MEASUREMENT OF ABSOLUTE SOLAR INFRARED RADIATION THROUGH THE ATMOSPHERE

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ABSTRACT

The University of Denver's Absolute Solar Transmittance Interferometer (ASTI) has been developed and employed to radiometrically measure the infrared solar radiance and irradiance at the Earth's surface for several ground-level altitudes ranging from 300 to over 14,000 feet. ASTI also has a major research role in making absolutely calibrated IR measurements of on-axis and off-axis transmittance and scattering properties of numerous cloud types. These measurements and results will provide radiometric information for implementing the IR properties of the atmosphere and cloud IR albedo into General Circulation Models (GCM). The ASTI instrument is described, along with the IR bands available and the radiometric calibration capability using NIST-standard calibrated lamps. The Langley plot technique has been used to conduct initial analyses and to plot the calibrated IR data for several atmospheric paths as a function of solar zenith angle and solar zenith angle. The exoatmospheric intercepts are provided for nine IR lines ranging from 4180 to 7481 cm⁻¹. Initial cloud spectra are provided over the IR band from 4000 to 10000 cm⁻¹ showing interesting properties.

Introduction

The University of Denver Atmospheric Physics Group has designed, developed and tested an IR interferometric instrument for use in absolutely calibrated measurements of solar radiance and irradiance at the earth's surface. The ASTI instrument has been built, tested, calibrated and used at several locations for measuring solar radiance at nearly all times of daylight hours, with emphasis on measurements at solar noon. The output of the ASTI Research Program is accurate and calibrated measurements of solar irradiance at various altitudes from near sea level to over 14,000 feet, and measurements of the IR transmittance and scattering properties of varied cloud types.

Background

Significant work was accomplished in the 1980's to measure absolute solar irradiance in the visible and near infrared, at the earth's surface and then through analytical techniques, extrapolate these data to the corresponding exo-atmospheric quantitative values as a function of wave number and air mass. The technique employed was the Langley Calibration Technique¹ through the use of modified Langley plots².

In the last few years, the need has strongly arisen for the absolute characterization of the solar IR irradiance at the top of the atmosphere and through various atmospheric paths to the earth's surface, and in addition, the IR transmittance and scattering properties of all cloud types. These required results will have a major impact in GCM work and in global and regional climate change assessments.

Characterization of solar IR downwelling through the atmosphere along with that of atmospheric aerosol absorption and scattering properties is needed to produce single scattering and scattering phase function albedo measurements for use in atmospheric corrections³. Accurate absolute radiometric calibration is required for the atmospheric
correction methods being developed by several investigators.

**ASTI Instrument Description**

The ASTI instrument is built as a portable instrument using as an interferometer a Bomem, Inc. (Quebec, Canada), Model MB-100. Figure 1 is a functional block diagram of ASTI, consisting of four subassemblies: 1) Bomem Interferometer, 2) Radiometric Optical Shelf, 3) Solar Constant Tracker, and the 4) NIST Radiometric Calibration Lamp. The Bomem instrument contains a folded Michelson interferometer designed for utility in the IR. It has an IR resolution capability ranging from 1 to 128 cm\(^{-1}\) with high and low gains incorporated into the electronics. The optical schematic of this instrument is provided in Figure 2, having a 25 mm aperture. The beamsplitter used within the instrument’s optical train is KBr.

The optical schematics for ASTI (Figures 3 and 4) show the optical path and the major components of this rather complex system. The solar irradiance is incident upon an entrance aperture consisting of an IR-enhanced elliptical flat mirror (M1, 45x68 mm) which is driven by a servo loop within the solar tracker. The solar optical beam is then turned into the interferometer’s optical train through one of its input ports. The interferometric IR output beam is then directed to the upper subassembly by a turning flat from one of the Bomem’s output ports. This shelf contains the main optics of ASTI, designed for absolute radiometric measurements.

The first optic in this subassembly encountered by the beam emerging from the interferometer is an IR-enhanced elliptical flat mirror (M2) which serves to direct the solar energy onto a circular flat (M3), which in turn reflects the beam through the circular solar spatial filter (F1) with selectable diameters ranging from 0.2 to 1.2 solar disk diameters.

![Figure 1 ASTI Functional Block Diagram](image1)

![Figure 2 Bomem MB-100 Optical Schematic](image2)
the selectable F3, F4 and F5 filters. The IR FWHM bandwidths of these filters are the following:

1) Long-pass, F3: 1950 to 5000 cm\(^{-1}\)
2) Medium-pass, F4: 4400 to 7100 cm\(^{-1}\)
3) Short-pass, F5: 6900 to 10300 cm\(^{-1}\)

Mirror M5 is a turning conic mirror used to focus the IR interferometric beam into the detector’s entrance aperture and onto the InSb detector element.

The IR detector is an LN2-chilled InSb type which has a detection band from about 1.0 \(\mu\)m to 5.7 \(\mu\)m, the cut-off. It has a specific detectivity \(D^*\) of 2E+11 cm Hz\(^{1/2}\)/W. The associated cryostat chills it to about 77 K. The sensitive area of the InSb material is 1 mm\(^2\).

The solar tracker is an azimuth-elevation angle tracking loop for the solar disk, with a static pointing accuracy of less than 500 \(\mu\)rad. It tracks the solar disk across the sky (2\(\pi\) sr) and points mirror M1 so that the solar irradiance beam is centered within the interferometer's entrance aperture and onto the circular spatial filter F1. Alignment procedures are used to verify and maintain this pointing relationship when ASTI is tracking the solar disk from horizon to horizon.

**ASTI Radiometric Calibration**

L1 in Figure 3 is the radiometric-calibrated tungsten ribbon-filament lamp (NIST Standard of Spectral Radiance, Optronics Laboratories, Inc.; calibrated from 1900 to 10500 cm\(^{-1}\)). The IR radiation from the lamp enters and follows the same optical train as does the solar beam. The spatial filter F1 used during this procedure is the one employed during the solar radiance measurements.

For solar measurements, the calibration interferograms are recorded for each of the three spectral filters (F3, F4, F5) using 2 cm\(^{-1}\) resolution. For cloud-solar transmittance measurements, all five filters are removed from the optical train on the upper shelf, and a resolution of usually 32 cm\(^{-1}\) is used.
The actual radiometric calibration calculation performed on the solar or cloud interferograms is

\[ I_{\text{rad}}(S) = \left[ \frac{I_A(S)}{I_A(L)} \right] S_{\text{manuf}}(\text{lamp}) G(v) \]  

(1)

where:

- \( I_{\text{rad}}(S) \) - Calibrated power spectrum: sun, cloud
- \( I_A(S) \) - Power spectrum obtained by ASTI
- \( I_A(L) \) - Power spectrum by ASTI for lamp L1
- \( S_{\text{manuf}}(\text{lamp}) \) - Radiometric spectrum for L1
- \( G(v) \) - ASTI instrument factor.

The lamp spectral data are provided with a spectral interval \( \Delta v \) of 5.565234 cm\(^{-1}\) along a smooth skewed bell-shaped curve. To apply this radiometric spectrum to those measured with ASTI, a cubic spline interpolation is used on the lamp spectral data to match the required \( \Delta v \) interval of the ASTI interferograms recorded for the sun or for clouds.

The repeatability accuracy for the radiometric calibration has been demonstrated to be less than one percent absolute, for each of the three IR band filters (F3-F5).

ASTI Radiometric Analytical Techniques

Solar Radiance Analysis

IR interferograms are recorded for all three IR spectral bands, at various times during daylight hours, usually from about 10:00 to 19:30 hours local time, as sun zenith angle permits. The resulting spectral data are then radiometrically calibrated with the NIST lamp technique discussed above. The units on the ordinate of the calibrated spectra are Watts/m\(^2\) sr cm\(^{-1}\), plotted as a logarithm, with the abscissa being wavenumbers (cm\(^{-1}\)).

The calibrated spectra for each day's run are then processed and plotted in logarithmic space using the Langley plot method\(^1\) obtained from the Bouguer-Beer Law,

\[ I(m) = I_0(m) e^{-\tau_v + \tau_{vg}m} + n(m) \]  

(2)

where:

- \( m \) - Relative air mass values for various zenith angle values at the times of measurement; \( m = m_0 \) is taken as straight up at the test site.
- \( I(m) \) - Transmitted solar spectral radiance (ground level) at wavenumber \( v \) over various relative air mass values \( m \) (collected solar flux being constant over ASTI's receiver aperture).
- \( I_0(m) \) - Exoatmospheric (top of atmosphere), or zero air mass solar spectral radiance at \( v \).
- \( n(m) \) - Nonlinear term for absorption and scattering effects.
- \( \tau_v \) - Atmospheric background absorption optical depth at \( v \), including aerosols and minimal gaseous absorption (not necessarily zero) being spectrally and spatially constant during measurement period \( \Delta t \).
- \( \tau_{vg} \) - Atmospheric gaseous spectral absorption optical depth due to minor atmospheric gases, being H\(_2\)O vapor, CO\(_2\), CH\(_4\), etc.; \( \tau_{vg} = 0 \) for background optical depth.

Making measurements for the background optical depths, the values \( \tau_{vg} = 0 \) and \( n(m)=0 \) (initially). In the usual manner, taking the naperian log of Eq(2) along with the above assumptions, we obtain,

\[ \ln I(m) = -\tau_v + \ln I_0(m) + n(m)/I_0(m)e^{-\tau_v} \]

\[ \ln I(m) = -\tau_v + \ln I_0(m) \]  

(3)

This is linear where the slope of the line is \((-\tau_v)\) and the intercept is \( \ln I_0(m) \), which relates directly to the solar radiance at the top of the atmosphere. The nonlinear term, being small, has been dropped during these initial analyses.

The spectral data obtained within the last few weeks has been calibrated radiometrically and subsequently plotted as Langley plots.
Cloud Scattering Transmittance Analysis

ASTI has been employed to measure the spectral scattering and transmittance of solar radiation for various types of clouds. The cloud spectra are radiometrically calibrated according to the same technique described above. The calibrated spectra are then a measure of the on-axis or the off-axis transmittance of the clouds, depending on ASTI's line of sight with respect to the solar zenith angle.

ASTI Radiance Measurements

This paper serves as an initial report describing nearly six month's work of an extensive long-term ASTI measurement program. The program purpose is three-fold:

1. Build and analyze a database of IR radiometric spectra as a function of altitude above mean sea level at four different altitudes, at the following locations: a) University of Denver, 5,400 feet elevation; b) Southern Great Plains Atmospheric Radiation Measurement Site (SGP ARM Site), Oklahoma, 319 feet; c) Echo Lake, Colorado, 10,600 feet; and d) Mount Evans Site, Colorado, 14,100 feet.

2. Build and analyze a database of IR radiometric spectra to provide a statistical basis for solar radiance and irradiance values as a function of altitude and for accurate extrapolation of these ground-based measurements to exo-atmospheric IR values.

3. Build and analyze a database of radiometric spectra for the IR transmittance characterization of various cloud types ranging from cirrus through cumulonimbus. This effort will be conducted as a function of season to the extent feasible, due to weather and conditions especially at the higher elevations.

Solar and Cloud Radiance Measurements

During March, April and May 1996, the ASTI instrument was extensively used to obtain solar and cloud IR interferograms and spectra at the University of Denver and at the ARM Site.

Initial Solar Radiance Results

The solar spectra were obtained for the three IR filter bands (low, medium and high) and the contiguous IR band from 2000 to 10000 cm\(^{-1}\). The solar spectra were radiometrically calibrated and then reduced to Langley plots in spectral regions of atmospheric background with very minimal gaseous absorption.

The following figures are the Langley plots for the three IR bands of ASTI measured at the SGP ARM Site in Oklahoma on April 18, 1996. The measurement times ranged from about 10:00 am to 19:20 CDT. Figure 5 shows the Langley plots for two lines at 4180 and 4507 cm\(^{-1}\) in the low pass filter region. The +'s on the lines are the actual data points used as a function of solar zenith angle and thus the effective atmospheric pathlength. These points are connected to aid in interpretation of the results. Figure 6 contains the Langley plots for five lines ranging from 5124 to 6695 cm\(^{-1}\). The actual data points are only shown on the lowest line to prevent excessive clutter for the closely spaced lines. Finally, Figure 7 contains the plots for two lines, being 6907 and 7481 cm\(^{-1}\).

The intercept values for each line were calculated, second term of Eq (3), and are presented in Table 1.

The data point at 4180 cm\(^{-1}\) represents a calculated value of \(\ln(L_{\text{m}})\), which equals 583.6491 Watts/m\(^2\) sr cm\(^{-1}\) in linear space at this wavenumber. It is the intercept of the Langley line with the ordinate of the plot, for
the solar radiance value just at the top on the atmosphere.

Table 1

<table>
<thead>
<tr>
<th>Spectral Line (cm⁻¹)</th>
<th>Intercept (ln(W/m² sr cm⁻¹))</th>
</tr>
</thead>
<tbody>
<tr>
<td>4180</td>
<td>6.3693</td>
</tr>
<tr>
<td>4507</td>
<td>6.3784</td>
</tr>
<tr>
<td>5124</td>
<td>6.3516</td>
</tr>
<tr>
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<td>7.0399</td>
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<tr>
<td>6907</td>
<td>7.0058</td>
</tr>
<tr>
<td>7481</td>
<td>7.1638</td>
</tr>
</tbody>
</table>

These data points represent that for only one day's measurements, as presented in this initial report. Many more measurements have been recorded in Oklahoma and in Denver which are currently in analysis.

Initial Cloud Transmittance Results

Figure 8 is a linear plot from 4000 to 10000 cm⁻¹ for three cloud IR spectra obtained in Denver on April 09, 1996. The tilde ~ appears in front of the ordinate units because the ASTI instrument factor, appearing in Eq (1), is still being analyzed for the configuration used to measure the cloud interferograms. The spatial filters F1 and F2, Figure 4, are removed to make such measurements due to the much lower signal level of the clouds relative to the sun. Radiometric calibration was performed without knowing the G(v) factor accurately.

The top spectrum (a) was obtained from a very bright white cumulus cloud (12:23 MDT, azimuth angle= -170°, elevation angle= -30°). The peak signal levels are nearly equal in the two bands between 7400-8700 cm⁻¹ and 9000-10000 cm⁻¹ and that in the band from about 5600 to 6700 cm⁻¹ is within a few percent of these two. Spectrum (b) was recorded (12:05 MDT, az. angle= -210°, el. Angle= -25°, plotted in dots). Spectrum (c) was obtained for a different cloud in the same cloud field, about six minutes later. Both were of light gray cumulus clouds. Notice is taken that the spectrum (b) has crossed over in ordinate position with that of spectrum (c) in comparing the 9000-10000 cm⁻¹ band to the 5600-6700 cm⁻¹ and 4100-4800 cm⁻¹ bands. In addition, the shape of (b) and (c) with respect to (a) in the 5600-6700 cm⁻¹ band has dropped off on the left shoulder; this is expected to be due to change of phase with respect to the (a) cloud. This measurement and analysis effort continues, to take advantage of the varied cloud types available during the annual cycle.

Acknowledgments

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Literature Cited

Figure 5 Langley Plots, Low Pass IR Filter

Figure 6 Langley Plots, Medium Pass IR Filter
Figure 7 Langley Plots, High Pass IR Filter

Figure 8 ASTI Cumulus Cloud Radiance Spectra