12 May 2021

MEMORANDUM FOR: Sounder Project Leads
LEO / JPSS Program Leads
Michael J. Scott, NASA
Jose Davis, NOAA/NASA
David Spencer, NOAA/NESDIS/OSAAP/Chief Technologist

FROM: Sid Boukabara, SAT chair, NESDIS, STAR BOUKABARA.SID.AHMED.1369422622 Digitally signed by BOUKABARA.SID.AHMED.1369422622 Date: 2021.05.12 11:27:20 -04'00'
Frank Gallagher, SAT co-chair, NESDIS, OSAAP GALLAGHER.FRANK.WOOLSEY.1264444663 Digitally signed by GALLAGHER.FRANK.WOOLSEY.1264444663 Date: 2021.05.12 11:38:46 -04'00'

SUBJECT: **Assessing Sounder Calibration Needs in the era of Smallsats/Cubesats**

Scope: This memo provides a deeper understanding of the temperature and moisture sounding instrument calibration needs, especially in the context of manifesting those instruments on smallsats and cubesats. It also explores what is critical versus what is less important in terms of calibration, intercalibration, anchoring satellite observations, and correcting for systematic and/or random errors, etc., in order to ensure high quality observations necessary to meet NOAA and NESDIS mission requirements. It also provides NESDIS with specific performance- and science-based recommendations regarding how to best address the calibration of a potential future smallsats sounding constellation. These recommendations are formulated by a set of core-SAT members (all Federal employees) based on SME expertise, fact-finding exercises, and previous projects' results. Contributions came from members or special invitees of the SAT, from within and outside of NOAA, and with participation from NESDIS data users, in particular, the NWS. This assessment is specific to infrared (IR) and microwave (MW) sounders.

Executive Summary:

- ***Fact:*** Intrinsic calibration of sensors is critically important. It cannot be replaced by NWP's VarBC or other statistical methods such as double differencing or intercalibration of sensors using anchor or reference satellites. This is due to the complexity and multidimensionality of the calibration process.
- ***Fact:*** NWP systems homogenize observing systems as part of the data assimilation process, assuming there are anchoring systems such as GNSS-RO sensors for temperature and radiosondes for temperature, moisture, and wind fields.
- ***Fact:*** Intercalibration of sensors' data (to a reference sensor) is not necessary for NWP and for physical retrievals, but is important and widely used for climate and some nowcasting applications.

- ***Recommend:*** NOAA to put effort in having accurate onboard calibration and robust designs for MW and IR sensors, as opposed to relying on either ground processing systems such as VarBC or on anchor/reference satellites.
- ***Recommend:*** NOAA to set up a joint group of SMEs (sensors engineers, remote sensing scientists, and NWP users) to propose a set of optimal sensor specifications requirements (spectral selections, noise, resolution, swath, temporal refresh, etc.) that leverage new technology and meets or exceeds NOAA requirements in the most cost-effective way.
- ***Recommend:*** NOAA pursue studying the feasibility to have a Government-central microwave calibration facility to ensure smallsats/cubesats pre-flight calibration assessment and characterization. Pre-flight calibration characterization is key for optimal exploitation of satellite data post-launch. This will also benefit any intercalibration for climate applications.
- ***Recommend:*** NOAA to initiate the exploitation of existing or upcoming smallsat data sets early (i.e. now) to build experience and to learn lessons on smallsat calibration while building readiness for the Sounder project.
- ***Recommend:*** NOAA undertake a targeted data denial experiment (OSE) to assess the value of calibration to NWP

Background:

Intrinsic, sensor calibration is essential for maintaining stability and quality assurance of Earth observations. It ensures that the measurements obtained are truly reflecting the Earth's geophysical characteristics being measured, and are not influenced by sensors' mis-characterized properties (antenna emissivity, gain, waveguide transmission factors, etc.), or other calibration issues. Accurate sensor calibration is critical for many NOAA applications including Numerical Weather Prediction (NWP) and climate monitoring. As part of the instrument calibration process, there are several pre-flight, onboard, and post-launch sensor characterization activities. The calibration process includes analyzing cold space views and well characterized warm targets, quantifying solar/lunar intrusions, and developing antenna pattern correction for side lobe errors. On-orbit inter-comparison corrections depend on the existence of a reference (occasionally called an "anchor") sensor to calibrate to. Other instrument inter-comparisons depend on double-differencing with an intermediate independent data set (such as model analysis fields). Scientists have developed over the years an NWP-specific system to bias correct environmental data, including satellite radiance data. This system, the Variational Bias Correction scheme (VarBC), is effective in reducing or eliminating some radiance biases associated with calibration or sensor design issues. For the purpose of NOAA's consideration of flying a constellation of sounding smallsats/cubesats, it is necessary for the SAT to provide sound recommendations on what should be considered important in terms of sensor characterization and calibration and what part of the overall calibration scheme should be left to be addressed by VarBC and other ground-based bias/calibration correction techniques. NOAA needs to be well informed on what we should be focusing on for the smallsat calibration when designing the sensors and the constellations. For example, we need to understand the answers to several questions: would onboard cold/hot calibration be sufficient to meet the calibration needs of NWP and climate monitoring? Do we need a high-performing anchor satellite to use as an observation reference? What type of calibration or sensor design issues are the most critical from an instrument perspective (for example linear/non-linear, solar contamination, and antenna emission effects) and which ones will be easily handled by VarBC and therefore does not require we invest significant resources to address or mitigate those observation errors?

Findings:

The need for robust and reliable instrument calibration: Proper NWP utilization of sensor observations as well as verification of compliance with meeting the Level-1 data requirements, depends on accurate and precise radiometric, spectral, and geolocation characterizations. A reliable calibration is tied to comprehensive on-orbit and pre-launch sensor characterization and testing. This helps to apply the corrections to reduce the effects problems such as orbital thermal and gain variations. Calibrated data increases reliability, maintainability, and repeatability of the data and allows NOAA to rapidly transition recently launched instruments to operations and for long-term monitoring and trending. VarBC is used to make measurements (in a data assimilation system) more uniform and globally consistent. VarBC corrections are a necessary step prior to using radiance observations in NWP. VarBC requires a representative and large amount of data to estimate bias correction and their dependence on predictors. VarBC does not correct for random errors in the sensor observations (noise). There are instances where VarBC does not work as well such as correcting for random instrument errors, regions with limited conventional observations, frequency shifts, non-linearity, and stray light effects. Table 1 shows a list of identified effects in microwave and infrared sensors handled by calibration. We include an assessment of whether these effects can be handled by VarBC or other ground processing statistical methods. Having stable, accurate observations benefits the assimilation process, increases the impact of the assimilated observations, and could help to anchor the data assimilation system. This is particularly important where observations are sparse and systematic model errors are large. Under this condition, a high probability exists of model biases negatively affecting observation bias during VarBC.

Types of Calibration important for MW and IR sensors:
There are many types of instrument and calibration issues, some are more easily correctable with data processing than others. But many require thorough knowledge of the instruments' characteristics. Consider some of the following important instrument characteristics:

- Solar intrusion (intermittent, localized in space and time) is an example of an instrument issue that is not easily correctable by VarBC or any other statistical or intercalibration-based methods
- Passband shapes (SRF) stability is critically important for a proper exploitation of the data. Instability of the SRF makes the exploitation of the data difficult.
- Geolocation calibration errors are essential to correct, especially for high resolution NWP.

The following table summarizes the different types of instrument and calibration issues important to temperature and moisture sounding. Included in the table are the impact on the observations and whether these could be corrected by VarBC and/or other ground processing techniques.

Instrument Calibration Issues	Impact on Measurement	Can it be corrected with VarBC?	Can it be calibrated on ground (or On-orbit: SNO, 3-way calibration, etc)?
Nonlinearity	Radiometric bias	No	**1:** Requires full on-ground/on-orbit sensor characterization as well as a robust sensor design to meet mission requirements. **2:** Benefits from frequent Intercomparisons and Intercalibrations.
Spectral errors (including Doppler shift effect)	Spectral and Radiometric bias	No	"1, 2"
Instrument reflector and antenna pattern effects	Radiometric bias	No	"1, 2"
Along-scan angle effects	Radiometric bias	Calibration should reduce this effect to reduce VarBC dependency/VarBC predictors at NCEP	"1, 2"
Orbital variation effects	Radiometric bias	Not Recommended to rely on VarBC to correct for fast and large orbital variation effects/VarBC predictors at NCEP	"1, 2"
Channel-to-Channel differences (due to detector differences in gratings spectrometers), FOV to FOV differences (in Fourier Transform Spectrometers)	Radiometric bias	Unfeasible for sensors with large number of detectors (like AIRS with > 2000 detectors/channels). Adds complexity (CrIS has 9 FOV/Band)	"1, 2"
Geolocation errors	Geometric and Radiometric bias	No	"1, 2"

Table 1. Calibration Assessment of MW and IR Sensors

Specific Questions Asked:

A number of specific questions, important for understanding the calibration needs, were asked to the SAT general audience. Some of these are summarized in the table below, along with an attempt to compile the answers.

	Questions	Answers
1	What calibration errors are covered by VarBC in NWP that should not be a concern for smallsats?	Small errors that vary with atmospheric scene parameters (such as angles), or change very slowly (CO_2 bias), and for which the VarBC has already appropriate predictors. Note: Impact of orbital drift on climate monitoring is however important (sampling of different time in the diurnal cycle).
2	What types of calibration errors are uncorrectable by VarBC and require sensor calibration?	Many, including: radiometric model non-linearity, frequency shifts, shifts that vary over < 2-3 weeks, Microwave antenna emission, stray light correction.
3	Do we need an on-orbit reference sensor to achieve acceptable calibration for smallsats/cubesats or is hot/cold reference type of calibration sufficient for	Although it does not hurt, a reference sensor is likely not needed for NWP as long as we have enough

	smallsats/cubesats (if possible)?	GNSS-RO measurements anchoring the atmospheric temperature and radiosondes anchoring atmospheric temperature, water vapor, and wind. Efforts should be made to have high quality instrument calibration for all flight instruments.
4	Importance of Anchor/Reference: Seems more important to cover Temp (through a RO sensor or radiosonde?), Wind (through sondes or wind lidar?) and moisture/precip. (?), rather than having a sensor reference in MW, IR, when it comes to NWP. Comments?	We should let NWP do the anchoring, these systems have the capability to integrate many sensors in an optimum way and to assimilate "anchoring" observing systems such as GNSS-RO for Temperature and radiosondes for T, q, and wind, which benefits all observing systems.

Relevance of NWP's VarBC for correcting Instrument calibration issues:

Some of the important points to keep in mind when considering VarBC as a way to correct observations are listed below. These show that VarBC has some strengths and weaknesses for the purpose of correcting satellite data.

- *Limitations of VarBC:*
    - Intertwined with QC process.
    - VarBC is model dependent and could correct for forward operator, model errors, as well as observations. Could be a sink for forward operator and model errors.
    - Limited number of predictors limits the applicability of VarBC for some types of corrections in the observations.
    - VarBC could lead, in some cases, to an unphysical space, especially when we do not have anchor observations (for example to major radiometric differences between SNPP and NOAA-20 ATMS that do not exist). This is true whether or not data intercalibration is done.
    - Requires large datasets to be fine-tuned (requires additional processing time, which is critical for short lifetime sensors).
    - Does not handle high frequency (short-term stability) and magnitude variation of calibration errors.
- *Strengths of VarBC*
    - Good for calibration errors due to phenomena with slow moving (long-term stability), linear impact features, as long as the appropriate predictor is accounted for in VarBC,
    - The spatial drift of sensors (e.g., orbit location) has no impact on NWP because of VarBC is sufficient to address these types of errors
    - VarBC is primarily for correcting biases. It is not good for correcting for noise errors, which are more difficult to reduce and are dependent on sensor characteristics.
    - VarBC homogenizes observations and combines sensors with anchoring observing systems such as GNSS-RO and radiosondes.

It is worth noting that NWP centers, through VarBC, can handle a number of calibration issues such as those that are linear, slow-moving, and have a known source codified in the predictor. In addition, it would benefit VarBCby having as many 'instrument' calibration issues corrected as possible in order to reduce time spent on the data calibration.
Observing systems add value to NWP by (1) increased accuracy/precision of sensors, (2) new observations that are not yet in the system (such as Aeolus), and (3) complementarity of time and space. An example was given by ECMWF on the complementarity of the Russian Hyperspectral IR sensor in the ECMWF system. Despite the fact that the accuracy of this sensor is not as good as CrIS, by having this sensor in a complementary orbit (1530 orbit), it still added value to the overall forecast.

Items to keep in mind related to Sensors Intercalibration and Anchor/Reference sensors:

- VarBC and data assimilation in NWP achieve the homogenization of radiances/observations as part of the data assimilation process. Intercalibration of sensors using statistical corrections is then not necessary.
- Intercalibration of different sensor data could introduce correlation errors in the observations, which would be detrimental in NWP data assimilation.
- Intercalibration is a multidimensional problem, which should account for bias as a function of scan angle, scene temperature, solar zenith angle, frequency, bandwidth, etc. which is difficult to achieve within a short-period of time.

- On-orbit intercalibration requires a significant number of coincident observations, very large datasets, which take a long time to collect. This adds complexity and delays and is hard to do in a reasonable time with instruments on different platforms having short individual lifetimes. This limits the practicality of an on-orbit calibration reference instrument for use with smallsats and cubesats.

- The general preference is to have a fleet of sounders that can provide high-quality, calibrated measurements. However, if a decision is made to consider flying a reference satellite (for climate applications for example), we suggest that the reference be long lived.

- It is important for NWP to have anchor sensors, but these anchor sensors are useful for specific geophysical information. For example, GNSS-RO data serves as the independent anchor for temperature (generally in the vertical layer band between 10-35 km). Radiosondes serve as the independent anchor for temperature, moisture, and wind. We do not necessarily need anchors associated with every type of sensor.

- Deploying a dedicated on-orbit calibration reference would be expensive, and it will likely not provide the broad spatial and spectral coverage needed to quickly calibrate new sensors with short lifetimes.

Summary of Facts and Recommendations by core-SAT:

Facts:

- Intrinsic calibration of sensors is critically important. It cannot be replaced by NWP's VarBC or other statistical methods such as double differencing or intercalibration of sensors using anchor or reference satellites.
- The sensor calibration should primarily rely on highly stable observations (e.g., views of deep (cold) space and/or stable internal (warm) calibration targets). An on-orbit calibration reference could potentially complement the calibration of sensors, but at likely a large expense
- NWP systems homogenize observing systems as part of the data assimilation, assuming there are anchoring systems such as GNSS-RO sensors for temperature and radiosondes for temperature, moisture, and wind.
- Intercalibration of sensors' data (to a reference sensor) is not necessary for NWP and for physical retrievals but is important and widely used for climate and some nowcasting applications.
- Comprehensive on-orbit and pre-launch characterization/testing with high standards should be performed and is needed.
- Mature calibration methodologies facilitate the calibration of multiple sensors and to minimize the complexity and delays of commissioning multiple satellites over relatively short times.
- VarBC requires a representative and large amount of data to estimate the bias correction. It is not recommended to rely on VarBC to handle sensor calibration errors (e.g., nonlinearity, spectral shifts, etc.).
- Minimizing geolocation errors is highly important for NWP, particularly over heterogeneous regions. If these sensors on smallsats aim at higher spatial resolution than the current instruments, accurate geolocation will be even more critical.
- Low inter-channel and spatial correlations are required in sounders to improve the assimilation performance and achieve positive impact of the assimilated observations.
- Sensors with low, random, and uncorrelated noise characteristics are required to accelerate the assimilation of IR and MW sounder observations on smallsats/cubesats.
- Pre-flight characterization of calibration parameters is very important to allow post-launch exploitation of the data.
- A large constellation of IR and MW sounders on smallsats/cubesats could be useful for improved regional weather forecasting due to increased temporal refresh.
- A demonstration mission can mitigate mission risks in the calibration and assimilation process, and reduce the time required to use the data.
- The assimilation of new observations is shortened if observations from a similar sensor(s) have been assimilated before due to less extensive acceptance tests to demonstrate the assimilation performance.

The SAT makes the following recommendations:

- ***Recommend:*** NOAA/NESDIS to dedicate considerable effort to having accurate onboard calibration for MW and IR sensors.
- ***Recommend:*** NOAA pursue the possibility to have a Government-central microwave calibration facility to ensure smallsats/cubesats pre-flight calibration assessment and characteristization. Pre-flight calibration characterization is key for optimal post-launch exploitation of satellite data.

- ***Recommend:*** NOAA to initiate the exploitation of data from existing or upcoming smallsat data sets early (i.e. now) to build experience and to learn lessons on smallsats calibration while building readiness for the Sounder project (NESDIS/NWS).
- ***Recommend:*** NOAA to set up a group of SMEs (sensor engineers, remote sensing SMEs, and NWP users) to establish a set of optimal sensor specifications requirements (noise, resolution, swath, temporal refresh, etc.) and Level-1 data requirements (precision, accuracy, stability, uncertainty, etc.). This should be for both the Program of record (POR) continuity component and additional measurement capabilities of the observing system.
- ***Recommend:*** NOAA undertake a targeted data denial experiment (OSE) to quantify the value of calibration in NWP
- ***Recommend:*** To include NCEP and other NWP centers users in the sensor's calibration and requirements discussion. The experience and feedback from the operational NWP environment are critical to enrich the discussion.