Lessons Learned and Initial Assessment of Small Satellite for Data Assimilation: Part I - TEMPEST-D

Ting-Chi Wu[1], Anton Kliewer[1], Milija Zupanski[1], Lewis D. Grasso[1], Wesley Berg[2], Richard Schulte[2], Heather Cronk[1], James Fluke[1], Philip Partain[1], Steven D. Miller[1], and Christian D. Kummerow[1,2]

1. Cooperative Institute for Research in the Atmosphere, Colorado State University, Fort Collins, Colorado
2. Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado
Corresponding author e-mail: ting-chi.wu@colostate.edu

1. Overall Goals

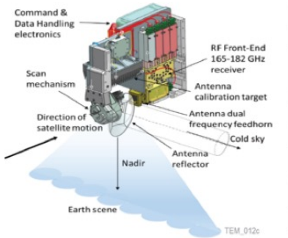
Explore quick and agile methodologies to entrain small-satellites that have limited lifetimes into the NOAA processing stream. Develop workflows that would allow NOAA, once it has identified an upcoming mission, to work with partners to ingest, calibrate, validate, and exploit these data in a minimum amount of time. The specific goals are the following:

- Assimilate TEMPEST-D radiances into FV3GFS and assess impact, focusing on regions and time periods of high uncertainty in FV3GFS that coincide with TEMPEST-D data
- Address, in coordination with JCSDA, the required flexibility and agility of the GSI system
- Address, in coordination with STAR, potential improvements in the O2R and R2O workflows and support systems

Please see poster by Anton Kliewer for Part II, which focuses on the ADM-Aeolus Lidar Wind

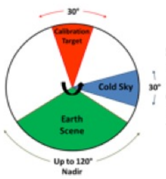
2. TEMPEST-D Technical Info and Cal/Val

Temporal **E**xperiment for **S**torms and **T**ropical Systems – **D**emonstration (TEMPEST-D)

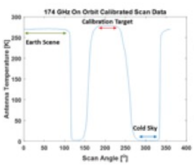


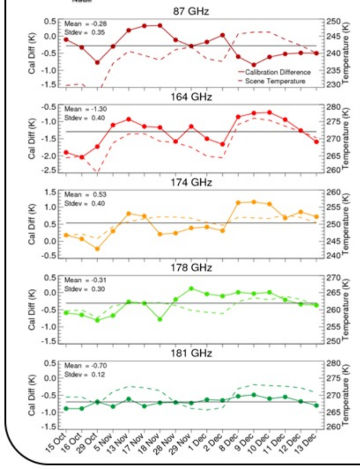
Specification	TEMPEST-D	MHS	ATMS
# of channels	5	5	22
Channel Freq. (GHz)	87, 164, 174, 178, 181	89, 157, 183±1, 183±3, 190	88, 166, 183±7, 183±3, 183±1
Mass	3.8 kg	63 kg	75 kg
Power	6.5 W	74 W	100 W
Altitude	400 km	820 km	820 km
Resolution at nadir	12.5 km (25 km@87 GHz)	15.9 km	15.8 km
NEΔT (K)	0.2, 0.3, 0.4, 0.4, 0.7	0.22, 0.34, 0.46, 0.40, 0.51	0.29, 0.46, 0.38, 0.54, 0.73
Integration Time	5 ms	18.5 ms	18 ms

Observing Profile



Time Series of Output Data





- Mass and power and cost of TEMPEST-D are a small fraction of that for the operational sensors.
- TEMPEST-D has a significantly shorter integration time indicating lower noise for equivalent samples.
- TEMPEST-D performs a two-point end-to-end calibration measuring cosmic microwave background ("cold sky") and ambient blackbody calibration target each revolution (30 RPM).
- Calibration requirements are 4 K absolute and 2 K precision.
- Results show variations in calibration differences by day based on composite results using all four reference sensors.
- The dashed lines indicate the mean scene temperature of the reference sensors, which varies based on the locations of the coincident observations. Correlation between the calibration differences and scene temperature suggest either potential temperature-dependent calibration errors or regional errors in the simulated Tb.
- Consistency over the ~2 month period of available data indicates a stable TEMPEST-D calibration, although uncertainties in the daily double difference estimates are large due to limited samples from coincident observations.

3. Data Quality Control (QC) and BUFR Format

The following tests are applied to consecutive satellite latitude and longitude as QC parameters:

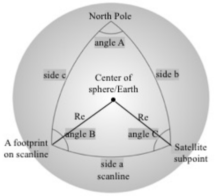
- Values of useTLE (indication of the healthiness of the satellite) must be 0
- Absolute values of the satellite orientation yaw, pitch, and roll must be less than 0.1 degrees
- Tempest-D altitudes must be finite
- Values of the satellite altitude must be continuous
- Values of the satellite zenith angle must be finite
- Pixel latitude and longitude must be finite
- Values of the scan angle must be finite
- Satellite latitude and longitudes must be finite numbers, and they were reported only when the scan angle was 0.0 (looking radially away from the Earth). Satellite latitude and longitude were computed as a linear interpolation between two consecutive reported sub-satellite positions.

Prepare TEMPEST-D data in BUFR format for GSI:

A BUFR file was created after the above QC filtering. The encoding program was written in Python using the py-ncepbufr package. The DX BUFR Table used for the encoding was modified from the DX Table found in the GDAS MHS and ATMS files.

4. Satellite Angles/Geometry for the CRTM

The Community Radiative Transfer Model (CRTM) is used by the NOAA operational GSI data assimilation system as the forward operator for the assimilation of the top-of-atmosphere (TOA) satellite radiance. In order to compute TOA radiance from the forecast model and compare with observations as part of the assimilation algorithm, the satellite zenith, satellite scan, and satellite azimuth angles are required by the CRTM. Although the satellite scan angle and satellite zenith angle are available in the original TEMPEST-D HDF5 file, satellite azimuth angle is not. As a result, the three angles were recomputed for a given pixel of TEMPEST-D using spherical trigonometry.

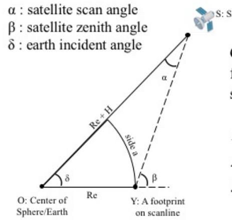


A spherical triangle is formed by the intersection of three great circles. Thus, *side_a* (scanline), *side_b* (co-latitude to satellite), and *side_c* (co-latitude to the footprint) are arcs of great circles in radians. In addition, *angle B* is the satellite bearing/azimuth angle where

$$angle\ B = \cos^{-1}\left[\frac{\cos(side\_b) - \cos(side\_c)\cdot\cos(side\_a)}{\sin(side\_c)\cdot\sin(side\_a)}\right]$$

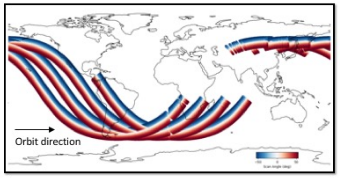
Knowing *side_b*, *side_c*, and *angle A*, *side_a* can be calculated as follows:

$$side\_a = \cos^{-1}(\cos(side\_b))\cdot\cos(side\_c) + \sin(side\_b)\cdot\sin(side\_c)\cdot\cos(angle\ A)$$



Given $\overline{OS}$=Re+H, $\overline{OY}$=Re, and *side_a* (hence δ), use the following three equations to find satellite scan angle (α) and satellite zenith angle (β):

1. $\overline{SY}^2 = \overline{OS}^2 + \overline{OY}^2 - 2\cdot\overline{OS}\cdot\overline{OY}\cos\delta$
2. $\frac{\sin\alpha}{\overline{OY}} = \frac{\sin\delta}{\overline{SY}} \Rightarrow \alpha = \sin^{-1}[\frac{\overline{OY}}{\overline{SY}}\cdot\sin\delta]$
3. $\beta = \alpha + \delta$

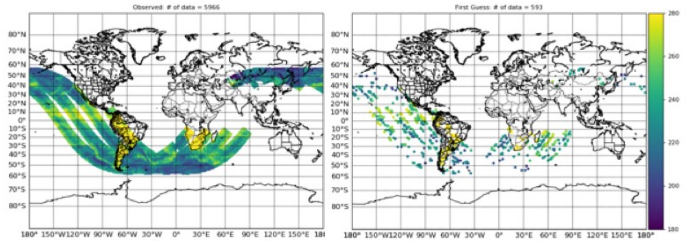


An example of the computed scan angle from four TEMPEST-D orbits between 0300 UTC and 0900 UTC of December 8, 2018. Along each orbit, scan angle on the forward left side is negative, while scan angle on the forward right is positive. The computed scan angles varies between approximately -55 degrees and + 55 degrees, which is close to the scan angle from the original TEMPEST-D HDF5 file.

5. Initial Assimilation using GSI with FV3GFS

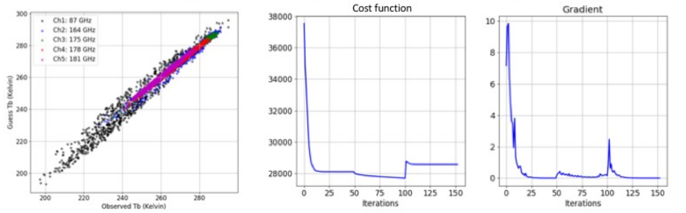
As an initial attempt to assimilate TEMPEST-D radiances into FV3GFS using GSI, the following procedures are considered:

- Use the MHS QC procedure in GSI to identify and remove cloudy pixels of TEMPEST-D from being assimilated (clear-sky radiance assimilation)
- Apply mass bias correction but no angle dependent bias correction (GSI uses a linear function to calculate scan angle, while the scan angle is provided by TEMPEST-D)
- 145 km thinning is used to be consistent with other satellite instruments assimilated in FV3GFS



An example of TEMPEST-D Channel 1 (87 GHz) brightness temperature assimilated into FV3GFS (resolution C768) with GSI for the 0600 UTC 8 December 2018 cycle:

- 50 % of the data were discarded because they were detected as cloudy pixels
- 17 % of the data were thrown away due to gross error check (i.e. observed minus guess brightness temperature exceeds 3 times the assigned error, which is 2.5 K)
- 22 % of the data were rejected because they did not pass inter-channel QC



The GSI-FV3GFS first-guess brightness temperatures appear to match observed TEMPEST-D brightness temperature for all channels, except for the 87 GHz. This is due to an error in the polarization of the CRTM coefficient files that we have recently identified, but not yet corrected. The global cost function and gradient shows that the GSI-FV3GFS system is performing well with the assimilation of TEMPEST-D data.

6. Key Lessons Learned and Future Work

- Small satellites may not have the level of data availability required for long-term assimilation (e.g. because of downlink issues, competing scientific priorities, or satellite design), which is essential to appropriately address bias that usually requires seasonal to annual assessment.
- Small satellite data products often do not natively contain all data fields required for data assimilation experiments and fields will need to be generated from the data that is available.
- Because small satellite missions do not have engineering and Cal/Val teams scrutinizing the data, the required quality control for data assimilation experiments must be discovered and applied through trial and error or connections to the instrument teams.
- Small satellite data will be provided in a variety of data formats, each of which will need to be uniquely converted to BUFR files for assimilation into GSI prior to running experiments.

➢ Incorporate the TEMPEST-D TPW retrieval algorithm to the QC procedure.
➢ Extend current work to all-sky radiance assimilation of TEMPEST-D.

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