Investigating Comparisons of Hyperspectral IR Sounders and RO in Radiance Space

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Outline

- Background
  - RO, Previous Work
- Methods
- Uncertainties
- Case Study

Answering the Question: “To what accuracy can we use the IR sounder measured radiances and radiative transfer to validate the atmospheric state temperature and water vapor (e.g from RO)??”

- Concluding Remarks

Background

Background

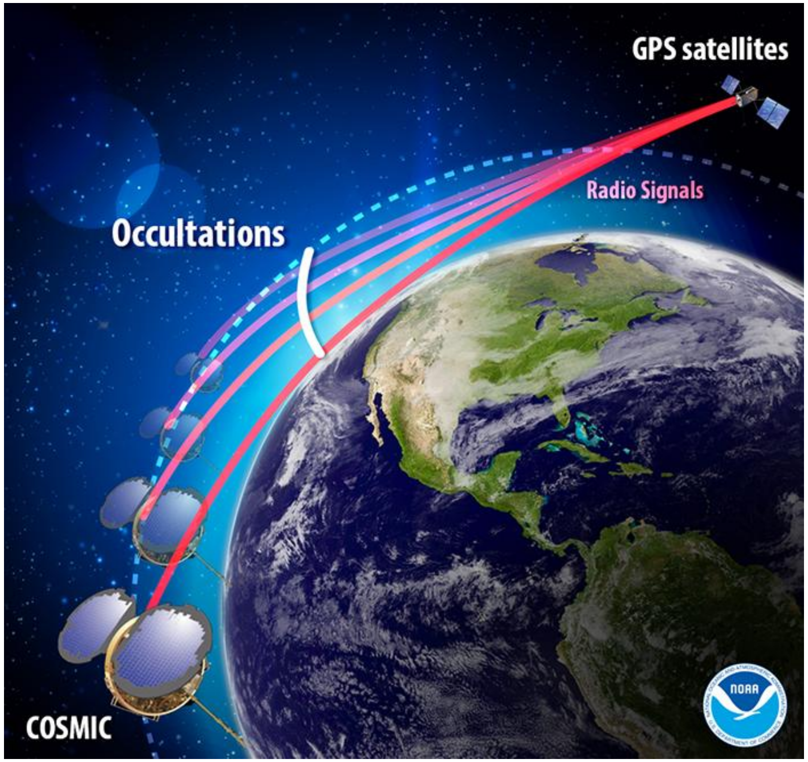
GNSS Radio Occultation (RO)

- GNSS signals and LEO receivers measure atmospheric bending angle

- Bending Angle → Refractivity → WV, T

- High vertical resolution (0.5 – 2km)†
- Low horizontal resolution (~300 km)†

- Temperature has high accuracy in UTLS (*0.3 K stochastic error btwn 30-250 hPa)
- Technology struggles to retrieve in BL



https://www.nesdis.noaa.gov/OPPA/cosmic2.php

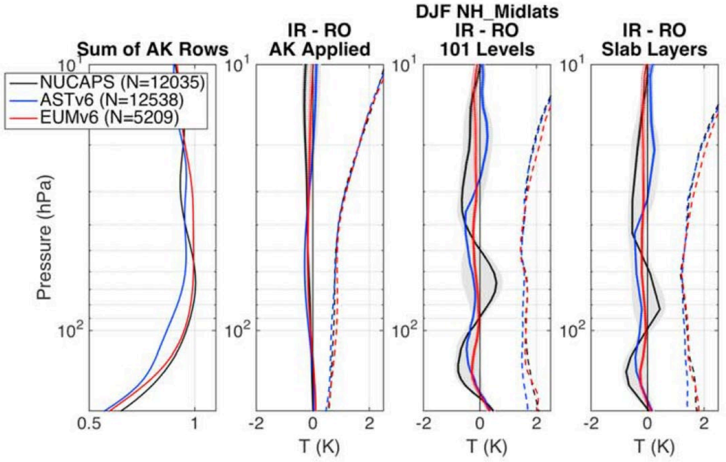
**ROMSAF VS 33 Report: http://www.romsaf.org/Publications/reports/romsaf_vs33_rep_v10.pdf*
†Kursinski et al., (1997) Observing Earth's atmosphere with radio occultation measurements using the Global Positioning System, JGR, 102.

Background

Previous Work*:*

1] IR temperature retrieval assessment using RO as reference (focus on UTLS):

- *Yunck et al., (2007), Use of Radio Occultation to Evaluate Atmospheric Temperature Data from Spaceborne Infrared Sounders, Terr. Atmos. Ocean Sci., 20, doi: 10.3319/TAO.2007.12.08.01(F3C)*
- *Divakarla, et al. (2014), The CrIMSS EDR algorithm: Characterization, optimization and validation, JGR Atmos., doi: 10.1002/2013JD020438.*
- *Feltz, et al. (2017), Assessment of NOAA NUCAPS upper air temperature profiles using COSMIC GPS radio occultation and ARM radiosondes, JGR Atmos., 122, doi: 10.1002/2017JD026504.*


Sum of AK Rows

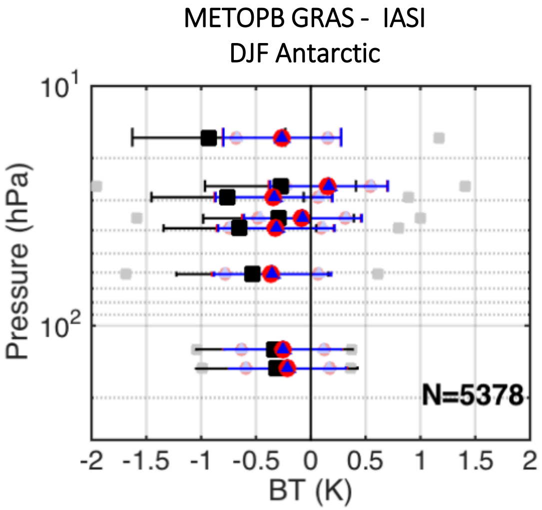
IR - RO AK Applied

DJF NH_Midlats IR - RO 101 Levels

IR - RO Slab Layers

2] RO temperature assessment using IR radiances as reference (via RT):

- *Feltz M., R. Knuteson, and H. Revercomb (2017), Assessment of COSMIC radio occultation and AIRS hyperspectral IR sounder temperature products in the stratosphere using observed radiances, JGR Atmos., 122, doi: 10.1002/2017JD026704.*
- *EUMETSAT ROM SAF Visiting Scientist Project Report: Assessment of Differences Between ROM SAF GRAS Derived Brightness Temperatures and Hyperspectral Infrared Brightness Temperature Observations, SAF/ROM/DMI/REP/VS/33, CDOP-2 VS No. 33.* *http://www.romsaf.org/Publications/reports/romsaf_vs33_rep_v10.pdf*


METOPB GRAS - IASI

DJF Antarctic

Other studies on RO and hyperspectral IR sounders:

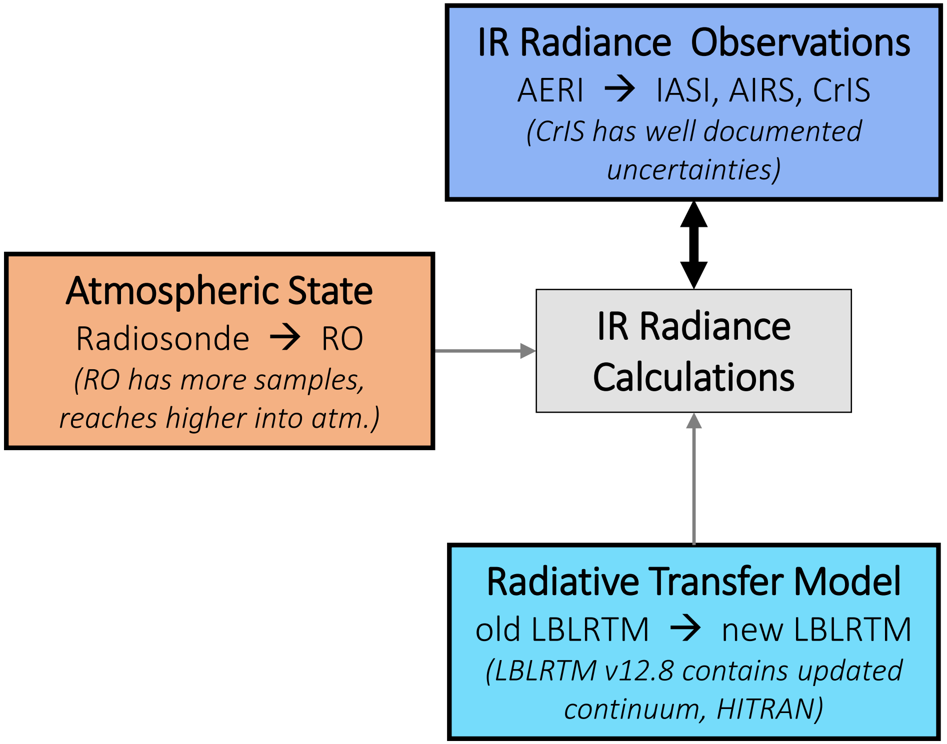
- ***Discussed SI traceability of each system to each other,*** *e.g. Cao et al. SPIE, 2018*
- ***Used RO to assess Radiometric Accuracy of CrIS Radiances,*** *e.g. Lynch et al., EUM Sat. Conf., 2018*
- ***Shown advantages of combining IR sounder & RO in retrievals,*** *e.g. Borbas et al. JGR 2003, JAMC 2008; Ho et al., JTECH, 2007; Lui et al., IEEE, 2015*

Background

Additional Application:
Infrared Radiance Closure Experiments

- Efforts in 90’s enabled refinements of radiosonde humidity calibration & WV molecular absorption lines using the AERI instrument (*Turner et al., 2004*)

- Later work was similarly done using aircraft and satellite based hyperspectral IR sounder measurements as a validation reference for other atmospheric state and model parameters (e.g. *Strow et al., 2006; Tobin et al., 2006; Masiello et al., 2011, …)*



IR Radiance Observations
AERI → IASI, AIRS, CrIS
(CrIS has well documented uncertainties)

Atmospheric State
Radiosonde → RO
(RO has more samples, reaches higher into atm.)

IR Radiance Calculations

Radiative Transfer Model
old LBLRTM → new LBLRTM
(LBLRTM v12.8 contains updated continuum, HITRAN)

Strow, L. L., (2006), Validation of the Atmospheric Infrared Sounder radiative transfer algorithm, J. Geophys. Res., 111, D09S06, doi:10.1029/2005JD006146.

Tobin, D. C., (2006), Atmospheric Radiation Measurement site atmospheric state best estimates for Atmospheric Infrared Sounder temperature and water vapor retrieval validation, J. Geophys. Res., 111, D09S14, doi:10.1029/2005JD006103.

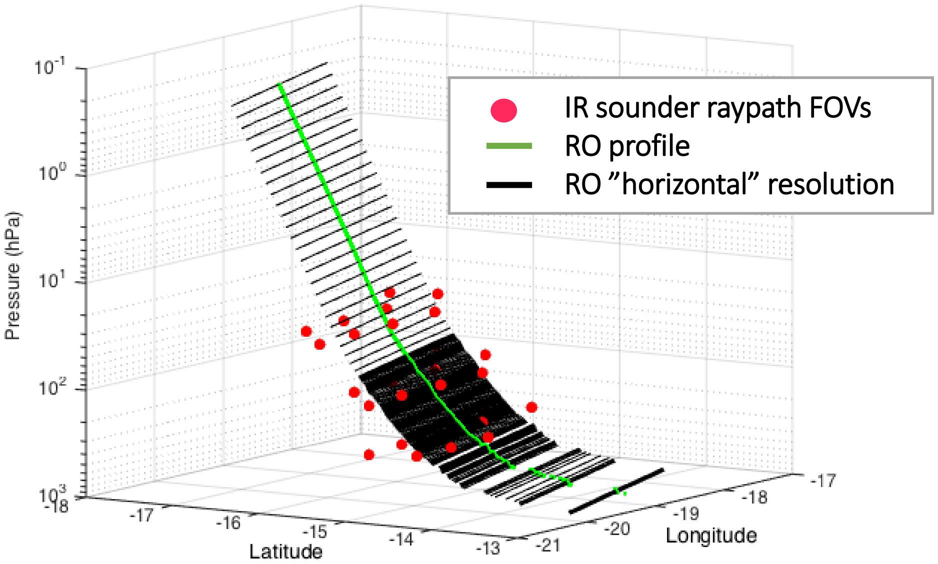
Turner, D.D., (2004), The QME AERI LBLRTM: A Closure Experiment for Downwelling High Spectral Resolution Infrared Radiance, J. Atmos. Sci., 61, 2657–2675, https://doi.org/10.1175/JAS3300.1

Masiello, G. et al. (2011), The use of IASI data to identify systematic errors in the ECMWF forecasts of temperature in the upper stratosphere, Atmos. Chem. Phys., 11, doi:10.5194/acp-11-1009-2011.

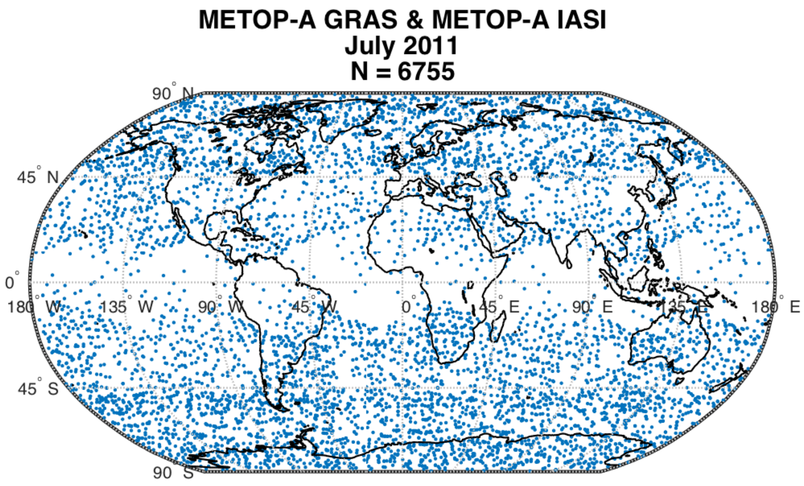
Methods

Methods: Matchup Scheme

Individual Matchup Case



Example Matchup Distribution

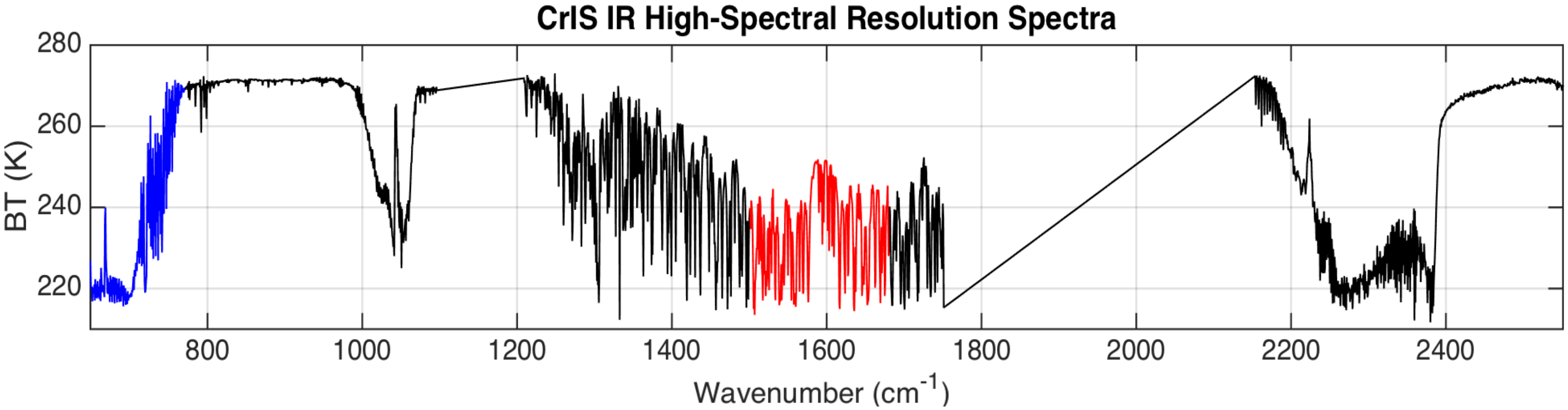


- Use profile-to-profile matchup method
  - Accounts for the unique RO profile geometry and horizontal resolution
  - <1 hr time criterion
- Distribution and number of matchups depends on orbital mechanics
- Method applicable to data from different platforms/processing centers

FOR MORE DETAILS: Feltz, M. et al. (2014), A methodology for the validation of temperature profiles from hyperspectral infrared sounders using GPS radio occultation: Experience with AIRS and COSMIC, JGR, doi:10.1002/ 2013JD020853.

Methods: Radiative Transfer

- Optimal Spectral Sampling Radiative Transfer Fast Model
  - Atmospheric and Environmental Research (AER)
  - Model Input: ECMWF Reanalysis, NOAA ESRL CarbonTracker and heavy molecules, NASA CAMEL Land HSR Emissivity V002 or Nick Nalli's Ocean Emissivity module



OSS Reference: Moncet, et al., Infrared Radiance Modeling by Optimal Spectral Sampling. Journal of the Atmospheric Sciences, Vol. 65, 2008, https://doi.org/10.1175/2008JAS2711.1

LBLRTM Reference: Clough, et al., Line-by-line calculation of atmospheric fluxes and cooling rates: Application to water vapor. Journal of Geophysical Reviews, 97, 1992, https://doi.org/10.1029/92JD01419

HITRAN Reference: Rothman, et al., The HITRAN2012 molecular spectroscopic database. Journal of Quantitative Spectroscopy & Radiative Transfer, 130, 4-50, 2013, https://doi.org/10.1016/j.jqsrt.2013.07.002

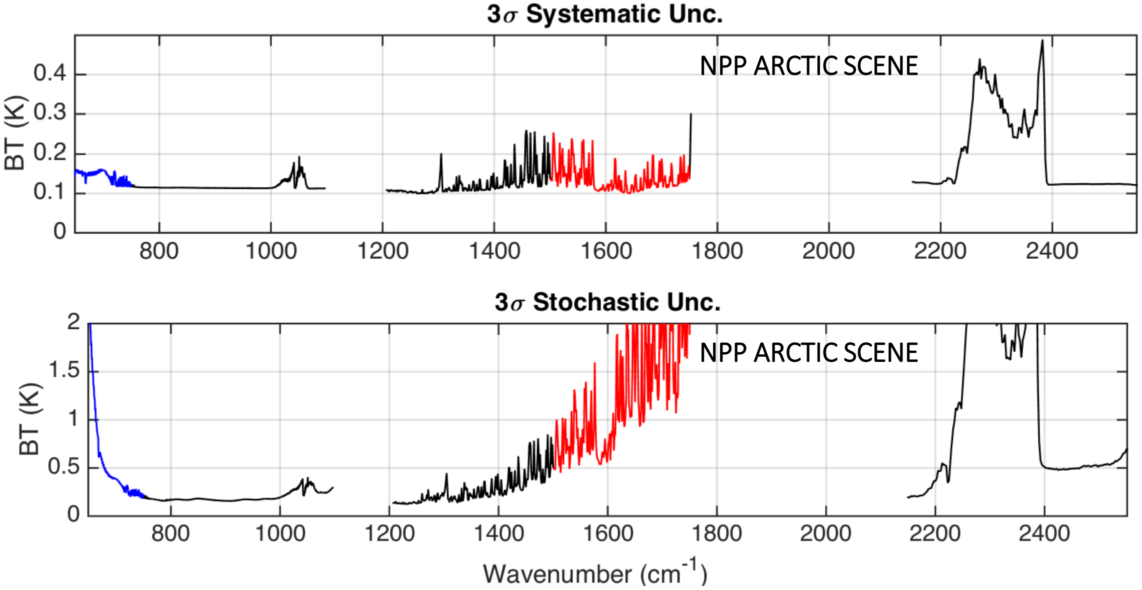
Uncertainties

1. Observations
2. Atmospheric State
3. Radiative Transfer Model

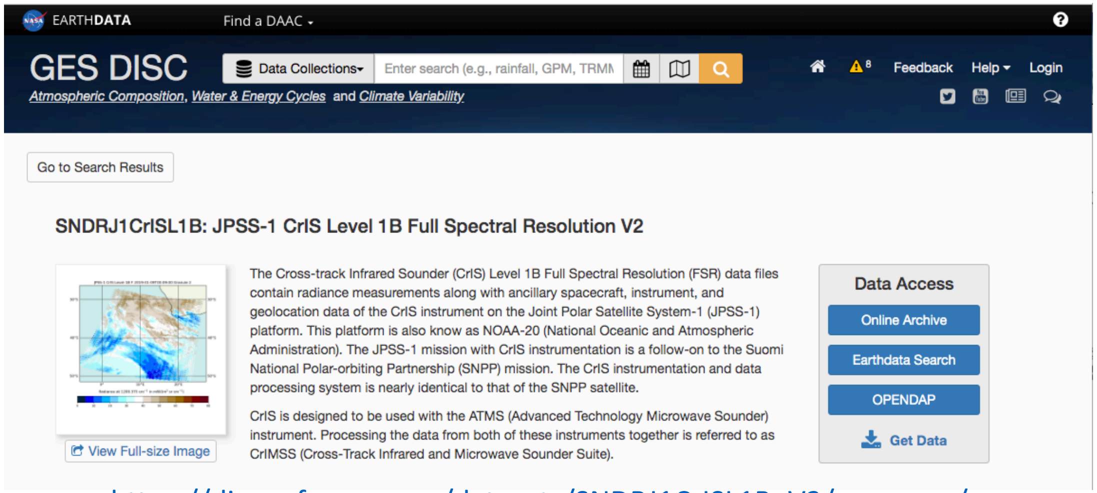
Uncertainties: CrIS Radiance Observations

-- Data provided by Joe Taylor of UW–Madison, SSEC --

- CrIS measurement uncertainty, for large data ensembles, is dominated by radiometric calibration
  - Estimates published for SNPP and created for NOAA-20 (Tobin et al., 2013)*
- Single sample error/noise estimated as the standard deviation of the ICT views



- Reprocessed CrIS radiance products available from NASA GES DISC
  - Noise estimates on each granule
  - Version 3 will make radiometric uncertainty estimates available-- provided as software and inputs



SNDRJ1CrISL1B: JPSS-1 CrIS Level 1B Full Spectral Resolution V2

The Cross-track Infrared Sounder (CrIS) Level 1B Full Spectral Resolution (FSR) data files contain radiance measurements along with ancillary spacecraft, instrument, and geolocation data of the CrIS instrument on the Joint Polar Satellite System-1 (JPSS-1) platform. This platform is also know as NOAA-20 (National Oceanic and Atmospheric Administration). The JPSS-1 mission with CrIS instrumentation is a follow-on to the Suomi National Polar-orbiting Partnership (SNPP) mission. The CrIS instrumentation and data processing system is nearly identical to that of the SNPP satellite.

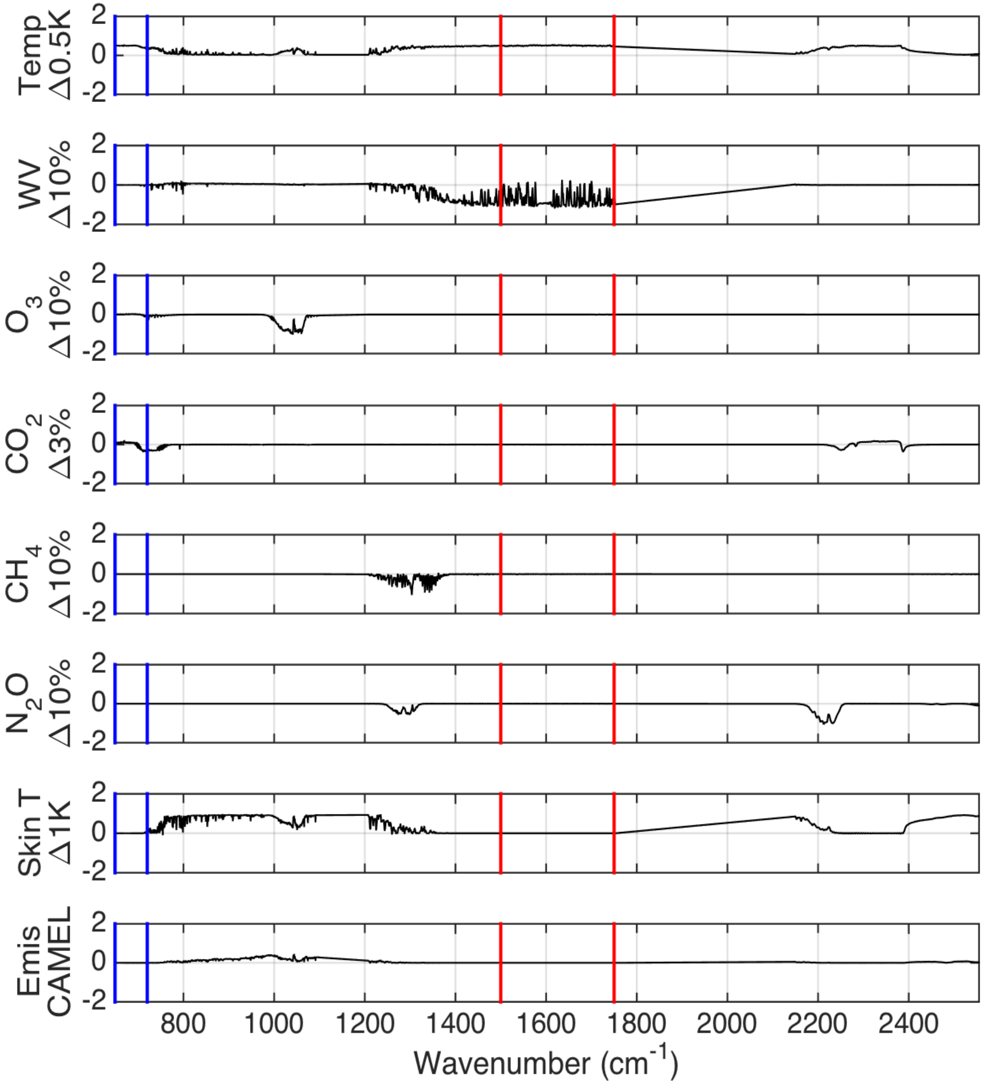
CrIS is designed to be used with the ATMS (Advanced Technology Microwave Sounder) instrument. Processing the data from both of these instruments together is referred to as CrIMSS (Cross-Track Infrared and Microwave Sounder Suite).

https://disc.gsfc.nasa.gov/datasets/SNDRJ1CrISL1B_V2/summary/

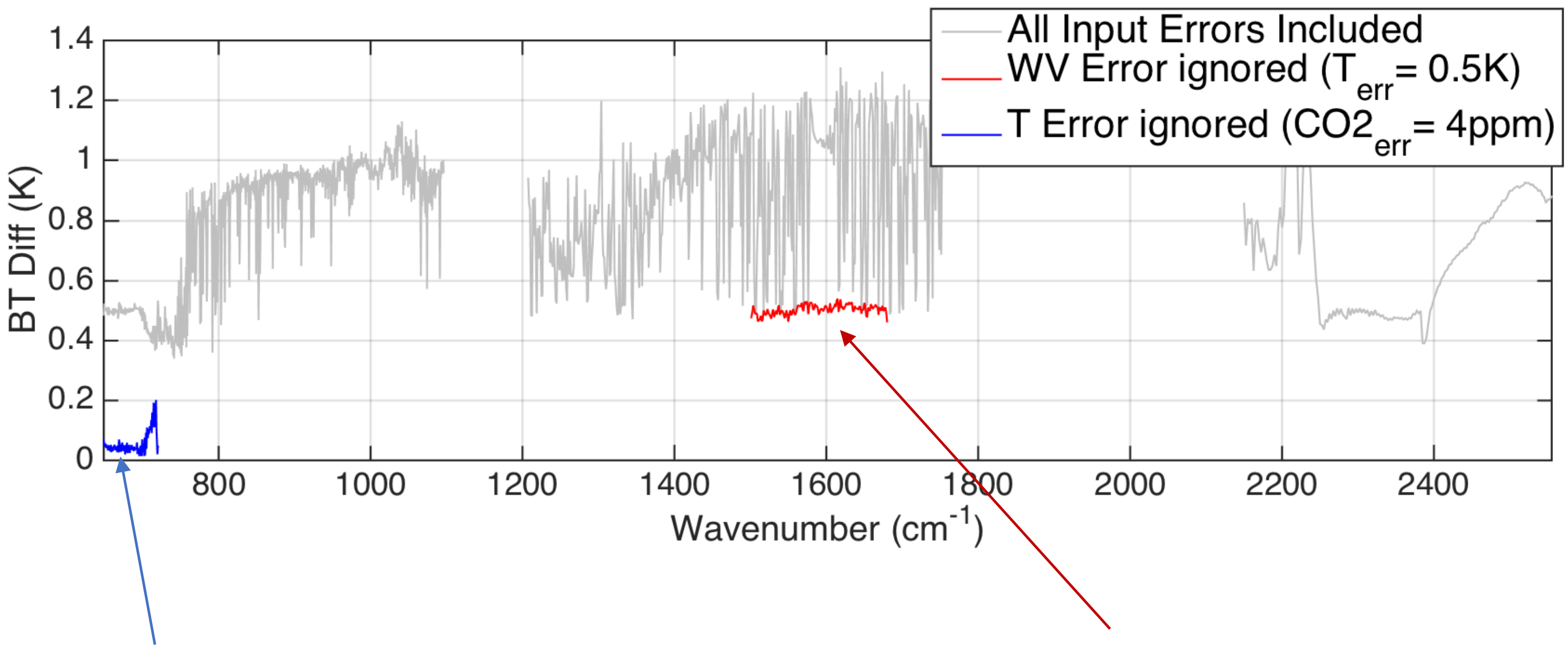
Tobin D. et. al., Suomi-NPP CrIS radiometric calibration uncertainty, JGR: Atmos., 118, 2013. https://doi.org/10.1002/jgrd.50809

Uncertainties: Atmospheric State

- Atmospheric state uncertainty estimation:
  - 1] Calculate sensitivities →
  - 2] Scale sensitivities to error estimates:
    - **T: 0.5 K**
    - **WV: 10 %**
    - **CO_2: 4 ppm**
    - O_3: 10 %
    - CH_4: 10 %
    - N_2O: 10 %
    - Skin T: 1 K
    - Sfc Emis: CAMEL V002
  - 3] Combine scaled sensitivities via RSS



Uncertainties: Atmospheric State



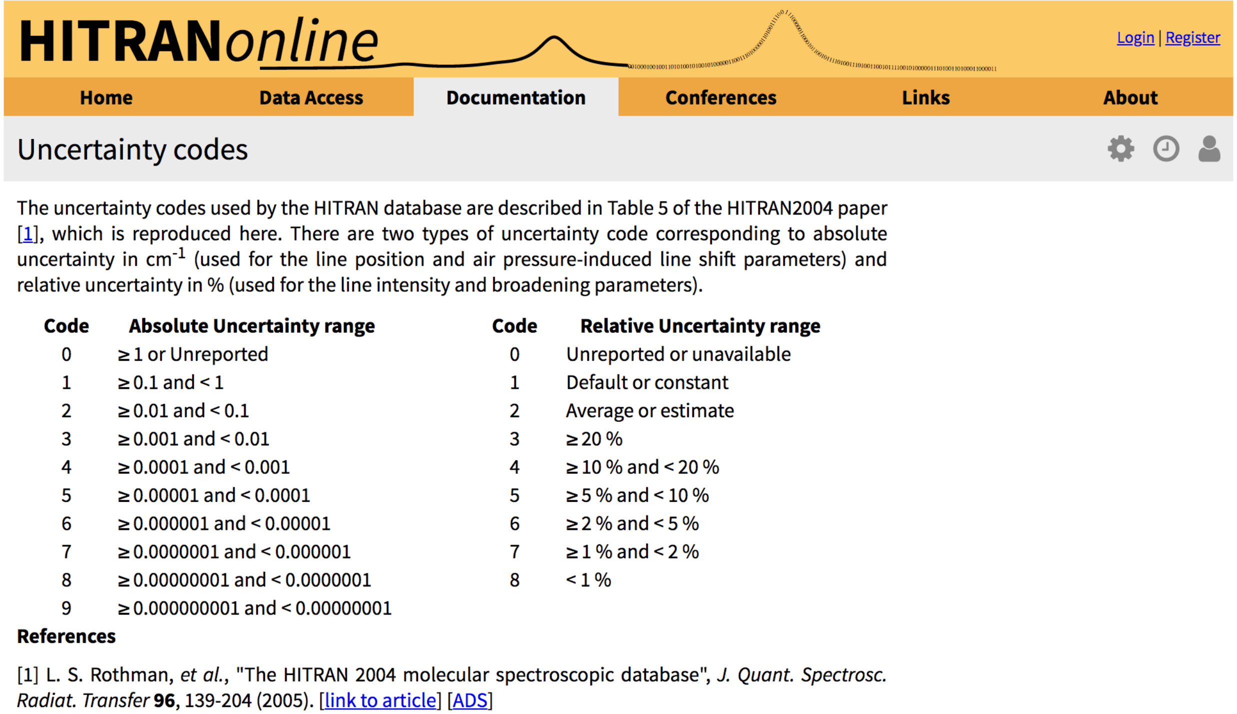
- 15 µm more sensitive to typical T errors than typical CO_2 errors
- Uncertainty in blue ignores T error and is dominated by contribution from 4 ppm CO_2 error → is **~0.05 K** for < 700 cm^{-1}

- 6 µm sensitive to both T & WV – ambiguity implies we can only validate WV to the degree we know T
- Uncertainty in red ignores WV error and is primarily due to T → is **~0.5K**

Uncertainties: Radiative Transfer Model

- HITRAN database provides “uncertainty codes” which describe uncertainty in the molecular line position and air pressure-induced line shift parameters, as well as the line intensity and broadening parameters (Rothman et al., 2005)

- 700 cm^{-1} region absorption features have very small uncertainties (<1% on coefficients)
- 1600 cm^{-1} region known to a lesser degree



Uncertainty codes

The uncertainty codes used by the HITRAN database are described in Table 5 of the HITRAN2004 paper [1], which is reproduced here. There are two types of uncertainty code corresponding to absolute uncertainty in cm^{-1} (used for the line position and air pressure-induced line shift parameters) and relative uncertainty in % (used for the line intensity and broadening parameters).

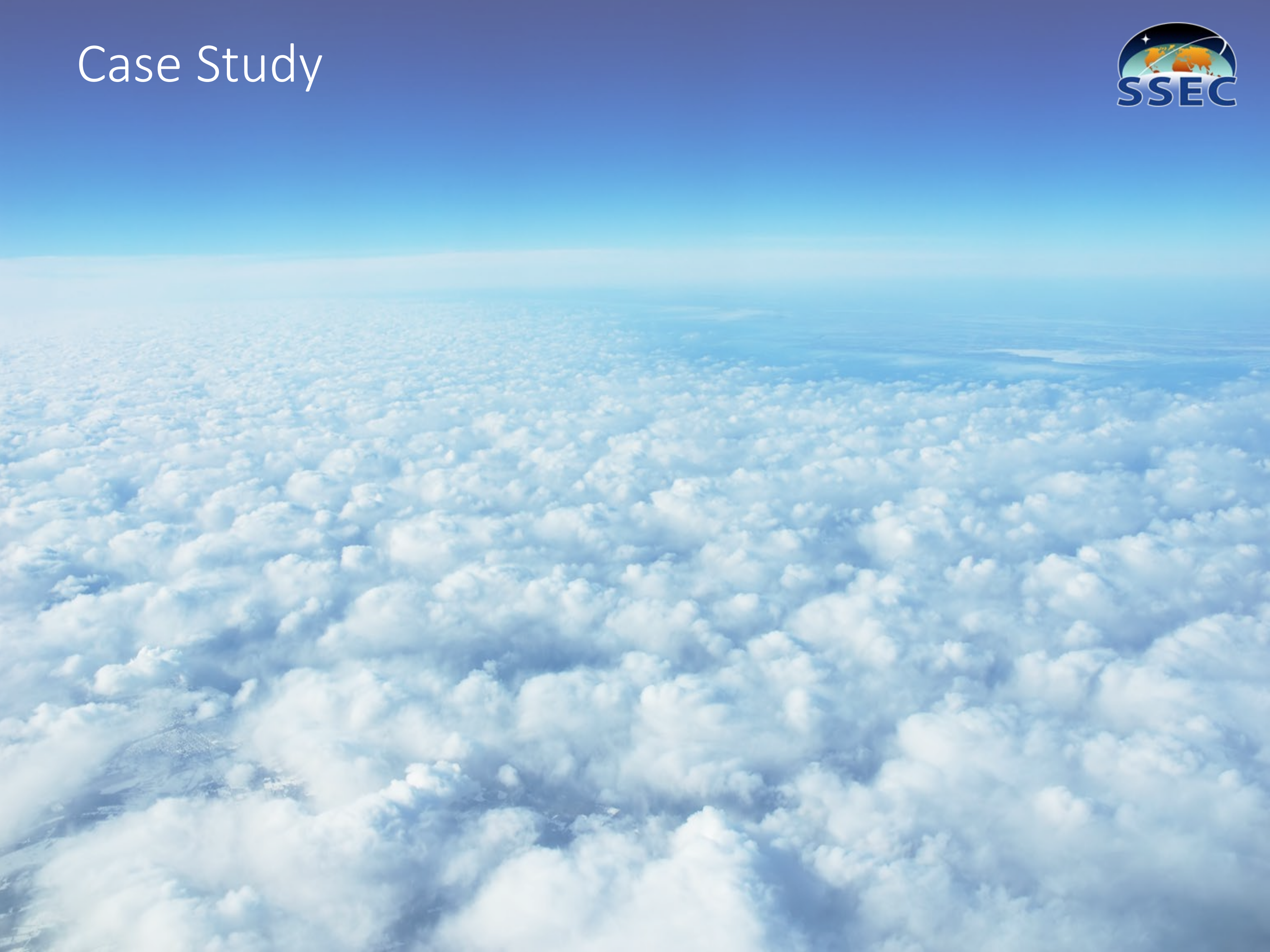
Code	Absolute Uncertainty range	Code	Relative Uncertainty range
0	≥ 1 or Unreported	0	Unreported or unavailable
1	≥ 0.1 and < 1	1	Default or constant
2	≥ 0.01 and < 0.1	2	Average or estimate
3	≥ 0.001 and < 0.01	3	≥ 20 %
4	≥ 0.0001 and < 0.001	4	≥ 10 % and < 20 %
5	≥ 0.00001 and < 0.0001	5	≥ 5 % and < 10 %
6	≥ 0.000001 and < 0.00001	6	≥ 2 % and < 5 %
7	≥ 0.0000001 and < 0.000001	7	≥ 1 % and < 2 %
8	≥ 0.00000001 and < 0.0000001	8	< 1 %
9	≥ 0.000000001 and < 0.00000001		

References

[1] L. S. Rothman, *et al.*, "The HITRAN 2004 molecular spectroscopic database", *J. Quant. Spectrosc. Radiat. Transfer* **96**, 139-204 (2005). [link to article] [ADS]

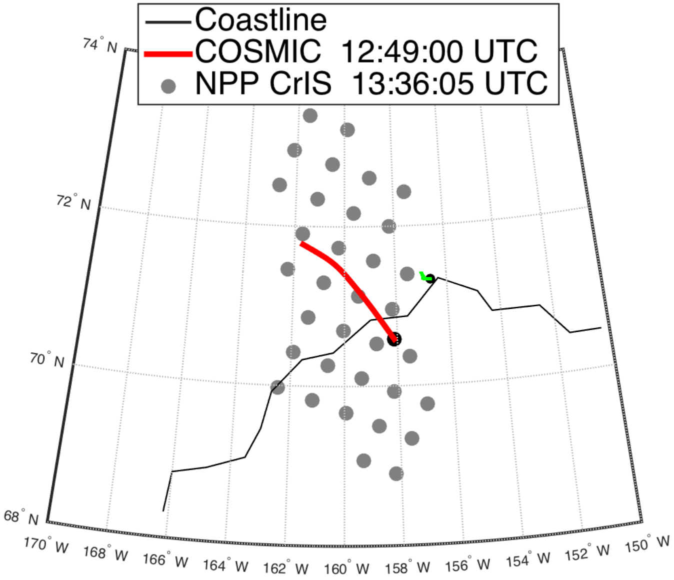
https://hitran.org/docs/uncertainties/

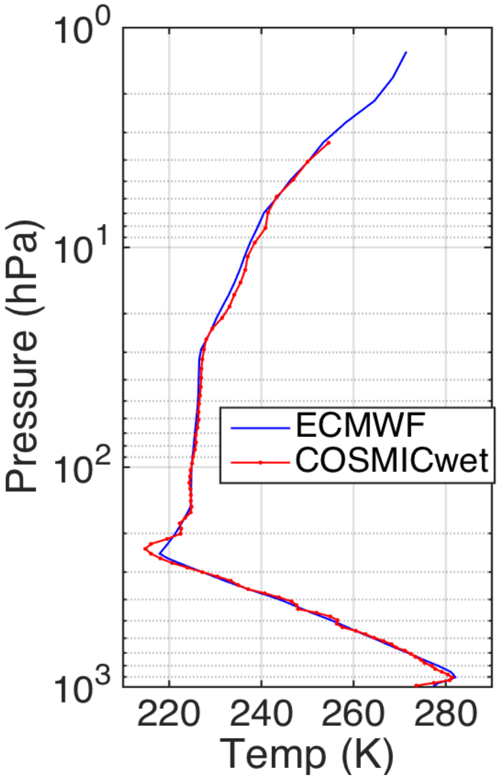
Case Study

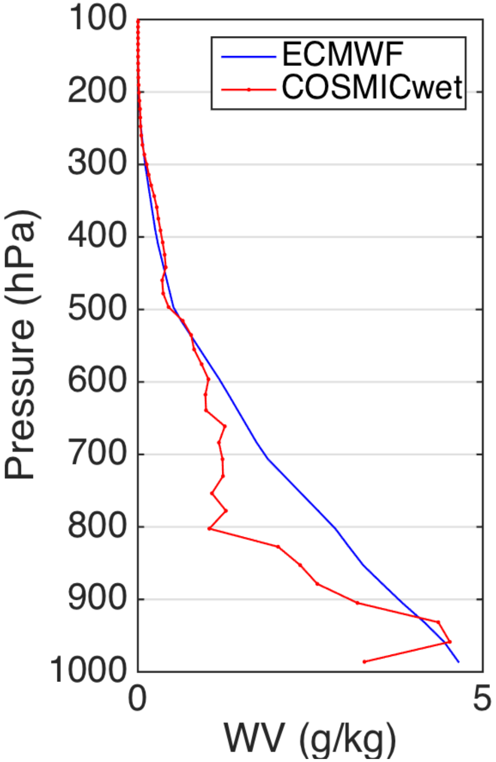


Case Study

North Slope of Alaska ARM Site
August 14th, 2014







UCAR COSMIC data obtained from the COSMIC Data Analysis and Archive Center: https://cdaac-www.cosmic.ucar.edu/

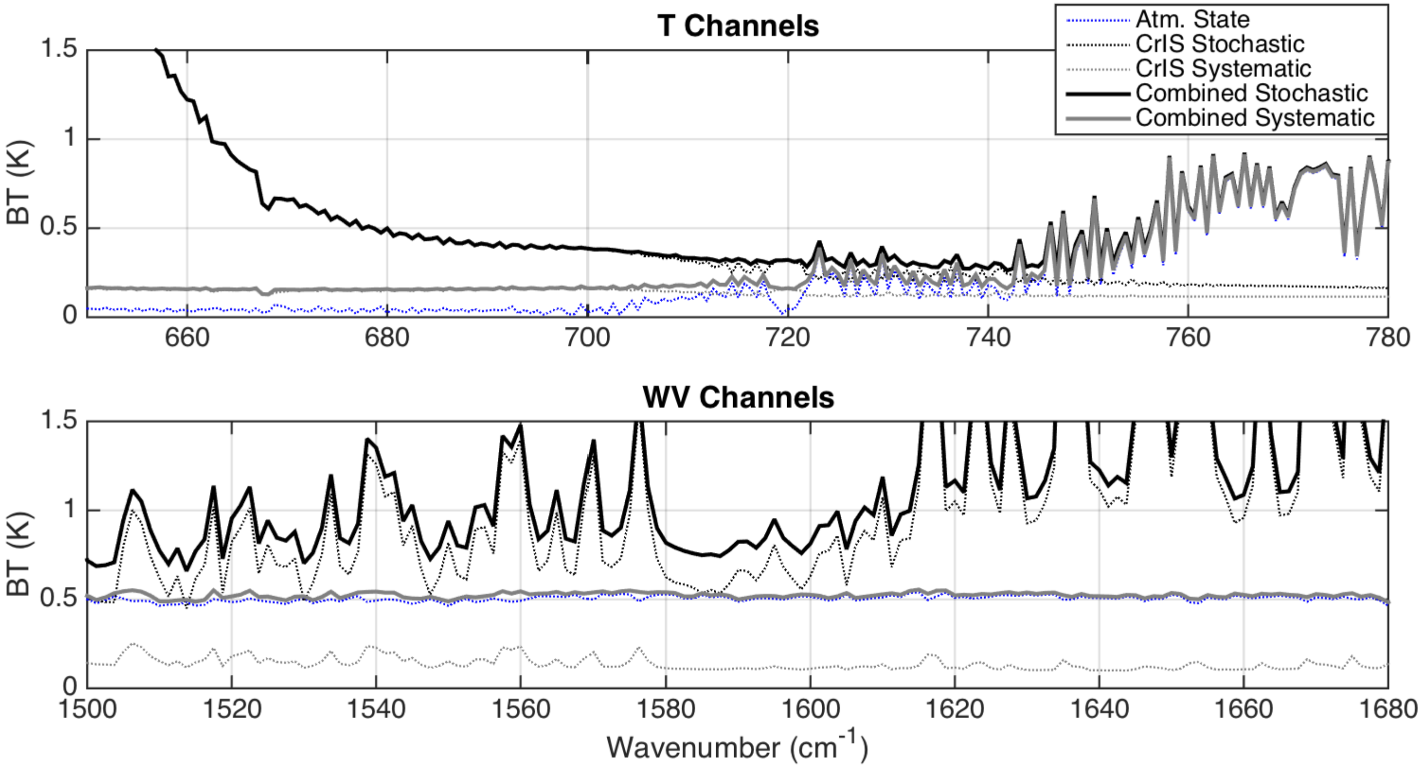
Case Study

NORTH SLOPE OF ALASKA ARM SITE
AUGUST 14TH, 2014

- Combined **systematic between 0.13-0.18 K** at < 700cm^{-1}
- Combined stochastic under 0.5 K between 680-740 cm^{-1}

- Combined **systematic ~0.5 K**
- Combined stochastic under 1-2 K

CALC-OBS COMBINED 3σ UNCERTAINTY

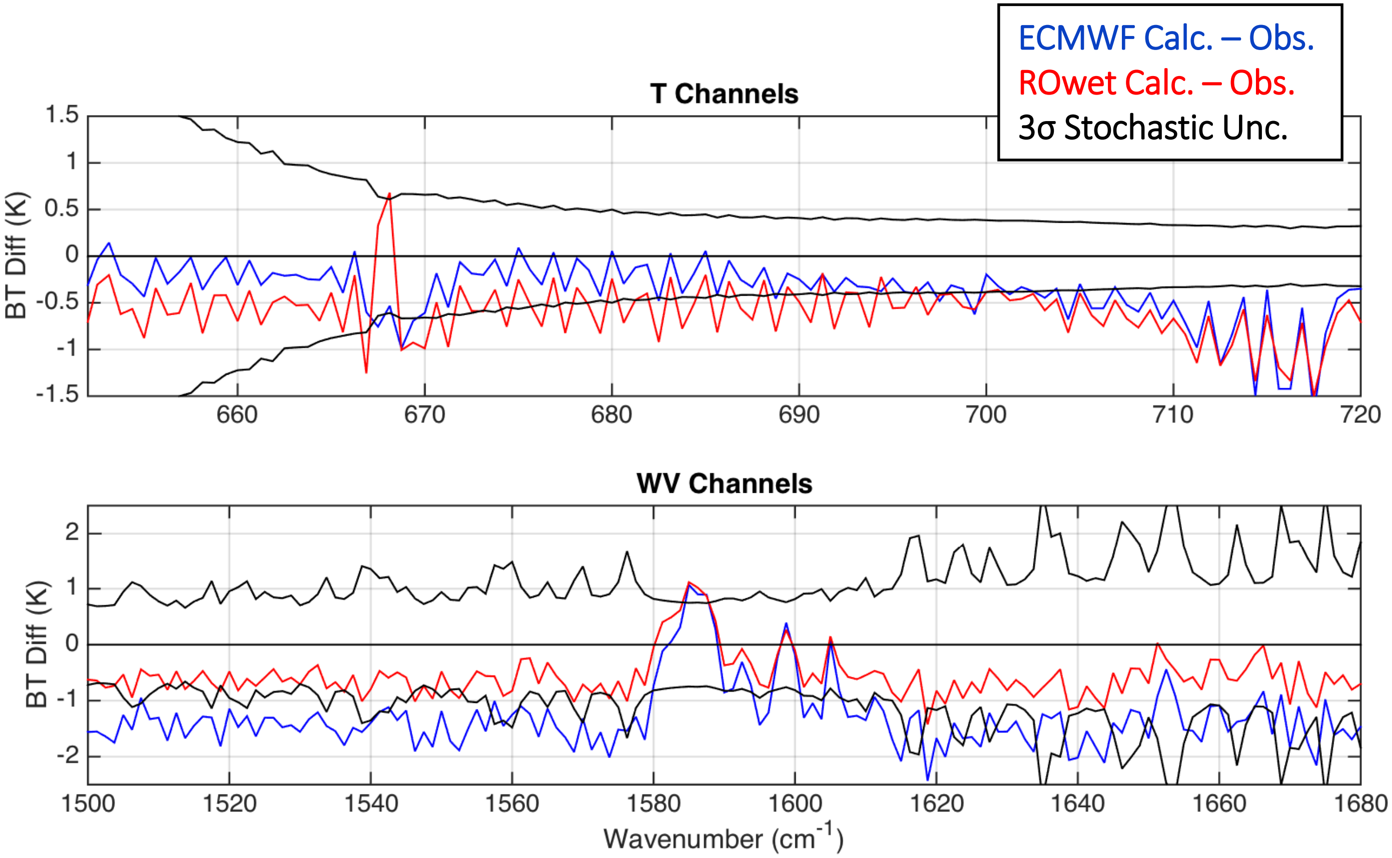


Case Study

NORTH SLOPE OF ALASKA ARM SITE
AUGUST 14TH, 2014

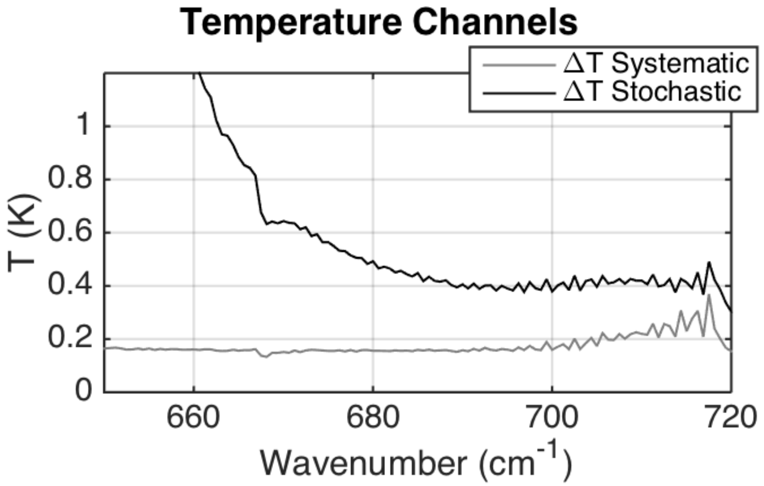
- Spectral regions exist where the calculations do and do not agree with the observations
- Suggests the uncertainties are small enough for us to be able to learn something from these comparisons

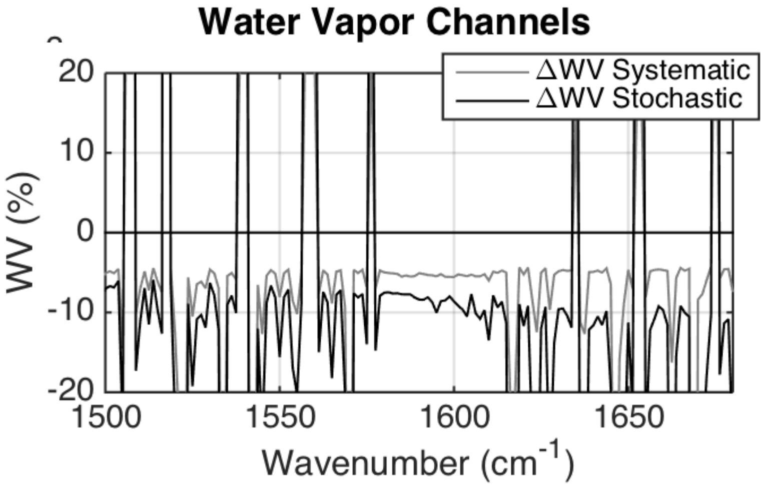
CALC-OBS DIFFERENCE



Case Study: Broad Conclusions

Question: To what accuracy can we use the IR sounder radiances and radiative transfer to validate the atmospheric state temperature and water vapor (e.g. from RO)??





- Minimum detectable upper-trop/lower-strat T
  - bias is ~0.2 K
  - single sample error is ~0.45 K

  (Based off of 4ppm CO_2 error & CrIS obs unc)

- Minimum detectable tropospheric WV
  - bias is ~6%
  - single sample error is ~10%

  (Based off 0.5 K T error & CrIS obs unc)

Concluding Remarks

Concluding Remarks

- Applications of RO and hyperspectral IR sounder comparisons:
    - IR T retrieval validation
    - RO T product validation
    - Radiative transfer closure experiments

- A radiance closure experiment using CrIS radiances as a validation reference showed:
    - The **single sample** minimum detectable
        - stratospheric T error is ~0.45 K
        - tropospheric WV error is ~10%
    - The **ensemble mean** minimum detectable
        - stratospheric T bias is ~0.2 K,
        - tropospheric WV bias is ~6%

- Future work:
    - COSMIC-2 operational wet profiles assessment using coincident observations from the operational NOAA-20 CrIS

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RADIO OCCULTATION METEOROLOGY

RO Vertical Resolution

- Taken from Kursinski et al., Observing Earth's atmosphere with radio occultation measurements using the Global Positioning System, JGR, 102, 1997. (https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/97JD01569)

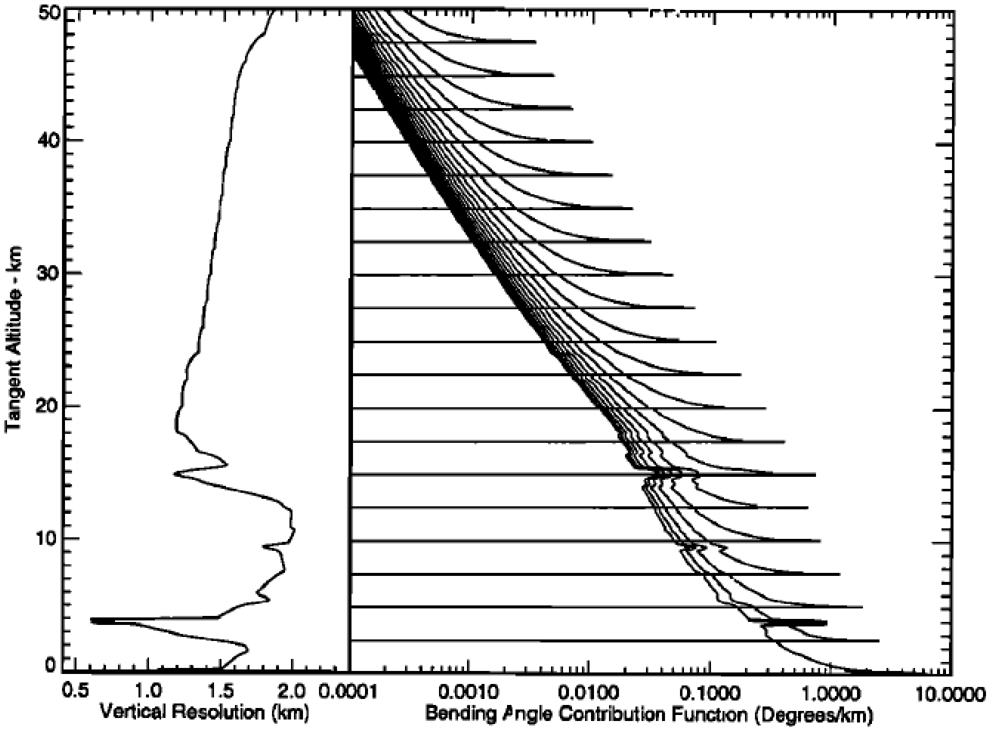

Figure 5. Bending contribution functions on the right and vertical resolution profile on the left for individual radio occultation bending angle measurements plotted as a function of altitude. Resolution is defined here as the vertical interval between the ray path tangent height and the height at which half of the total bending has been accumulated. These curves are calculated for a refractivity profile derived from radiosonde temperature and humidity profiles, assuming spherical symmetry. Radiosonde 1200 UT, July 11, 1991, Hilo, Hawaii.

RO Temperature Uncertainties

- Figure from EUMETSAT ROM SAF Visiting Scientist Report # 33: http://www.romsaf.org/Publications/reports/romsaf_vs33_rep_v10.pdf

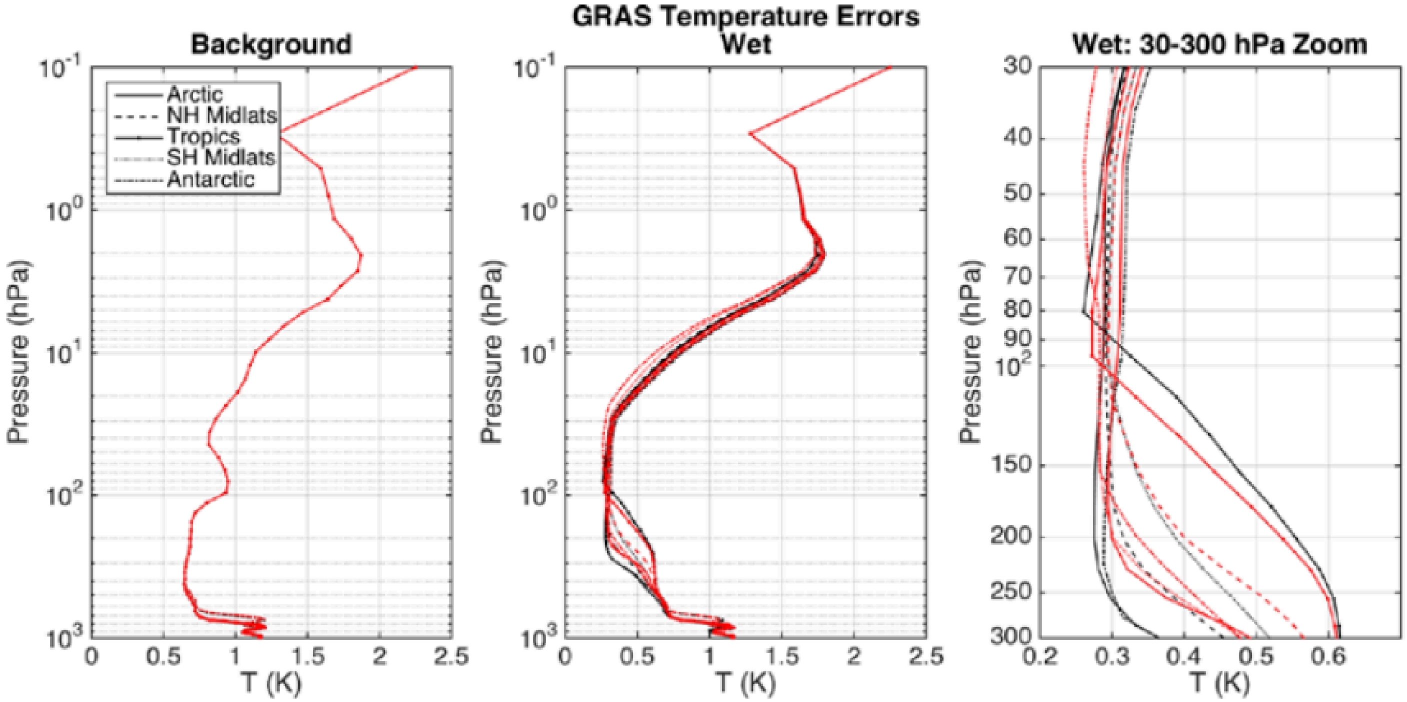

Figure 5.4 *GRAS background (left), and wet (middle, and right zoomed) stochastic temperature error profiles for each of the 5 zones overlaid for the DJF (black) and JJA (red) seasons.*

RO Temperature Uncertainties

- Figure from EUMETSAT ROM SAF Visiting Scientist Report # 33: http://www.romsaf.org/Publications/reports/romsaf_vs33_rep_v10.pdf

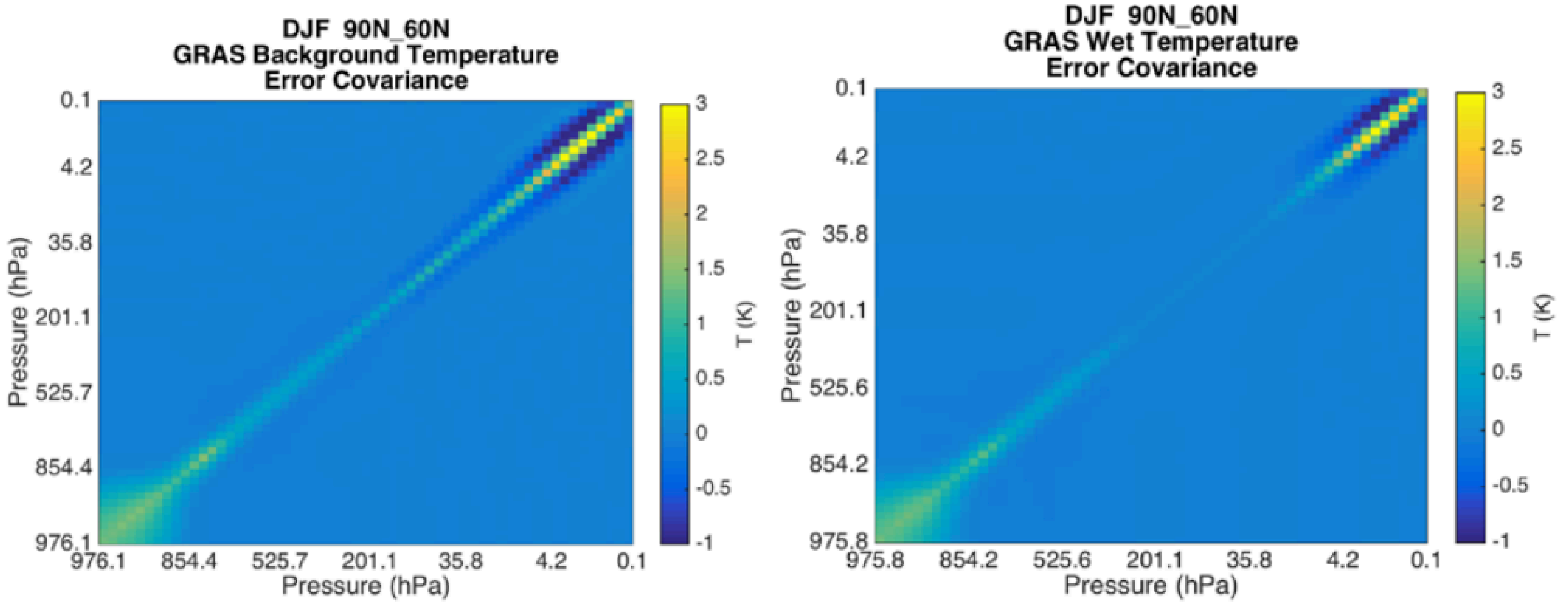

***Figure 5.3** GRAS global, annual background temperature error covariance matrix plotted on pressures corresponding to the DJF Arctic (left), and the GRAS DJF Arctic representative wet temperature error covariance (right) in temperature space.*