Project Description

Introduction: Universidad Metropolitana (UMET) a member of the Ana G. Mendez University System (AGMUS), with a history of serving economically disadvantaged minority Hispanic students, seeks to integrate graduate and undergraduate student education with research in atmospheric and space science by enhancing the instrumentation of the lidar laboratory at the Arecibo Observatory through the proposal **Puerto Rico Atmospheric Major Research Laser Instrumentation Program (PR-LASER**). This effort is a partnership between AGMUS through UMET and its Puerto Rico Optical Sciences Institute (PROptScI), the lead institution, the Arecibo Observatory (AO), which is administered by the NSF-funded National Astronomy Ionosphere Center at Cornell University, and the CEDAR Resonance and Rayleigh Lidar Consortium Technology Center (CRRL/CTC) at the University of Colorado at Boulder (UCB).

Partner Institutions. The following are brief descriptions of the partner institutions:

Universidad Metropolitana (UMET). AGMUS has three main campuses, Universidad del Turabo (UT), Universidad del Este (UNE), and UMET with a total enrollment of close to 40,000 students. UMET, with its main campus in Cupey, San Juan, Puerto Rico, and three smaller campuses, has an enrollment of 8,317 undergraduate students and 1,811 graduate students (Office of the Vice Presidency of Planning and Research, 2008). UMET offers degrees in four major schools: Science and Technology, Business Administration, Health Sciences, and Education, the last of which offers a PhD degree. The School of Science and Technology currently enrolls 725 students and offers bachelor's degrees in Chemistry, Computer Science, Biology, Cellular Molecular Biology, Environmental Science and Applied Mathematics. It also includes a School of Environmental Affairs that offers an MS degree in Environmental Affairs. We are now establishing a new program in Optical Sciences and Engineering at PROptScI.

CEDAR Resonance and Rayleigh Lidar Consortium Technology Center (CRRL/CTC). CRRL/CTC is an upper atmospheric research facility hosted by the University of Colorado-Boulder (UCB) and supported by the NSF under grant ATM-0545353. Its mission is to develop and disburse technologies to advance upper atmospheric (stratosphere, mesosphere and lower thermosphere) lidars. CRRL/CTC works to unite, advance, and share lidar technology development and personnel to ensure CRRL lidar facilities achieve the highest potential possible. It also forges and fosters infrastructure to enable collaboration and support for the NSF science community, contribute to long-term planning and vision, extend technical support to other lidar programs, and to expand the consortium. CRRL teams educate, train, and support undergraduate, graduate students and professionals through active university-based lidar research programs, summer school programs, hands-on experience and a guest investigator program. All these activities aim to increase lidar contributions to NSF CEDAR and aeronomy collaborative science activities.

Arecibo Observatory. The Arecibo Observatory is the world's largest single-dish radio-radar telescope and is recognized as one of the most important national centers for research in radio astronomy, planetary radar and terrestrial aeronomy. It operates on a continuous basis providing observing time, electronics, computer, travel and logistic support to scientists from all over the world on a proposal-based peer-reviewed system.

Objectives

The objectives of this program are to: 1) enhance research activities in atmospheric science at the world-class Arecibo Observatory facilities in Puerto Rico by implementing new laser technology for the Doppler lidar program; 2) support the acquisition of a state-of-the-art laser transmitter that improves access to and increases use of modern research and training instrumentation by scientists, engineers, and students; 3) to implement a research training program in science, technology, engineering and mathematics (STEM) fields in atmospheric science and optics for undergraduate and graduate students in Puerto Rico; 4) to increase the number of students pursuing advanced degrees in remote sensing and atmospheric research.

Instrument Location: Arecibo Observatory lidar laboratory.
The lidar laboratory was built in 1997 to specifically house Arecibo's lidar systems, and with additional capacity to support one or more visiting lidars. The laboratory is located approximately 300 m west of the radio telescope at an altitude of 360 m above MSL. Its floor space is 1600 square feet, and it has sufficient electrical capacity for multiple laser systems, including single and three-phase circuits. There are three high-capacity recirculating water chillers for lasers, and additional water chillers for water-cooled detectors. The laboratory includes four 80-cm diameter and one 40-cm diameter telescopes that are coupled to detection systems employing PMT and APD detectors.

Instrument Code: MRI-71 (other).

The Purpose of this Proposal

The purpose of this proposal is to acquire a state-of-the-art laser transmitter for the potassium Doppler resonance lidar at the Arecibo Observatory. This will represent a substantial upgrade over the current transmitter, which, after nearly 15 years, has had a respectable lifetime for a high-energy pulsed laser and has many obsolete components. In that time technology development has greatly advanced at the laser manufacturer, Light Age, Inc. The development of the laser for the UCB MRI Fe Doppler lidar [*Chu et al*., 2008] in collaboration with (this proposal's Senior Collaborator–SC) Prof. Xinzhao Chu's group at the University of Colorado (UCB) will benefit this project enormously. The new laser will enhance the capabilities of the Arecibo lidar and improve mesosphere and lower thermosphere (MLT) observations. Among the expected gains for MLT research at Arecibo are: improved accuracy and precision of temperature measurements, improved time and altitude resolution, the capability of making full vector wind measurements, and improved measurement capabilities under full daylight conditions. We also expect to gain in system reliability, as 15 years is considered a long life for a high-power pulsed laser, and the current system has recently experienced frequent and occasionally extended down times.

The alexandrite laser has proven itself to be highly reliable and dependable. It has many advantages for resonance lidar, such as spectral resolution, long pulses, and low peak power for high average power, which mitigates saturation and allows more power to be applied to the metal layer [e.g. von Zahn and Höffner, 1996; Eska et al., 1999]. We are familiar with five alexandrite-based upper atmosphere lidar systems currently in operation. The instrument is described in detail below. Here we summarize the improved specifications that Light Age will implement in the new laser system and how those will help lidar measurements.

The principal improvement in the laser is in its longitudinal mode stability. This means simply that every pulse emitted by the laser will have the same absolute frequency and the same spectral structure to a very high tolerance. This is critical for wind measurements, as uncertainty in these parameters directly impact the measured Doppler shift in the measured fluorescence spectrum of the mesospheric potassium. It also greatly benefits the long-term accuracy and reliability of temperature measurements for climatological and global change research.

Also improved in the new laser system are in its pulse energy, average power, and spatial mode. While operating at the same repetition rate, we anticipate a 20%–60% improvement in laser pulse energy, which will improve the signal proportionately. The laser will also have a higher-quality spatial mode, which will improve the signal by an estimated 20%. Any output energy that is not in the principle TEM00 spatial mode is lost to the receiver, as it falls outside its field-of-view, and this is an issue with the current laser. During daylight operations these bring an improved signal-to-background ratio that will improve the data quality by a factor of the square root of the fractional increase in signal, meaning a 20% to 35% reduction in error bars for the temperature measurements. Table 1 shows the expected improvement in temperature measurement precision for both day and night, based on both improved power and spatial mode. The third row is for once we implement the avalanche photodiode detector, which was purchased for the daytime upgrade [*Friedman et al.*, 2003; *Gardner*, 2004].

Table 1: Temperature precision before and after laser upgrade for T=200K, 10 minute integration, 3 km average.

	Night ΔT at peak	Night ΔT at RMS	Day ΔT at peak	Day ΔT at RMS
Current	3.7 K	6.3 K	10 K	25 K
After upgrade	<3 K	<5 K	<8 K	<20 K
With APD	<1 K	<2 K	<4 K	<9 K

Research Activities to be Enabled or Enhanced

The science studies enabled by this proposal will seek to both extend the work to date on MLT climatology [*Friedman and Chu*, 2007] and semidiurnal tides [*Friedman et al.*, 2009, 2010a,b], and to explore science made possible by combining unique capabilities afforded by the co-located lidars and the ISR [e.g. *Tepley et al*, 2003; *Raizada et al*., 2004; *Zhou et al*., 2005]. The improved resolution, accuracy and precision of the lidar that will result from the proposed transmitter upgrade will enable new research opportunities at both high-time and range resolution and long-term, e.g. global change studies.

MLT Semidiurnal Thermal Tides

In studies that combined lidar-measured MLT temperatures from Maui and Arecibo with SABER measurements, we have evaluated longitudinal variability of semidiurnal thermal tides [*Friedman et al.*, 2009]. These have shown that for much of the year, the lidar-measured semidiurnal amplitudes and phases for the two locations substantially agreed, as well as showing good agreement with the SABER-derived (from the TIMED satellite) parameters. However, for January there is considerable disagreement, which is supported by satellite measurements [*Pancheva et al., 2009*]. In Figure 1, we show the semidiurnal phases and, in Figure 2, the amplitudes for the six months included [*Friedman et al.*, 2009; Figures 1 and 2]. The fact that the ground-based and space-based tidal amplitude measurements do not always agree points to the need for lidar measurements of the diurnal tide. We used Hough-mode

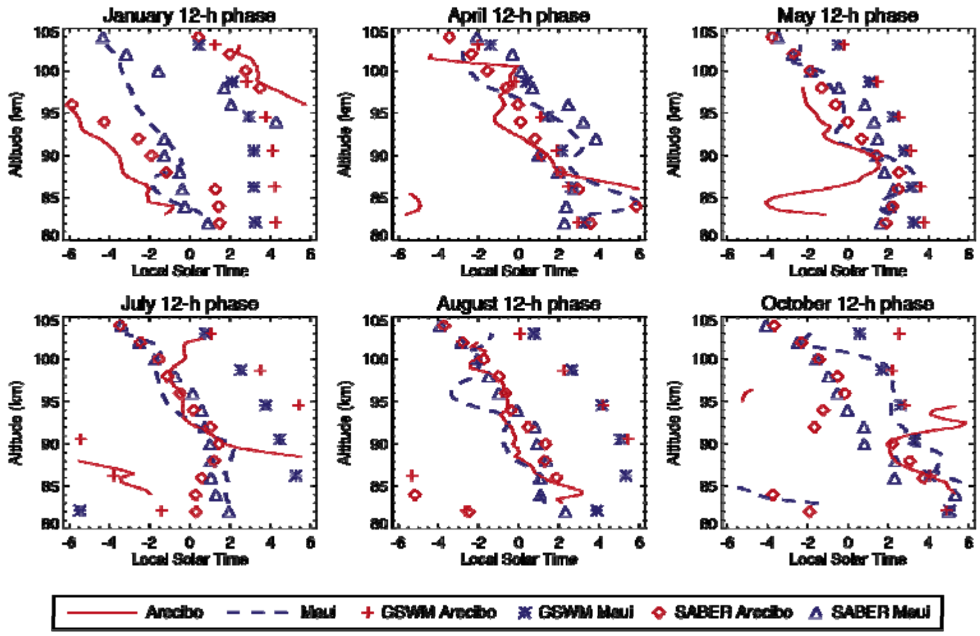

Figure 1. Semidiurnal tidal phases as measured by lidar and SABER, along with the results of the GSWM-02 model. Arecibo is shown in red, Maui in blue. The lines are for lidar, open symbols are SABER, and the +/* symbols are for GSWM. (from *Friedman et al.* [2009])

analysis on the longitudinally distributed measurements by SABER to show that the principal difference between winter months and the remainder of the year is that the (2, 3) (latitudinally asymmetric) mode disappears in winter. However, it does not explain the 6-h phase shift between summer and winter for Arecibo and –2-h shift for Maui. Although our analysis appears to show that the semidiurnal interpretation is justified, there are enough differences between semidiurnal amplitudes as measured by SABER compared with the localized lidar measurements to suggest that diurnal and non-migrating tides may be substantially involved [*Forbes et al.*, 2008; *Friedman et al.*, 2009; 2010a]. Studies have shown that the diurnal temperature tide for Arecibo's latitude, though small, is not insignificant [*Xu et al.*, 2009 and references therein]. This upgrade will help enable a full study of the tides and waves that result in this seasonal anomaly.

As tides provide a substantial contribution to the total dynamical energy budget of the atmosphere, any attempt to quantify that budget requires full inclusion of the coherent inputs. The improvements to the lidar resulting from this proposal will help us to fully account for the coherent tidal effects on the thermal structure of the MLT region for Arecibo. To this end, the new laser system will improve daylight observing capabilities by increasing the signal above the background level via higher power and improved spatial mode of the laser. With the improved spatial mode the field-of-view can be further narrowed, with a quadratic reduction in the background level. The new laser system offers benefits for long-term studies of the variability of the tides, as with many other topics of study (such as planetary waves, the interannual or solar cycle variations in seasonal or mean temperatures and metal atom densities, semi-annual oscillation (SAO), quasi-biennial oscillation (QBO), and long term temperature trends related to global change [*Xu et al.*, 2009; *She et al.*, 2009].

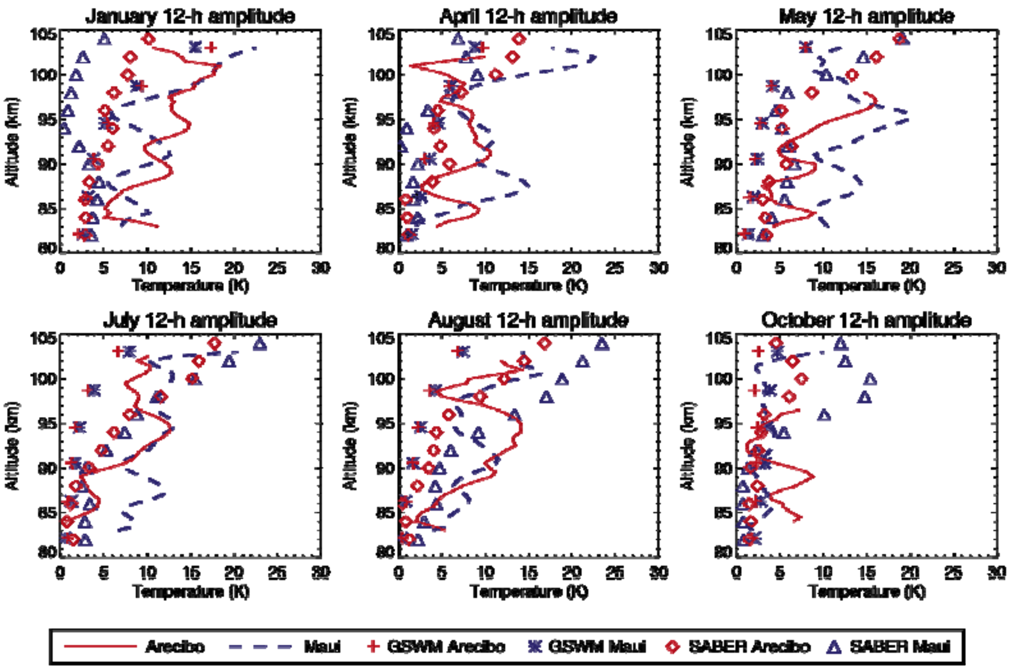

Figure 2. Semidiurnal tidal amplitudes as measured by lidar and SABER, along with the results of the GSWM-02 model. Arecibo is shown in red, Maui in blue. The lines are for lidar, open symbols are SABER, and the +/* symbols are for GSWM. (from *Friedman et al.* [2009a])

MLT Climatology

Illustrated in Figure 3 is the first complete climatology of the Arecibo nocturnal mesopause thermal structure. This seasonal climatology shows a few unique features including a three-level mesopause: a high mesopause altitude (~100 km) in summer, a medium mesopause altitude (~96 km) in late autumn and winter, and a low mesopause altitude around the spring equinox (~91 km). The mesopause is cold in the solstices (~171 K in summer, ~176 K in winter) and warm around equinoxes, particularly late autumn when it is near 195 K, while the spring mesopause temperature is close to 185 K. The lower thermosphere around 100 km at Arecibo shows a decreasing temperature from spring to summer when it reaches its coldest temperature, which is contrary to the increasing temperature observed at all mid-latitude locations. Semiannual variations in the seasonal temperature have amplitudes as large as the annual variations through most of the MLT altitude range at Arecibo. The seasonal variation also shows a residual inversion layer near 90 km in summer [*Friedman and Chu*, 2007]. This is different from what has been observed at mid and high latitudes, or even subtropical Maui where the mesopause shows a winter high altitude (~101 km) and a summer low altitude (~87 km) [*Chen et al.*, 2000; *Chu et al.*, 2005; *States and Gardner*, 2000a; *She et al.*, 2000; *Pan et al.*, 2002; *Pan and Gardner*, 2003; *Kawahara et al.*, 2004]. *States and Gardner* [2000b] have shown that the residual inversion might be the result of incomplete sampling of the diurnal tide.

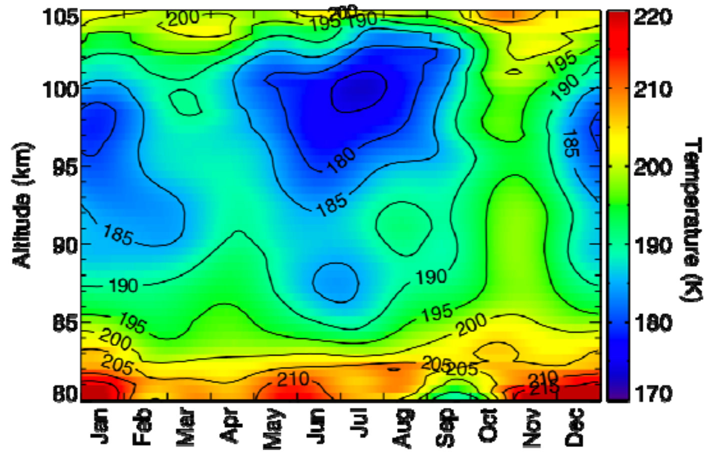

Figure 3. Seasonal nocturnal mean temperature structure for Arecibo.

The upgrade to the laser transmitter requested here will greatly benefit such climatological studies, as the Arecibo lidar is now making measurements that will eventually include most of the diurnal cycle and remove the uncertainty in the climatology introduced by this under-sampling. This upgrade will improve the accuracy of the measurements and benefit the averaging of multiple years to form a single composite year, as shown in Figure 3. It will also improve the temperature precision by SNR improvements critical to daylight measurements.

Daylight Lidar Measurements

In Figure 4, we show one of the first measurements of MLT-region temperatures made since the implementation of a Faraday filter in the lidar to mitigate the high background levels introduced by the daylit sky. In this observation, the sun rose shortly before 0600 local time, while the lidar measurements were able to continue until past 0830. Sky conditions were not the limiting factor in these observations, and we expect to be able to extend them much later into the day, when the solar elevation angle may be 60° or more. By improving the signal level above the background, we can extend the altitude range, which narrowed from ~80–101 km in darkness to 84–97 km in daylight due to the high signal-to-background ratio. The new laser gives us the possibility of increasing the signal-to-background ratio by a factor of 2 or more, with a concomitant extension in the altitude range of temperature measurements. This range will depend on K layer conditions, and the background level, which is dependent on sky conditions such as dust loading and cirrus clouds.

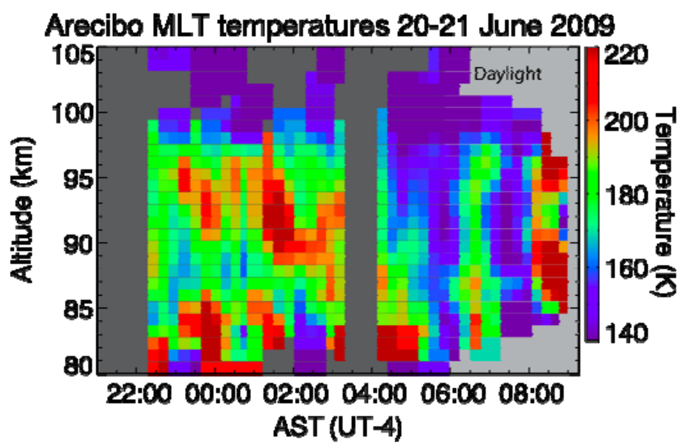

Figure 4: Temperature profiles recorded with the Arecibo K lidar on 20–21 June 2009. The dark gray shaded area is at night and light gray shading during the day.

Other Enabled Research

There are many research opportunities enabled by Doppler lidar, particularly when accompanied by the Arecibo Incoherent Scatter Radar (ISR). This proposal will help to open new possibilities. Daylight temperature measurements coupled with ionospheric radar can result in direct measurements of atmospheric density and its modulations. Enabling lidar wind measurements opens the possibility to make momentum and energy flux divergence measurements, which, when coupled with the ISR, can be done during day and night. Improved precision and time resolution of Doppler measurements will enable gravity wave studies. We expect these will also help us to understand the differences in tidal structures revealed in *Friedman et al*. [2009; 2010a,b]. Improvements in the daytime measurements and system reliability will make possible multi-day measurement campaigns that will reveal modulations of tidal motions in the MLT, caused by planetary waves. We expect that observational runs to observe these and other phenomena will be proposed by MLT researchers, both those currently in as well as from without Arecibo's user community.

Using Fe as the MLT tracer can potentially improve lidar signal by an order of magnitude. The CRRL/CTC Fe lidar will demonstrate its capabilities. Should we determine it advantageous to convert the Arecibo Doppler resonance lidar to an Fe system, Prof. Chu's CRRL/CTC will be heavily involved. This overhaul would require the greatly improved spatial mode quality and reduced frequency chirp of the new system.

Description of the Research Instrumentation and Needs

Table 2. Laser Specifications

	Guaranteed	Goal
Wavelength range	760–800 nm	770 nm operational
Pulse Energy	160 mJ @ 770 nm	>160 mJ @ 770 nm
Repetition Rate	25 Hz	30 Hz
Average Power	4 W	5 W
Linewidth	<10 MHz	
Chirp	<10 MHz	
Spectral Stability		<1 MHz
Spatial Mode	TEM00	TEM00

Table 2 shows the expected specifications for the new lidar transmitter. Light Age, working with Prof. Chu, has made considerable improvements in the design of the laser cavity and its internal components that will benefit the Arecibo lidar. We have worked closely with Light Age to identify the most important specifications for the Arecibo MRI laser. Given the benefit of co-PI Friedman's 15 years' experience with the original ring laser and SC Chu's recent acquisition, we are in a good position to understand both the capabilities of the laser system and the requirements for lidar. Table 2 lays out a set of critical parameters.

Along with operational specifications, maintenance issues are critical to address. In the early years of the current system, serious failures were annual events, generally in the power supplies or Q-switch crystals. In time, Light Age has made those components far more reliable. From 2002–2008 we had only two major failures causing a few months' down time. Since September 2008 we have had more, mostly from failures in obsolete major sub-systems in the laser. Typical operational time between maintenance is 300 hours, which corresponds to about 30 nocturnal observing runs. We carry out maintenance 2–3 times per year, and each takes roughly a half day. These require about $2000 in supplies each time, which are purchased with materials and supplies funds that Cornell allocates to the lidar program. Major repair costs include Q-switches and power supplies (~$10k each). We will consider having a maintenance contract for the laser, but our experience has been that having this contract does not improve service from the manufacturer, and that we have been just as well off without it.

Below, we describe some of the technical advances that the new laser will provide for us.

I. Extended cavity length: resulting in three major improvements in the laser performance.

First: Expanded beam diameter within the cavity better matches the gain volume of the laser rods. In this way, energy is extracted from a greater volume, improving the system efficiency and increasing output power, while high order laser modes are suppressed. Higher efficiency also reduces the frequency chirp, or spectral broadening of the laser spectrum towards the blue.

Second: Longer laser pulses are a geometrical effect of the longer cavity. These have the additional benefit of the lower gain density. The longer laser pulse has important benefits for measurements of mesospheric potassium as high laser peak power can saturate the fluorescence, which ultimately limits the lidar signal. A longer laser pulse reduces the peak power of the pulse for the same energy, thus reducing the saturation and allowing for higher pulse energy to be employed to increase signal.

Third: Frequency chirp is reduced through a geometrical factor. The chirp produces a dynamic variation in cavity length, and thus wavelength, during the laser pulse. If the cavity (L) is longer, $\Delta L/L$, and thus the blue shift, is proportionally less.

II. Improved injection seeding stability

Light Age has made a number of improvements in its “Active Cavity Length Stabilization” (ACLS) technology that will greatly benefit the Arecibo laser through improved laser performance and stability. This is vital to future wind measurements.

The alexandrite laser uses an injection seeding technique that monitors the resonance between the alexandrite cavity and the seed laser frequency and fires the alexandrite only when they are precisely resonant. The current system suffers occasional periods, sometimes lasting seconds (10s-100s of laser pulses) where the laser does not actually produce an output pulse. There is also considerable temporal jitter in this method. The improved ACLS makes the pulse occur at the same location on the gain curve, and the frequency chirp and power are consistent from pulse to pulse. This consistency makes the output spectrum very stable, the key to winds.

III Seed laser

The improved alexandrite laser makes more demands on the seed laser. For this reason, we have asked Light Age to use the latest external cavity diode laser from Toptica, Inc., the DL Pro, along with line stabilization and narrowing hardware based on a K vapor cell and an FPGA-based feedback system. These improve the accuracy and stability of the laser locking by two orders of magnitude over the current system. This seeder will have no negative systematic effects on the measurements, while the current system has dither that introduces a few m/s uncertainty in wind measurements.

Figure 5 shows the optical arrangement of the new lidar transmitter.

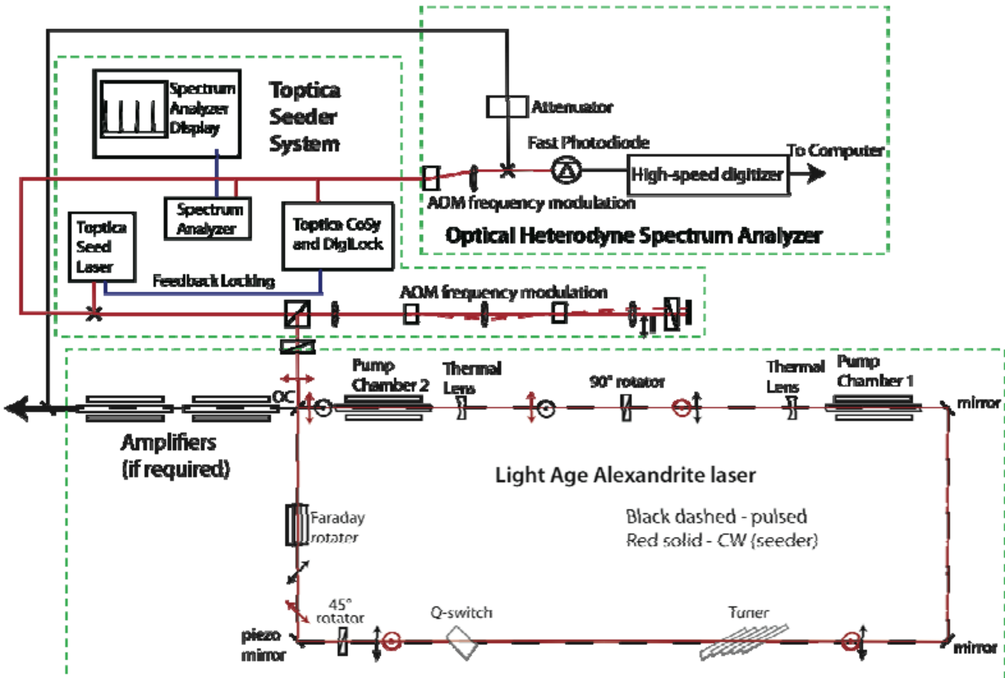

Figure 5. Diagram of the Light Age Alexandrite Laser with seed laser and spectrum monitoring system.

Results from prior NSF support for PI Dr. Juan Arratia

The NSF-sponsored Model Institutions for Excellence Project has had a remarkable impact on the Ana G. Méndez University System during the 13 years of its existence, especially in the area of undergraduate research under the leadership of Dr. Juan F. Arratia, Director and PI. This Project (Cooperative Agreement DMS-9988401 and Grant HRD-0348742) provided AGMUS and Universidad Metropolitana in particular with over $25 million with the following impacts: **Pre-college**: 2256 high school students have participated since 1997 through the two MIE pre-college programs: the Saturday Academy and Summer Adventure Research Training (SART). All of the students have conduct research with an undergraduate mentor and a faculty mentor. At the end of each session (3/year), each student group presents its results. 100% of these students have graduated from high school and entered college; 85% have chosen STEM majors. **Scholarships**: 525 students received at least one semester of MIE scholarship, most including full tuition and a monthly stipend. Additionally, two grants: the AGMUS Institute of Mathematics (DMS-0822404) providing funds for 20 students per year until spring semester 2013, and the Caribbean Computing Center for Excellence [CCCE] (CNS-0940522) are being implemented at present. **Internships**: All MIE Fellows conduct research during the semester with STEM faculty. It has provided research opportunities in summer internships to 500 students at US institutions and abroad. The Project established a network of over 100 STEM mentors at leading universities in the US and abroad. **UMET Symposia**: Three pre-college and two undergraduate research symposia are held each year. 1,250 pre-college students have made presentations at pre-college symposia and 550 undergraduates have made presentations at undergraduate symposia at UMET. Participation in research at the undergraduate level has reached HBCU and other universities in the US mainland. **Student Presentations and Publications**: 300 student research outcomes were presented at national and international conferences such as SACNAS, NCUR, IEEE, and ACS. **Transfer to graduate school**: Over 100 students from AGMUS have transferred to graduate school during the last 14 years. Five have completed PhD degrees in Mathematics (3) and Pharmacy (2) and ten are candidates for PhD degrees in Psychology, Cellular Molecular Biology, Geology, Chemistry, Mathematics, Biology and Astronomy.

Results from prior NSF support for co-PI Dr. Jonathan Friedman

The Arecibo Observatory is operated by the National Astronomy and Ionosphere Center at Cornell University and is supported by NSF cooperative agreement grant numbers ATM-0630533 and AST-0431904. In addition, Dr. Friedman has received support from NSF grants ATM-0535457 and ATM-0525621. The former funded development of the daytime lidar capability, and the latter supported high-time-resolution observations of mesospheric potassium with the goal of directly detecting meteor trails. The lidar has produced data for seasonal studies of the potassium density structure [*Friedman et al*., 2002], temperature structure [*Friedman*, 2003; *Friedman and Chu*, 2007], and for the longitudinal structure of the semidiurnal temperature tide [*Friedman et al*., 2009; 2010a]. It has also produced observations of the metal layer topside [*Höffner and Friedman*, 2004; 2005]. It has been used for comparisons with Na, Ca, Ca^+ and total ion layers [*Tepley et al*., 2003; *Raizada et al*., 2004; *Zhou et al*., 2005], a detailed study of sporadic layers (paper in preparation), and modeling of mesospheric K chemistry [*Delgado et al*., 2006]. It has also helped characterize gravity wave-driven dynamics [*Smith et al*., 2005; *Larsen et al*., 2004; 2007].

This program has recently supported several graduate students: Mr. Rubén Delgado completed a Masters' degree in 2003 and is currently writing his PhD dissertation. Dr. Jonathan Fentzke completed his PhD in 2009. Ms. Paloma Farias completed a Master's degree in summer 2008 and Mr. John Smith completed a Master's in April 2009 and is currently continuing towards his PhD. Smith developed a new data acquisition system while supported for Arecibo daytime lidar development (ATM- 0919786, PI Chu). Undergraduates Jocelyn Seal, Israel González, Darlene Maldonado, Emanuel Méndez, Raúl Navedo and Carlos Ramos have participated in this program. Ms. Seal, supported by the NAIC cooperative agreement, won the 2007 ASEE–□□□ Honorary Society Award for her paper describing her work on this project [*Seal*, 2008]. Mr. González and Ms. Maldonado were supported under an NSF REU grant and developed the Faraday filter test station. Ms. Maldonado intends to complete a PhD degree.

Results from prior NSF support for Prof. Xinzhao Chu, who is a Senior Collaborator on this proposal.

(1). ATM-0545353 – Consortium of Resonance and Rayleigh Lidars / Consortium Technology Center (CRRL/CTC) ($728,566, 8/2006 – 8/2011, CTC PI: Xinzhao Chu; CRRL PI: Jeffrey Thayer); (2). ATM 0723229 — MRI: Development of a Mobile Fe-Resonance/Rayleigh/Mie Doppler Lidar ($1.2M, 8/2007 – 8/2010, PI: X. Chu)

Under the support of the CRRL/CTC grant, Dr. Xinzhao Chu leads the establishment of a lidar consortium technology center at the University of Colorado at Boulder for the CEDAR community. The CRRL/CTC is leading innovation and development of new lidar technology, and supporting lidar groups within and outside the consortium for lidar development, operation and science study. After about four years of work, the CTC is producing good technologies for the CEDAR community to improve lidar measurement accuracy, precision, resolution, and ranges. The CTC is also training graduate students and post doc for the next-generation lidar researchers. As this proposal demonstrates, the CTC is providing technical expertise and support to the greater lidar community (see http://crrl.colorado.edu/ for more information). The MRI grant supports the development of a Major Research Instrumentation Fe-resonance/Rayleigh/Mie Doppler lidar at UCB. Lots of new lidar technologies have emerged from this project, and several key technologies, like the pulsed alexandrite ring laser, optical heterodyne detection of pulsed laser spectrum and new frequency control of laser pulses, are readily applied to the current Puerto Rico lidar project. These two grants have resulted in about 15 refereed journal papers and conference proceedings, and are supporting two PhD dissertations and several independent studies with undergraduate and graduate students.

Impact on Research and Training Infrastructure

The Arecibo Observatory is one of the best-equipped upper atmospheric research facilities in the world. As such, it is of vital interest to the observatory, its scientific user base, and the broader atmospheric and space physics communities for it to maintain state of the art observing capabilities. Doppler lidar is critical to mesosphere-thermosphere research at Arecibo, and the addition of new measurement capabilities and increased reliability of the lidar operations are fundamental to its mission. This proposal will open the door for a young lidar scientist to join the program and enable a new education, research and training facility at PROptScI. These are both important elements to improving the research and training infrastructure in Puerto Rico.

The MRI laser acquisition will broaden the participation of students at the undergraduate and graduate levels in science and engineering research, and in particular by women, underrepresented minorities, and persons with disabilities who will be provided with the opportunity to learn laser technology and conduct state-of-the-art research. To this end, with NSF permission and should this proposal be funded, we have asked NAIC to transfer the existing alexandrite laser from Arecibo to the UMET/PROptScI facility in Barceloneta, where students will get hands-on experience. They will investigate optimal cavity design and gain-induced frequency chirp. The UMET+AO partnership will result in new undergraduate courses in optics, lasers, and remote sensing at PROptScI and UMET students will participate in research and observing activities at AO. During both the academic year and the summer, students will be able to learn the system theory of operation, undertake monitor and control projects, and develop improved performance methods. Students will also learn about techniques for single-mode pulsed and CW lasers, high-resolution laser locking control techniques (including phase-locked-loops, the Pound-Drever-Hall method, and frequency-modulation), and monitoring techniques. Students will develop software tools using LabVIEW® to record data and monitor measurements, and using optical design programs to optimize laser cavity design. At AO, students will be involved in the integration of the new transmitter into the lidar and will participate in observations, gaining experience with remote sensing, lasers, and electro-optics.

With the experience gained at AO and PROptScI, students will be well prepared to contribute to lidar research. We will strongly encourage the best students to continue with their research experience at the graduate school level. The collaboration between UMET-AO and the CRRL/CTC opens a door to direct access to a first rate program. For non-UMET students who wish to carry out lidar research at AO, PROptScI will provide lidar systems training. Using "long-term" data sets (1 solar cycle or more), students can investigate trends in mesopause-region temperatures. These are critical to validating global change models, such as that of *Roble and Dickinson* [1989], in which they showed that the mesopause region should cool in response to tropospheric warming; cooling has been seen, but not in all observations [*Keckhut et al.*, 1995; *She et al*., 2000; *Beig et al*., 2003; *She et al*., 2009].

Management Plan:

Facility Management

The facility in which the instrument will be located is the lidar laboratory at the Arecibo Observatory. The laboratory was described above. Once the laser system is put into operation, co-PI Dr. Jonathan Friedman will oversee its general operation and report directly on it to the PI, Dr. Juan Arratia. As Dr. Friedman will be assuming responsibility for PROptScI, Arecibo will hire a new lidar scientist at the post-doc or Research Associate level (see NAIC commitment letter). The maintenance of the laser will be the responsibility of the Arecibo engineering support staff, and again all maintenance activities will be reported to the PI. Scheduling observations with the Arecibo K lidar will go through the existing NAIC proposal process, which employs external peer review as well as a review panel, that together determine which proposals will be scheduled, how and when. Proposers should coordinate with Dr. Friedman and/or other members of the Arecibo Space and Atmospheric Sciences (SAS) department, as well as the PI.

The MRI laser is to be designated "UOPA", or "User-owned, public access," according to the Arecibo designation for an instrument that is installed on site by a collaborating institution, where the instrument belongs to that institution, and they are ultimately responsible for it. However, the instrument is to be maintained and operated by the Arecibo Observatory for the benefit of its broader user base. In the case of the new K lidar transmitter, once the grant period is complete, Arecibo will undertake full responsibility for operation and maintenance of the system. As this is a replacement for existing instrumentation, it does not increase Arecibo's responsibilities, such as costs and time commitments. With NSF permission and NAIC management consent, the replaced laser will be transferred to UMET’s Barceloneta campus where it will become part of the PROptScI institute’s laser training, education, and R&D program (see NAIC commitment letter).

Scientific Management

The scientific management will oversee the two branches of the project. First is the laser, from its specification, construction and installation to its operations and science production. Second is the participation of students and student minorities in Puerto Rico, which will be coordinated carefully with operations and developments at Arecibo.

The Arecibo Observatory scientific and engineering staff will be primarily responsible for the first branch. They have the technical expertise needed to maintain and operate the laser system. Dr. Friedman will assume responsibility for this until a new staff member is recruited and hired. The new staff member will take over day-to-day responsibilities after training from Dr. Friedman. The operational costs will be assumed by the Arecibo Observatory. The project PI will be informed of all operations and maintenance.

The project PI, Dr. Arratia, will be responsible for the second branch. This will be centered at UMET. Students involved with the MRI lidar will be trained in techniques and safety at PROptScI by Dr. Friedman, or at Arecibo by Dr. Friedman or other qualified personnel.

Plans for attracting and supporting new users include posting information on the Arecibo Observatory and UMET web pages for the scientific community and pre-college, undergraduate and graduate students. The CEDAR website will also contain up-to-date information on the program. Postings will include possible projects, ongoing and new, as well as conferences and workshops. Operations, data previewing, usage and downtime information will be included.

The Role of co-PI Jonathan Friedman

Dr. Friedman is an expert in laser technology, with 25 years of experience in lasers, electro-optics, and general optical techniques, and thus has the expertise to handle multi-user accessibility and use of facilities by the scientific community and the community in general. Of those 25 years, he has been involved in the lidar field for 21 years, 18 of those at the Arecibo Observatory as a post-doc, research associate, and senior research associate. He has 15 years of experience with alexandrite laser and external cavity diode laser technologies. He is a recognized expert on the use of Rayleigh and resonance lidar techniques for scientific studies of the stratosphere, mesosphere and lower thermosphere and is an active member of the CEDAR community and the CRRL/CTC. He is a pioneer in the use of atomic and molecular vapor cell-based filters for high-resolution spectroscopy measurements, such as those undertaken by lidars. In addition to his position at the Arecibo Observatory, he holds adjunct faculty positions at UMET and at the University of Puerto Rico at Río Piedras, where he serves on the PhD committee of Ruben Delgado. He has also served on MS and PhD committees for Dr. Jonathan Fentzke (2009), Ms. Paloma Farias (2008), Mr. Johannes Wiig (2009), and Mr. John Smith (2009) from UCB. He was a primary technical advisor at Arecibo for Cornell graduate students Dr. Paul Castleberg (1996) and Dr. Stephen Collins (2002).

The Role of the CRRL/CTC

The CRRL/CTC at UCB, represented by Senior Collaborator Prof. Xinzhao Chu, will provide expert advice and interactions to ensure the performance of the laser meets expectations based on experience with the UCB-MRI laser. The CRRL/CTC also carries out extensive education programs in lidar technologies and operations. Promising students going through the UMET program and participating in this grant will be encouraged to participate in CRRL/CTC training, and to apply to graduate school at UCB to do lidar research and technology development.

Although for the purposes of this proposal, the CRRL/CTC participation will be limited to these roles, the collaboration has substantial future value. As mentioned, the CRRL/CTC trains students and scientists in the technology, operations, and science of lidar. We expect that CRRL/CTC prepared students and scientists to participate in campaigns that will use the Arecibo K lidar and other facilities to undertake science studies.

Administrative Structure and Governance

The project headquarters will be at UMET and AO. The PI will be Dr. Juan F. Arratia, Executive Director of the Student Research Development Center, an AGMUS student-based organization. Dr. Arratia is a senior administrator and mentor with experience implementing Cooperative Agreements at UMET. Dr. Arratia will report to the Chancellor of UMET for the period of the grant in matters related to the project. Dr. Arratia was awarded the 2007 US Presidential Award of Excellence in Science, Engineering and Mathematics Mentoring. The co-PI, Dr. Jonathan Friedman, adjunct faculty member at UMET and Senior Research Associate the Arecibo Observatory, will have primary technical responsibility for all aspects of the new laser system. These include operation and maintenance of the lasers and associated equipment. In that role, Dr. Friedman will also be primarily responsible for the training of new users, particularly the new lidar scientist at NAIC and students from UMET, but also including graduate students from other collaborators, in the proper use and maintenance of the system. Dr. Friedman will report to Dr. Arratia for matters related to this project. Senior Collaborator Prof. Xinzhao Chu from the CRRL/CTC at UCB will have an advisory role as to the performance of the laser system. She will also help recruit, evaluate, train, and advise promising students who go to UCB for lidar training schools and/or graduate studies.

The PI, co-PI, and the staff (Administrative Director and Secretary) at UMET and AO will coordinate all the activities of the project agenda. The PI will coordinate all communication with local government, municipalities, high schools, industry and commerce, professional organizations, and non-profit institutions. The PI's responsibilities include day-to-day operation of the project, planning and implementation of all project activities, reporting and direct interactions with the funding agency, and external funding development. The consultant will assist the PI in the implementation of the administrative and research activities with scientists.

The Implementation Team will be comprised of the PI, co-PI, the Administrative Director, and the evaluator. The Team will meet every month to implement daily project activities and carry out tasks and activities outlined in the proposal, and to coordinate project work.

The Administrative Director will report to the PI and will assist the PI in the proper financial administration of all activities. In addition, the Director and the staff will support the students in their visits and research. They will be part of the Implementation Team and will be active participants in all major activities. The Administrative Director will be part of the Implementation Team. The Project Evaluator will be in charge of the formal evaluation of all project activities.

Table 2. Timetable for Implementation of Activities

Dates	**Activity**
August 2011	Selection of project personnel
September 2011	Finalize laser design, Design project web page
August-November 2011	Issue purchase order
September 2011	Selection of student team for project
Sept 2011 – May 2012	Student engineering and research activities
June – July 2012	Shipping and Installation of laser system
Aug 2011 – Jul 2012	Implementation of laser, initial tests and observations
Mar 2012 – Aug 2012	Workshops and conferences for students and the community
Jul 2012	Annual report to NSF
Jul – Nov 2012	Test and calibrate laser
Aug 2012 – Jul 2013	Evaluation of project activities
Mar 2013 – Jul 2013	Workshops and conferences for students and the community
Jul 2013	Final report to NSF

Performance Assessment/Evaluation

The evaluation will be carried out by experienced evaluator Ms. Magie De León. The evaluator will design and develop a master evaluation plan, and will conduct project assessment/evaluation for the two-year project period.

Key indicators will be measured throughout project implementation to assure the overall project goals and objectives are reached. Constant communication between the PI, consultants, staff and the evaluators will assure on-time feedback and appropriate actions by the administration. A master activity database will be designed to record pre-college and undergraduate performance and follow-up, and progress in project activities.

The annual formative evaluations will focus on the process and will collect continuous feedback from participants in the program in order to revise the program as needed. This will be done through observations made by the evaluators, informal talks with participants, and group discussions with focus groups to gain feedback. The final summative assessment will measure the overall impact of the project, and outline improvements made under the award period.

The evaluation will document the implementation strategies, lessons learned, and best practices to achieve the program goals and objectives. The evaluator will deliver annual evaluation reports to project leadership. A summative evaluation report will be delivered at the end of the project period. The evaluation reports will demonstrate and disseminate the student, teacher and scientists' progress and project program performance to members, NSF, and other stakeholders.

Dissemination Plan

Dissemination of the project agenda and outcomes is a critical component for the project. Reaching the community, partners, collaborators and all stakeholders will be a priority. Arecibo, through the NSF-funded CEDAR community, will announce the improved lidar as soon as it is operational. Other means of communication include AGU-EOS, exhibit tables at meetings such as CEDAR, AGU, AGMUS Undergraduate Research Symposium, ILRC, or OSA, personal contact, bulletin boards, flyers, TV, the Internet, and conferences to keep a constant flow of information to persons who might be interested. A web page for the international program will be designed at http://srdc.suagm.edu to document all major activities of the project. Research outcomes will be disseminated through peer-reviewed publications and conference proceedings.

As part of the dissemination activities, the students who conduct research at the Arecibo Observatory will present their research results at the annual Undergraduate Research Symposium held at AGMUS in September of every year. Scientists and researchers from the STEM fields, as well as STEM researchers and summer mentors, will be invited to attend the symposium. STEM majors from universities in Puerto Rico will benefit from student presentations and the opportunity to network with scientists and researchers in a scientific environment. Students will also disseminate their research outcomes at national conferences like SACNAS, NCUR and STEM professional meetings. The PI, co-PI and Senior Collaborator will disseminate the project results at national and international meetings.