

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

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## Introduction

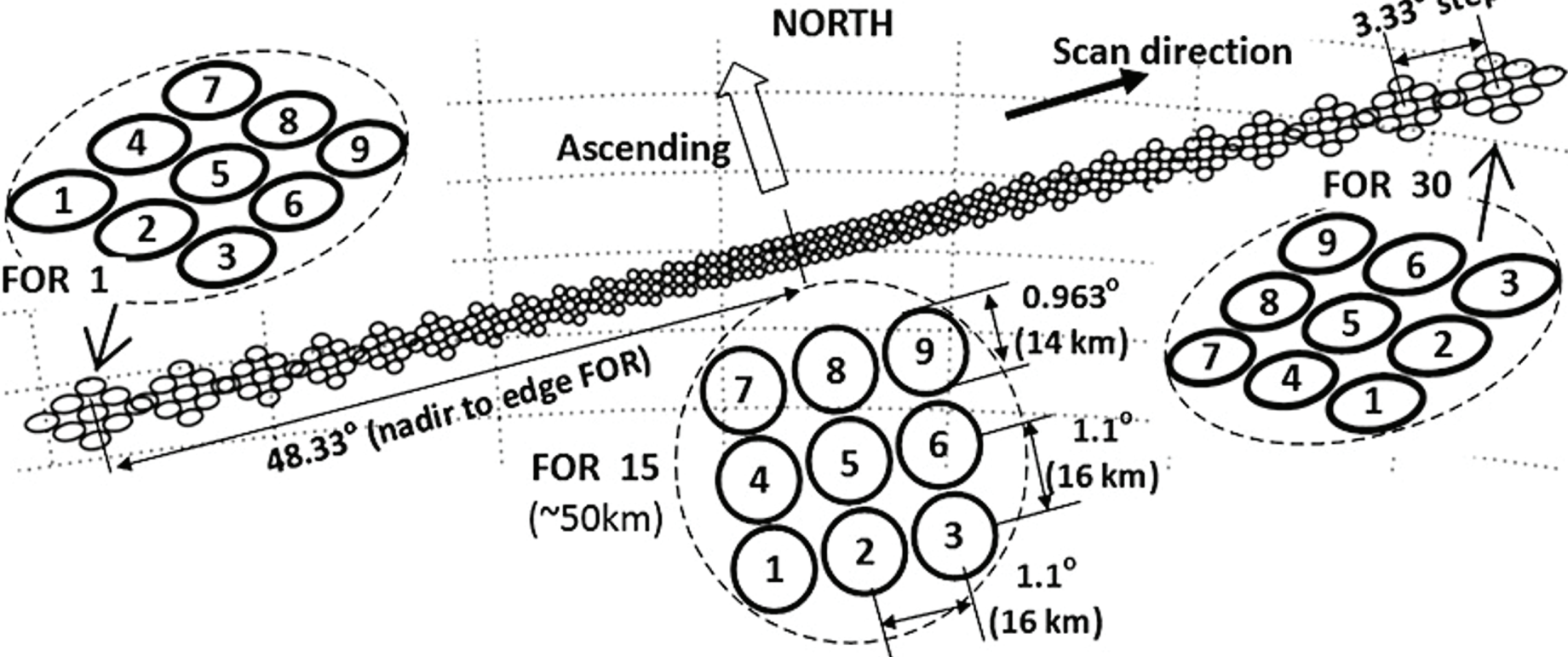

- Both the Earth velocity and Satellite velocity contribute to the relative velocity between the Earth observation and instrument
- The Doppler velocity is the dot product of the net velocity vector and the unit line of sight vector
- CrIS has a large cross-track swath (Max sat zenith angle near equator 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

## 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

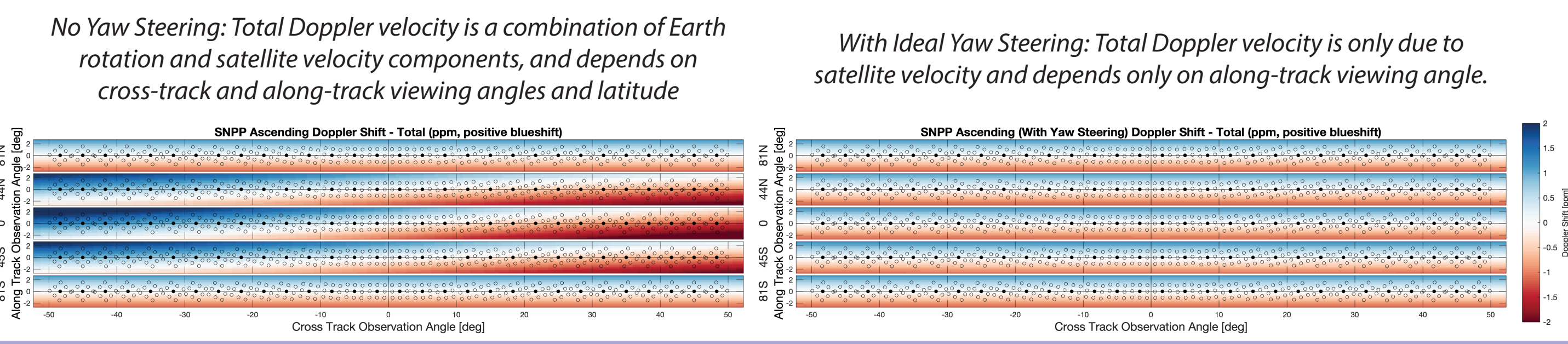
- Pupil Imaging System
- 3 spectral bands
- 3x3 FOVs per band
- 14 km footprint diameter at nadir
- PV MCT detectors



45° barrel-roll scene select mirror (SSM): CrIS field of regard (FOR) rotates with scan angle

### A Note on Yaw Steering

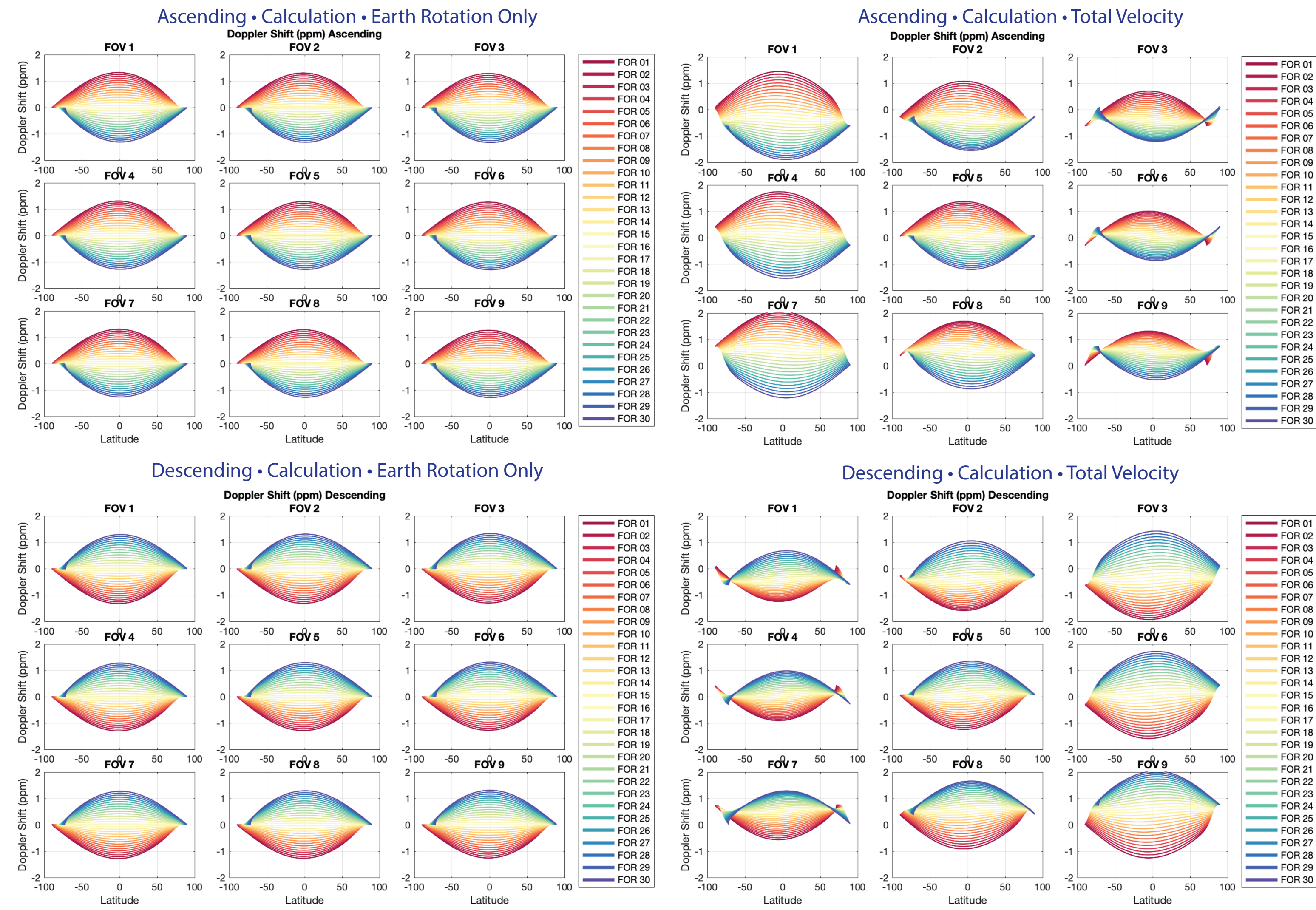
- It is possible to adjust the yaw angle ( $\zeta$ ) of the satellite, in order to mitigate Doppler shift on the measured radiances. This is referred to as “yaw steering”
- The yaw is smoothly varied over the orbit, such that the projection of the Earth velocity and the spacecraft velocity vectors in the **cross track plane sum to zero** (i.e. such that there is no relative velocity between Earth and satellite in **cross-track direction**). For the SNPP/JPSS/METOP orbits, the required yaw angle variation is  $-4^\circ < \zeta < 4^\circ$ .
- Yaw steering is not implemented on SNPP or the JPSS satellites, but is implemented on METOP**
- Yaw steering **does not** eliminate the Doppler shift for fields of view that have a non-zero along-track viewing angle



## 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);  $dopp_{\text{frac}} = (v_{\text{dopp}}/c) \cdot 1e6$



- 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

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

#### Doppler Shift due to Earth Rotation

- $\Omega \approx 7.292 \text{ rad/sec}$ ,  $R \approx 6378.137 \text{ km}$  @ equator, therefore  $v_E \approx 0.465 \text{ km/sec}$  @ 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

- $v_{\text{SAT}} \approx \sim 7.5 \text{ km/sec}$  (roughly 16x maximum Earth velocity)
- Maximum  $\sim 1.5^\circ$  along-track angle from nadir near edge of swath
- $7500 \text{ m/s} \cdot \cos(88.5^\circ) = \mathbf{196 \text{ m/s Doppler velocity}}$
- $196/397 = 49\%$  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

### 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]

$$\frac{\Delta v}{v} = \frac{\Omega R}{c} \sin(\theta_{\text{zenith}}) \cos(\lambda_{\text{lat}}) \sin(\phi_{\text{azimuth}})$$

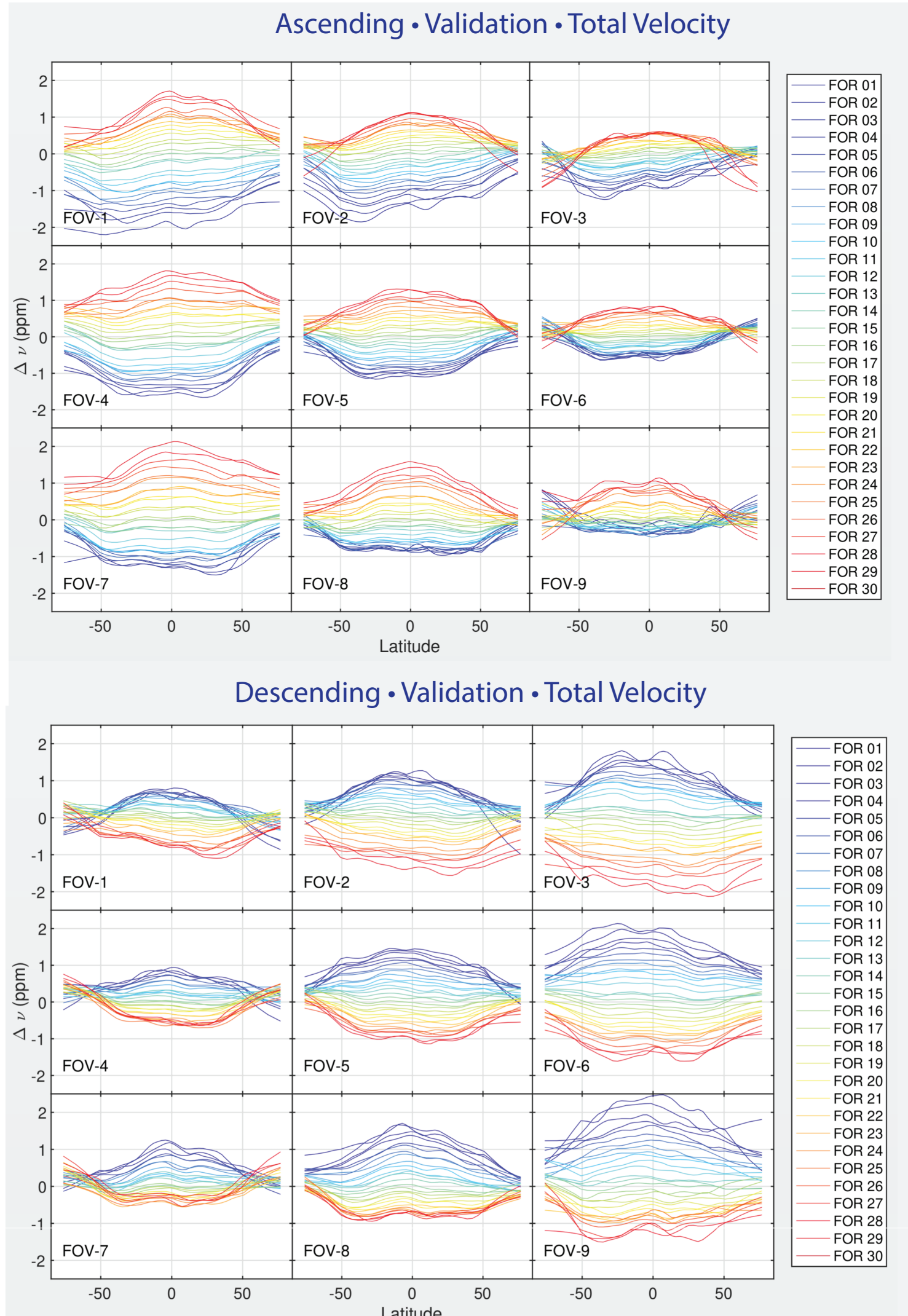
- Latitude dependent, largest effect near equator at large sat zenith angles
- $\Omega R$  is the Earth rotation velocity at the equator
- $\Omega R \cos(\lambda_{\text{lat}})$  is the Earth rotation velocity at given latitude
- $\sin(\theta_{\text{zenith}})$  and  $\sin(\phi_{\text{azimuth}})$  project the Earth velocity  $\Omega R \cos(\lambda_{\text{lat}})$  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  $\sim 1.1^\circ$  to  $\sim 1.5^\circ$
- Along-track component of FOV angle will be FOR dependent
- Not dependent on latitude
- FOV and FOR dependent

### 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 plots to the left are simply ordered by FOR (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.

### References

- 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  
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- L. Strow, "Correcting CrIS Doppler Shifts: Observations", CrIS SDR Team Telecon, 2019-10-23
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- 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