

Shorter contribution

Sounding the lower atmosphere using a ground-based hyperspectral infrared sounder - the Bureau of Meteorology AERI

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The use in Australia of a ground-based hyperspectral infrared (IR) sounder to continuously profile the atmospheric boundary layer (1-3 km) is described. The automated system developed for this purpose represents an important new capability providing significant information for the verification and improvement of numerical weather prediction (NWP) and climate models in the boundary layer and also a potential new capability for making significant contributions to operational weather forecasting and to applications such as fog prediction. The system described here comprises a Fourier Transform Spectrometer covering the spectral range 3 to 18 μm with a spectral resolution of better than 1 cm^{-1} . The interferometer is housed in a weatherproof enclosure and is controlled from and provides information to the Bureau of Meteorology Head Office in Melbourne. The method used to retrieve temperature and moisture profiles in the planetary boundary layer from downwelling spectral radiance observations is described. The system provides high temporal resolution soundings (approximately every seven minutes) of temperature and water vapour concentration and for the first time provides high temporal resolution depiction of important mesoscale features in the planetary boundary layer. The paper describes examples of the utility of the system and shows where hyperspectral observations may provide useful information for assessing and improving the planetary boundary layer in numerical weather prediction models.

Introduction

In early 2002 the Australian Bureau of Meteorology (the Bureau) developed the capability to continuously sound the lower part of the troposphere using a Hyperspectral Ground-based Infrared Fourier Transform Spectrometer. This type of instrument is commonly called an Atmospheric Emitted Radiance Interferometer (AERI) (see Revercomb et al. 1993; Smith et al. 1993; Feltz et al. 2003). The system has

been built around a BOMEM model MR 100 Interferometer, is housed in a purpose-designed weatherproof enclosure and is controlled remotely from the Bureau's Head Office in Melbourne. The reason for developing this capacity was to evaluate the utility of the AERI for research and operations in the Bureau. In particular, the system enables a detailed examination of the lower atmosphere/planetary boundary layer during dynamic meteorological events such as frontal passages and convective outbreaks, and can also assist in predicting important weather phenomena, such as fogs. It has also allowed a quantitative examination of the precision of the simulated boundary layers of NWP and climate models used by the Bureau, through a comparison of numerical

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model output with Bureau AERI (subsequently abbreviated to B-AERI) observed profiles. In addition it is planned to use the instrument for a number of other applications including the measurement of hyperspectral surface emissivity and for it to be one of the tools used in developing effective techniques to allow the specification of hyperspectral surface emissivity over the Australian region. Very accurate specification of hyperspectral emissivities is necessary to effectively sound the lowest part of the troposphere from space.

Here we briefly describe the fully automatic hyperspectral sounding system. We describe its components, its fabrication and its automation to allow continuous lower tropospheric monitoring. We also describe the methods used to obtain lower tropospheric soundings and provide some initial results from the system.

Background

Sounding the lower atmosphere for temperature and moisture using a ground-based infrared hyperspectral interferometer was first demonstrated in 1988 during the Ground-Based Atmospheric Profiling Experiment (GAPEX). In that experiment the High-resolution Interferometer Sounder (HIS) aircraft instrument was employed looking upward from the surface. The temperature and moisture retrievals obtained from the radiance data were found to contain significant information when compared to radiosonde data which were used as ground truth (Smith et al. 1990). This system evolved into the original ground-based system, the Atmospheric Emitted Radiance Interferometer (AERI) prototype developed for the US Department of Energy Atmospheric Radiation Measurement (ARM) program and finally the current operational version of the instrument (Revercomb et al. 1993; Smith et al. 1993), a fully automated, self-referencing instrument (Revercomb et al. 1988) that allows continuous monitoring of the atmospheric downwelling IR emission. This remote sensing approach can now be used to produce vertical temperature and water vapour profiles in the planetary boundary layer at high temporal resolution. The quality of the retrieved profiles has been verified in a number of situations. For example, the error characteristics of the data have been gauged by comparison with radiosondes in both clear and cloudy conditions over a six-month period of operation at the Department of Energy, Cloud and Radiation Testbed site at Lamont, Oklahoma. The comparison has demonstrated the ability of the AERI to resolve significant thermodynamic features of the planetary boundary layer with high temporal resolution (Smith et al. 1999).

The hyperspectral ground-based infrared sounding system

A schematic diagram and photographs of the hyperspectral infrared sounding system can be seen in Fig. 1. The B-AERI measures downwelling atmospheric emitted radiance from $3.3 \mu\text{m}$

(3020 cm^{-1}) to $19 \mu\text{m}$ (520 cm^{-1}) with a narrow zenith field of view. Sky radiance spectra referenced to calibrated black bodies are produced about every seven minutes and contain the mean and standard deviation of zenith sky spectra during a sky dwell period of about 200 s. The sky dwell period is composed of 90 Michelson interferometer scans. The remaining time is spent viewing two internal reference targets. The real-time output consists of radiances corrected for all instrument effects and referenced to the internal black bodies. Figure 2 illustrates typical clear-sky measurements of downwelling atmospheric infrared emission at the surface as observed at Melbourne Airport (38° S , 145° E) on 23 February 2006.

The B-AERI comprises two major assemblies: the interferometer/optics bench assembly and the electronics support equipment. Figure 1 shows photographs and a block diagram of the system. Air from outside the B-AERI enclosure, is moved through sections of the enclosure, exposing the front-end optics and calibration black bodies to ambient temperature, while allowing the interferometer and the electronics support equipment to operate at enclosure temperature.

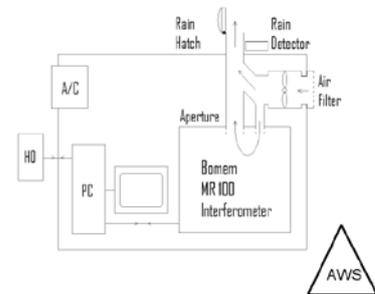
The B-AERI enclosure measures 1.35 m (w) \times 1.75 m (l) \times 1.17 m (h) internal dimensions (see Fig. 1, left panel), and has access doors on three walls with an air conditioner on the fourth. The enclosure wall and ceiling material has double-layer sheet steel sandwiching 50 mm polystyrene foam insulation. A curved fly roof covers the top of the box enclosure and extends beyond to also cover the external parts of the air conditioner and associated heat exchanger. The fly roof enhances the thermal protection and water sealing of the enclosure roof.

The B-AERI instrument observes the downwelling infrared radiation via an aperture in the roof of the enclosure that is wide enough to be fully excluded from the instrument's field of view. The aperture of the instrument is protected from precipitation through use of a motor-driven rain hatch connected to a programmable infrared rain detector.

Estimating temperature and moisture profiles

The retrieval methodology is similar to the method described in Smith et al. (1999) although differences exist particularly in relation to data pre-processing and in establishing the *a priori* atmospheric state. An initial first guess is established by combining surface observations at the interferometer with forecast profiles from a high-resolution mesoscale model (Meso-LAPS which is a high-resolution implementation of the Bureau's Limited Area Prediction System, LAPS (Puri et al. 1998)). An iterative solution of the radiative transfer equation is then used to generate a final temperature and moisture profile. Here we describe the fast forward model used with the radiative transfer equation when estimating radiances from temperature and moisture profiles, the local tuning methodology for improving the accuracy of the local fast forward radiative transfer calculation and the nonlinear physical inversion methodology.

Fig. 1 The enclosure at Melbourne Airport (left), the layout of the interferometer and computer in the enclosure (centre) and a schematic diagram of the B-AERI (right) including an automatic weather station (AWS).



The forward model

The fast forward model is a variant of RTTOV (Eyre 1991; Garand et al. 2001). The model is generated by using a line-by-line radiative transfer model, FASCOD (Clough et al. 1981), and the HITRAN molecular spectroscopic database (Rothman et al. 2003) to compute monochromatic optical depths for dry air, water vapour and ozone, for a set of atmospheric profiles on a fixed pressure grid. These monochromatic optical depths are converted to atmospheric transmittances, which are then convolved with the spectral response function of the interferometer to yield effective transmittances. The effective transmittances are apodised and are then converted back into effective layer optical depths. Regressions are then used to relate these optical depths to the atmospheric state at each pressure level, for each spectral region. This is undertaken for dry air (which includes all absorbing gases other than water vapour and ozone), water vapour, and ozone. The fast model then computes radiance by using these regressions to obtain the optical depths at each level and for each spectral element for dry air, water vapour and ozone. These optical depths are then combined for each layer and the radiative transfer calculation is completed. Figure 2 shows a comparison between radiances calculated from radiosonde observations using this fast forward model and B-AERI observations for the spectral regions used to estimate temperature and moisture profiles. The comparison is for 23 February 2006 and shows very good consistency between observations and theoretical estimates.

The inversion methodology

The interferometer measures IR radiation spectra ($520 - 3020 \text{ cm}^{-1}$) with a spectral resolution better than 1 cm^{-1} . These hyperspectral radiance observations are used to produce vertical temperature and water vapour profiles every seven minutes for the lowest 3 km of the troposphere. The vertical temperature and water vapour profiles are generated by inverting the radiative transfer equation. The seven-minute time sampling allows high vertical and temporal resolution boundary-layer information to be obtained during dynamic

meteorological situations such as frontal passages (see, for example, Fig. 3). It also allows examination of:

- the effects of surface heating;
- the level of accuracy of numerically modelled boundary layers;
- atmospheric stability; and
- a number of important meteorological situations such as conditions before the onset of fog.

The inversion methodology has two steps. First, an initial temperature and water vapour profile is obtained from the Bureau's operational Meso-LAPS NWP model which is adjusted so the lower levels are consistent with surface observations. Then, an iterative physical solution of the radiative transfer equation (RTE), using the adjusted Meso-LAPS profile as the initial guess, is performed to give the final temperature and water vapour profile.

The initial temperature and water vapour profile is not only used as a first step to provide an optimal solution to the RTE, but also ensures a reasonable solution in the atmospheric regions where the information content of the radiances for determining the temperature and moisture profile is limited, for example, above 3 km (Smith et al. 1999).

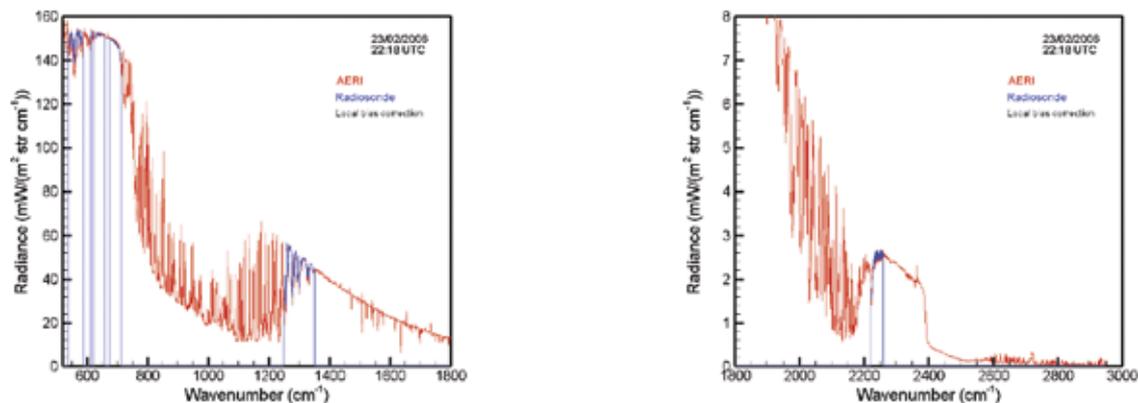
The physical iterative solution of the RTE provides the final temperature and moisture profile retrieval. The final solution is obtained through iterative application of an inverse of a simplified version of the RTE and satisfies the observed B-AERI spectrum through systematic adjustment of the initial guess profile (Smith et al. 1999). During each iteration, temperature and water vapour mixing ratio adjustments are made to minimise the differences between observed and calculated spectra. The physical retrieval algorithm usually converges in fewer than twelve iterations.

The radiative transfer equation to be inverted is

$$R_{\nu} = \int_{p_s}^0 B_{\nu}(T) \frac{d\tau_{\nu}(p_s, p)}{dp} \quad \dots 1$$

where R_{ν} is the spectral radiance at wave number ν , $\tau_{\nu}(p_s, p) = \exp[1/g \int_{p_s}^p (k, k'_q) dp]$ and $\tau_{\nu}(p_s, p) = \prod_i \tau_i(p_s, p)$

Fig. 2 An example of an B-AERI infrared radiance measurement at 2218 UTC on 23 February 2006. The red-coloured regions indicate the part of the spectrum measured by the B-AERI. Temperature and water vapour profiles are derived using the B-AERI forward model and physical retrieval algorithm in the blue regions of the spectrum bordered by blue vertical lines. In this case the blue spectra have been calculated using a contemporaneous co-located radiosonde.



is the total transmittance of the atmosphere between the surface, pressure p_s and pressure level p . Π_i is the product for i absorbers, $B_v(T)$ is the Planck radiance corresponding to temperature T , p is the atmospheric pressure, g is acceleration due to gravity, k and k' are the absorption line and continuum absorption coefficients, respectively, and q_i is the mixing ratio of the i th absorbing gas. When modelling clouds the treatment is similar to that of Smith et al. (1993, 1999).

When solving the RTE equation for atmospheric temperature $T(p)$ and the water vapour mixing ratio $q(p)$ through a linearisation of the RTE and using numerical recursion methods (similar to Smith et al. (1999)), it is important to note that the weighting functions ($d\tau(p_s, p)/dp$) in the RTE decrease exponentially with altitude, with the rate dependent on the strength of the absorption. Hence, the radiance signal δR_v (the perturbation from the first-guess radiance) is dominated by contributions from near the surface with rapidly decreasing sensitivity to contributions from higher levels. This altitude sensitivity characteristic could lead to numerical instability of the direct inverse because of the strong correlation of the weighting functions among different spectral channels (i.e. lack of linear independence of the system of equations). However, the rapidly diminishing sensitivity of the observed radiance with altitude enables a stable recursive procedure to be used, whereby the temperature and moisture mixing ratio values are obtained in a sequential fashion starting at the surface and moving vertically upward.

The spectral regions used in the solution for the temperature and water vapour profiles are the blue regions shown in Fig. 2. These regions are straightforward to use in that they are not affected by non-uniformly mixed gases other than water vapour (i.e. the spectral regions where ozone, carbon monoxide, methane and chlorofluorocarbons are significant have been avoided).

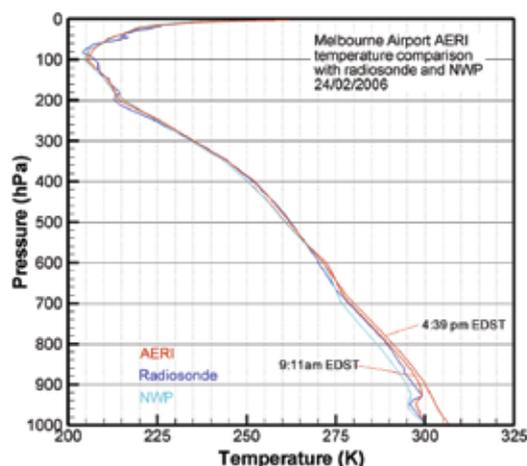
To correctly account for forward model spectroscopy and regression errors, it has been necessary to determine a bias error spectrum for the retrieval algorithm. That is, when converging to a solution using this iterative method, a bias must be added to the calculated radiance to alleviate systematic computation errors and instrumental bias errors. Differences between calculated and observed radiances have been obtained from clear radiosonde profiles of temperature and water vapour and coincident B-AERI observations. These residual differences have been averaged over two days in February to obtain a bias spectrum. This same bias, used for all examples shown here has been able to provide satisfactory results.

Soundings from the AERI have a vertical resolution of around 10 m at 10 m elevation from the surface and this vertical resolution changes to around 0.6 km at 1 km elevation (Smith et al. 1999). The temperature accuracy is near 1 K and the accuracy in estimating the water vapour profile is near 10 per cent. An example of the application of the inversion methodology can be seen in Fig. 3. Here temperature profiles near 9:00 am Eastern Daylight Saving Time (EDST) and mid-afternoon for Melbourne Airport on 24 February 2006 are shown. The profiles are the B-AERI temperature profile at 9:11 am and 4:39 pm EDST, the radiosonde profile at 9:00 am EDST and the NWP first-guess profile at 9:11 am EDST. The 9:11 am EDST B-AERI trace is seen to be close to the radiosonde observations and has captured the low-level inversion in a way consistent with the vertical resolution of the sounding system.

Initial results

AERI data can be used for several important applications. For nowcasting they can be used to monitor and assist in the forecasting of dynamic mesoscale events such as the passage of cold fronts. An example of this can be seen in the

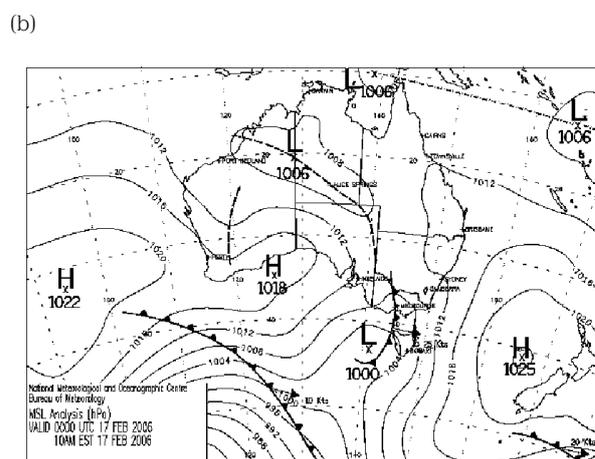
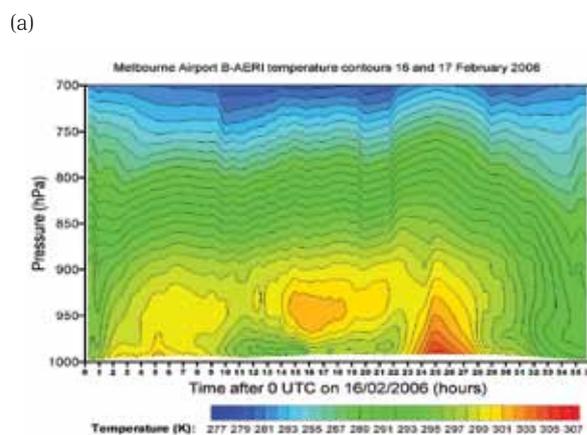
Fig. 3 The B-AERI temperature profiles at 9:11 am EDST and 4:39 pm EDST, the radiosonde profile at 9:00 am EDST and the NWP first guess profile at 9:11 am EDST for Melbourne Airport on 24 February 2006.



mean sea-level pressure (MSLP) analysis in Fig. 4(b), where a cold front is seen moving across central Victoria at 0000 UTC on 17 February 2006. The B-AERI time-height temperature cross-section (Fig. 4 (a)) clearly shows a mild day with a maximum temperature of around 28°C in Melbourne on 16 February. This was followed by a mild night with a strengthening nocturnal inversion, as warm pre-frontal air from the north swept across Melbourne mixing to the ground and warming the surface temperature prior to sunrise. On 17 February there was rapid heating in the late morning and early afternoon to a maximum temperature of around 35°C near midday. Subsequently there was a rapid reduction in temperature with the passage of the cold front and the temperature dropped to 28°C by 0400 UTC (3:00 pm EDST) and by 0900 UTC (8:00 pm EDST) had dropped to around 20°C.

Another important application of B-AERI data is the examination of the accuracy of boundary-layer mesoscale forecasts from the Bureau's numerical weather prediction systems. In the example shown here (Figs 3, 5 and 6), the interferometer has been used to examine forecasts from the Bureau's 0.5 km resolution mesoscale forecast system (Meso-LAPS). In clear conditions the B-AERI instrument has been used to provide continuous profiles of temperature and water vapour at Melbourne Airport. Data from two days are shown here which demonstrate the utility of the AERI instrument. The continuous B-AERI observations and first-guess fields used on 23 and 24 February (Figs 5 and 6 respectively) clearly demonstrate parts of the mesoscale forecast (e.g. 2100 UTC 23 February 2006 and 1000 UTC 24 February 2006) where improvements can be made to the boundary-layer forecast. These times were associated with sunrise and sunset respectively, and the causes of the difference between the model atmosphere and the observations are now being examined with a view to improving boundary-layer simulations.

Fig. 4 (a) B-AERI time-height temperature cross-sections measured at Melbourne Airport on 16 and 17 February 2006 and (b) the MSLP analysis valid for 0000 UTC 17 February 2006.



The future

The B-AERI has been shown to be a powerful tool able to monitor changes in the thermodynamic structure of the planetary boundary layer. As a result it can provide valuable information when examining the effects of surface heating, the accuracy of numerically modelled boundary layers, atmospheric stability, and in a number of important meteorological situations such as conditions before the onset of fog. The data from the instrument are currently being used effectively in a number of studies and their unique ability to provide high temporal resolution monitoring of temperature and moisture in the planetary boundary layer makes them a valuable data source. It is anticipated the accuracy of the system will be improved in the near future through an improved inversion methodology and utility of the system will be further enhanced by taking measurements in conjunction with a wind profiler.

Fig. 5 B-AERI time-height temperature cross-sections measured at Melbourne Airport from 0000 UTC 23 February to 1400 UTC 24 February 2006.

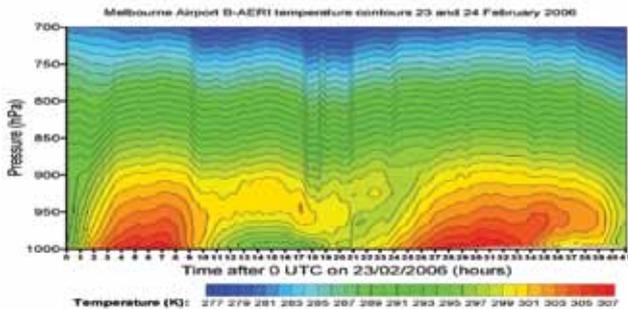
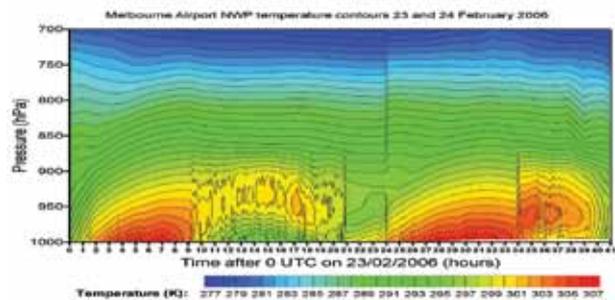


Fig. 6 Time-height temperature cross-sections used as the first guess for B-AERI time-height temperature cross-sections for Melbourne Airport from 0000 UTC 23 February to 1400 UTC 24 February 2006. These were derived from surface data and the Bureau of Meteorology Meso-LAPS model initialised at 0000 UTC 23 and 24 February 2006 and post-processed every hour.



Summary and conclusions

This paper has described the development and installation of a Hyperspectral Ground-Based Infrared Fourier Transform Spectrometer (the Bureau of Meteorology AERI). It has described in some detail the ground-based system, its weather proof enclosure, the key characteristics of the system (including the characteristics of its spectral observations), the method for the inversion of the radiance spectra to temperature and moisture profiles and has provided some examples of the utility of the system. It has also noted some of the many potential applications of the system in the Australian region. Results to date both in Australia and overseas indicate that this system has the potential to make a significant contribution to meteorology in Australia.

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