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Progress Toward Ultra-Stable Lasers for Use in Space

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INTRODUCTION

This is a summary of a research project that has come to be known as SUNLITE, initially standing for Stanford University NASA Laser In-space Technology Experiment. It involves scientists from the NASA Langley Research Center (LaRC), Stanford University, the National Institute of Standards and Technology (NIST) and the Joint Institute for Laboratory Astrophysics (JILA) and a growing number of other institutions. The long range objective of the SUNLITE effort is to examine the fundamental linewidth and frequency stability limits of an actively stabilized laser oscillator in the microgravity and vibration-free environment of space. The ground-based SUNLITE activities supporting that objective will develop a space-qualified, self-contained and completely automated terahertz oscillator stabilized to a linewidth of less than 3 Hz, along with a measurement system capable of determining laser linewidth to one part in 10^{16}. The purpose of this paper is to discuss the critical technologies needed to place stabilized lasers in space and to describe the progress made by the SUNLITE project to develop these technologies.

SUNLITE grew out of LaRC's interest in developing laser sources for remote sensing of the atmosphere. It became clear in the mid-1980's that the stringent requirements imposed by the long term, unattended operation of lasers in space could be satisfied by the emerging semiconductor diode laser pumped solid state laser technology [1,2]. Research supported by LaRC and directed by R. L. Byer at Stanford University's Ginzton Laboratories led to the development of an extremely stable, diode pumped, solid state laser operating as a non-planar ring oscillator (NPRO) [3,4]. This laser, now in commercial production, has a free running linewidth of about 5 kHz, a relative frequency stability of one part in 10^{10} [6]. During this same period of time, work at NIST and JILA at Boulder, Colorado under J. L. Hall refined techniques for the active stabilization of lasers through the development of the Pound-Drever-Hall frequency modulation locking technique [7,8]. This technique replaces the laser cavity as a frequency reference standard with an extremely high finesse external reference cavity ($Q > 100{,}000$) and this has led to record frequency stability. Using the active stabilization technique developed at NIST, the Byer group was able to reduce the linewidth of their Nd:YAG laser to 0.3 Hz (one part in 10^{15}) -- 20 times above the shot noise limit [9,10].

The narrow laser linewidth achieved in these experiments was broadened by the technical noise in the laboratory environs. Attempts to further improve the stability of lasers in ground based laboratories have been limited by environmental and microseismic noise and by gravity induced distortions in the optical devices used as frequency references. Both the noise and gravity effects will be significantly reduced in the space environment. The broadening of a laser's linewidth due to laboratory induced vibration should be removed by taking it to space; furthermore, the reduction of body forces on the reference cavity should also improve performance. Consequently, it is expected that these laser oscillators would operate even more stably in space where vibrational and gravitational effects are significantly reduced.

Demonstrating the improved performance of stabilized lasers in free-flight is the crucial first step to providing a compact, automated, high brightness light source for use in space. Space is the uniquely appropriate environment for a variety of important applications of ultra-stable lasers. These applications include deep space coherent communications, time transfer among satellite systems (for example, in the global positioning system, GPS), astrometry, laser radar for location and docking and laser-gyro rotation sensors. Ultra-narrow linewidth lasers will also enable fundamental scientific investigations such as the detection of gravity waves and new tests of the theory of relativity. Stabilized lasers will provide the fundamental oscillator for a new generation of optical clocks with accuracy up to one part in 10^{17}, orders of magnitude better than current atomic clocks.

SUNLITE PROGRAM OBJECTIVES

The SUNLITE project is developing a basic understanding of the phenomenological processes involved in the design of ultra-stable lasers for use in space. Eventually, when deployed in space, SUNLITE would enable the verification of improved stability of laser oscillators in the space environment and demonstrate that this stability is limited by photon shot noise. The specific technological products of the SUNLITE project will be a completely autonomous Nd:YAG laser oscillator, whose frequency is actively stabilized by locking it to a high finesse reference cavity and a measurement system capable of characterizing the laser linewidth variations to one part in 10^{16}; both the stabilized laser and its measurement system were designed to meet the requirements of a space mission.

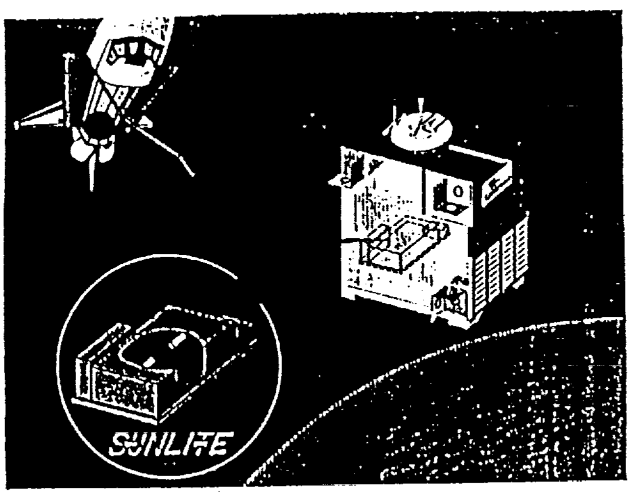


Figure 1. Schematic diagram of the deployment of the SPARTAN carrier by the Space Shuttle and the SUNLITE instrument within it.

THE SUNLITE INSTRUMENT

The purpose of this instrument is to demonstrate narrow linewidth operation of lasers in the quiet environment of space. This involves building the laser oscillators into a small, rugged and autonomous package which incorporates a measurement system to characterize their performance in space. This characterization is accomplished by comparing the temporal characteristics of laser linewidth variations obtained from the beatnote signal of two actively stabilized lasers.

The following paragraphs describe the instrument package as it was originally designed for a spaceflight technology demonstration. The vibration-free and thermally quiet environment is provided by free flight on the Spartan carrier, a structure designed by Goddard Space Flight Center. Spartan is carried to orbit on the Space Shuttle, released from the Shuttle for approximately 40 hours of free flight and then retrieved by the Shuttle and returned to earth. Figure 1 shows the location of the SUNLITE instrument package on the Spartan carrier.

Instrument Overview

The SUNLITE instrument will consist of three actively stabilized lasers configured to execute two experiments and a system to measure the linewidths of these lasers. A digital signal processor provides for autonomous control of the instrument; custom designed mounts and packaging techniques serve to isolate the entire instrument from its environment. The three lasers are arranged on an optical bench which is isolated from components not required for laser stabilization and the low noise frequency measurement.

The instrument layout, sketched in Figure 2, consists of the optical bench and cover, an electronics box, and the hard disc drive canister, all fastened to a main mounting plate bolted to a bulkhead plate within the Spartan spacecraft. The instrument is entirely enclosed within Spartan, with no view to the exterior environment, so the SUNLITE instrument is relatively isolated from cyclical orbital temperature changes. The mounting plate is aluminum, with stiffeners milled in to increase the stiffness without undue mass. The thermal conduction of the aluminum acts to dissipate local hot zones on the mounting plate. The mounting plate is connected to the Spartan bulkhead by long bolts with thermoplastic standoffs to decrease the thermal connection to Spartan. The thermal mass of the plate will absorb thermal transients from the spacecraft.

The optical bench is of sandwich construction, with Super Invar plates on each side of an aluminum honeycomb core. The extremely low coefficient of thermal expansion (CTE) of the Super Invar will reduce the changes in shape and size of the bench due to temperature extremes and limit the transfer of heat from the powered components on the bench to the transient-sensitive components, such as the reference cavities. The honeycomb core gives the plate a high stiffness to minimize warping when the bench goes from a 1-g environment on Earth to the micro-g environment of space. The bench is fastened to the aluminum mounting plate using a three-point mounting technique. Two of the mounting points use a flex-beam mount to allow expansion and contraction of the aluminum plate without inducing stresses in the Invar bench. This will minimize warping of the bench due to thermal changes in orbit. These mounts are to be fabricated from stainless steel to isolate the optical bench components from the thermal changes at the mounting plate.

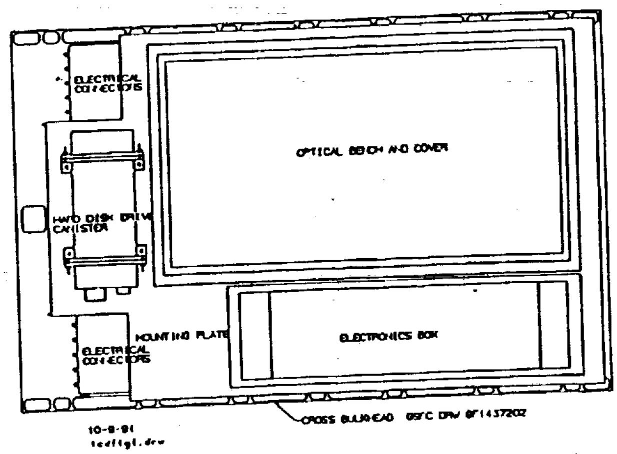


Figure 2. Instrument layout: optical bench and cover, electronics box and hard disc drive canister.

The components on the optical bench are arranged as shown in Figure 3. The optical paths are indicated by solid lines. Many of the optical component mounts incorporate varying degrees of adjustability so that the system can be manually aligned with a high degree of precision. All components incorporate some type of locking function so that the component can be locked in place when final alignment is achieved. All component mounts have been designed to meet space-flight requirements for stress margins and minimum normal modes of vibration; many have been fabricated.

The lasers used in the instrument are Nd:YAG lasers operating as monolithic non-planar ring oscillators (NPRO) made by Lightwave Electronics (Model 120-01A). The free running linewidth of these lasers has been measured to be between 1 and 5 kHz. Each laser includes a piezo-electric transducer bonded to the laser ring which provides linear tuning of the frequency with a coefficient of 1 MHz per volt. They are also tunable with temperature over a 15 GHz range with coefficient -1.2 GHz per volt.

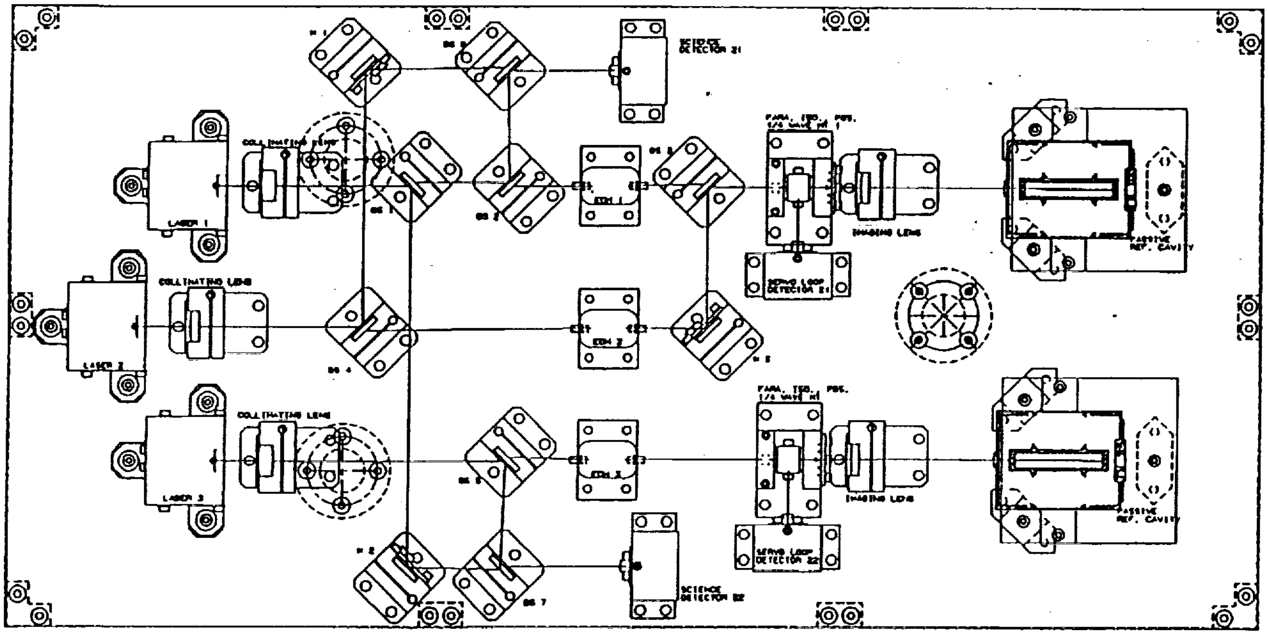


Figure 3. Layout of optical bench components. Optical paths are represented by solid lines.

The electronics box contains twelve electronics cards which are each separately accessible for rework after assembly. This box is bolted directly to the mounting plate to allow for dissipation of heat from the electronics. The hard disc drive canister is a sealed package containing two commercial type 120 Mbyte hard disc drives; it has already been fabricated. These disc drives have survived flight-level environmental testing for thermal and vibration levels.

The electronics subsystem is designed as a general purpose control and data acquisition system. The centerpiece of this system is the TI SMJ320C30 digital system processor. The system clock runs at 33 MHz and the processor is capable of 33 MFLOPS and 16 MIPS. Solid state RAM stores data when vibration is a concern and there is 48 Mbytes of static RAM. For long term, nonvolatile data storage a SCSI bus links the processor to 240 Mbytes in two Winchester type hard disc drives. This SCSI bus could handle up to seven drives. There are 96 data acquisition channels designated for environmental measurement. The measurement of laser frequency is performed by a single 9"x9" printed circuit.

Laser frequency measurement is accomplished by mixing down the science photodetector output which is the beatnote signal between two stabilized lasers. The downconversion requires two stages and includes a frequency synthesizer in the final stage. The output at this point has frequency between 0.5 and 40 KHz. This signal is analyzed by a time interval counter with a time resolution of 60 picoseconds. Each period can be measured to provide a minimum measurement time of 25 microseconds.

The Measurement Concept

In order to examine the stability characteristics of the most stable laser oscillator developed to date it is necessary to compare the performance of one laser oscillator with that of another. This will be accomplished by analyzing the noise spectral density in the heterodyne beat note from two laser oscillators to determine the laser linewidth. The three lasers are configured for two independent experiments. In one experiment, two of the lasers are locked to separate high finesse reference cavities forming two independent stabilized oscillators. In the other experiment, two lasers will be locked to adjacent modes of a single cavity. In either case the heterodyne beat note signal is mixed down to audio frequencies and analyzed.

The instrument will measure successive periods of the beatnote signal and reciprocate these to obtain successive frequencies from which the mean frequency and Allan Variance can be calculated. This zero crossing method was chosen because it requires less memory space for the raw data and less computer time to extract the noise components.

Design Considerations for Critical Components

It is useful to look at the laser oscillators as a control system with the laser as the plant, an optical frequency discriminator as the reference point and the PZT (Pb (Lead) Zirconium Titanate) piezo-electric material bonded to the laser cavity as the actuator which applies the error signal back to the plant [11]. The actual control technique employed is a form of frequency modulation (FM) locking called Pound-Drever-Hall locking [8,9] (See Figure 4). In this technique the laser is phase modulated and coupled into a high finesse cavity. The optical signal reflected from the cavity experiences a dispersive phase shift centered on the cavity resonance. The dispersive nature of this phase shift is recovered and converted into a voltage to correct excursions of the laser frequency from

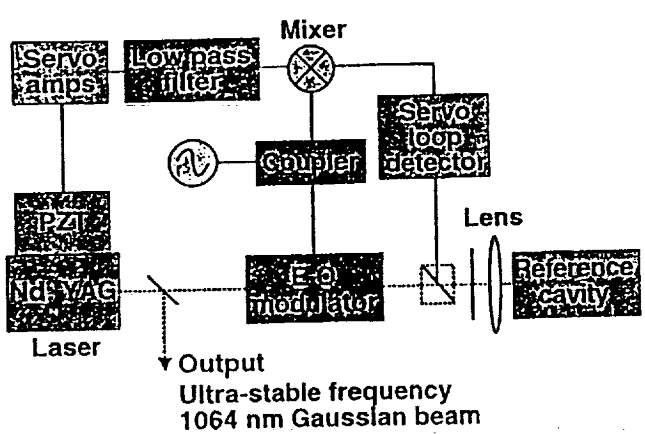


Figure 4. Schematic diagram of the Pound-Drever-Hall, FM Locked Laser Oscillator.

the cavity resonance frequency. Seen from a controls system point of view, the laser frequency discriminator includes the reference point to which the laser frequency is compared and controlled and the optical and electronic components needed to generate an error signal which can be applied to the actuator. The frequency reference used is a stable, standing optical wave cavity or resonator. The error signal is produced by phase modulating the laser and detecting the modulation frequency as modified by the complex, dispersive phase response of the cavity with a photodetector.

Reference cavity

The most critical component of this discriminator is the optical reference cavity, consisting of a pair of high reflectivity (R=0.99998) mirrors separated by a low coefficient of thermal (CTE) expansion glass spacer. The cavity's length determines its resonant frequency with subatomic length changes causing significant changes in the resonant frequency. In fact, it is in search of an environment which does not cause the cavity length to change that leads to putting these oscillators in space. Vibrational noise is reduced significantly in space so that thermal noise becomes the dominant driver of fluctuations of the reference cavity length. In the current design, the cavity temperature is controlled passively.

The design of the reference cavity must accommodate several often contradictory objectives. The reference cavity must remain stable in position and undistorted throughout the processes of alignment, test, launch and operation. The cavity must be sealed from the environment to avoid contamination of the mirrors. The mechanical design of the support must be rugged enough to allow it to survive launch vibrations without motion, yet the thermal path must be limited so that the cavity remains thermally stable during operation. The position of the mount must remain fixed with respect to the other components during any thermal cycles which may occur. The difficulty of meeting the design objectives led to the design, fabrication and test of a prototype cavity mount used to test methods of supporting the cavity and to verify the thermal and structural modeling of the cavity mount. The initial prototype was thermally and structurally tested and met all thermal and structural requirements The latest design includes precision adjustment capability as well as improvements in thermal isolation and material selection.

The new design, shown in Figure 5, as generated by the Pro-Engineer CAD software, incorporates three mounting feet which are separately adjustable to meet alignment requirements for adjustability. After alignment, the feet are locked down by fastening a through-bolt and potting with epoxy. A reinforced thermoplastic is used for the mount, which minimizes the thermal path to the cavity.

The glass cavity is supported inside a sealed Super Invar case. The case is evacuated and sealed to ensure that the cavity will not be contaminated during ground testing. The low CTE of the Super Invar will minimize stress and distortion of the glass cavity due to thermal gradients. The glass cavity is supported within the casing by thin titanium alloy struts. These minimize the thermal path to the cavity, while avoiding the outgassing which would exist if a thermoplastic were used within the case. The mirrors at the ends of the cavity are optically bonded to the glass spacer to ensure that there is no material other than the low expansion

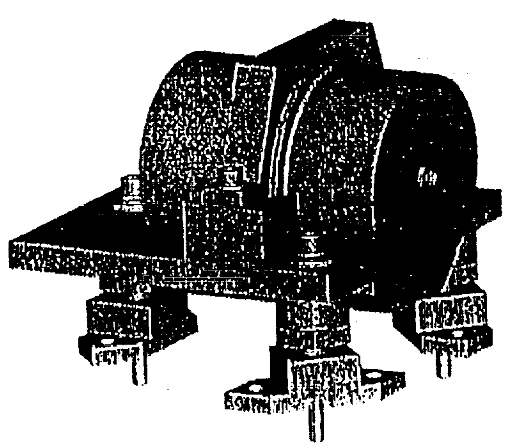


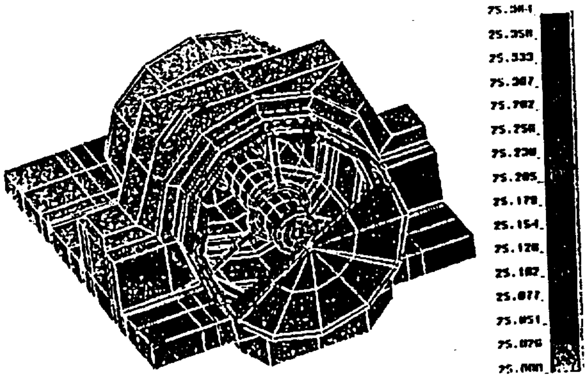
Figure 5. Current design of the reference cavity and mount.

glass between the mirrors. The viability of this optical bond to withstand the thermal and vibration environments has been verified by test. The entire stack-up of materials gives an effective vertical CTE that is approximately equivalent to the other optical mounts, so that the cavity change in height with temperature is equal to that of other components.

The spacer between the mirrors is made of Corning ULE 7971, an ultra-low expansion glass. The room temperature CTE of the glass, as well as the CTE averaged over the range 0 to 35 C, can be specified to be as low as $0 \pm 2 \times 10^{-9}$ / C. However, the instantaneous or actual CTE varies over the operational temperature range of the instrument (10 to 25 C) from about -2×10^{-8} to $+2 \times 10^{-8}$ / C. Thus, it must be assumed in the worst case that the instrument will be at one extreme or the other and the magnitude of the CTE will be 2×10^{-8} / C.

Thermal and structural models of the new cavity and mount design have been developed. An integrated process is used throughout design and analysis, such that the exact geometry of the design model can be used for both thermal and structural analysis. The cavity and mount were designed using the CAD package Pro-Engineer. As shown in Figure 5, this software allows not only detail design and drawing generation, but also yields a realistic solid model of the component. The model was then imported into the solid modeling software PATRAN. Thermal and structural analyses were run using the same model, thus avoiding any introduction of errors or approximations. The calculated temperature distribution can be used to determine thermally-driven distortions of the cavity, and these can be added to the distortion caused by the load change from 1-g to 0-g, see Figure 6. The exact position of the mirrors with respect to each other can thus be determined for the worst case, and the effect on the linewidth can be calculated.

Thermal analysis of the cavity has shown that an initial temperature increase, with a transient level as high as 0.002 K/min, is caused by the dissipation of a small fraction of the laser



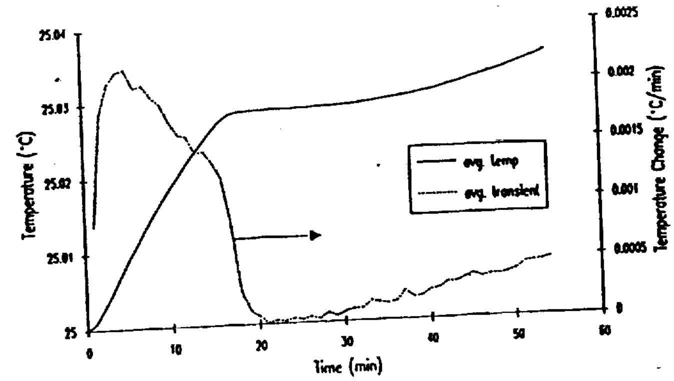


Figure 6. Black and white representation of the temperature distribution after one hour of operation, calculated by PATRAN.

Figure 7. Average temperature and thermal transient of the reference cavity during operation.

energy at the cavity mirrors. The exact assumptions are that a finesse of 100,000 for the cavity leads to about 85W of laser energy resident in the cavity, of which one ppm (<100 μW) is absorbed at each mirror. After the first 20 minutes, the transient decreases to about 20 μK/min; this is partially due to the change in input from two beams to one at 16 minutes into the experiment. The transient then gradually increases due to the heat from powered components on the optical bench, reaching roughly 400 μK/min at the end of an hour [12]. This is shown in Figure 7. If the power from these components were diverted away from the bench, the transient could be held below 50 μK/min. This level of passive temperature control with a PZT spacer allows a 3 Hz laser heterodyne linewidth to be achieved when locking to adjacent modes of a single cavity [9,10]. It is therefore expected that, with improved design, thermal noise will not limit the heterodyne linewidth until the millihertz region is reached.

There is another thermal effect on the cavity which has not been fully evaluated but must be considered in any flight version: the transient thermal effects from the spacecraft itself. These are caused not only by the changing of the orbit environment from sun to shadow, but also by the slow change of the spacecraft from its equilibrium in the Shuttle bay to a new orbital equilibrium.

An initial estimate of the spacecraft behavior, based on analysis and test data from the Spartan program at Goddard Space Flight Center, is that the worst case transient of the bulkhead mounting location is 2 K per hour. Assuming an unfavorable combination of spacecraft behavior and start-up time for SUNLITE results in cavity transients as high as 0.006 K/min before SUNLITE begins operation. This background transient acts as a lower bound so that the initial transient due to laser heating of the mirrors reaches about 0.01 K/min, and after this dissipates the transient does not drop back lower than 0.006 K/min [12], see Figure 8.

Optical Alignment

A second critical issue in the frequency discriminator is the alignment of the zero order Gaussian laser beam to the axial mode of the

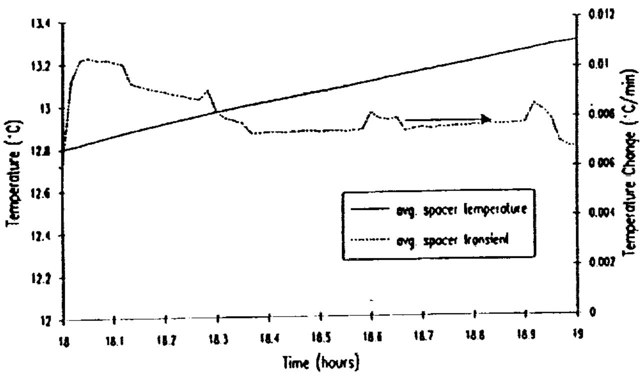


Figure 8. Average temperature and thermal transient after maximum spacecraft transient.

reference cavity. This requires high resolution in the motion of several optical components and that all components maintain alignment after experiencing the violent shuttle launch conditions. We define the coupling constant to be the ratio of the power in the transmitted axial mode to the total power incident and impose a lower limit of 85% on the coupling constant. This coupling constant provides a measure of the total light incident on the servo-loop photodetector which determines the maximum servo-loop signal to noise ratio (SNR). From this lower limit a total angular displacement and a linear translation of the laser axis can be specified. When these total displacements are evenly divided between the critical components in the optical train individual tolerances can be specified. Current preliminary estimates are 100 μrad and 10 μm total angular and linear displacements per component.

Electro-optic Phase Modulator

The third critical component of the discriminator is the phase modulator. Ideally, this crystal would provide pure phase modulation (PM) to the laser light. However, due to the sensitivity of the modulation process to polarization and to imperfections in the material an AM component is introduced into the discriminator which is indistinguishable from PM to the servo-loop detector [13]. This "noise" is then impressed upon the laser frequency by the actuator. These effects can be minimized by the growth of extremely pure modulation crystals and coatings and the production of accurately polarized laser beams.

Servo-loop Detectors

The physical limit to a Pound-Drever-Hall locked laser's frequency stability is the photon shot noise in the beam incident on the servo-loop photo-detector. Therefore, the photo-detector/preamp must be shot noise limited for optimum performance. This condition requires a very low noise bandpass filtered preamp and a certain minimum level of optical power incident on the photodetector. The current instrument uses Epitaxx 75T InGaAs photo-detectors with responsivity of 0.5 A/W and an Anadigics ATA03010F1 GaAs preamp with < 2 picoamps per root Hz noise referred to the input and a loaded transimpedance of 8K. Approximately 100 μW of optical power is incident on the detector when the laser is resonant with the cavity.

Measurement System

The measurement system determines laser frequency noise by mixing down the output of the science photo-detector to the range 0.5 to 40 KHz. This is done in two stages. First, the photo-detector output is mixed with an oscillator (the Primary Reference Oscillator, PRO) with frequency determined by measuring the free spectral range of the actual flight cavities (≈ 3 GHz). The output of this mixer is then amplified and mixed with a frequency synthesizer tunable, from 0 to 100 MHz, to produce a signal with a frequency that can be measured with millihertz resolution. For a 40.00 KHz frequency each period must be measured with a resolution of 60 picoseconds. The limiting factor in this measurement will be the phase noise of the oscillators used to mix down the original photo-detector output. The phase noise required at 1 Hz from the carrier for the PRO is -20 dbc per root Hz and -35 dbc for the synthesizer base oscillator.

Optical Bench Thermal and Structural Modeling

Maintenance of the experiment alignment after launch and during the thermal environment in space is critical. Several of the components are being tested to verify alignment stability after exposure to environmental extremes. However, the alignment can also be affected by changes in the optical bench structure itself, as mentioned earlier. To evaluate this effect, an integrated analysis procedure has been developed that includes the design software, structural and thermal analysis models, and the optical model. The optical bench and component layout has been generated in the CAD software package ANVIL. The exact design is then brought into the solid modeling software PATRAN. Structural analysis of launch stresses and normal modes analyses are carried out as usual in one of several available structural analysis packages. Also, the structural analyst can determine the exact deformations of the bench due to the change from 1-g to 0-g. The thermal analysis of the same structure is carried out by translating the bench model from PATRAN to SINDA-85. The resulting temperatures for each point on the bench are then ported back to the structural analyst for calculation of the thermally-driven deflections of the bench. Color maps and animations of the deflections are vivid and effective methods of finding the driving forces behind certain effects, and identifying areas of maximum deflection. The thermal deflections are added to the 1-g driven deflections to yield comprehensive worst case deflection values. The deflections calculated for each optical surface are exact since the original placement is taken directly from the design software. A software program has been developed to translate the translations and rotations of each separate optical component into the optical analysis software, CODE-V. The translator actually builds a new CODE-V model based on the deflected positions of each optical surface. The optical analyst can then determine if the optical performance is unacceptably degraded by the deformations.

APPLICATIONS OF ULTRA-STABLE LASERS IN SPACE

Many scientific and engineering applications of ultra-stable lasers are uniquely well suited to the space environment. These include both measurements which can be made only from space and new technologies enabled specifically by access to space. The following paragraphs describe some of these applications; many more remain to be discovered.

Gravity wave detection

One of the most revolutionary applications of technology emerging from this program is the family of gravitational wave detectors able to probe interactions among the most massive entities in our universe. Using laser gravitational wave interferometers in space to detect gravitational pulses with periods up to a few hours, events involving the motion of large masses, such as the collisions of black holes, can be studied. Ground based systems on a smaller scale (~ 4 km arms) are being designed, but such devices will have a low frequency cutoff of about 100 Hz. In a proposed experiment titled "Laser Gravitational Wave Observation in Space" (LAGOS), a 1 mW cw laser operating at the fundamental linewidth limit allows the measurement of gravity waves in a one million kilometer interferometer in orbit around the sun [14]. This experiment is enabled specifically by the recent advances in solid state laser technology including the very recent studies on laser stabilization. Several gravity wave research groups throughout the world have begun studies of stabilized solid state lasers for gravity wave detection. In fact, the development of the fm stabilization technique comes from the gravity wave community [15].

The gravity wave detector was considered impossible a few years ago because no appropriate laser source could approach the power and linewidth requirements. The power requirements for this application have already been met and in fact it has recently been demonstrated that the narrow linewidth of an injection source is preserved in high power amplifier pulses it seeds [16]. Further development, beyond the SUNLITE objectives, will be required to achieve the millihertz linewidths required for this instrument. These linewidths are achievable with subsequent generations of the SUNLITE oscillator.

Deep Space Communications

The Deep Space Network (DNS) has identified the need for frequency standards with better stability than the hydrogen maser and stabilized solid state lasers have the potential for providing such stability in a substantially smaller and less massive device. Currently, two way, transponded communication between earth based stations and space craft use doppler shift information to determine orbit parameters and/or navigational information. Coherent detection is now used only on the earth station. Plans for coherent detection on spacecraft, either to improve sensitivity of the earth to space system or to enable communication between spacecraft, will require oscillators with significantly more stability [17]. The planned development of (DSN) requires increased stability both to improve communications from earth to space and to enable coherent communication between spacecraft.

Optical Clock Technology

The laser oscillator used in the SUNLITE experiment has a potential for an accuracy of one part in 10^{17}. This extraordinary stability coupled with recent demonstration of sub-Kelvin temperatures and sub-doppler spectroscopic techniques make it possible to conceive of an optical clock having a short term oscillator or flywheel based on a solid state laser stabilized, in the long term, by interrogating a laser cooled atom or a trapped ion. The flywheel oscillator in the atomic clocks in current use are based on quartz oscillators. Replacing these with an optical frequency oscillator represents a significant advance in clock technology [18]

Tests of Relativity

Several tests of the special and general theory of relativity are possible with sufficiently stable lasers. Recent studies have suggested that a 100 fold increase in the sensitivity of a space based Kennedy - Thorndike experiment is possible with a stabilized solid state laser. This effort coincides with NASA's long term interest in contributing to fundamental understanding of space and time [19].

Laser Cooled Atoms

Another, equally fundamental study, involves the use of stable laser sources to probe the behavior of laser cooled atoms in the reduced gravity environment of space. Attempts to study the behavior of small ensembles of atoms at temperatures in the tens of microkelvin are hindered by the short observation times available in the 1 g environment. Observation times in space can increase the observation time by a factor from 10 to 100 [21].

Astrometry

Coherent visible sources enable astrometry in the visible region of the spectrum. The coherence of the diode pumped laser oscillator in the SUNLITE experiment will have a direct impact on the design and performance of the POINTS coherent interferometric telescope. The increased stability of a space based laser oscillator, possible with frequency shifted to the visible region of the spectrum, will enhance the sensitivity of the POINTS coherent interferometric telescope [20].

SUMMARY AND CONCLUSIONS

The recent, dramatic improvements in the short term frequency stability of externally stabilized solid state lasers are approaching a limit due to technical noise sources in the laboratory. Space offers an environment where these noise sources are eliminated and where gravitational effects are reduced. The original proposal for the SUNLITE project was to extend the work of terrestrial laboratories by incorporating the externally stabilized laser and measurement system into a free fall experiment. A conceptual design of an instrument to do this is broadly described in this paper. Various implementations of this design have been examined and a brassboard for the autonomously controlled stabilized laser and measurement system is under construction and testing. In carrying out the design and testing of this experiment significant progress in the qualification of critical optical and electronic components for use in space has been made. This progress is catalogued in Table 1.

At the present time, the SUNLITE experiment, as a test and calibration for ultra-stable lasers in space, has been removed from the space flight manifest; research on the development of autonomous, ultra-stable lasers for space based laser metrology continues at LaRC. Timely development of several other space projects that utilize stabilized lasers depend upon the phenomenology being developed by this effort. In order to insure that this technology remains available to the larger community of possible users and that related, developing technology is responsive to the needs of that community, a SUNLITE Science Team has been formed. Membership on this team is open to anyone with an interest in stabilized lasers or their use in space. Interested persons should contact any one of the authors at NASA Langley Research Center, Hampton VA, 23665, (804) 864-1000. A list of the current membership appears as an appendix.

A reasonable next step in the progression of the SUNLITE project would be a proposal utilizing this technology in a science experiment that could be flown in the near term. The SUNLITE team at LaRC is willing to lend its experience to the development of such a proposal.

APPENDIX I: MEMBERS of the SUNLITE Science Team

The Steering Committee for this Science Team consists of: Robert L. Byer, Stanford University, Palo Alto, CA; John Hall, JILA, Boulder, CO; Martin Buoncristiani, NASA Langley Research Center and Jack Bufton, NASA Goddard Space Flight Center

Members of the Science Team include: David Allan, NIST, Boulder, CO; Peter Bender, University of Colorado; David Begley, Ball Electro-optics / Cryogenics Div.; C.E.Byvik , WJ Schafer Associates, Inc., Reston, VA; Benjamin F. Chao, NASA Goddard Space Flight Center; Oscar L. Colombo, NASA Goddard Space Flight Center; Tim Day, New Focus, Inc., Mountain View, CA; Benjamin P. Dolgin, JPL , Pasadena CA; Paul Lett, NIST, Gaithersburg, MD; Demetrios Matsakis, U.S. Naval Observatory, Washington, DC; Jim Phillips, Smithsonian Observatory, Cambridge, MA; and Bonnie Schumaker, JPL, Pasadena, CA .

Table 1. ***Pioneering Accomplishments by the SUNLITE Project***

Integration of design, structural, thermal and optical analysis disciplines to predict optical performance directly from structural/thermal modeling.

First integration of a commercially available hard disk drive into a flight qualified package.

First use of optical contact bonding for space-flight components at LaRC.

First testing of metric fasteners at LaRC for yield and ultimate strengths, as well as for torque versus preload.

Demonstrated the most complex board design and layout ever attempted at LaRC.

First use of 32 bit processor (TI TMS320C30) designed into a spaceflight instrument at LaRC.

First use of SCSI interface and commercial, lap-top data storage technology for spaceflight.

First demonstration of autonomous control of laser frequency for spaceflight (currently at ten kilohertz resolution).

Developing the capability to fabricate high finesse (F> 100,000) optical cavities with optical bonding techniques.

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CHRISTOPHER NEWPORT
cnu
UNIVERSITY

December 9, 1992

Dr. Frank Allario, Director of Electronics
MS 117
NASA Langley Research Center
Hampton, VA 23681

Dear Frank,

Representatives from NASA Centers and other government laboratories, from major universities and industry attended the SUNLITE Science Team met October 29, 30 at Boulder, Colorado. Enclosed is a report of that meeting.

It was clear to me that members of the Science Team all agreed on the value of technology developed by SUNLITE and that it augments and in some cases enables critical elements of their own individual research projects. Consequently, they are committed to support an aggressive program that will build on the progress that SUNLITE has made and lead to the use of stabilized lasers in space soon. It was also clear that they recognized the good work that has already been done on analysis, modeling and testing of the critical components of a stabilized solid state laser and the unique capability for this work that has been developed at Langley by Steve Sandford and Ruth Amundsen.

The Science Team is now gathering additional information on launch possibilities and will then develop a detailed proposal for a specific science experiment. This experiment will be a modification of the latest SUNLITE experiment along the lines suggested by John Hall and will both gather new scientific and engineering data on the performance of the stabilized lasers and observe the effects of the earth and the instrument's carrier on laser frequency. The proposal will also stress the importance of results it will obtain to existing NASA missions such as POINTS and OSI and to nascent projects such as TIDES.

One important specific suggestion made by the team was to have someone from Headquarters appoint a Science Team. Two persons who might be suitable to do this would be Mike Kaplan or Bob Stachnick. We need your advice and guidance on this matter and in general, on a strategy to implement the Science Team's proposal. I will make an appointment to speak to you about this soon.

Sincerely,

A. Martin Buoncristiani
Professor of Physics

cc: Stephen Sandford
Ruth Amundsen

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SUNLITE Science Team Meeting Report

On October 29-30, 1992 the SUNLITE Science Team met at the Joint Institute for Laboratory Astrophysics (JILA), at the University of Colorado. The following persons attended the meeting:

Name	Affiliation	Phone/FAX
Ruth Amundsen	NASA LaRC	(804)864-7044/7202
Pete Bender	JILA	(303)492-6793
Martin Buoncristiani	NASA LaRC	(804)864-1569/7944
Robert Byer	Stanford U.	(415)723-0226
Ben Chao	NASA/Goddard	(301)286-6120/286-2562
Oscar L. Colombo	U. of MD/GSFC	(301)286-4480/286-2562
Tim Day	New Focus	(415)961-2108
Rick Fleeter	AeroAstro	(703)709-2240/0790
Eric Gustafson	Stanford U.	(415)725-2159
John Hall	JILA	(303)497-3126
Greg Herman	NASA LaRC	(804)864-8616/7894
Leo Hollberg	NIST	(303)497-5770
James Koziana	NASA LaRC	(804)865-0900
Danny Krebs	NASA-GSFC	(301)286-7714
Frank McLoughlin	AeroAstro	(415)940-1637/1635
Fred Raab	Caltech	(818)356-4053
Nick Sampas	Stanford U.	(415)725-2157
Steve Sandford	NASA LaRC	(804)864-1836/7944

Those attending were grateful to JILA for its hospitality and to Peter Bender for making the local arrangements.

The meeting consisted of two sessions. The first session, on the afternoon of October 29, consisted of a series of short presentations reviewing recent research on the stabilization of solid state lasers and outlining the technical requirements of potential uses of stabilized lasers in space. The second session, on the morning of October 30, was an open discussion attempting to reach a consensus on the status of the science and technology relating to stable lasers in space and to develop a program for continued research and development in this direction that is acceptable to NASA. A copy of the meeting notice which includes a program is appended.

Session 1

In the first session the following information on requirements for space-based applications of stabilized lasers was presented.

1.) The Bachall commission has already recommended an astrometric interferometry mission. This will require the use of lasers stabilized for extended periods of time. At present, there are two competing projects, POINTS and OSI:

POINTS (Contacts: Jim Phillips, Bonnie Schumaker)
Observation of stars approximately 90 degrees apart. Stabilized laser is used to monitor six distances which determine the interferometer geometry and for full aperture metrology.

required stability ~ 10^{-9} over periods of 3-300 minutes
5 micro arcsecond accuracy
distance measure ~ 50pm (overall error budget)
10 year operation

OSI (Orbiting Stellar Interferometer)

10 micro arcsecond accuracy
Distance to 340 pm

2.) LIGO (Contact: Fred Raab) Ground based 4km arm interferometer (precursor to LAGOS)

$\Delta L/L \sim 10^{-24} /(Hz)^{0.5}$

LIGO has different requirements for laser stability than SUNLITE in that the cavities are stabilized as part of the measurement process (ac-stability) and the effect of laser frequency variation is reduced by the nearly equal lengths of the interferometer arms.

3.) TIDES (Contact: Oscar Colombo, Ben Chao)

Description: two satellites co-orbiting at about 600 km height, in polar orbit, at some 500 km separation.
Requirements: acceleration between satellites measured with an acceleration r.m.s. error spectrum that is flat at the 10^{-12} g $/(Hz)^{0.5}$ level between 10^{-4} and 10^{-2} Hz; data rate: 10 second intervals. Long term stability (counting drift and glitches): no worse than 1 part in 10^{8} over several years.

Scientific goals: Measure changes in solid earth, atmosphere and oceans by sensing their gravitational signatures. These are changes that have scientific and practical potential for understanding climate evolution and the dynamic properties of the earth's interior. The data from TIDES, alone or in combination with other types of information taken from satellites or on the ground, can be quite significant in understanding the short-term issues of global change that pre-occupy decision-makers today. For example, TIDES would have a totally unique ability to monitor changes in deep ocean currents over the whole planet. These currents comprise the bulk of ocean circulation and have a big influence on climatic changes. No way of doing synoptic monitoring of those currents exists today, or is contemplated in the future, with anything like the spatial resolution (400 km) or coverage, or with the temporal resolution (once per week) that TIDES could provide. Another important application would be monitoring, on a weekly basis, changes as small as 1 cm in snow cover or in ice depth, weekly, with 400 km resolution. Annual rise in sea level rate could be measured to within 10% of its present value, so any significant acceleration should be easily detected.

4.) John Hall emphasized that significant science is possible in a modified SUNLITE experiment and reintroduced a plan he originally suggested in September 1991. This would take advantage of the progress made in scientific and engineering data analysis to date.

Outline of Hall's Program for a modified SUNLITE Science Mission

Lock 2 lasers to 2 cavities, with diagnostics and redundancy, heterodyne readout of beat frequency, store all data, telemeter "quick look" data

Objectives and Requirements
- a) linewidth experiment needs:
  - micro-gravity vibration environment
  - < micro-Kelvin/min temp rate

  take 3 sets of data
  - millisec samples for 10s
  - 10 ms samples for 100s
  - 0.1 s samples for 10,000s
- b) reference cavity noise experiment
  - Look for "earthquakes"
  - Look for non-thermal drift -- "creep" (10s averages for entire flight)

Flight Success Criteria
- a) Demonstrate Hertz-level linewidth of individual laser/cavity systems
- b) Demonstrate predictability at Hertz/min level over t ~ 10s to hours
- c) Demonstrate sub-milli-strate sub-milli-Hertz noise levels with 2 lasers locked to the same cavity

New Scientific/Engineering Data Expected
- a) rate and nature of stress-relief events in the μ-gravity environment: bulk processes vs noise in optical contacts
- b) temporal relaxation after change
- c) stability through liftoff trauma
- d) signature at harmonics of the slow spin rate, at 10-15 cycles/orbit, cavities rotate in horizontal plane, 256 x increment of the General Relativity Coriolis term

5.)Leo Hollberg suggested incorporating a laser stabilized in the long term (perhaps by locking to I_2, although a better standard is desired) in the experiment.

6) AeroAstro, a small company involved in small satellite technology, has joined the Science Team's efforts to conceptualize alternative designs of a spacecraft andthey are happy to help SUNLITE team members in this regard.

Session 2

In the second session the discussions on how to present a program plan to NASA headquarters developed the following points.

1.) There is some uncertainty in developing a strategy for future development of SUNLITE arising from the recent NASA reorganization and this uncertainty needs to be removed.

2.) Past experience has indicated that after projects reach a certain size they cannot be justified on the basis of technology development. Consequently, a strong scientific objective is required.

3.) To focus the discussion Peter Bender introduced a range of possible strategies.

a.) pick one specific experiment (for example, John Hall's modification of SUNLITE) as the sole basis for the experiment.

b.) argue that, in this case, a technology development program is, in fact, justified because of the importance of stabilized lasers to future applications.

c.)–consider that the scientific objective of SUNLITE is deferred to the objectives of eventual users; that is it enables later experiments. Pick perhaps 3 projects with strong support (POINTS, OSI, a geodesy mission {TIDES} or gravity wave mission {LAGOS/SAGITTARIUS}) and couple SUNLITE results to those missions.

After some discussion it was decided to adopt a plan combining a) and c). That is, to develop a single science experiment like that suggested by John Hall and to aggressively argue that this work also would help to enable 2 or 3 specific missions which have strong support.

The objective would be to propose a project whose total cost was less than 5 million dollars and whose first flight would be in 3 years.

Bob Byer suggested that NASA may not be the appropriate agency for support for this effort citing NRL's long term interest in clocks and in relativity and a recent MOU between administrators of NASA and DOE. It was agreed that non-NASA support could be sought in parallel with efforts to gain NASA support.

Recommended Actions

1.) To understand the implication of the recent NASA reorganization for the future of SUNLITE.

2.) It is necessary to investigate further:
- other possible launch options (Spartan, piggyback, free flyer...)
- other packaging options (gas can, small shuttle payload,...)
- the orbital requirements for specific experiments proposed
- other possible experiments

3.) To modify the existing SUNLITE experiment along lines suggested by John Hall to gather scientific and engineering data on the performance of stabilized lasers in the micro-gravity environment and to observe the influence of orbital parameters and the instrument carrier on the laser frequency.

4.) To consider a possible sequence of 2 or 3 SUNLITE experiments (POINTS, OSI, a geodesy mission {TIDES} or gravity wave mission {LAGOS/SAGITTARIUS}) representing a steady increase in difficulty.

5.) To have a Science Team appointed from NASA Headquarters, supported by, for example, Mike Kaplan and/or Bob Stachnick.

6.) To consider beginning ground testing for reliability now. Several technical issues, such as glitches occurring during cavity operation, aging and /or radiation damage of the cavity spacer material, cavity motion and the influence of gravity on optical elements can be studied on earth and this can begin immediately.

Program for the SUNLITE Science Team Meeting
October, 29-30, 1992
Joint Institute for Laboratory Astrophysics, Boulder, Colorado

Meetings will be held on the 10th floor of the JILA Tower, (part of the Duane Physics Complex at the University of Colorado)

Continuation of the work on the development of stabilized lasers for use in space requires a plan of action that clearly addresses the requirements of as many eventual users of this technology as is feasible. A meeting to develop this plan and to define a SUNLITE experiment that materially advances the technology of stabilized lasers in space will be held on the date and place above. The objectives of this meeting are:

1) to review the status of research on stabilized (solid state) lasers for use in space and to review the technical needs of potential users of stabilized lasers in the fields such as earth science, planetary science, astronomy, relativity and gravitation, time and frequency standards, spacecraft operations, etc.;

2) to determine
- -- reasonable objectives for future effort in this direction,
- -- a priority and timetable for these objectives,
- -- a strategy for the immediate next steps;

3) to outline a proposal (to NASA Headquarters) for a space experiment that would advance this work.

October 29: Reports on Recent Activity and Requirements for Applications

Introduction			
2:00	Martin Buoncristiani	LaRC	SUNLITE from the Langley Perspective
2:15	Bob Byer	Stanford	SUNLITE at Stanford University
Recent Results			
2:30	Jan Hall	JILA	Overview of Laser Stabilization at JILA
2:45	Leo Hollberg	NIST	Overview of Laser Stabilization at NIST
3:00	Nick Sampos	Stanford	Recent Results from Ginzton Laboratory
3:15	Steve Sandford	LaRC	Status of SUNLITE research at Langley
Applications of Stabilized Lasers in Space			
3:30	Bonnie Schumaker	JPL	Scientific Applications of Stabilized Lasers
3:45	Peter Bender	JILA	Requirements for LAGOS: A mission for low frequency gravitational waves
4:00	Oscar Colombo	Goddard	Global Gravity Change in 2001
4:15	Fred Raab	LIGO	Requirements for the LIGO program
4:30	Peter Bender	JILA	Requirements of the POINTS program
4:45	Fleeter/McLoughlin	AeroAstro	Low Cost Space Programs

October 30: Working Sessions -- Development of Plans for Next Steps

8:30	Discussion of Major Technical Issues: Thermal stability, Reliability of laser systems, ...
10:00	Break
10:30	Discussion and Prioritization of Goals
12:00	Lunch
1:30	Structure of a Proposal for a SUNLITE Experiment
3:00	Summary and Recapitulation
4:00	Adjourn

Suggested accommodations for visitors to Boulder -- Highland Inn [1-800 525-2149]. For further information contact Martin Buoncristiani, 804 594-7192 (FAX 804 594-7772), e-mail: martinb@pcs.cnu.edu