Compact SWIR Imager for Mapping Temperature in the Upper Mesosphere Lower Thermosphere

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ABSTRACT SA55B-1749

Nighttime imaging of SWIR OH emission in the upper mesosphere/lower thermosphere region around 87 km altitude have proven useful over the past decade in providing large-area remote sensing of mesospheric temperatures, as well as intensity maps showing the propagation and dissipation of atmospheric gravity waves and small-scale features known as ripples. The pioneering instrument designed at the Center for Atmospheric and Space Sciences, Utah State University, the Advanced infrared Mesospheric Temperature Mapper (AMTM), has up until now been the only instrument routinely providing high spatial and temporal resolution temperature maps inferred based on large field of view imagery obtained at SWIR wavelengths. The intensity ratio of OH rotational emissions of P1(2) at 1523.68 nm to P1(4) at 1542.79 nm is central to the measurement of mesospheric temperature.

We present a new, compact version of a SWIR OH-imager that has the same overall signal-to-noise performance and accuracy of measurement as the AMTM instruments. Our design is based on the Keo Sentry line of visible and near infrared all-sky imagers that have been operational for decades in aeronomy and auroral research. We describe how our instrument leverages innovative new technologies and novel techniques to perform mesospheric thermal mapping within a very compact form-factor. We present preliminary data and examples of temperature maps. We also describe our calibration method in some detail, as careful calibration is critical to valid inversion of the data.

OPTICAL TEMPERATURE MEASUREMENTS OF THE MESOSPHERE AND THERMOSPHERE

Optical methods for the measurement of mesopheric and thermospheric temperature from ground based facilities have been employed for decades. The technique of comparing the brightness of two or more emission lines from hydroxyl in the region around 87 km altitude was pioneered by Meriwether in the 1970's and is the basis for the MTM (Pendleton, et al., Taylor, et al.), AMTM (Pautet, et al.) and the Keo Scientific Sentry MTM temperature mappers.

Other optical methods of determining the temperature of this region of the atmosphere are presented in a comparison table in the 2014 paper by Pautet, et al., and have similar measurement errors, but much smaller fields of view. These instruments include a Fourier spectrometer, a Fourier transform spectrometer, a Michelson interferometer, and a more traditional spectrometer.

The AMTM is a proven instrument design and provides a comparable or better atmospheric OH temperature measurement compared to other ground based methods. The optical configuration is straightforward in these imager-based instruments. The Keo Scientific instrument is particularly compact by comparison, leveraging the heritage of the Keo Sentry all-sky imager product line. The fisheye lens on the front of the instrument was designed by Keo Scientific for this project but is also viable in the visible spectrum range to the near infrared with a change of AR coatings for the lens elements. The filter designs are specific to the optical configuration adapted from the Keo Scientific Sentry imagers, and have aggressive passband shapes when compared to other SWIR filters for similar imagers.

Our full calibration routine is close to completion. The imager has been field tested by both Keo Scientific (in Canada) and KOPRI (in Korea), our combined effort to finalize and validate the temperature map inversion is imminent.

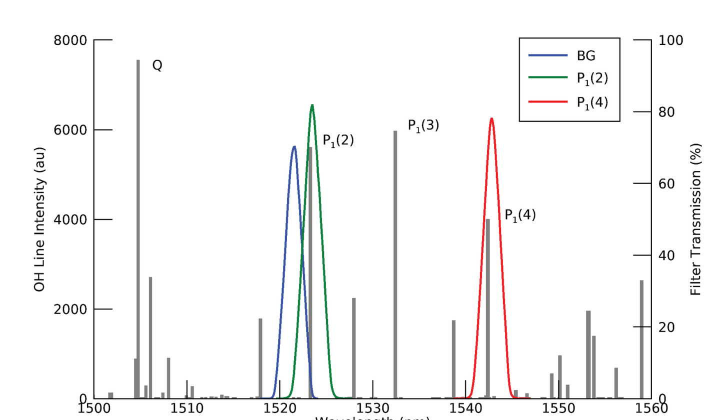
SWIR IMAGER DESIGN AND CURRENT APPROACH

Current SWIR imager designs largely rely on InGaAs sensors, which are photodiode arrays read out in rows or columns not unlike silicon CMOS sensors. These sensors are noisy compared to silicon CCDs, but have reasonable dark current performance when cooled to -90C. The optical design relies on telecentric optics where the narrow band filter passband design depends on the cone angle of the rays passing through the filter. The cone angle for the AMTM filter is approximately f/11, where the cone angle for the Sentry MTM is f/5, which leads to the more compact imager size.

The SWIR fisheye lens designed and manufactured specifically for this instrument is pictured here on the left. The lens is a 30 mm focal length, f/3.5 180° fisheye lens optimized and AR coated for the wavelength range of 1000 nm to 1700 nm. The field of view of the instrument is limited at the primary image plane using a Lyot stop.

The filter throughput at the OH wavelengths has to be high and throughput at adjacent atmospheric emission wavelengths has to be low. A quick estimate for bandpass shape is to compare the combined received intensity of all adjacent wavelengths to the square root of the received intensity of the desired wavelength. If the Schott noise of the signal wavelength is greater than the combined contribution of the background spectrum in a filter channel, that becomes a reasonable first estimate of the design filter function. A more sophisticated analysis can be performed for the instrument when the real filters are measured.

The filter functions of the two OH channels and the background channel are superposed on a synthetic spectrum. The spectrum is supplied courtesy of Philippe Rousselot, University of Franche-Comte.



INNOVATION

The Keo Sentry MTM has a 120° circular field of view where the image from the fisheye and telecentric converting optics is brought into focus at a Lyot stop. This primary image Lyot stop is crucial for limiting scattered light in the imager. The filter wheel follows the Lyot stop.

The narrow background channel filter achieves a 1 nm FWHM passband shape and reveals almost no sky emission in the spectral region of this filter as can be seen in the image shown on this poster in the rightmost column.

The six-position filter wheel includes a wideband filter (an uncoated filter substrate) to help calculate the filter passbands while measuring the response of the system to a tunable laser. The laser and wideband filter are also useful in deriving the absolute transmission of the OH and background filters, necessary for an absolute response calibration.

A dark frame filter is used in the field for dark current measurements. For SWIR cameras, the contribution of thermal photons from some camera components is not negligible. Our solution is a custom filter that has zero transmission but has the same effective emissivity of the filters used when imaging the sky intensity.

DATA INVERSION AND CALIBRATION

Data inversion from image to creation of a temperature map is a multistep process involving dark subtraction, background subtraction, field flattening, conversion to brightness and finally calculation of the sky temperature from the brightness ratio.

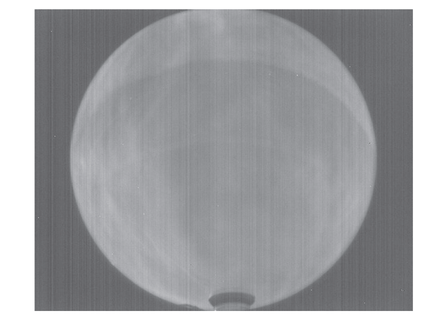
The dark subtraction requires the acquisition of dark frames (or dark images) which are used to subtract off the fixed pattern noise of the InGaAs photodiode array, as well as all of the traditional non-signal counts in the pixels. The background subtraction is used to remove the broadband continuum emission present in the spectral passband of the OH filters, and is performed in spectral density space. The field flattening step is required to account for vignetting and the intra-filter variation in transmission of the narrow band filters at the OH emission wavelengths. Conversion to absolute units can then be performed, the ratio of the hydroxyl line emissions can be calculated and the temperature of the OH layer can be estimated using the equation (from Pautet, et al.)

$$T_r = 259.58 / \ln(2.644\, R),$$

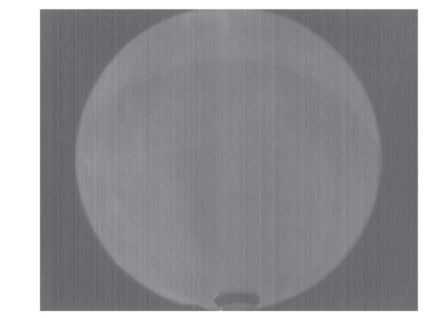
where R is the brightness ratio of P1(2) to P1(4).

DERIVED TEMPERATURE MAP

Raw images are acquired with an equal integration period for sky images in the background channel (1521 nm center wavelength and a 1 nm passband) and for the two OH channel of OH P1(2) at 1523.68 nm and P1(4) at 1542.79 nm. The example images presented here have 30 second integration periods for the three sky channels and the dark frame. The wideband image exposure time is 3 seconds.

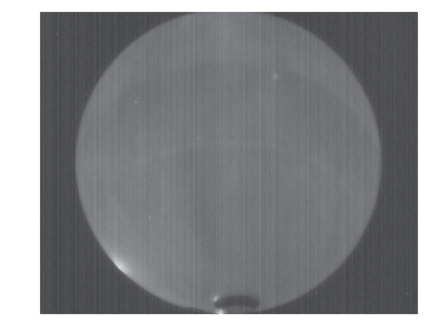


30 second exposure of P1(2)



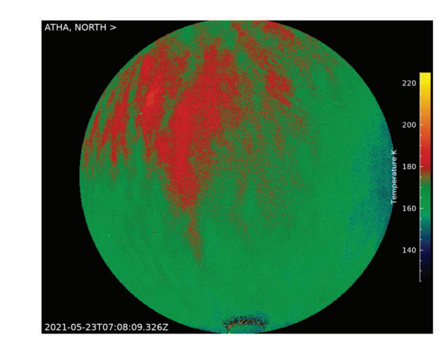
30 second exposure of P1(4)

30 second exposure of the background



3 second exposure to capture wideband emission

The data inversion process is implemented on these images to produce the following temperature map.



Corrected Temperature Map

The range of temperatures in this temperature map is consistent with the temperatures expected at the test location in Athabasca, Alberta, Canada, on May 23, 2021. We would like to thank Dr. Martin Connors for hosting us for two test campaigns of this instrument.

So far we have successfully performed two campaigns in Canada and two campaigns in South Korea.

CONCLUSION

We have successfully designed and built a short wave infrared imager to measure the temperature of the OH layer in the upper mesophere and lower thermosphere. We have demonstrated the capability of this instrument to acquire high quality data and have tested the data inversion algorithm according to the calibration measurements we have completed. There is ongoing work to fully validate the inverted data, before the instrument is deployed in the Antarctic for it's intended science mission.