Doppler Shift Correction of the Cross-track Infrared Sounder (CrIS) Observed Radiances

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Introduction

- Both the Earth velocity and Satellite velocity contribute to the relative velocity between the Earth observation and instrument
- The Doppler velocity is the dot product of the net velocity vector and the unit line of sight vector
- CrIS has a large cross-track swath (Max sat zenith angle near equator of 59.9°) and small along-track viewing angles (~1.1° to ~1.5°, FOR dependent)
- Based on the large difference in cross-track and along-track angles, it is reasonable to expect that the Doppler shift of an observation will be primarily due to the Earth's rotation coupled with the large cross-track view angles
- However, the satellite velocity is roughly 16x the maximum Earth velocity

Doppler Shifted CrIS Observations due to Earth Rotation

- The fractional doppler shift due to Earth rotation projected onto the cross-track viewing angle can be described by [1,2]

$$\frac{\Delta v}{v} = \frac{\Omega R}{c} \sin(\theta_{zenith}) \cos(\lambda_{lat}) \left| \sin(\varphi_{azimuth}) \right|$$

- Latitude dependent, largest effect near equator at large sat zenith angles
- ΩR is the Earth rotation velocity at the equator
- $\Omega R \cos(\lambda_{lat})$ is the Earth rotation velocity at given latitude
- $\sin(\theta_{zenith})$ and $\sin(\varphi_{azimuth})$ project the Earth velocity $\Omega R \cos(\lambda_{lat})$ in the direction of the cross-track component of the LOS unit vector
- The equation above does not address the projection of the satellite velocity in the direction of the along-track component of the LOS unit vector (large satellite velocity and small along-track LOS angle result in a non-negligible Doppler velocity)
- Latitude dependent, largest effect near equator at large sat zenith angles
- Primarily FOR dependent, little FOV dependence

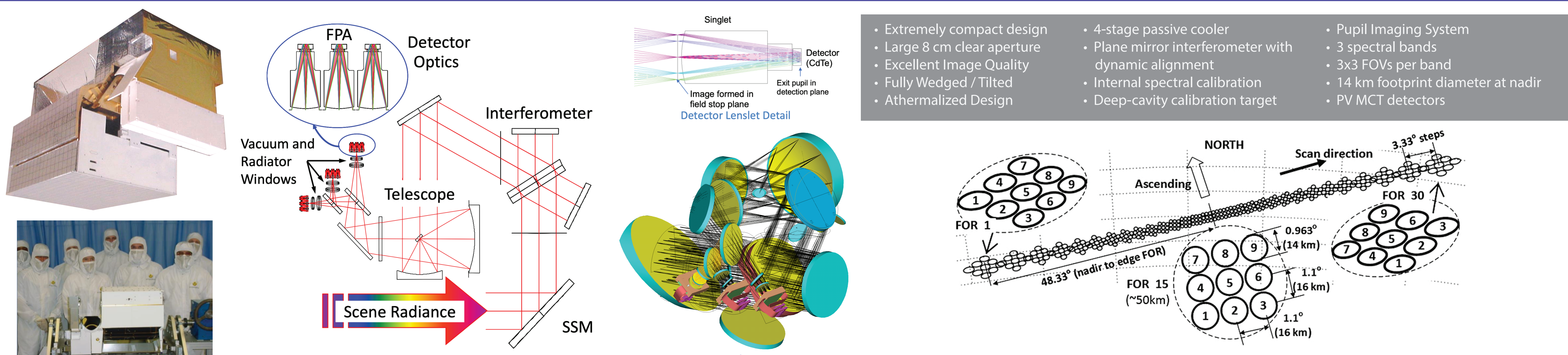### Doppler Shifted CrIS Observations due to Satellite Velocity

- Primary dependence is on along-track component of sat zenith angle.
- CrIS FOV position rotates with scan angle
- Due to CrIS FOV rotation with SSM rotation, maximum along-track angle for each FOR ranges from ~1.1° to ~1.5°
- Along-track component of FOV angle will be FOR dependent
- Not dependent on latitude
- FOV and FOR dependent

A "Back of the Envelope" Comparison of Expected Doppler Shift due to Earth Rotation and Satellite Velocity

Doppler Shift due to Earth Rotation

- $\Omega \approx 7.292$ rad/sec, $R \approx 6378.137$km @ equator, therefore $v_E \approx 0.465$ km/sec @ equator
- For a granule near equator (2018JD091,NOAA20): 397.1 m/s max Doppler velocity
- For a granule near North Pole (2018JD091,NOAA20): 0.0015 m/s min Doppler velocity

Doppler Shift due to Satellite Velocity

- $v_{SAT} \approx$ ~7.5km/sec (roughly 16x maximum Earth velocity)
- Maximum ~1.5° along-track angle from nadir near edge of swath
- 7500 m/s • cos(88.5°) = 196 m/s Doppler velocity
- 196/397 = 49% of the magnitude of the maximum Doppler velocity due to Earth rotation (at the equator near edges of cross-track swath)
- Potentially the dominant contributor to Doppler shift of observations for high latitudes or near-nadir cross-track viewing angles

[1] Y. Chen, et al. "Detection of Earth-Rotation Doppler Shift from Suomi National Polar-orbiting Partnership Cross-track Infrared Sounder." Applied optics 52.25 (2013): 6250-6257 https://doi.org/10.1364/AO.52.006250
[2] L. Strow, "Correcting CrIS Doppler Shifts: Observations", CrIS SDR Team Telecon, 2019-10-23
[3] J. Taylor, "Doppler Shift and Correction for CrIS Observed Radiances: Impact of Satellite Velocity", CrIS SDR Team Telecon, 2019-11-13
[4] L. Strow, "Validation of the UW (Joe Taylor) Theoretical Calculations of Spacecraft + Earth Rotation Doppler Shifts using NOAA20", CrIS SDR Team Telecon, 2021-04-21

The CrIS Sensor

- Extremely compact design
- Large 8 cm clear aperture
- Excellent Image Quality
- Fully Wedged / Tilted
- Athermalized Design

- 4-stage passive cooler
- Plane mirror interferometer with dynamic alignment
- Internal spectral calibration
- Deep-cavity calibration target

- Pupil Imaging System
- 3 spectral bands
- 3x3 FOVs per band
- 14 km footprint diameter at nadir
- PV MCT detectors

Figures include material from Predina, ITT/Exelis, May 2009 • Han, NOAA NESDIS, November 2013 • Barnet, STC, April 2017 • Revercomb, UW-SSEC, November 2018

Calculation and Validation of Doppler Shift of the CrIS Spectrally Resolved Radiance Observations

Calculation

- The plots below show the calculated Doppler shift versus latitude, FOV, and FOR for one orbit of NOAA-20 data for two cases
  (1) Doppler shift due to relative velocity between observed scene and instrument accounting for Earth rotation only
  (2) Doppler shift due to total relative velocity between observed scene and instrument (including Earth velocity and Satellite velocity contributions)
- UW-SSEC geolocation code used to calculate Doppler velocities
- Calculated Doppler velocity converted to fractional doppler shift (ppm); $dopp_{frac} = (v_{dopp}/c)*1e6$

Validation (Larrabee Strow, UMBC)

- Frequency shifts are derived from cross-correlations of observed radiances to ECMWF-computed radiances, which are frequency shifted until the maximum correlation occurs. Quality control provided by magnitude of correlation at peak
- Uses only high-quality clear scenes (ocean)
- Large amount of data used (all clear scenes for calendar year 2018)
- Frequency measurements: performed each day, for 40 equal-area latitude bins
- No "removal" of absolute calibration, FOV calibration nearly perfect
- Higher latitude bins are sparsely populated, and lack of data for higher latitudes required smoothing. Uses an 8-point (latitude) LOWESS (quadratic) smoother
- The results shown here use the midwave water vapor band
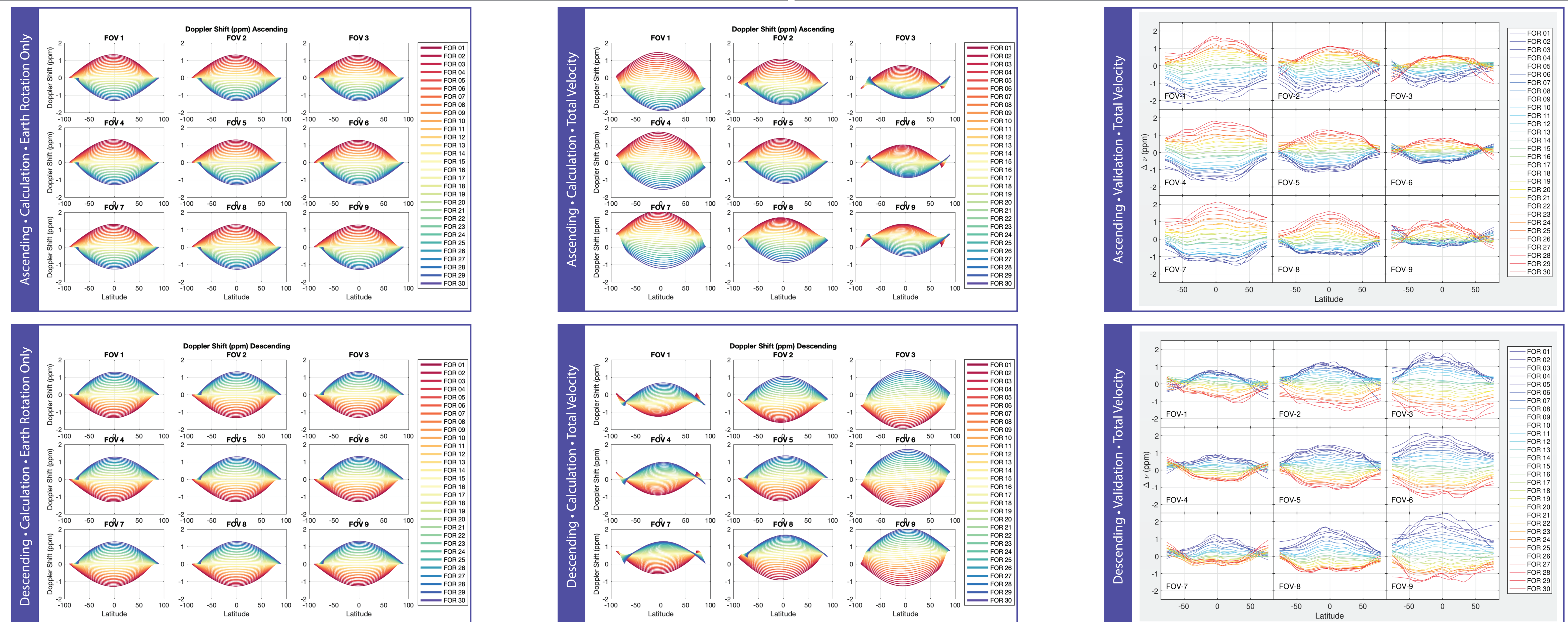
Note that the FOV numbering in the above plots are simply ordered by FOV (1-3 in the top row of the FOR) and thus are flipped vertically compared to the FOR diagram illustration in the CrIS Sensor section in which FOVs 1-3 are in the bottom row for the nearest nadir FORs.

- Extremely good agreement between theory and observation for the combined effects of Earth-rotation and spacecraft motion Doppler shifts
- Separation of these two motions is clearly evident in the observed data, along with the expected variation with ascending versus descending orbits
- Both the magnitude of the shifts, and their dependence on latitude, FOR, and FOV show good agreement
- Even the small sign switch for high latitudes, for example for ascending FOV-9, is evident in the observations
- Correction for the Doppler shift due to Earth rotation has been included in the CrIS NASA L1b Version 3 product
- Correction for the full Doppler shift due to Earth rotation and satellite velocity is planned for the CrIS NASA L1b Version 4 product
- The contribution of the satellite velocity to the total Doppler shift of the observations is not negligible for a relatively small (1.1° - 1.5°) along-track view angle