Analysis of Temperature and Humidity Sounding Using Compact Mid-Wave Infrared Instruments

C. P. Lampen*, S. Lampen and J. A. Hackwell - The Aerospace Corporation
*caleb.p.lampen@aero.org

I. Background

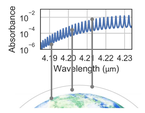
Infrared sounders currently use the long-wave IR (LWIR), 15 µm CO_2 band for temperature retrievals. However, measurement of LWIR radiation requires large optical apertures and cold detectors, driving up the size and complexity of the instrument.
Here we show instrument trade studies for mid-wave IR sounder, illustrating potential for temperature and humidity sounding exclusively in mid-wave IR (MWIR).

A. What is sounding?

Altitude sampling

- Absorption spectrum of chemical determines amount of light absorbed as a function of wavelength
- Atmospheric penetration proportional to absorption

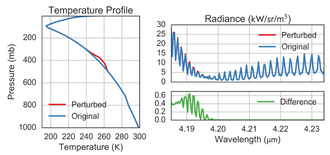
➡ Mapping between wavelength and altitude in atmosphere



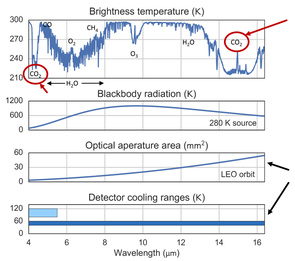
Temperature measurement

- Increase in temperature results in increased observed radiance
- Change occurs in several parts of spectrum

➡ Mapping between temperature and radiance (light)



B. Instrument design consideration for IR sounders



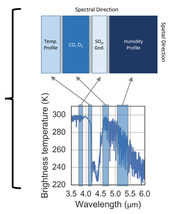
- CO_2 drives LWIR requirements
  - Can also measure CO_2 in MWIR
- More radiance from atmosphere in LWIR
- LWIR requirements drives optical aperture size and cooling requirements

➡ Sounding exclusively in MWIR reduces size and power use of instrument

C. New technologies enable sounding in MWIR

Focal plane array (FPA) technology advancement
- Digital focal plane arrays enable low noise measurements
- Large area enables pushbroom collection and improves spectral sampling

Dispersive optical design with FPA filter
- Selective sampling of spectrum
  - Only interested in discrete bands of spectrum
  - Dispersive optical designs and custom filters on focal plane array enables high spectral resolution in bands of interest
- Design re-orders bands on focal plane to optimize focal plane real estate



FPA filter with spectral areas of interest

Sections of spectrum measured

II. End-to-End Sounder Simulation and Evaluation

We have brought together a matched suite of tools which can be used to evaluate MWIR sounder concepts by performing a complete end-to-end simulation of the sounding process. This includes an industry standard forward model (LBLRTM [1,2]), a signal chain analysis of the sensor system to realistically model noise, and a simple retrieval algorithm.

Atmospheric Radiation Model

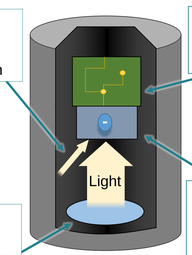
LBLRTM
- Line-by-line radiative transfer model
- High resolution spectral model needed for high-resolution spectroscopy
- Generates Upwelling radiation and Analytic Jacobian

Full Sensor Simulation

Simulated radiance

Cavity
- Thermal Emission

Electronics
- Read-out Noise



Optics
- Light attenuation

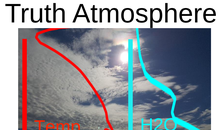
Detector
- Conversion gain
- Dark current
- Shot noise

Signal

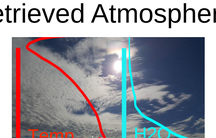
Inverse Model

Gauss-Newton Algorithm
- "DRAD" method used to reduce impact of linearization pseudo-noise [3]
- Principal Component Analysis applied to state vector

Truth Atmosphere



Retrieved Atmosphere



Compare

References

[1] Clough, S. A., M. W. Shephard, E. J. Mlawer, J. S. Delamere, M. J. Iacono, K. Cady-Pereira, S. Boukabara, and P. D. Brown, Atmospheric radiative transfer modeling: a summary of the AER codes, Short Communication, *J. Quant. Spectrosc. Radiat. Transfer*, **91**, 233-244, 2005.
[2] Clough, S.A., M.J. Iacono, and J.-L. Moncet, Line-by-line calculation of atmospheric fluxes and cooling rates:Application to water vapor,*J. Geophys. Res.*, **97**, 15761-15785, 1992.
[3] Northrop Grumman Space Technology, "Cross Track Infrared Sounder (CrIS) Volume II, Environmental Data Records (EDR) Algorithm Theoretical Basis Document ATBD", Northrop Grumman Space Technology, Redondo Beach, CA, Feb. 8, 2007.
[4] Borbas, E. E., Suzanne Wetzel Seemann, Hung-Lung Huang, Jun Li, and W. Paul Menzel, 2005: Global profile training database for satellite regression retrievals with estimates of skin temperature and emissivity. Proceedings of the XIV. International ATOVS Study Conference, Beijing, China, University of Wisconsin-Madison, Space Science and Engineering Center, Cooperative Institute for Meteorological Satellite Studies (CIMSS), Madison, WI, 2005, pp.763- 770.

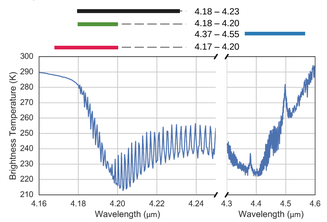
III. Mid-wave IR sounder trade studies

Trade-studies were performed under ideal conditions to provide a proof-of-concept for a mid-wave sounder. Simulated tropical ocean nighttime soundings were performed on NOAA-88 profiles taken from the CIMSS clear sky global training database [4]. It was assumed that surface properties, atmospheric pressure, and CO_2 levels were known a priori. For reference, current sounders measurement accuracy requirement is ~1K for temperature accuracy and 20% ppmv error for humidity retrieval accuracy with a goal of 10%.

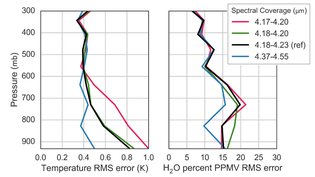
A. Spectral coverage trades

CO_2 band spectral coverage

Spectral bands for trade studies



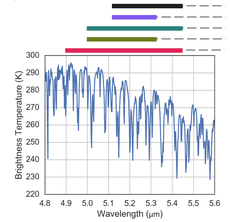
Temperature, H_2O Error
Constant spectral resolution (0.35 nm), Reference water band



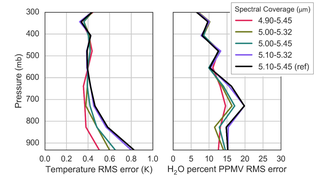
- Viewing highly transparent regions of the atmosphere degraded accuracy (4.17 µm test), which may indicate retrieval algorithm improvement area
- For tests on below 4.23 µm, measuring above 4.2 µm did not improve accuracy
- Improved temperature sensing improved H_2O retrieval

H_2O band spectral coverage

Spectral bands for trade studies



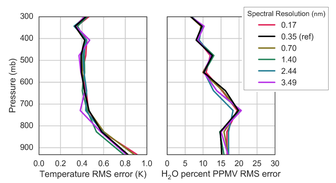
Temperature, H_2O Error
Constant spectral resolution (0.42 nm), Reference CO_2 band



- Measuring above 5.32 µm did not improve accuracy
- Extending coverage to shorter wavelengths improved retrieval accuracy for both temperature and H_2O retrievals

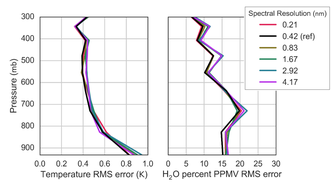
B. Spectral resolution trades

CO_2 resolution trade studies – Temperature, H_2O
Constant spectral coverage (4.18 – 4.23 µm), Reference water band

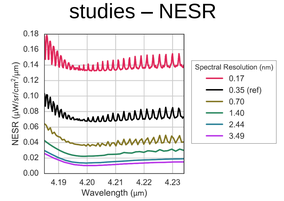


- Large changes in spectral resolution had little effect
- Small spread around 500 mb and 750 mb, but no trends with spectral resolution magnitude
- As spectral resolution becomes finer, NESR increases which negatively effects retrieval accuracy (see right)

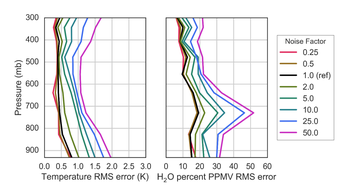
H_2O resolution trade studies – Temperature, H_2O
Constant spectral coverage (5.1-5.45 µm), Reference CO_2 band



CO_2 resolution trade studies – NESR



C. Noise scaling factor trades



- Reducing noise below reference design does not significantly improve retrieval accuracy
- Large increases in noise factor degrade retrieval accuracy, especially around 750 mb
- Reference design is shot noise limited

Reference Design

CO_2 Band	Spectral Coverage (um)	4.18 – 4.23
	Spectral Resolution (nm)	0.35
H_2O Band	Spectral Coverage (um)	5.1 – 5.45
	Spectral Resolution (nm)	0.42

Dispersive spectrometer, f/2 optical system – pushbroom collection, 2 sec integration time, 18 µm pixel pitch

Conclusions

- Sounding exclusively in mid-wave IR reduces instrument requirements
- Developed full end-to-end sounder modeling tool
- Demonstrated successful proof of principle for temperature and humidity sounding using solely mid-wave IR