2011 WORKSHOP ON FAR-INFRARED REMOTE SENSING
Meeting Summary

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INTRODUCTION

A workshop was held in Madison, Wisconsin, USA on November 8–9, 2011 that focused on the scientific questions associated with the far-infrared portion of the electromagnetic spectrum. Compared to other spectral bands in the electromagnetic spectrum, the far-infrared is relatively underexplored. This was primarily due to the lack of instrumentation that could make accurate, spectrally resolved radiance measurements in the far-infrared coupled with the fact that the atmosphere is opaque at the surface over much of the Earth. Over the last decade, several new instruments have been designed, many field experiments have been conducted, and significant advances have been made. This workshop provided a forum for leading scientists to discuss recent results and the unanswered questions in this spectral band that need to be addressed. The workshop covered several topics, including clear and cloudy sky radiative properties, climate and climate sensitivity associated with radiation, remote sensing of water vapor and clouds, instrumentation, and future missions and experiments.

The workshop was attended by leading scientists in the field. There were 30 participants, of which 7 were international; a list of the participants is shown in Table 1. The workshop presentations were organized into the general topical areas. Short summaries and primary conclusions of each presentation are given below. The full agenda and copies of the presentations are available at the workshop website:
http://www.ssec.wisc.edu/ farir_workshop/2011/

Table 1: Workshop participants

Name		Affiliation	Name		Affiliation
Ralf	Bennartz	University of Wisconsin SSEC	Harri	Latvakoski	Utah State University SDL
Fred	Best	University of Wisconsin SSEC	Tiziano	Maestri	University of Bologna
Lei	Bi	Texas A&M University	Guido	Masiello	University of Basilicata
Giovanni	Bianchini	Nello Carrara Institute of Applied Physics	Sergey	Mekhontsev	National Institute of Standards and Technology
Shepard	Clough	Clough Associates	Aronne	Merrelli	University of Wisconsin AOS
James	Davies	University of Wisconsin SSEC	Eli	Mlawer	Atmospheric and Environmental Research
Lionel	Doppler	LATMOS and Free University of Berlin	Martin	Mlynczak	NASA Langley Research Center
John	Dykema	Harvard University	Jonathan	Murray	Imperial College London
Robert	Ellingson	Florida State University	Luca	Palchetti	Nello Carrara Institute of Applied Physics
Daniel	Feldman	Lawrence Berkeley National Laboratory	Claire	Pettersen	University of Wisconsin SSEC
Jonathan	Gero	University of Wisconsin SSEC	Michael	Poellot	University of North Dakota
Denny	Hackel	University of Wisconsin SSEC	Hank	Revercomb	University of Wisconsin SSEC
David	Hoese	University of Wisconsin SSEC	Rolando	Rizzi	University of Bologna
Robert	Holz	University of Wisconsin SSEC	Joe	Taylor	University of Wisconsin SSEC
Xianglei	Huang	University of Michigan	David	Tobin	University of Wisconsin SSEC

PRESENTATION SUMMARIES

John Dykema: Recent investigations have demonstrated the potential for placing strong constraints on radiative feedbacks in climate models using observations of far-infrared emission spectra made from satellites. Several widely cited studies identify uncertainty in radiative feedbacks as the leading source of uncertainty in projections of climate on timescales of decades. The implications of climate change for energy policy, agriculture, and security have been examined through analysis of climate modeling experiments, providing quantitative methods for assessing the value of improved climate projections to societal objectives. Far-infrared measurements can therefore contribute directly these societal objectives by providing constraints on radiative feedbacks associated with water vapor and ice clouds.

David Turner (presented by Aronne Merrelli): Field experiments conducted in 2007 led to large changes (up to a factor of 2) to the foreign- and self-broadened components of the water vapor continuum model in the far-infrared, with some changes in the mid-infrared. Climate model simulations were performed using the baseline (circa 2006) and updated water vapor continuum coefficients. The differences between the two climate simulations showed that the updated water vapor continuum parameterization resulted in a dynamical response in the modified model, with changes in the temperature, relative humidity, and cloud amount profiles; changes in the latter impacted both the cloud radiative forcing and the heating associated with cloud convective processes.

Daniel Feldman: A method of directly retrieving heating rate profiles from space-borne radiometers was presented. The method accounts for correlated uncertainties between different atmospheric layers, as well as the lack of spectrally resolved radiance observations in the far-infrared, on the derived cooling rate profile. Currently, spectrally resolved mid-infrared and broadband infrared observations are yielding information about the far-infrared cooling, but ultimately, spectrally resolved far-infrared radiance observations are required.

Luca Palchetti: The Radiation Explorer in the Far InfraRed (REFIR) project is a multi-agency project in Italy with the goal of characterizing the emitted infrared spectral radiance in the 100–1100 cm^{-1} range. A detailed discussion of the REFIR-PAD, a prototype system that uses room temperature detectors instead of cryogenically cooled ones, was presented. Data from this system, collected in a range of recent field experiments, is being used to evaluate radiative transfer model and cirrus absorption model accuracy, and is paving the way for future far-infrared satellite sensors.

Eli Mlawer: The Atmospheric Radiation Measurement (ARM) Program of the U.S. Department of Energy sponsored two field campaigns to reduce the uncertainty of far-infrared spectroscopic parameters that are key determinants of mid-to-upper tropospheric radiative processes. To achieve this scientific objective, both Radiative Heating in Underexplored Bands Campaigns (RHUBC) were held in extremely dry locations: RHUBC-I was held in Barrow, Alaska, in February-March 2007, while RHUBC-II was held in the Atacama Desert of Chile in July-October 2009. Analysis of RHUBC-I spectral measurements of far-infrared radiation indicated that the previously determined values of water vapor foreign continuum absorption in this region were too high. The water vapor column amounts encountered during RHUBC-II ranged as low as 0.2 mm; analysis of RHUBC-II measurements is ongoing.

Giovanni Bianchini: The REFIR-PAD was deployed during the RHUBC-II experiment in Chile where it collected data over approximately 40 measurement days during conditions where the precipitable water vapor was as low as 0.2 mm. The calibration accuracy and noise level of the instrument was presented. The data were then used to retrieve profiles of temperature and water vapor; comparisons with radiosondes illustrate the accuracy of the retrieval method as well as the observations themselves.

Shepard Clough: The formalism for the calculation of radiation transfer in the far-infrared is well established, as is our understanding of the collisional physics. Measured and modeled radiance validations have been performed with the LBL_CRA line by line model for AERI-ER measurements at the North Slope of Alaska (NSA) from 380–900 cm^{-1} and for REFIR-PAD measurements in Chile (altitude 5400 m) from 200–850 cm^{-1}. The dominant sources of error are attributable to the collisional water vapor line widths from the HITRAN line parameter file and in one case from the neglect of line coupling. With modifications to the continuum and the widths and the inclusion of line coupling, the residuals are within 1–2 mW / (m^2 sr cm^{-1}). No evidence has been found supporting faster spectral content in the continuum.

Guido Masiello and Carmine Serio: Atmospheric emitted spectral radiance observations recorded with two moderate spectral resolution Fourier Transform Spectrometers, REFIR (Radiation Explorer in the Far InfraRed) and I-BEST (Interferometer for Basic observation of Emitted Spectral Radiance of the Troposphere), during the ECOWAR campaign in the Alps in 2007, have been used to check the consistency of state-of-art forward models and continuum absorption modules. It has been shown that the current module for the water vapor continuum (MT_CKD 2.5.2, released in 2010) performs quite well relative to the previous model version (2.1, released in 2007); for example, the newer model improves the agreement with observations in the microwindow at 403 cm^{-1}. The ECOWAR dataset suggests that the current MT_CKD 2.5.2 model parameterization, while much improved relative to earlier versions of the continuum model, needs additional absorption in the 360–600 cm^{-1} range.

Lionel Doppler: The radiative transfer code MOMO of the Free University of Berlin has been applied to the clear-sky mid-latitude standard atmosphere in far-infrared (15–100 μm). Several results, consistent with current knowledge, are found: a) water-vapor plays a huge role in the emission and absorption of the gases, as well as N_2 up to 35 μm, b) cooling-rates in the far-infrared correspond to 10–20% of the cooling-rates of the middle infrared, depending on the altitude, and atmospheric state, c) a spectroscopic study points out the necessity of having high spectral resolution for the computing of the TOA fluxes (at least 0.1 nm), and d) a sensitivity study points out the large influence of the water-vapor continuum on the TOA fluxes and on heating-rates.

Jon Murray: Airborne field experiments were conducted over the Swiss Alps in July and August 2009 as part of the Continuum Absorption by Visible and Infrared Radiation and its Atmospheric Relevance (CAVIAR) project. The field campaign was a radiative closure study designed to measure the absorption strength of the water vapor continuum in the spectral region covering the mid- to far-infrared. This campaign used the Tropospheric Airborne Fourier Transform Spectrometer (TAFTS), a far-infrared interferometer operating between 20–120 μm (80–500 cm^{-1}). Measurements of the strength of the foreign-broadened water vapor continuum between 85–420 cm^{-1}, derived from the field campaign, were presented. These measurements have been compared to the MT_CKD 2.5 model parameterization and show good agreement above 300 cm^{-1}. Below 300 cm^{-1}, the TAFTS continuum measurements and the model parameterization deviate, requiring an increase in the parameterization of the continuum strength of MT_CKD 2.5 of between 10% and 50% to match the TAFTS measurements.

Aronne Merrelli: In order to investigate the utility of far-infrared spectra for clear sky temperature and water vapor profiling, information content analyses were performed using an optimal estimation framework applied to line-by-line calculations of upwelling radiance. The framework was applied to both far-infrared and mid-infrared spectra to compare the far-infrared measurements to the current state of the art for passive infrared clear sky profiling. The results are strongly dependent on the assumed noise level within each instrument, but with equivalent noise levels in both measurements, the far-infrared shows similar temperature profile information and an advantage in the upper troposphere water vapor profile.

Lei Bi: Single-scattering and radiative properties of ice crystals in the atmosphere are fundamental to remote sensing studies of cirrus clouds. A spectrally consistent database of the optical properties of ice crystals was developed on the basis of nine representative ice habits, an updated index of refraction, and the state-of-the-art computational methods. The database consists of 51 wavelengths ranging between 15–100 μm and 189 different particle sizes (defined in terms of the particle maximum dimension) ranging from 2–10,000 μm.

Tiziano Maestri: During the ECOWAR-COBRA experiment (Italy, 2007), cirrus clouds were observed by multiple ground-based sensors (interferometers and a lidar) and a dedicated Vaisala radiosonde system. Spectral radiance measurements in the 100–1100 cm^{-1} spectral range are used to test the theoretical optical properties of mid-latitude ice clouds in the far-infrared part of the spectrum by inferring microphysical and optical properties from mid-infrared (800–1000 cm^{-1}) spectral channels and then comparing forward simulations and data over the whole measurement spectral interval. The results demonstrated that downwelling brightness temperatures in the far-infrared are sensitive to cloud microphysical properties. Nevertheless, the brightness temperature sensitivity to typical changes in atmospheric parameters, such as water vapor concentration and temperature profiles, is of the same order of magnitude. Upwelling radiance simulations show lesser sensitivity to changes in atmospheric parameters suggesting a clear advantage in the characterization of far-infrared cirrus cloud radiative and optical properties by means of airborne or satellite measurements.

Xianglei Huang: An algorithm was presented that directly derives spectral flux over the entire longwave spectrum from the Atmospheric Infrared Sounder (AIRS) radiances.

The algorithm was validated against synthetic radiances and fluxes as well as the outgoing longwave radiation (OLR) from the collocated Clouds and Earth's Radiant Energy System (CERES) instrument on the Aqua satellite. Consistently good agreement was found with CERES OLR for both clear-sky and all types of cloudy-sky scenes. The algorithm was then used to derive the flux and cloud radiative effect over each individual absorption band and, as a case study of their application in climate studies, such band-averaged quantities were used to evaluate counterpart outputs from three global circulation models (GFDL AM2, NASA GEOS-5, and Canadian CCCma CanAM4). The evaluation quantitatively disclosed the compensating effect between the water vapor far-infrared band and the mid-infrared window bands for each GCM; this further demonstrated the merit of such band-by-band cloud radiative effect in GCM evaluations and cloud feedback studies.

Martin Mlynczak: Results from two new instruments, the Far-Infrared Spectroscopy of the Troposphere (FIRST) and the In-Situ Net Flux within the Atmosphere of the Earth (INFLAME), were presented. FIRST is an interferometer developed to observe the far-infrared portion of Earth's emission spectrum; measurements from the RHUBC-II field campaign in the Atacama Desert were shown in comparison with model calculations. The INFLAME instrument, which directly measures the spectral net flux of radiation within the atmosphere from an aircraft, was introduced. INFLAME has provided the first direct measurements of the spectral net radiative flux and cooling rates over the entire infrared spectrum in the atmosphere from 1.5 to 10 km altitude. Work continues on characterizing these instruments and their measurements.

Harri Latvakoski: The FIRST instrument is a spectrometer designed to observe the far-infrared (10–100 μm) emission of the atmosphere from the ground or a high-altitude balloon; it has successfully been used in both configurations. Laboratory based recalibration is currently being performed on the instrument. The LWIRCS (Long-wave infrared calibration source) is a 2–100 μm blackbody (originally designed for calibration of FIRST) that has been tested with the NIST transfer radiometer (TXR) and found to agree with the TXR radiance scale to within the TXR uncertainty of ~130 mK. The CORSAIR blackbody is a recently built prototype blackbody designed to show ability to meet the blackbody needs of CLARREO (Climate and Absolute Radiance and Refractivity Observatory); performance test results to date are positive.

Sergey Mekhontsev: Long-term absolute measurements of the Earth spectral radiance in the infrared are essential for climate change modeling and prediction. Proposed climate science missions, along with weather sounders, require rigorous pre-flight radiometric calibration, as well as validation of techniques for maintaining the traceability in space. This report provided an update on recent progress in the area of thermal and far-infrared metrology standards at NIST, and discussed the techniques and instrumentation under development, which may help to achieve climate benchmark data quality for future space missions, as well as support other applications.

Hank Revercomb: The University of Wisconsin-Madison Space Science and Engineering Center (UW-SSEC) and Harvard University (HU) submitted a successful joint proposal entitled "A New Class of Advanced Accuracy Satellite Instrumentation for the CLARREO Mission" to the NASA Instrument Incubator Program (IIP). This project demonstrates technology readiness for a new infrared Climate Benchmark and inter-calibration mission named Zeus (for the ancient Greek god of sky and weather, law, order and fate) recently submitted to the NASA Earth Venture 2 opportunity. The key components of the Zeus mission are an accurately calibrated FTIR spectrometer, the Absolute Radiance Interferometer (ARI); and an On-orbit Verification and Test System (OVTS) providing direct SI traceability to fundamental physical properties that consists of an On-orbit Absolute Radiance Standard (OARS), an On-orbit Cavity Emissivity Monitor (OCEM), and an On-orbit Spectral Response Monitor (OSRM); all with coverage from 3–50 µm. More detailed talks followed on the ARI (*Joe Taylor*), OARS (*Fred Best*), and OCEM-heated halo method (*Jonathan Gero*).

Joe Taylor: The objective of the University of Wisconsin NASA IIP effort is to advance the technological development of advanced accuracy instrumentation for the measurement of absolute spectrally resolved infrared radiances (3.3–50 µm) with high accuracy (<0.1 K, k=3, brightness temperature at scene temperature) for climate benchmark measurements from space. The UW-SSEC is building a demonstration test-bed, which includes an FTS instrument and calibration and validation system to demonstrate the feasibility of the far- and mid-infrared instrumentation for a Climate Benchmark Mission. A review of the Absolute Radiance Interferometer (ARI) instrument design and current status was presented.

Fred Best: Key elements of an On-Orbit Absolute Radiance Standard (OARS) that can be used for end-to-end verification of Earth scene radiance measurements have been demonstrated in the laboratory at the University of Wisconsin and are undergoing further refinement under the NASA IIP. The OARS will meet the stringent requirements of the next generation of infrared remote sensing satellite instrumentation, including climate benchmark missions. As an example, instrumentation designed to measure spectrally resolved infrared radiances with an absolute brightness temperature error of better than 0.1 K will require high-emissivity (>0.999) calibration blackbodies with emissivity uncertainty of better than 0.06%, and absolute temperature uncertainties of better than 0.045 K (k=3). The OARS will be capable of providing absolute radiances within these uncertainties covering the 220–320 K brightness temperature range. The new technologies that underlie the OARS were presented with updated results of laboratory testing that demonstrate the required accuracy. The underlying technologies include on-orbit absolute temperature calibration using the transient melt signatures of small quantities (<1 g) of reference materials (gallium, water, and mercury) imbedded in the blackbody cavity, and on-orbit cavity spectral emissivity measurement using a heated halo (see *Jonathan Gero*).

Jonathan Gero: The Heated Halo is a component of the On-orbit Absolute Radiance Standard (OARS), which provides a robust and compact method to measure the spectral emissivity of a blackbody, in-situ. Measurement of the blackbody radiance, including the reflection from the Heated Halo thermal source, and knowledge of key temperatures and the viewing geometry allow the blackbody spectral emissivity to be calculated with high accuracy. Emissivity measurements of a 0.999 emissivity blackbody have been demonstrated with the Heated Halo using the Scanning High-resolution Interferometer

Sounder (S-HIS) as well as the Absolute Radiance Interferometer (ARI) in the 3–50 μm spectral range, with a measurement uncertainty better than 0.0006 across most of the thermal infrared.

SUMMARY

This was a very successful workshop, allowing leaders in the field to present and exchange ideas regarding various issues regarding far-infrared measurements, modeling, and associated studies. Measurements from past field campaigns were described, as well as the instruments designed to make measurements in the far-infrared portion of the spectrum. These measurements have been very useful for improving our understanding of the atmosphere, radiative closure studies, and improving radiative transfer models, particularly for the water vapor continuum. The field experiments have resulted in substantial changes in the parameterization of the water vapor continuum, sometimes up to a factor of 2; furthermore, the most recent experiments suggest that some additional modifications to the water vapor continuum model are still needed. The utility of ground-based, airborne and satellite observations in the far-infrared has been clearly demonstrated; however, there was also a call for more laboratory measurements of water vapor spectroscopic parameters, and in particular absorption line widths. Several modeling efforts were also discussed, including spectroscopic models, cloud models, as well as comparisons between observations and general circulation models. There was a consensus amongst the participants about the need of improved instruments for the ongoing characterization of the far-infrared atmospheric spectrum. The case was made for the need for satellite-based spectrally resolved far-infrared radiance observations, which would provide constraints on radiative feedbacks, which in turn aid societal objectives such as sound energy policy, agriculture and security.

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