Enabling Technologies for the CLARREO Mission

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Abstract. **The Climate Absolute Radiance and Refractivity Observatory (CLARREO) mission defined in the recent Earth Science Decadal Survey requires observations of Earth's thermal infrared spectrum at very high accuracy and stability, across essentially the entire, energetically-significant portion of the spectrum. The Instrument Incubator Program (IIP) has been supporting the development of measurement technology to achieve these goals for several years now, through the Far-Infrared Spectroscopy of the Troposphere (FIRST) and the In-Situ Net Flux within the Atmosphere of the Earth (INFLAME) projects. With the commencement of the new Calibrated Observations of Radiance Spectra from the Atmosphere in the far-Infrared (CORSAIR) IIP project, we will continue the development of the enabling technologies to meet the requirements of the CLARREO mission. We will review the ongoing projects and discuss the new CORSAIR project in light of their contributions to enabling the CLARREO mission.**

I. INTRODUCTION

In 2007, the United States' National Academy of Science, at the request of NASA, NOAA, and the US Geological Survey, released a report entitled "Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond" [http://www.nap.edu/catalog/11820.html; *National Academy Press*]. The first of its kind for Earth science, this "decadal survey" recommended a series of space missions for NASA and NOAA to undertake over the course of the next decade to further our knowledge of the Earth system. Along with the missions themselves, the decadal survey provided a notional schedule for implementation of these missions. Among the first set is a mission called the Climate Absolute Radiance and Refractivity Observatory or "CLARREO." A primary objective of the CLARREO mission is to improve our knowledge of climate change through the measurement of the Earth's infrared emission spectrum at very high accuracy and traceable to the international system of units (Système International or SI) and radiometric standards. An additional objective of the CLARREO mission is to make measurements that can be used to cross-calibrate other orbiting sensors.

The CLARREO mission envisions a series of very accurate and stable interferometers (Fourier Transform Spectrometers, FTS) measuring the infrared spectrum at high accuracy and stability. The nominal measurement requirements from the decadal survey are:

Spectral Range: 5 to 50 μm (2000 to 200 cm^{-1}).
Spectral Resolution: 1 cm^{-1}
Instantaneous Field-of-View: ~ 100 km
Absolute accuracy: 0.1 Kelvin
SI Traceability: Entire spectrum
Time to record 1 spectrum: Several seconds

The focus of our efforts is on technology demonstration necessary to achieve the accurate measurement of the far-infrared (far-IR) portion of the Earth's emission spectrum, those wavelengths longer than 15 μm. The far-IR spectrum has not been comprehensively observed from space for the purposes of climate science. The scientific need for measurement of the far-IR, beyond that contained in the decadal survey, is given by *Mlynczak et al*. [2001]. A major review paper on the importance of the far-IR [The Far-Infrared Earth, *Harries et al*., 2008] will soon be published in *Reviews of Geophysics*. The far-IR contains over half of the outgoing longwave radiation exiting the Earth and its atmosphere; it is fundamental to determining the radiative feedback from water vapor associated with climate change; it is responsible for approximately half of the greenhouse effect that keeps the Earth at temperatures habitable by humans; and it contains a large portion of the radiative effects of cirrus on climate. CLARREO, with far-infrared measurements, will literally open a new window on the observation of Earth's climate. An apt analogy is witnessed in the astrophysical sciences wherein major discoveries are obtained each time a new portion of the spectrum is comprehensively observed from space for the first time. It is expected that similar discoveries will be obtained when comprehensive far-IR observations commence from space in CLARREO. Far-IR observations were endorsed with unanimity at the CLARREO workshop hosted by NASA in July 2007 [http://map.nasa.gov/clarreo_presentations.html, Infrared Breakout Group Recap].

II. Instrument Incubator Projects

A. Introduction

Langley Research Center and its partners have been developing and demonstrating new technologies for the measurement of infrared and far-infrared emission spectra since 2001. The primary sponsor of this work has been the NASA Earth Science Technology Office (ESTO) through its Instrument Incubator Program (IIP). The purpose of IIP is to reduce risk for future space flight missions through investment in new technologies prior to mission development. New technologies are to be demonstrated in a relevant environment. Successful developments emerge from the IIP typically at Technology Readiness Level 6 (TRL-6).

At present Langley is working several Instrument Incubator projects. All of these projects are related to the needs of the CLARREO mission. One project, the Far-Infrared Spectroscopy of the Troposphere (FIRST) instrument has "graduated" from the IIP and is now involved in scientific observation campaigns competitively funded through the NASA Radiation Sciences Program and the Department of Energy. We will review each of these projects in turn and discuss their contributions to the upcoming CLARREO mission.

B. The FIRST Project

The FIRST project was proposed to and selected in the IIP solicitation in 2001. FIRST developed and demonstrated the technology required to measure the far-IR portion of the Earth's emission spectrum. The specific technologies demonstrated were: a high-throughput Fourier Transform Spectrometer (FTS) capable of daily global sampling coverage from low earth orbit; a broad bandpass beamsplitter enabling the measurement of the entire infrared spectrum on a single focal plane; and far-infrared focal plane technology.

The FIRST instrument was demonstrated "in a relevant environment" according to ESTO requirements on a high-altitude balloon platform on June 7, 2005, from the Columbia Scientific Balloon Facility in Fort Sumner, New Mexico. Lofted to ~ 27 km altitude by an 11 million cubic foot helium-filled balloon, the instrument operated nominally for approximately 5 hours. Approximately 15,000 spectra were recorded, spanning essentially the entirely thermally significant portion of the infrared spectrum [*Mlynczak et al.*, 2006].

Shown in Figure 1 below is a single spectrum recorded by FIRST during the demonstration flight. The spectrum was recorded in clear sky conditions (as were all the spectra that day).

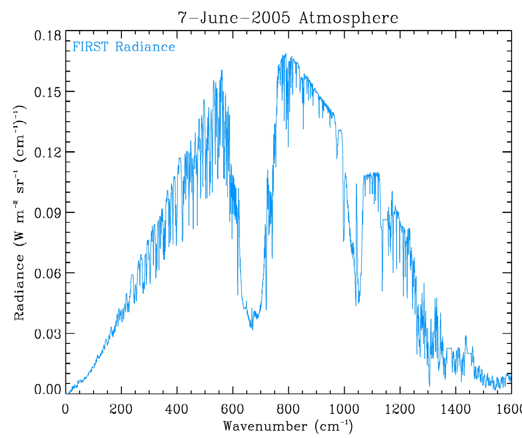

Fig. 1. Clear-sky infrared spectrum of the Earth and its atmosphere measured by the FIRST instrument from an altitude of ~ 27 km on June 7, 2005.

During the flight the Aqua satellite passed over the FIRST instrument at around 2:25 p.m. local time. A goal of the FIRST project was to compare its measurements with those of other sensors in order to validate the calibration. The Atmospheric Infrared Sounder (AIRS) instrument on the AURA satellite records infrared spectra between 4 and 15 mm and thus measures the mid-infrared portion of the spectrum coincident with FIRST. Comparisons between FIRST and AIRS in this region of the spectrum illustrate excellent agreement, especially considering the vast difference in scope of the two projects.

FIRST flew again from Fort Sumner in September 2006 in support of CALIPSO validation. The instrument again performed nominally and recorded several thousand more spectra over a flight lasting again about five hours. As in 2005, the Aura satellite and the rest of the "A-train" of satellites overflew the FIRST balloon shortly after 2:00 p.m. local time. Again the comparison of infrared spectra shows excellent agreement between AIRS and FIRST.

The clear-sky far-infrared spectra in 2005 were much larger than in 2006, as shown in Figure 2. The lower radiances in 2006 are attributed to a colder lower troposphere in 2006 than in 2005, by as much as 25 degrees, as evidenced by the temperature profiles retrieved from the AIRS instrument during the satellite overpasses.

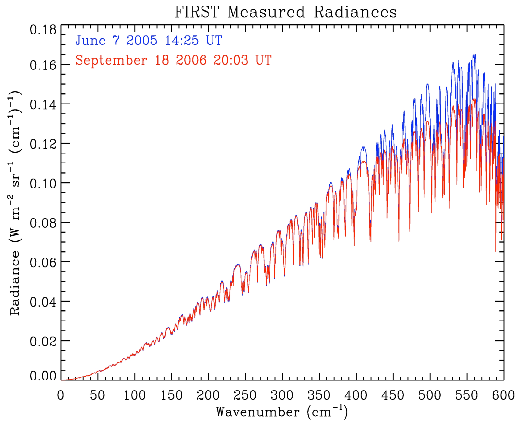

Fig. 2. Far-IR spectra measured by FIRST in June 2005 (blue curve) and in September 2006.

In contrast to the 2005 flight, by the time of the satellite overpasses in 2006, FIRST had drifted over a field of low cumulus clouds near the border of New Mexico and Texas. This offered a unique chance to observe the effects of clouds in both the mid-infrared and the far-infrared simultaneously.

Going forward the FIRST instrument will participate in an upcoming ground-based science campaign, the Radiative Heating in Underexplored Bands Campaign, part II, or RHUBC-II, sponsored by the Atmospheric Radiation Measurement (ARM) program of the Department of Energy. The campaign will take place from August to October of 2009 in Chajnantor, Chile in the Atacama desert. From the location on top of a mountain at approximately 5.2 km (17,000 ft) FIRST and a host of other instruments will observe the atmosphere in the zenith view. FIRST's participation in RHUBC-II is sponsored jointly by NASA through a competitive proposal to the NASA Radiation Sciences Program (Far-Infrared Observations of the Radiative Greenhouse Effect, FORGE)

The Atacama desert is one of the driest locations on the planet, and the elevated location of the campaign places the instruments above virtually all of the water vapor in the atmosphere, enabling the spectral development of the far-IR to be observed from the ground. Due to the opacity of the far-IR and the quantity of water vapor, far-IR spectra are not observable from the ground at sea level. This is illustrated in Figure 3 in which synthetic downwelling spectra computed at 4 km altitude and at sea level are shown.

It is anticipated that the RHUBC/FORGE campaign will offer substantial new science through the observations of water vapor spectroscopy; derivation of middle tropospheric radiative cooling rates; and observations of the radiative effects of cirrus clouds in the far-IR.

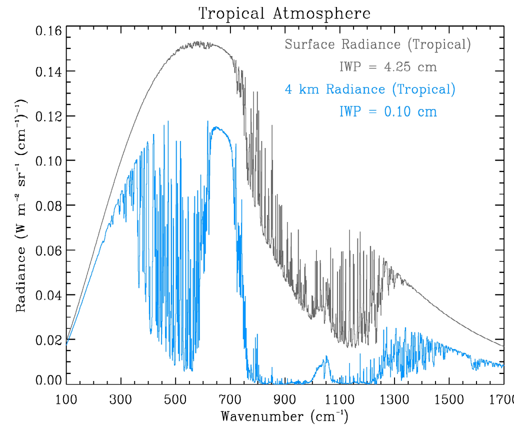

Fig. 3. Synthetic downwelling infrared spectra at the Earth's surface (black curve) and at 4 km.

In summary, the FIRST project has helped to open a new window on the infrared spectrum of the Earth. It has developed technology (FTS systems; beamsplitters; focal planes) that will enable routine space-based observations of the far-IR during the upcoming CLARREO mission.

C. The INFLAME Project

The fundamental equations solved in every atmospheric model include the momentum and continuity equations and the thermodynamic equation or equivalently, the first law of thermodynamics. The main terms in the first law that must be determined are the rates of atmospheric heating and cooling due to absorption of solar radiation and emission of infrared radiation. The radiative heating rate dT/dt is determined from the expression

$$\frac{dT}{dt} = \frac{-1}{\rho\, c_p}\frac{dF_{net}}{dz} \qquad (1)$$

where ρ is atmospheric density, c_p is the heat capacity at constant pressure, and F_{net} is the net radiative flux at altitude z. The net flux is simply the difference between the energy flowing upward and downward through an aperture of unit area, or $F_{net} = F^{\uparrow} - F^{\downarrow}$. The change in net flux with altitude is the net flux divergence, dF_{net}/dz, and is proportional to the rate dT/dt at which radiation heats or cools the atmosphere. The net fluxes are usually separately determined for the visible (solar) and the infrared (thermal) parts of the spectrum.

Determining the net radiative flux, the flux divergence, and heating rates remains a fundamental goal of many NASA projects. For example, the Clouds and the Earth's Radiant Energy System (CERES) project presently operating on the EOS Terra and Aqua satellites produces net flux and flux divergence data products for several broad atmospheric layers. These are not, however, direct measurements. NASA field experiments have had measurement goals including the determination of net radiative fluxes and heating rates within cirrus clouds.

The measurement of vertical profiles of atmospheric radiative heating was also identified as a Critical Observation in the NASA Suborbital Missions of the Future Workshop held in July, 2004. The workshop report called for the measurement of "vertical profiles of shortwave heating rates in polluted and unpolluted clear and cloudy skies", and that the measurements be "in regions impacted by major pollution sources such as megacities and industrial regions in different climatological regimes." The workshop reported that net flux measurements would improve the evaluation of climate sensitivity to forcing of aerosols and would also impact weather forecasts and the understanding of the role of heating rates on cloud and precipitation processes. In addition, the workshop reported that measurements of the vertical profile of heating would also impact understanding of the carbon cycle through better understanding of absorbing aerosols and could provide capability for detecting bioaerosol sources and dispersion.

The understanding of the role of aerosols and clouds in climate forcing remains a key issue. Recent studies have emphasized the importance of flux changes due to tropospheric aerosols which can alter the heating rate (i.e., net flux divergence) profile, particularly near the boundary layer, with possible effects on convection and cloud formation.

The In-situ Net Flux within the Atmosphere of the Earth (INFLAME) project was selected for development in the Instrument Incubator Program competition of 2004. The project is being carried out at the NASA Langley Research Center.

Our goal is to measure the shortwave and longwave net flux with sufficient stability to derive tropospheric heating rates in 1 km layers that are accurate to within 10%. Using the calculations presented in the last section we estimate that this requires measuring the net flux with a stability of 0.2% per km and 0.8% per km in the shortwave and longwave spectral regions, respectively. It is important to note that while measuring the net flux divergence requires that the instrument response be very stable, it does not require a similar level of absolute accuracy in measuring the net flux. If the calibration errors are stable and independent of altitude then the relative uncertainty in the net flux divergence will be no greater than the relative uncertainty in the net flux measurement.

The INFLAME instrument measures the net flux by using a low-resolution Fourier transform spectrometer (FTS) to observe the upward and downward flux simultaneously using the two inputs of the same instrument. The two complementary outputs of the FTS can be transformed to produce spectra proportional to the difference between the two inputs. Shown below in Figure 4 is the notional measurement concept.

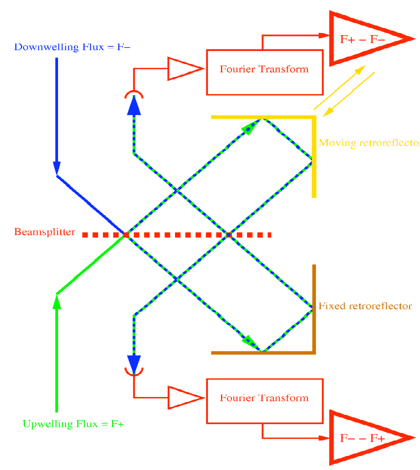

Fig. 4. INFLAME measurement concept. Upwelling and downwelling fluxes are directed into the two FTS inputs. The Fourier transform of the two outputs yields the net flux.

To illustrate both the nature of the measurement and some of the systematic errors that must be considered, consider an experiment that attempts to measure the net flux by measuring the temperature difference between two horizontal plates separated by insulation (e.g., the original flat plate "poor man's" radiometers developed by V. Suomi at the University of Wisconsin). The top surface of the top plate and the bottom surface of the bottom plate have high-emissivity coatings to make them good absorbers, so that in principal the temperature difference between the top and bottom plates provides a measurement of the net flux. The first problem that arises when trying to derive the net flux from the temperature difference is that the emissivity of most coatings depends on the angle of incidence, so that more radiation from the zenith (or nadir) is absorbed while more radiation from near the horizon is reflected. The second problem is that the temperature change for both surfaces needs to be corrected for the effect of convective heat loss, and the correction depends on the orientation of the surface and differs for the top and bottom surfaces. Convective heat loss can be reduced by using a window, but then corrections need to be derived for reflection and absorption in the window. In either case the errors in the corrections do not cancel when calculating the temperature difference

We address the first problem (variable emissivity with angle) by using Winston cone concentrators to partially collimate the flux passing through upward and downward facing entrance apertures, thus minimizing errors caused by the instrument response depending on the angle from the zenith (or nadir.) We address the second problem (temperature variability and convective heating) by using a pair of low-resolution FTS (one for the shortwave and one for the longwave flux) to measure the net flux directly. This has the advantage of converting most of the instrument background into a common-mode signal that is cancelled in the instrument, as well as moving all the optics with the exception of the entrance apertures into the body of the instrument where they can be controlled thermally.

To achieve high stability we start with the following design assumptions: make the primary measurement a differential rather than absolute measurement; make most instrument offsets into common-mode signals that cancel in the FTS; reduce or eliminate thermal gradients in the instrument; and maintain high resonant frequencies for the mechanical structure.

Using two separate spectrometers allows us to optimize the mirror coatings, beamsplitter, and detectors for each wavelength range. The upward and downward apertures are defined by the f/6.5 Winston cones shown piercing the instrument housing. The cone outputs are coupled into a single Offner relay system that reimages the two cone apertures onto the FTS retroreflectors. After the beams recombine at the beamsplitter the two outputs are focused onto smaller cones to concentrate the signal flux onto the detectors. The use of flux concentrators is important for the longwave FTS where the SNR is detector noise limited, and may not be necessary for the shortwave channel where we expect to be shot-noise limited. The detector outputs are recorded and later transformed to produce spectra that are proportional to the net flux. The instrument housing is evacuated to reduce acoustic coupling to the thin-film beamsplitter used for the longwave FTS.

The net flux will be measured directly in the atmosphere by deploying the INFLAME instruments on a Lear Jet. The instruments will be mounted in the wing tip tanks. The aircraft will slowly ascend from near the surface to approximately 40,000 feet in altitude, recording the profile of net flux. As indicated by Equation 1, the derivative of the vertical profile of net flux gives the rate at which the atmosphere is heated. The concept for aircraft operation is shown in the notianal diagram below.

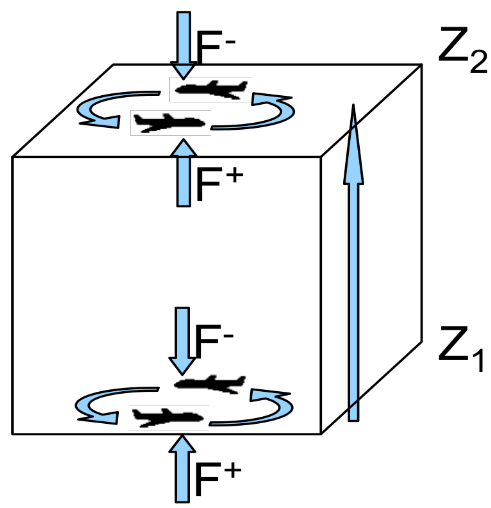

Fig. 5. Approach to measuring vertical profile of net flux in the atmosphere with the INFLAME instruments.

The contribution of INFLAME to the CLARREO mission will be the demonstration of extremely stable 4 port FTS systems and the establishment of science measurement capability to measure directly within the atmosphere processes that CLARREO will be determining from outside of the atmosphere.

D. The CORSAIR Project

With the release of the Decadal Survey and the nominal high-level requirements for the mission given in the Introduction above, it is clear that there are several areas of technology that need to be developed to achieve the goals of the mission, in addition to those already developed under FIRST and INFLAME. Specifically, sensitive detectors for the far-IR that do not require cryogenic cooling are required. In addition, radiance standards that are SI-traceable in the far-IR must be developed, as must techniques to monitor the emissivity of the on-board calibration blackbodies in the far-IR.

To address these needs Langley Research Center partnered with industry (Raytheon Vision Systems; Space Dynamics Laboratory; and ITT, Inc.) and other government laboratories (JPL, NIST) to develop the Calibrated Observations of Radiance Spectra from the Atmosphere in the far-Infrared (CORSAIR) proposal for the Instrument Incubator Program opportunity solicited by NASA in 2007. The CORSAIR proposal was selected in April 2008 and the team is now preparing to implement the proposed work effort. We will touch briefly here on the proposed scope of work in the CORSAIR effort.

D.1 Warm detectors

To meet the anticipated CLARREO measurement requirements on a small satellite will require detector technologies that do not need cryogenic cooling. Current far-IR detection technologies (e.g., silicon bolometers) typically require cooling to liquid helium temperatures (4 Kelvin or lower) and are not viable options for long-term spaceflight missions due to the absence of cryocoolers. The volume of liquid helium required for passive cooling to 4 Kelvin is also prohibitive. Current off-the-shelf technologies, e.g., pyroelectric detectors have relatively low responsivity and tend to be susceptible to acoustic and microphonic effects. They are also known to be hygroscopic.

We have proposed under CORSAIR to develop and demonstrate a new class of detectors for the far-IR. Specifically, Raytheon Vision Systems of Santa Barbara, CA has been developing antenna-coupled devices for detecting infrared radiation at terahertz (THz) frequencies (1 THz corresponds to a wavelength of 300 μm). The objective of this task for CORSAIR is to extend the technology to operate into the far-infrared at frequencies as high as 20 THz (15 μm). this is achieved by a combination of increasing the length of the antenna arm and modifying the Schottky diode that forms the detector element in the device. The devices operate at room temperature. The effort leverages substantial prior investment from other government agencies and Raytheon internal research and development sources. It is anticipated that the sensitivity of these devices will be 100 times larger than that of conventional pyroelectric devices as measured in the specific detectivity of the detector. The detectors will undergo comprehensive testing and evaluation in the FIRST instrument at Langley. These tests will occur during the third year of the effort and will provide demonstration of the technology at TRL 6.

D.2 Calibration Standards in the Far-IR

Perhaps the single facet that sets CLARREO apart from other Earth science missions is the requirement to make radiance measurements of the Earth's infrared spectrum that are traceable to international measurement standards. To achieve this requires that international standards (referenced to the SI system) exist for laboratory calibration, and that the measurement can be shown to be SI-traceable on orbit for the duration of the mission.

In the far-IR there are presently no SI radiance standards. An objective of the CORSAIR proposal is to establish these. Space Dynamics Laboratory, working with the National Institute of Standards and Technology and the Langley Research Center will establish these and will develop a prototype blackbody radiance source for the CLARREO mission that is SI-traceable in the far-IR. This part of the CORSAIR team will also develop and demonstrate techniques to monitor the emissivity of the blackbody on orbit, something that is essential to demonstrating continued on-orbit SI-traceability.

D.3 High efficiency beamsplitters

Although the FIRST project demonstrated beamsplitter technology for the far-IR, and although the FIRST instrument demonstrated an ability to measure essentially the entire infrared spectrum, there are regions in the FIRST spectra where absorption features in the beamsplitter substrate are sufficiently large to substantially degrade the measurement. As defined in the decadal survey, the CLARREO mission must measure the spectrum continuously between 5 and 50 μm, or equivalently, between 2000 and 200 wavenumbers (cm^{-1}). It is likely that this spectral range will be covered by two separate FTS instruments when CLARREO is flown; however, it is possible that resource limitations and other factors may impose the necessity of only one instrument. In that event, a high efficiency, broad bandpass beamsplitter will be required to span the required range of wavelengths. ITT, Inc. and Langley will work jointly on the design and testing of different beamsplitters for the effort.

III. SUMMARY

The upcoming CLARREO mission represents an exciting measurement challenge essential to understanding the climate change of the planet. In recognition of these challenges NASA Langley and its partners have been developing and demonstrating the technologies to measure the infrared, and especially the far-infrared, spectrum for several years now. We are developing technologies to enable Fourier Transform Spectrometers in space that operate over the energetically significant portion of the Earth's thermal emission spectrum (~4 to ~ 100 μm). these measurements will be accurately calibrated, referenced to SI standards, and verified in orbit that the standards are met through the duration of the mission.

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