ABSTRACT
This paper describes the recent progress and planned upgrades to an already developed long range scanning stage, previously referred to as the Sub-Atomic Measuring Machine (SAMM) [1]. Presented are improvements to achieve a resolution of ten picometers from the laser interferometers and efforts to decrease the positioning noise and lower the measurement uncertainty. The final upgrade will be the addition of an atomic force microscope with a high bandwidth vertical axis to measure precision artifacts.

INTRODUCTION
The Sub-Atomic Measuring Machine, developed by M. Holmes, has a neutrally buoyant platen floated in silicone oil over four linear motors. The motors are a novel Halbach array linear motor design that positions the stage in six degrees-of-freedom. A Zerodur target mirror and measurement sample assembly is elevated above the oil's surface by a flexure-based Kelvin clamp coupled to the platen. The metrology frame, also of Zerodur, holds three 4-pass laser interferometers and three capacitance gages which read against the target mirror / sample holder. An enclosed metrology chamber above the oil level provides increased stability and environmental isolation from the laboratory. A closed loop control system positions the stage in the travel volume.

Previously, the stage demonstrated sub-nanometer positioning noise [2]. At this time there is little need to redesign the mechanical aspects; therefore the major thrust area for current upgrade on the SAMM is the metrology system. The control system has been updated to National Instruments hardware and software to increase the bandwidth and improve disturbance rejection. The laser interferometer electronics have been altered to reach a resolution of 10 picometers. At the same time, the laser delivery is being upgraded to working helium neon lasers offset locked to an iodine stabilized laser. Significant effort has been placed on the refractive index variation and methods to correct the interferometer measured displacement for these changes. The capacitance gage electronics have also been upgraded in an effort to reduce the noise in these sensors as well.

ULTRA-PRECISION INTERFEROMETRY
The interferometers used on the SAMM are based around a heterodyne laser source. Therefore, the light intensity monitored by the photodetector is time varying at the heterodyne frequency and has a phase term that depends on the difference in optical paths between the reference arm and the measurement arm of the interferometer. The interferometers on SAMM are designed such that at the “home” position the reference arm and measurement arm mirrors are equidistant from the interferometer cube resulting in zero deadpath. This minimizes the effects of the environment because both arms effectively see the same refractive index at home. The travel from home is plus or minus 12.5 millimeters, minimizing the maximum optical path length difference to 12.5 millimeters rather than the total travel of 25 millimeters. A phase change results for a change in displacement or a change in refractive index in the interferometer arm. It is unfortunate that the interferometer cannot distinguish between a change in refractive index and a change in measurement arm length. Methods to correct for this undesirable refractive index variation are discussed in the following sections as are the considerations for displacement resolution and wavelength stability.

Resolution Considerations
Upgrades now allow a positioning resolution of 10 pm from the laser interferometers. Commercially available laser systems do not meet these resolution requirements even with stage’s 4-pass interferometer optics. The detection scheme used on the SAMM down converts the laser heterodyne frequency to increase the detection resolution. This frequency shift comes at the expense of the
stage velocity but is acceptable for this application. The laser heterodyne frequency is 20 MHz based on the previously used commercial laser. The reference signal and detector signals are mixed to 8 kHz in custom electronics. Note that the laser interferometers and detectors still operate at 20 MHz instead of 8 kHz to minimize interference that may be more likely at lower frequencies. Zero crossing detectors convert the conditioned signals to TTL signals that are sampled by time interval analyzers. Displacement is determined from the time interval between pulses on the measurement signal as compared to the reference signal. In this way, the time resolution of the time interval analyzer limits the position resolution. The time interval analyzers have been upgraded from 20 ns resolution to a time resolution of 12.5 ns.

The theoretical resolution of the laser interferometers on the SAMM now reaches the 10 picometer specification. This has been demonstrated experimentally for the entire detection scheme with the exception of the detectors, which are currently the main source of noise in the system [3].

**Stable Laser Delivery System**
A higher power laser source is in development and is expected to improve the detector signal to noise ratio. The Zygo 7702 laser head is being discarded in favor of a laser tube offset locked to an iodine-stabilized laser (ISL) with an acousto-optic modulator providing the 20 MHz heterodyne frequency split [4]. The power increase from this laser is in addition to the wavelength stability advantage. The working laser for the SAMM will be offset locked from this source. Significant effort has focused on matching the stability of the iodine-stabilized laser in the working laser. Fast pressure variations were found to cause an uncontrollable disturbance on the thermal control of the sealed cavity laser tube. Passive pressure decoupling now limits the peak to peak frequency variation between the ISL source and the working laser within a few parts in $10^{11}$.

Figure 1 shows the layout of the optical components to complete the assembly of the offset locked laser delivery system. The light that escapes from the dim end of the tube is used for the lock-in procedure and the bright end is used as the signal for the interferometers. The bright source passes through an acousto-optic modulator and prism and results in at least 1.0 mW of usable power after the heterodyne split. The dim end combines with the ISL supply in a beamsplitter. A polarizing optic interferes the polarization states of the two light beams before the avalanche detector. The lock-in is completed by closing the loop on the frequency monitored by the detector and controlling the voltage to a heater fixed radially on the laser tube using a digital PID control algorithm. A more detailed description of this system is given by C. Stroup et al. [5].

**Refractive Index Variations**
With increasing demands on ultra-precision machines and metrology instruments, the sources of error that were previously of little influence now dominate the error budget. One of these sources relevant to interferometry is the refractive index. For example, recent research with frequency comb lasers has increased the wavelength stability to even greater levels. However, when using this technology for interferometry in air, the uncertainty is dominated by the uncertainty in the refractive index. The refractive index alters the wavelength of light passing through a medium and combines with the interferometer position measurement. A change in refractive index appears in the measurement as a length change leading to an error in the true position unless proper corrections are made. The variation of the refractive index adds to the uncertainty of interferometer-based positioning stages and measuring machines even with mathematical corrections based on temperature, pressure and humidity. State-of-the-art environmental
sensors will only allow corrections in air to an uncertainty of approximately $1 \times 10^{-7}$. Vacuum provides orders of magnitude improvement but practical implementation is difficult and not considered for the SAMM. For this application, helium has proven to be an attractive alternative.

**Using Helium in Precision Measurements**

The mathematical correction in helium can have an uncertainty as low as $1 \times 10^{-9}$ or better, two orders of magnitude improvement over air [6]. The absolute refractivity is approximately 8 times lower for helium as compared to air. This relaxes the required accuracy of the atmospheric sensors to meet the same accuracy in helium as that of air. In essence, the sensors can be a factor of 8 less accurate. The thermal conductivity is approximately 5.75 times greater for helium as compared to air at standard temperature. This allows the sealed chamber to dissipate heat faster and reduce thermal gradients that are inevitably troublesome in precision systems even when the heat loads from the instrument are minimized.

**FIGURE 2. Pressure and temperature variations during the purge process from air to helium.**

The main disadvantages of the use of helium in the SAMM are purging, purity, leakage and pumping effects. The design of SAMM does not permit pumping to extreme vacuum levels for purging. Figure 2 shows the pressure and temperature variations during a purge process in creating the helium environment. The number of purge cycles need to reach the desired level of purity was calculated theoretically. In this case, 19 iterations were used whereby the pressure was reduced by at least half of an atmosphere and then back filled above atmospheric pressure with helium. Notice the work on the gas from pumping results in a temperature swing of approximately 7° C as measured with a single point measurement by a thermistor suspended in the chamber. This temperature swing has also been observed using a shielded thermocouple monitoring surface temperature. The resulting temperature after the purge process approaches the initial temperature. These temperature swings can create thermal stresses in the assembly of components and require significant time for the thermal gradients to subside prior to measurement initiation.

**Wavelength Tracking Interferometer**

After purging the chamber to a certain purity level of helium, containment and contamination become the major concerns. It was decided to over pressurize the chamber with helium in an effort to solve the contamination issue. This decision was based on diffusion calculations and experiments that concluded the helium leakage would occur at a faster rate than diffusion.

**FIGURE 3. Layout of the wavelength tracking interferometer on the SAMM metrology frame. (White lines representing the laser beams are added for clarity.)**

To address the purity concerns and more accurately correct the laser interferometers, a custom wavelength tracking interferometer was added. In this way, any leakage of the helium or change in purity will be compensated and monitored by the tracker. The optical design eliminates beam mixing and mounts to the existing metrology frame, see figure 3. Lines have been added to indicate the optical path in the reference arm and the measurement arm denoted by $f_1$ and $f_2$, respectively. The paths of
the discarded beams are not shown but in practice are present in the system since the pellicle beamsplitter is non-polarizing. The optical path length difference is approximately 0.8 m.

For preliminary experiments a Zygo 7702 laser was used. A birefringent prism was added inline between the laser head and tracker optics to separate the beam into individual frequency components. In the end, a new laser delivery scheme similar to the one previously described will be used such that the two polarization states will not be recombined after the acousto-optic modulator.

FIGURE 4. Pressure and temperature variations and the resulting tracker response to the laboratory air deviation.

FIGURE 5. Pressure and temperature variations and the resulting tracker response to the sealed helium environment deviations.

Figure 4 and figure 5 show the pressure and temperature variations and the resulting tracker response in air and helium, respectively. As expected, the data in air show a pressure dependence of approximately 0.36 ppm/mmHg. The helium data show a reduction in the pressure sensitivity of approximately 8 to 0.045 ppm/mmHg. In the end, closed loop control of the chamber pressure will reduce the amplitude of the variations further lowering the uncertainty in the compensation.

SUMMARY AND CONCLUSION
Efforts are underway to upgrade the metrology components on the Sub-Atomic Measuring Machine. These upgrades include a helium atmosphere for enhanced resolution to 10 pm and a custom wavelength tracking interferometer. An offset locked laser delivery system will further lower the uncertainty and provide direct traceability to the definition of the meter. With the scheduled updates completed and the integration of a new atomic force microscope, the measuring machine will be well suited for ultra-precision measurements of various samples. The first measurements will be used to map the repeatable errors of the stage such that these can be compensated. Other samples will include calibrated artifacts to verify the accuracy of the positioning system.

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REFERENCES