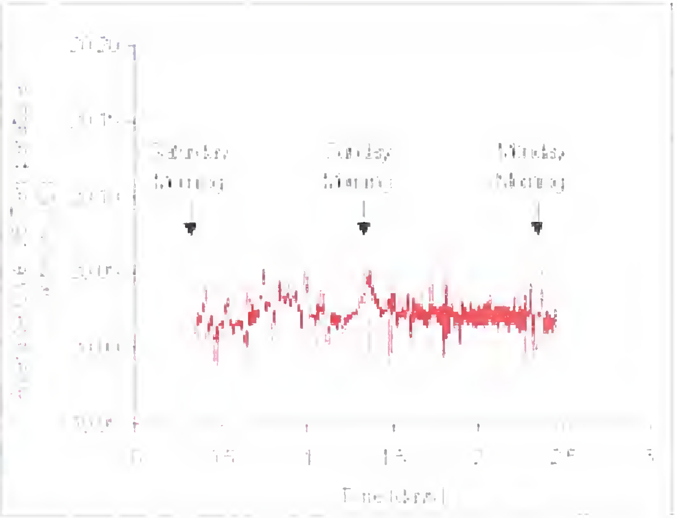


Figure B2: Air Temperature Control System of XCALIBIR Laboratory







36 sensors spanning table area

- 60 cm x 45 cm grid array 30 cm above table

Figure B3: Layout of XCALIBIR Components.
DMI - *displacement measuring interferometer.*

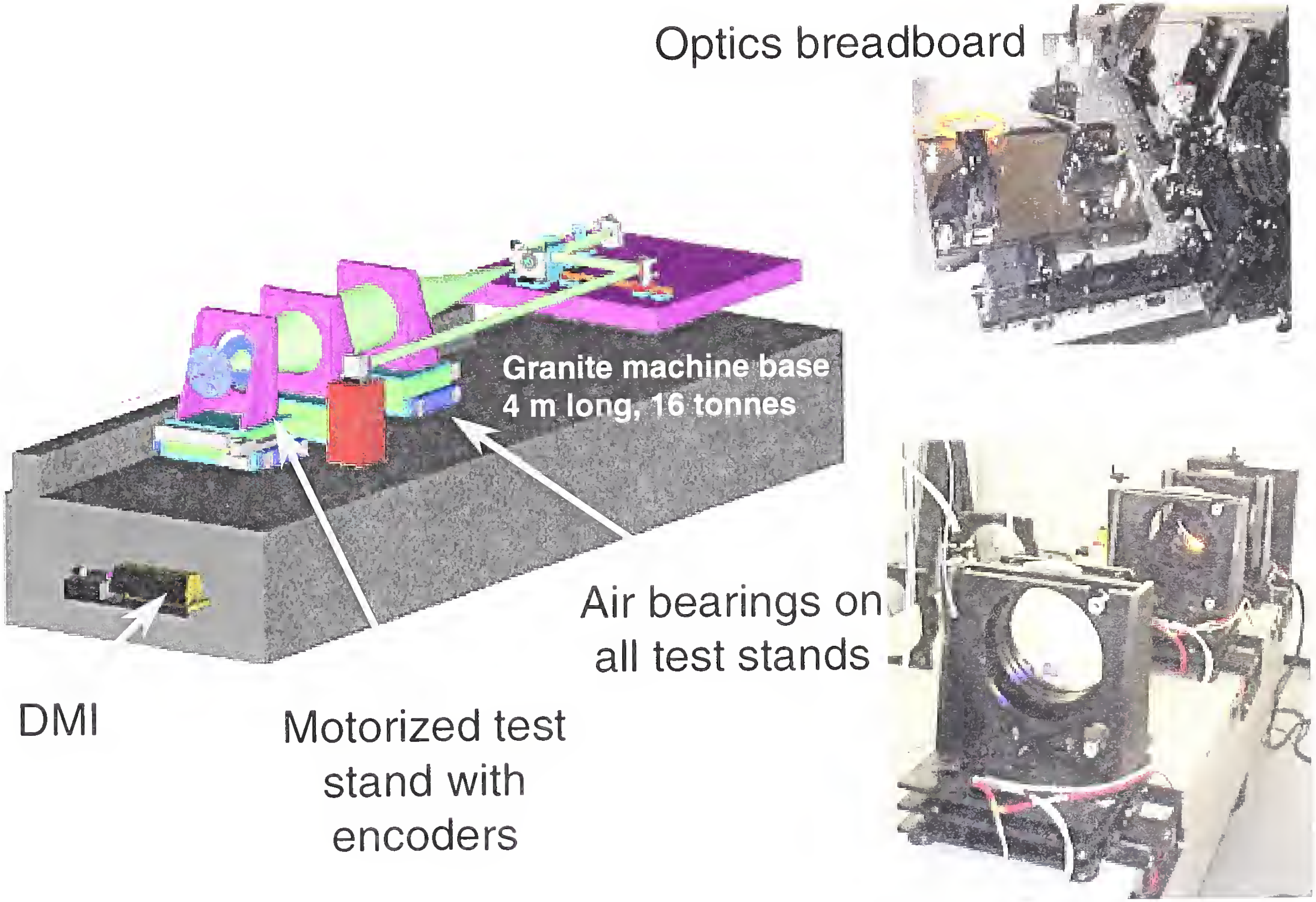
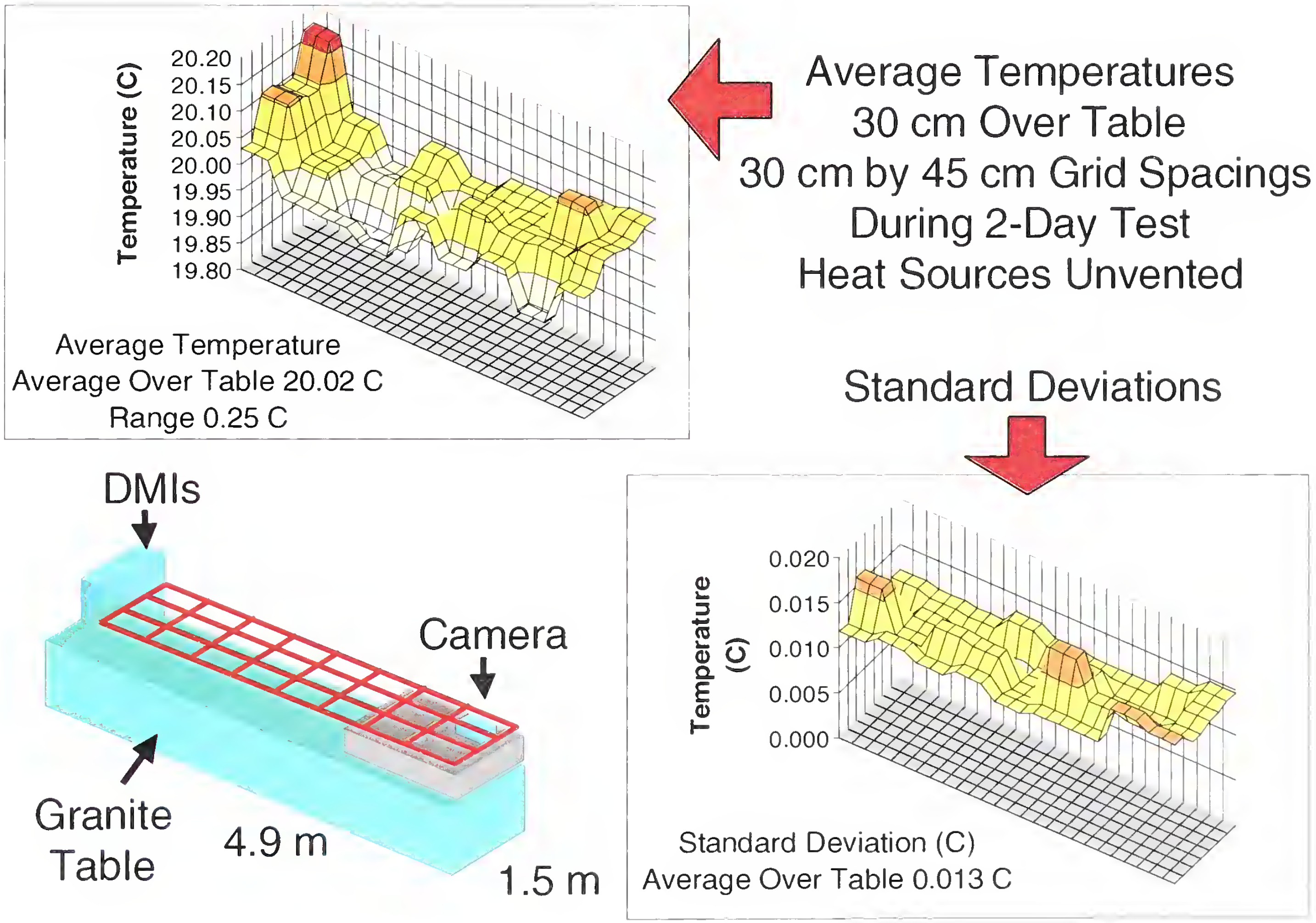


Figure B4: Temperature Measurements in the XCALIBIR Laboratory.
DMI - *displacement measuring interferometer.*



Average Temperatures
30 cm Over Table
30 cm by 45 cm Grid Spacings
During 2-Day Test
Heat Sources Unvented

Standard Deviations

Average Temperature
Average Over Table 20.02 C
Range 0.25 C

Standard Deviation (C)
Average Over Table 0.013 C