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Atmospheric Remote Sensing using FIRST (Far Infrared Spectroscopy of the Troposphere instrument)

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Abstract: - FIRST is a hyperspectral FTS instrument which is capable of measuring the atmospheric far-infrared to mid-infrared radiation. It has a spectral coverage ranging from 50 to 1600 cm^{-1} and a nominal spectral resolution of 0.625 cm^{-1}. It was developed under the NASA Instrument Incubator Program and successfully completed a technology demonstration flight in June 2005 aboard a high altitude balloon launched from Ft. Sumner, NM. This paper will describe some preliminary results from the balloon flight. Comparisons of FIRST observed radiances with those of AIRS [2] and with radiative transfer model calculations show that the FIRST spectral is well calibrated with good spectral coverage and good noise equivalent change in radiance.

Key-Words: - Remote sensing, radiative transfer model, atmospheric radiance, far-infrared spectrum

1 Introduction

The FIRST instrument is a Michelson FTS developed by the Langley Research Center in partnership with the Space Dynamics Laboratory (SDL) of Utah State University and the Harvard-Smithsonian Astrophysical Observatory. It was developed under the NASA Instrument Incubator Program to demonstrate the technology for next generation of space-based sensors. Dr. Marty Mlynczak is the principal investigator of this project. A paper by Mlynczak et al. [1] has been written on the overview of the FIRST instrument design concept, flight test and preliminary results. The FIRST instrument has a high-throughput (0.47 cm^2-sr) optical design covering the wavelength range from approximately 50 - 1600 cm^{-1} with a single, broad band-pass beam splitter. Its focal plane is sized to hold 100 detectors but presently is populated with 10 (2 at each corner and 2 in the center). The nominal spectral resolution of FIRST is 0.625 cm^{-1}. As required by the Instrument Incubator Program, the FIRST interferometer conducted a flight demonstration on June 7, 2005 from Ft. Sumner, New Mexico, on a high altitude research balloon. The payload operated at an altitude of 27 km for approximately 5.5 hours, recording about 15,000 spectra. The sky conditions that day were clear and the atmosphere was quite dry. The NASA AQUA satellite passed the FIRST instrument directly overhead at approximately 20:25 UT time.

The spectral coverage and spectral resolution of the FIRST instrument makes it useful in studying microphysical properties of clouds, atmospheric moisture and temperature profiles, surface skin temperatures, surface emissivities, and radiation energy in the far- and mid-infrared region [3, 4]. Preliminary studies on the calibration, validation and modeling of the FIRST spectra will be discussed.

1 Radiance calibration

The FIRST instrument has three observation configurations. The first one is looking down at the earth, measuring upwelling radiation of atmosphere and the earth's surface. The second mode is looking at an internal blackbody calibration target. And the third mode is looking out the cold space. Figure 1 shows an example of interferograms taken by the FIRST instrument looking down on the earth. This interferogram contains information on the atmospheric radiation, the earth's surface emission, the instrument self-emissions, and the instrument response function. To obtain a calibrated earth-scene spectrum, all three interferograms taken at the above mentioned configurations are transformed into spectral domain. These spectra have both real and imaginary components because the phase response functions introduced by the instrument are not corrected. The signal observed by the instrument detectors can be separated into various components:

$$R_\nu^{raw} = F_\nu (R_\nu^{external} + R_\nu^{instrument} e^{i\varphi_\nu}) e^{i\phi_\nu}$$

where the subscripts ν represents frequency, R^{raw} is the complex radiance spectrum observed by the FIRST instrument; F is the instrument response function, $R^{external}$ is the absolute incident radiance of external sources, and ϕ is normal phase response function of the instrument. $R^{instrument}$ is the background spectral radiance from internal instrument components such as beam splitter, mirrors and windows, and φ is the anomalous phase response function of the background. The product of $R^{instrument}$ and $e^{i\varphi}$ is a complex spectrum and can be thought as a constant term since the instrument temperature does not change within a short period of time.

Giving three complex spectra with varying external radiation sources and fixed internal instrument emission, we can solve for calibrated external radiation term, the instrument response function, and external phase function using three linear equations. The calibrated earth scene spectrum can be obtained according to the following equation [see reference 7]:

$$R_{earth}^{calib} = real\{(\frac{R_{eaeth}^{raw} - R_{space}^{raw}}{R_{hot}^{raw} - R_{space}^{raw}})[B(T_{hot}) - B(T_{space})]$$
$$+ B(T_{space})\}$$

where R^{calib} represents calibrated radiance spectrum; B is the Planck function calculated at the FIRST channel frequencies and at the calibration target temperature. Subscripts *earth, hot, and space* represent three observation configurations. The hot calibration target temperature (T_{hot}) was measured during the flight and is well known. For a satellite-based instrument, the radiation from space is very small in the far- and mid- infrared region. But for the balloon-based observation, there are some contributions from the downwelling atmospheric radiations. For this preliminary study, the atmospheric emission features are removed by interpolating between the wings of emission lines. This will lead to some errors in the calibrated spectrum near the center of 15.8 μm CO_2 band. We plan to improve the treatment of downwelling radiations in the future calibration process using approach similar to the approach by MIPAS team [8].

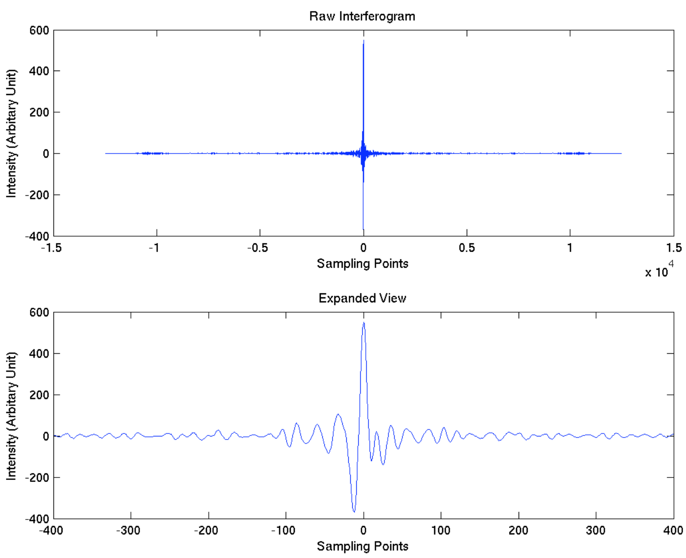

Figure 1. An earth scene interferogram taken by the FIRST instrument. Upper panel: the whole interferogram. Bottom panel: the expanded view near zero optical path difference.

3 Radiance validation and modeling

The radiance levels recorded in the atmospheric window region indicate a surface skin temperature of approximately ~319 K. Comparisons of skin temperature derived from the coincident CERES, AIRS, and MODIS measurements on the AQUA satellite are all within 1 K of the FIRST value. The upper left plot in Figure 2 shows a calibrated FIRST spectrum and a collocated spectrum observed by the AIRS instrument onboard of AURA satellite. The other 3 panels in Figure 2 are expanded view of the same radiance comparison. The latitude and longitude of the balloon at the time when the FIRST spectrum was taken are 34.97N and 104.95W respectively. The AIRS latitude and longitudes are 34.91N and 105.06W, respectively. The agreement between FIRST and AIRS is very good considering different spectral resolutions and observation platforms of the two instruments. Near the center of the 15 μm CO_2 band, the AIRS sensor is sensitive to temperature in the upper atmosphere while the FIRST instrument is only measuring atmosphere below 27 km. Therefore, the difference in this spectral region (650-720 cm^{-1}) is expected. In the window region from 800 to 950 cm^{-1}, the agreement is very good since the atmospheric transmittance is very high and the contribution from above the balloon altitude is negligible. For spectral regions that are sensitive to water emissions (1200-1600 cm^{-1}), the contributions are mainly from altitudes below 27 km. The agreement between FIRST observed radiance and AIRS observed radiance is good in spite of differences in spectral resolution, observation geometry, and ground footprint size. It should be mentioned that the AIRS spectral resolution decreases as the frequency increases, while the FIRST resolution remains constant. If we degrade the spectral resolutions of both AIRS and FIRST to a common grid, the agreement should be very good since we do not see any bias between the two spectra. In the ozone spectral region (1000-1070 cm^{-1}), the agreement is not expected to be good since there are still significant amount of ozone above 27 km.

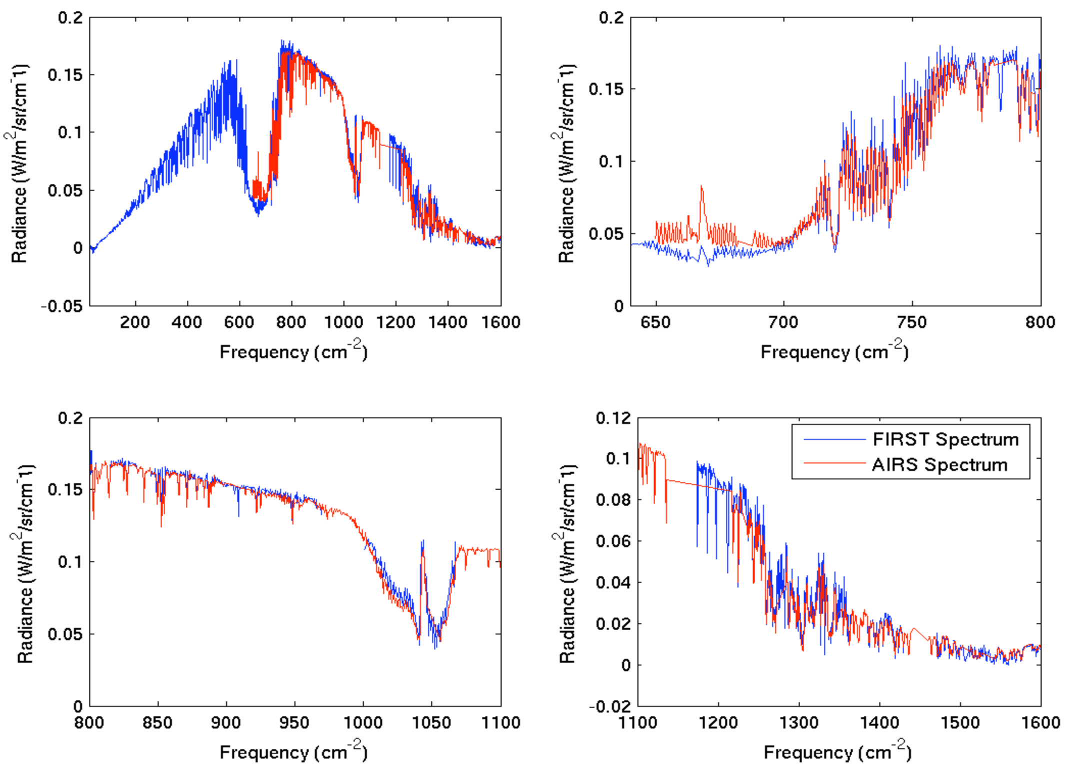

Figure 2. Comparison of FIRST and AIRS observed radiances recorded on 7 June 2005.

For accurate atmospheric property retrievals and atmospheric radiation modeling, we need to further quantify the FIRST absolute radiance calibration and instrument line shape function by performing radiative transfer modeling of the observed spectra. There are some radiosondes taken at Albuquerque, New Mexico. The latitude and longitude of this radiosonde station are 35.05N and 106.62W, while the latitude and longitude of the balloon location are 34.97N and 104.95W. The time of the radiosonde launches (18:00 UT and 24:00UT) were different from the time of the FIRST observations. We have calculated radiance based on radiosondes and surface skin temperature from AQUA MODIS instrument and the agreement between the modeled and observed FIRST radiances are good. We further modeled the FIRST radiance using AIRS retrieved atmospheric temperature, moisture, and ozone profiles, surface emissivity and surface skin temperature as input to the radiative transfer model. These quantities are fed into a line-by-line radiative transfer model (LBLRTM) and the monochromatic radiance is convolved with the instrument line shape function of the FIRST instrument. In this case we choose to use a Hamming apodization function to minimize side lobes of the unapodized spectrum. No attempts are made to correct for the instrument self-apodization at this time. The radiosondes and AIRS retrieved profiles used in the radiative transfer modeling are shown in Figure 3. The surface emissivity from AIRS retrieval is also shown in figure 3. The surface skin temperature from AIRS retrieval is 318.9 K. These AIRS products are obtained from NASA DAAC and are processed using AIRS version 4 algorithm [4, 5].

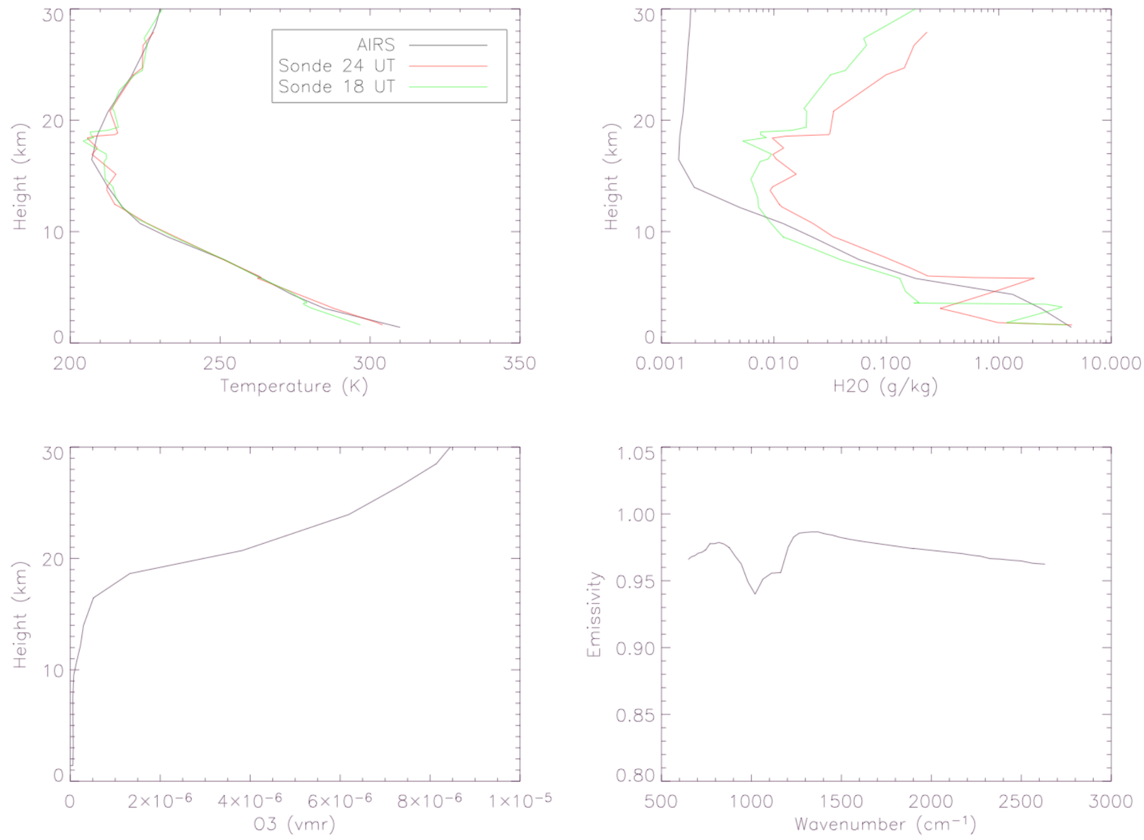

Figure 3. Temperature, moisture, and ozone profiles from radiosonde and AIRS retrievals. The emissivity is from AIRS retrieval.

Figure 4 shows the resulting comparison of an FIRST observed spectrum and a LBLRTM calculated spectrum. The bottom panel is the difference of the two. Some blank spaces are spectral features that have been removed due to the absorption characteristics of the Mylar beam splitter. Overall, the agreement between the observation and model radiances is very good. The discrepancy near the CO_2 band center is due to the CO_2 emission features in the cold space view that have not yet been removed in the calibration process. The high frequency residuals are mainly due to the effect of the instrument self-apodization. The agreement should improve after we characterize this effect. Some differences in water lines are probably due to the spatial variation of water vapor in the atmosphere. The AIRS Level 2 retrieval product is derived for a ground footprint of 45 KM, while the FIRST ground footprint is only about 0.2 km. Since the FIRST spectral range covers both the pure H_2O rational lines (50 to 550 cm^{-1}) and ν_2 vibrational band (1200-1600 cm^{-1}), it will be very useful in validating the water spectroscopic line parameters including water continua.

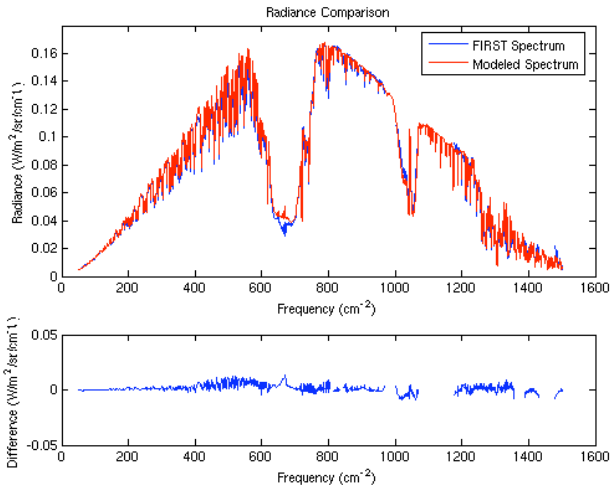

Figure 4. Comparison of FIRST observed radiance and the radiance calculated using a line-by-line radiative transfer forward model. The bottom panel is the difference of the two.

These results described above indicate that the FIRST instrument is exceptionally well calibrated for a brand-new sensor.

4 Conclusion

Preliminary studies on the FIRST spectra taken on June 7, 2005 show that the instrument is well calibrated. The FIRST radiance compares well with collocated AIRS overpass observations. The radiances in window regions agree very well with other broad band sensors such as MODIS and CERES onboard of AQUA satellite. Radiative transfer model calculated spectra using radiosondes and AIRS retrieval products shown good agreement with observed FIRST radiance indicating good radiometric calibration and good instrument spectral characteristics. Further studies will be done on the absolute calibration and the instrument line shape characterization. Retrievals will be done to obtain temperature, moisture, and ozone profiles from the FIRST spectra. Surface skin and emissivity values will also be retrieved in our future studies. We will study the impact on the vertical resolution and accuracy of the moisture profile retrieval by including pure water rational lines in the retrieval system.

The FIRST instrument is now at NASA Langley where it is undergoing more testing and calibration. The dataset from the June 2005 flight is being analyzed and the full pre-flight calibration is being applied to the observations.

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