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Radiative Heating in Underexplored Bands Campaign (RHUBC–II) Science Plan
August - October 2009
Cerro Toco, Atacama Astronomical Park

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Principal Investigators: Dave Turner, University of Wisconsin – Madison
Eli Mlawer, Atmospheric and Environmental Research, Inc.

Campaign Logistics: Kim Nitschke, Los Alamos National Laboratory
Jim Mather, Pacific Northwest National Laboratory

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1. Overview and Objectives

The purpose of this document is to provide details for a proposed climate research measurement campaign sponsored by the United States Department of Energy Atmospheric Radiation Measurement (ARM) Climate Research Facility (http://www.arm.gov) for the period of August-October 2009 in the Atacama Astronomical Park.

The main objectives of ARM are to study the interaction of solar and terrestrial radiation with clouds and aerosols and to improve the representation of these processes in climate prediction models. The ARM Climate Research Facility (ACRF) includes permanent fixed research sites at several climatically diverse regions: the Southern Great Plains (SGP); the North Slope of Alaska (NSA); and the Tropical Western Pacific (TWP). ACRF also includes a mobile facility that has been deployed in Germany, Niger, and China. ACRF also carries out short term experiments at the fixed sites and at other locations to address specific science issues.

A recurrent theme in ARM has been obtaining high spectral resolution measurements of infrared radiation emitted by the Earth's atmosphere for the purpose of improving radiative transfer models. These improvements have resulted in modifications to radiation components of climate models. One of the last frontiers of this field of study is a detailed characterization of the radiative properties of the atmosphere in the far infrared region at wavelengths greater than 15 micrometers. At these wavelengths, the atmosphere is typically opaque at the surface so no information can be obtained about this part of the spectrum. However, this part of the spectrum is very important for radiative processes in the middle and upper troposphere (higher than approximately 5 km).

Normally, measurements of the atmospheric emission spectrum in the far infrared are only possible from aircraft. Such measurements are very expensive and only provide a few short periods of observations. However, the Atacama Desert exhibits unique characteristics for making these measurements from the ground. The key requirement is very low column amounts of water vapor and the lack of clouds over the site. In the Atacama Desert region at altitudes above 5000 m, the precipitable water vapor (PWV) amounts are expected to be on the order of 0.15 mm. This is incredibly dry and opens up portions of the infrared spectrum that cannot be observed anywhere else in the world.

To take advantage of the unusual conditions in the Atacama Desert region, we propose to conduct the *Radiative Heating in Underexplored Bands Campaign (RHUBC) II* from August to October 2009. We propose a three-month deployment to make detailed observations of the 1) downwelling infrared radiation in the 17-100 μm (10-600 cm^{-1}) rotational water vapor and 6.7 μm (1350-1850 cm^{-1}) υ_2 water vapor bands, 2) downwelling solar radiation in near-infrared (1 – 3 μm) water vapor bands, and 3) downwelling microwave radiance near the 183.3 GHz water vapor absorption line. This experiment builds upon the experience and knowledge gained in RHUBC-I, which was conducted at the ACRF NSA site in February through March 2007 under conditions with low PWV (i.e., PWV ~ 1 mm), but still a great deal larger than the PWV amounts found in the Atacama.

The primary scientific goals of RHUBC-II are:

- To conduct clear-sky radiative closure studies in order to reduce the key uncertainties in the water vapor spectroscopy, including the foreign-broadened water vapor continuum and water vapor absorption line parameters. This campaign will provide a data set with extremely low water vapor conditions (PWV << 1 mm), and collected at nearly typical mid-tropospheric temperatures and pressures.

- To investigate the radiative properties of cirrus in the far-IR using the spectrally resolved observations from the ground-based interferometers. The micropulse lidar (MPL) will provide accurate cloud boundaries for the IR calculations, as well as cirrus optical depth, which will maximize the scientific value of this data set.

It is anticipated that the ultimate impact of RHUBC-II will be increased knowledge of mid-to-upper tropospheric radiative processes and, therefore, improved simulations of future climate.

We successfully organized and conducted the first version of this experiment, RHUBC-I, at the ACRF NSA site in Barrow, Alaska, from February 22 to March 14, 2007. This experiment included the deployment of two additional 183-GHz microwave radiometers (the ground-based scanning radiometer [GSR] and MP-183) to complement the operational G-band vapor radiometer (GVR) at the NSA site, and two additional far-infrared interferometers (the tropospheric airborne Fourier transform spectrometer [TAFTS] and a second atmospheric emitted radiance interferometer – extended range [AERI-ER]) to complement the operational AERI-ER at the site. Due to the low solar elevation angles at this time, RHUBC-I did not have a solar component. An extremely valuable data set was collected during RHUBC-I, including 1) the first side-by-side comparison of multiple 183-GHz microwave radiometers, 2) the first side-by-side comparison of two unique interferometers that operate in the far-infrared, and 3) the expansion of the number of low PWV cases collected at the NSA site by a factor of 3.

For RHUBC-II, we propose to deploy a combination of instruments from ACRF in the Atacama Astronomical Park to address the uncertainties and science questions remaining following the RHUBC-I deployment. RHUBC-II will build upon the successes of RHUBC-I and allow us to collect a data set in significantly drier conditions than at the NSA site during RHUBC-I. This data set will be unique because it will be collected at mid-tropospheric pressures and temperatures, and will have high-spectral-resolution data in the near-infrared portion of the spectrum. To meet these objectives, we propose that far-infrared interferometers, one near-infrared interferometer, and 183-GHz microwave radiometers be deployed with the ARM Mobile Facility (AMF). It is imperative that the combination of interferometers covers the majority of the electromagnetic spectrum, from at least 1 µm out to 50 µm in wavelength. This experiment presents ARM with a terrific opportunity to contribute substantially to the evaluation and improvement of the parameterization of the crucial radiative processes in strongly absorbing water vapor bands in climate simulations, thereby allowing ARM to even more comprehensively attack its primary goal “to improve the treatment of cloud and radiation physics in global climate models in order to improve the climate simulation capabilities of these models.”

2. Instrument Descriptions

A variety of instruments are required to meet the scientific goals of RHUBC-II. These include instruments for measuring the infrared atmospheric emission spectrum and the near-infrared solar transmission spectrum as well as a variety of instruments to characterize the atmospheric state. Water vapor measurements are particularly important because of their strong impact on the infrared and near-infrared radiances at the surface. Instruments are listed in Table 1 and are described below.

Table 1. RHUBC-II instrument list.

Instrument	Description
FIRST	Far-infrared spectroscopy of the troposphere
AERI-ER	Infrared spectrometer covering the range 3.3 to 25 microns
ASTI	Solar tracking spectrometer covering the range 1 to 5 microns
MP-183	183 GHz microwave radiometer to retrieve PWV
MPL	532 nm micropulse lidar for cloud and aerosol profiles
Ceilometer	Near-infrared lidar with a maximum range of 7 km
PSP	Broadband hemispheric Eppley pyranometer
PIR	Broadband hemispheric Eppley pyrgeometer
8-48	Broadband hemispheric Eppley pyranometer
NIP	Broadband Eppley pyrheliometer (narrow field of view)
Solar tracker	Kipp and Zonen tracker for broadband radiometers
Met station	Temperature, humidity, wind, pressure, precipitation
MFRSR	7-channel, multi-filter rotating shadowband radiometer
Digicora-III	Receiver for radiosondes
RS-92 sondes	T/RH/P radiosondes with 403 MHz telemetry

2.1 AERI-ER

The atmospheric emitted radiance interferometer (AERI; Knuteson et al., 2004a,b) is a passive automated ground-based interferometer that measures downwelling infrared radiance at 0.5 cm^{-1} resolution over the range 3.3 to 25 µm (3000 – 400 cm^{-1}). The ARM Program has deployed AERIs at nearly all its climate research facilities, and extensive data sets (more than a decade at the SGP site and nearly eight years at the NSA site) have been collected. The AERI has been the focal point for several radiative closure studies in the ARM Program, and we have extensive experience working with this instrument. Due to its well-understood nature, its spectral overlap with the other far-IR instruments in the experiment will be of great value.

Figure 1. The atmospheric emitted radiance interferometer (AERI).

2.2 FIRST

Figure 2. The far-infrared spectroscopy of the troposphere (FIRST).

The far-infrared spectroscopy of the troposphere (FIRST) instrument was recently developed at NASA Langley Research Center. The FIRST is a passive instrument that measures downwelling infrared radiance at 0.625 cm^{-1} resolution over the range 6.25 to 100 μm (1600 – 100 cm^{-1}). The FIRST consists of a scene select mirror, a Fourier transform spectrometer (FTS), aft optics, a detector assembly, and associated electronics [Mlynczak et al., 2005, 2006]. The FTS and aft optics are cooled to ~180 K by liquid nitrogen, the detectors are cooled to 4.2 K by liquid helium, and the rest of the instrument is at ambient temperature.The FIRST was deployed at the University of Wisconsin – Madison from 21-28 March 2007 so that FIRST and AERI (normal-range) observations could be compared. Good data were collected by both systems at a time during which the PWV was approximately 8 mm, and our preliminary analysis indicates promising agreement between the two systems. A short publication on these results is in preparation.

2.3 MP-183

The MP-183 is a passive microwave radiometer that was developed and built by Radiometrics Inc. The MP-183 uses a single blackbody and a noise diode / dicke switch combination (similar to the microwave radiometer [MWR] and microwave radiometer profiler [MWRP]) to monitor the gain of the radiometer. Periodic views of a liquid-nitrogen target are used to monitor the calibration of the noise diode. It utilizes a single frequency agile synthesizer to measure emission from 170.0 to 183.31 GHz at user-selectable frequencies. The MP-183 is thus a single sideband instrument. The bandpass is 1 GHz. Radiometrics has garnered tremendous experience in building and operating MWRs in long-term autonomous mode and this experience was incorporated into the design of the MP-183.

Figure 3. The MP-183.

2.4 ASTI

Figure 4. The absolute solar transmittance interferometer (ASTI).

The absolute solar transmittance interferometer (ASTI; Hawat et al. 2002) is a passive solar tracking radiometer. The ASTI has a resolution of 0.6 cm^{-1} (half width at half maximum) and a spectral range of 1 to 5 μm (10000-2000 cm^{-1}). The ASTI has a narrow field-of-view equivalent to the central 16% of the solar disk. The instrument is calibrated using a reference tungsten lamp with a maximum temperature of 2800 K. Tests done to determine the accuracy and stability of the instrument, in conjunction with the lamp's rated uncertainty of 1-2% (wavelength dependent), yield an absolute uncertainty of less than 5% and a relative uncertainty of approximately 1%.

2.5 MPL and Vaisala Ceilometer

The micropulse lidar (MPL; left panel below) is a lidar designed primarily to determine the altitude of clouds overhead. The MPL transmits a narrow eye-safe beam of laser light with a wavelength of 523 nm into the atmosphere; the energy scattered back to the transceiver is collected and measured as a time-resolved signal. From the time delay between each outgoing transmitted pulse and the backscattered signal, the distance to the scatterer is inferred. Besides real-time detection of clouds, post-processing of the lidar return can also characterize the extent and properties of aerosol or other particle-laden regions.

Figure 5. The micropulse lidar (MPL; left) and the Vaisala ceilometer (VCEIL; right).

The Vaisala ceilometer (VCEIL; right panel) is a lidar designed to determine the alitude of low clouds and to provide backscatter profiles of aerosols. Like the MPL, the VCEIL emits a narrow eye-safe beam. The wavelength of the VCEIL beam is 905 nm. The maximum vertical range of the VCEIL is 7.5 km.

2.6 Surface Radiation

In addition to the three spectrometers, the suite of RHUBC-II instruments will include a variety of passive radiometers. A set of four radiometers (left) will provide continuous measurements of downwelling broadband shortwave (solar) and longwave (atmospheric or infrared) irradiances. These will each be Eppley radiometers and will be mounted on a Kipp and Zonen 2AP solar tracker. Three separate shortwave instruments provide the total hemispheric irradiance, the diffuse irradiance, and the direct solar beam irradiance. The total hemispheric irradiance is measured by an Eppley precision spectral pyranomter (PSP), the diffuse irradiance is measured by an Eppley 8-48 (or Black and White) pyranometer, and the direct solar beam is measured by an Eppley normal incidence pyrheliometer (NIP). The broadband infrared irradiance is measured by an Eppley precision infrared radiometer (PIR). The Black and White radiometer and the PIR are both shaded from the direct sun with shading arms on the solar tracker.

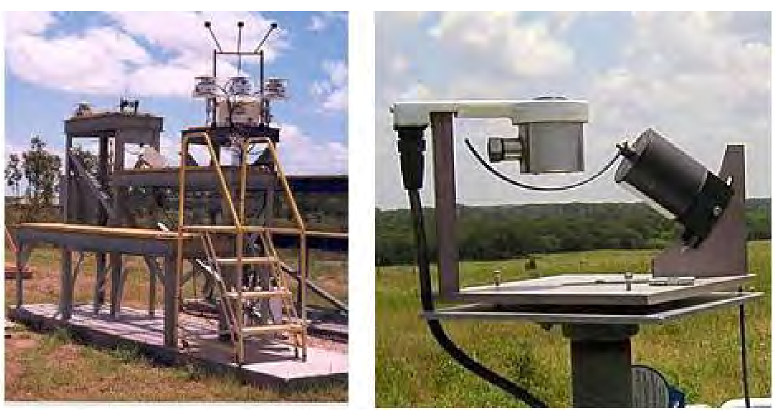

Figure 6. A set of four radiometers.

In addition to the broadband Eppley radiometers, a multi-filter rotating shadowband radiometer (MFRSR; right panel above) measures the three solar components (total hemisphere, diffuse, and direct solar beam) in one broadband channel and six narrowband (bandwidths are approximately 10 nm) channels. With the direct solar beam measured in six narrowband channels, it is possible to derive aerosol optical properties.

2.7 Atmospheric State

We will measure temperature, humidity, and pressure both at the surface using passive in situ sensors mounted on a small tower (left) and aloft using periodic radiosondes (right). We also will measure wind speed and direction at the surface. Currently we are not planning to measure wind aloft with the radiosondes. Measurements from the radiosondes will be collected with a Vaisala Digicora-III receiver using VHF telemetry in the range 400-406 MHz.

Figure 7. Passive in situ sensors mounted on a tower (left) and periodic radiosondes (right).

2.8 RF Interference

As noted in the individual instrument descriptions, most of the instruments to be deployed for RHUBC-II are passive and emit no electromagnetic radiation. Two of the instruments are lidars, which emit a narrow vertical beam of eye-safe light energy in the visible or near-infrared. Two instruments emit RF energy that will need to be evaluated for potential interference to existing instrument in the Atacama Astronomical Park: the MP-183 radiometer and radiosondes. The MP-183 is a passive instrument but it includes an internal RF noise reference. There is at least one similar radiometer operating in the Atacama Astronomical Park already. We do not expect this to be a problem but raise the issue because some of the telescopes operate in this frequency range. The radiosonde package consists of all passive sensors, but data from the package to the ground station receiver is transmitted in the 400- to 406-MHz meteorological band.

3. Proposed Location

The successful accomplishment of RHUBC-II can occur only if the campaign is held at a location with very low PWV and a high incidence of clear skies, conditions similar to those required for the installation of large astronomical observatories. One site has been identified that satisfies all of these criteria. The Atacama Desert in northern Chile has one of the driest climates in the world, in part due to the blocking effect of the Andes preventing moisture from entering either from the ocean or from the Amazon basin (Radford and Holdaway, 1998). Due to the clear and dry conditions, a plateau in this desert, Llano do Chajnantor (67° 45′ W, 23°1′ S, average altitude 5000 m), has been identified by major astronomical organizations as a most favorable location for situating a number of observatories, most notably the Atacama Large Millimeter Array (ALMA) project. The European Southern Observatory (ESO) evaluated several potential mountain top observatory locations for the installation of the ALMA facility (Erasmus 2002), eventually deciding on the Chajnantor plateau (over sites in Argentina and Bolivia) for its combination of excellent atmospheric conditions and satisfactory infrastructure.

In February of this year, four representatives from the ARM Program (Kim Nitschke, Jim Mather, Dave Turner, and Eli Mlawer) visited possible experiment sites after first meeting with Dr. Monica Rubio in Santiago. The ARM group visited a variety of sites in the CONICYT science preserve during the period February 9-12, 2008. We rated these sites according to both scientific and logistic criteria. Important scientific criteria were to locate as high as possible (to minimize the PWV at the site) and to minimize obstructions to the east because one of our key instruments will track the direct solar beam in the early morning. Key logistics considerations are accessibility and work required to prepare the site.

Figure 8. Annotated map indicating locations of the three preferred sites on Cerro Toco.

With these considerations in mind, our preferred sites are on Cerro Toco. The locations of our preferred sites on Toco are shown on Figure 8. Our first choice site (labeled “Toco A” on the map) is along the road from ACT toward the sulfur mine, at a bend in the road at an altitude of 5320 m (according to our GPS). This site has the highest elevation with reasonable access that we found and it has a good view to the east (which we need for our solar measurements). Our second choice site (labeled “Toco B”) is along this road but closer to ACT at an altitude of 5150 m, and the third choice is adjacent to ACT. The coordinates and elevations for these three sites are given in Table 2.

These sites were chosen in part because of easy access; however, some road improvement work may be necessary to ensure safe access to the site both for the set up and operations. The need for road work will be evaluated through discussions with local civil contractors. We will require that our operations area be close to level and some earth work will be necessary at any of these three sites to achieve this. We will provide additional information about site works as that becomes available.

Table 2. Toco site coordinates.

Site	**Latitude**	**Longitude**	**Elevation (m)**
Toco A	22^o 57.429’ S	67^o 46.269’ W	5322
Toco B	22^o 57.435’ S	67^o 46.939’ W	5147
ACT	22^o 57.511’ S	67^o 47.234’ W	5083

4. Site Description

The RHUBC-II site will include several shipping containers (typically with a 6.1 m x 2.4 m footprint) for instruments and a generator. Figure 9 shows the currently planned configuration for the instrument area. The required area is approximately 40 m x 40 m. The coordinates of the three candidate sites were obtained with a hand-held GPS with an uncertainty of +/- 15 m. Consequently, these points do not necessarily represent a particular point within the instrument field. The precise boundaries of the site will have to be determined through a follow-up site visit and discussions with CONICYT.

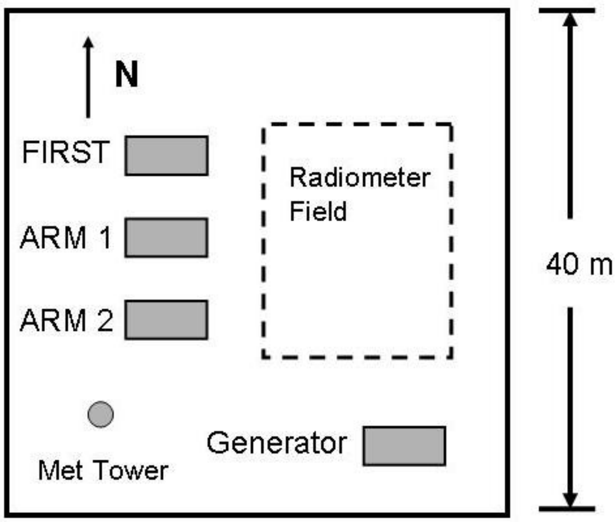

Figure 9. RHUBC-II site configuration. Shaded rectangles indicate the proposed locations of shipping containers that will serve as on-site shelters. The dashed rectangle indicates the primary instrument field. All RHUBC-II instruments will be deployed within the fenced perimeter indicated by the heavy solid line.

All RHUBC-II instruments will be located within a fixed boundary indicated by the solid line in Figure 9. Currently we are planning to install a fence on this perimeter with the approval of CONICYT. This fence will be removed at the end of the experiment. Instruments from the FIRST shelter and one of the ARM shelters will be rolled out onto the radiometer field on mornings when staff members are on site. Also there will be several fixed instruments in this area including the broadband radiometers and the 183-GHz microwave radiometer.

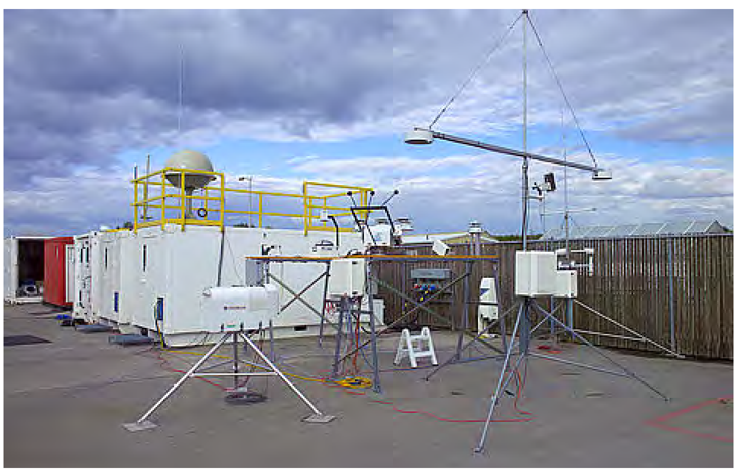

Figure 10. Container for deployment. The two containers nearest the instrument field above are among those to be deployed for RHUBC-II. Many of the instruments in the foreground are among those to be deployed for the campaign.

5. Operations Plan

5.1 Staffing

We currently plan to have approximately four people in the field throughout the RHUBC-II deployment. All of these people will be needed throughout the set-up and tear-down portions of the experiment. Some of the on-site staff will be ARM investigators from the United States; however, we also have begun discussions with AstroNorte to provide assistance during the campaign. During the actual measurement portion of the campaign, we expect to rotate the team with three people on site on a given day. We will be developing the on-site staffing schedule over the next few months. We are following ALMA guidelines to develop a safety plan for our staff during the campaign. We have already met with ALMA safety staff and will confer with them again as we develop our safety plan. The majority of the instruments will operate continuously and unattended, but a few will require staff on site. Each of the spectrometers, the FIRST, AERI-ER, and ASTI will have be rolled out from one of the shelters to the radiometer field each observation day, and staff will be required on site to launch radiosondes. We have not developed a detailed operations schedule yet but tentatively plan to operate these hands-on instruments approximately five days each week.

On observation days, the plan will be to arrive at the site approximately 1-2 hours before dawn in order to have the spectrometers operating by sunrise. This timing is driven both by the need to measure sunrise with the ASTI and because we expect to find the lowest water vapor amounts at that time, as well as the lowest wind speeds. While calm conditions are not critical for our measurements, high winds will complicate the radiosonde profiles (because they will drift away from the site) and may raise dust that could influence our radiometric measurements. The site will be staffed until approximately local noon when the spectrometers will be packed up. We expect a typical operating day to include approximately 7 to 8 hours on site with approximately 6 hours of spectral measurements. During the on-site period, we plan to launch 3 to 4 radiosondes to capture the development of the boundary layer as the sun rises.

5.2 Consumables

It is very likely that we will provide our own power with a diesel generator. This will require storing diesel fuel on site and arranging periodic fuel deliveries. We also will arrange deliveries of liquid nitrogen and liquid helium. The FIRST requires both and the ASTI requires liquid nitrogen. We have talked to several scientists who use both cryogens in the park and are developing our plan for maintaining our supply.

6. Local Contacts

The Atacama Astronomical Park is an ideal location for the RHUBC-II experiment both in terms of the physical characteristics of the area and the ongoing scientific activities within the park. In our preliminary visit to the region in February, we made contact with many individuals associated with the park in order to assist us with our planning and to ensure that we do not impact negatively the work going on there. As mentioned in the previous section, we have begun discussions with AstroNorte to assist us in our operation. Their experience with working on the astronomical projects in the park will be (and has already been) very important for us. We also have met several times with different representatives from ALMA and participated in discussions of local issues through the Chajnantor Working Group (CWG) mail list.

During our visit with Dr. Rubio in Santiago, we expressed an interest in establishing connections with scientists interested in atmospheric science issues in the Atacama Desert. This query led us to meet with Dr. Michel Cure at the University of Valparaiso. Dr. Cure is starting a project to forecast water vapor amounts over the Atacama Astronomical Park, which we expect will be very complementary to our project. During our visit with Dr. Cure in Valparaiso, we also met with Dr. David Rabanus (APEX Station Manager), and Dr. Miguel Gonzalez from the Northern Catholic University in Antofagasta. This meeting was very useful for learning more about the Astronomical Park and for developing possible collaborations. We also met with Dr. Jose Rutllant and Dr. Humberto Fuenzalida at the University of Chile. There was no obvious overlap between their work and ours, but we did obtain further useful information about the meteorology of the region through that meeting.

7. Project Schedule

We plan to collect data between August and October 2009, targeting the time of year in which PWV is typically the lowest and cloud cover is at a minimum. Prior to shipment to Chile, instruments will be shipped to the ACRF SGP site in Oklahoma where some of the instruments will be run through a test phase and the shipment will be consolidated. This test will be carried out during April/May 2009.

April 2008	Submit application to CONICYT
August/Sept 2008	Follow-up visit to Santiago/San Pedro for logistics planning
April 1, 2009	Begin beta-test of FIRST spectrometer in Pagosa Springs, Colorado
April 1, 2009	Begin site preparation on Cerro Toco
May 15, 2009	End beta-test; begin pack-up of all equipment
June 1, 2009	Ship instruments from beta-test site in Colorado
July 15, 2009	Complete site preparation on Cerro Toco
July 15, 2009	Begin Instrument set-up on site
August 1, 2009	Begin data collection
October 31, 2009	End data collection and begin tear-down
November 7, 2009	Begin site dismantle and ground remediation
November 21, 2009	On-site work completed

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