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# THE IMPORTANCE OF NUMERICAL WEATHER PREDICTION AND DATA ASSIMILATION SYSTEMS IN THE CALIBRATION AND VALIDATION OF CURRENT AND FUTURE SATELLITE SENSOR MEASUREMENTS SENSITIVE TO ATMOSPHERIC TEMPERATURE AND HUMIDITY

*Steve Swadley[1*], **Nancy Baker[1]**, Gene Poe[1], Ben Ruston[1] and William Bell[2]*

*[1]Naval Research Laboratory (NRL), Monterey, CA, USA*
*[2]European Centre for Medium Range Forecasting (ECMWF), Reading, UK*

## *1. INTRODUCTION*

Most operational Numerical Weather Prediction (NWP) centers have the capability to assimilate satellite radiance data directly using variational Data Assimilation Systems (DAS). The direct radiance assimilation method has led to significant improvements in forecast skill, with the NOAA AMSU-A instrument being the pathfinder in the radiance assimilation efforts. Necessary components of the direct assimilation method are the routine monitoring of (1) the departures from the observed radiances (OB) and those computed using radiative transfer and a short term forecast from the NWP model, termed the background (BK), and (2) bias correction scheme. For temperature sounding radiances, the measurement uncertainty requirements for forecast skill improvement are very demanding. Uncertainties of the bias corrected departures must be of the order 0.25 K or less in order to improve the analysis and skill of the subsequent NWP forecast (Bell, 2008). This uncertainty requirement is often at or below the sensor calibration error and noise levels, so that the routine monitoring of the patterns of the global departures can often detect problems with sensor data such as increased channel noise, channel failures, calibration drift, field of view intrusion and other calibration anomalies.

## *2. THE CAL/VAL PROCESS*

The purpose of the Calibration and Validation (Cal/Val) efforts is to verify the end-to-end instrument radiometric performance including the long- and short-term stability, the noise equivalent delta temperature (NEDT) or count (NEDN), and the absolute calibration accuracy. The calibration and validation of the sensor data records (SDRs) typically includes: early orbit evaluation, initial assessments, system calibration, and anomaly detection. The validation of the environmental data records (EDRs), or derived products, includes the detection of systematic biases, characterization of the errors and recommendation for algorithm improvements.

* *Corresponding Author Address:* Steve Swadley, Naval Research Laboratory, Monterey, CA 93943-5502; steve.swadley@nrlmry.navy.mil

Historically, the Cal/Val process has relied heavily on the collection of correlative geophysical measurements, such as radiosondes, buoy reports, aircraft observations and other routinely collected global measurements. Special observational campaigns such as dedicated radiosonde and dropsonde observations coincident with the satellite overpass times, Lidar observation campaigns, aircraft under flight campaigns equipped with specialized sensors such as interferometers or radiometers with frequencies similar to the satellite sensor, or sensors measuring quantities related to the EDR products have all shown to be of great value to the Cal/Val process (Kunkee, 2008, Swadley, 2008a). The Simultaneous Nadir Overpass (SNO) methodology of matching collocated radiance measurements in the polar regions has also shown to be a valuable tool for cross-calibrating satellites with sensor measuring similar frequencies (Wang, 2007). The drawbacks with the above methods are the limited temporal and spatial coverage.

## *3. THE DATA ASSIMILATION PROCESS*

Modern 3- and 4-dimensional variational DAS combine a relatively accurate short range NWP model forecast with a variety of temporally matched observation, and produce an analysis consistent with the mass/wind balances observed in nature. The model background, or state vector, is mapped into the observation space using a forward operator, and the departure is the new information or innovation to adjust the background. In the case of satellite radiances, the forward operator is provided by a fast radiative transfer model. Experience has shown that the raw radiance departures must be bias corrected in order for the radiance innovations to have a positive affect on the analysis and subsequent NWP forecasts. The mean raw radiance departures, or systematic biases can arise from radiative transfer errors, sensor biases, model bias, the radiance preprocessing steps, and quality control procedures (Auligne, 2007). The raw radiance departures are defined as:

$$\mathbf{y} - H(\mathbf{x}) \tag{1}$$

where $\mathbf{y}$ is the observation vector, $\mathbf{x_b}$ is the NWP model background state vector, and $H(\mathbf{x})$ is the observation operator. Bias corrections can be done in either a static offline manner (StaticBC) or within the minimization step taking advantage of all the available (VarBC) and updated each analysis cycle.

The Static BC formulation can be expressed as follows:

$$\begin{aligned}\tilde{H}(\mathbf{x},\boldsymbol{\beta}) &= H(\mathbf{x}) + b_{Scan} + b_{AirMass} \\ &= H(\mathbf{x}) + b_{Scan} + \beta_0 + \sum_{i=1}^{N} \beta_i p_i(\mathbf{x})\end{aligned} \quad (2)$$

where $b_{Scan}$ is the channel and position dependent offset, $b_{AirMass}$ is the air mass dependent bias, and $\beta_i$ is the coefficient for a given predictor, $p_i$. NRL uses the 850-300 hPa and 200-50 hPa thicknesses as predictors. For the SSMIS an ascending/descending flag, with values of 1.0 for ascending and -1.0 for descending is an additional predictor.

The coefficients for the Static BC are found by minimizing the following cost function:

$$\begin{aligned}\mathbf{J}(\boldsymbol{\beta}) = &\frac{1}{2}\left[\mathbf{y} - \tilde{H}(\mathbf{x_b},\boldsymbol{\beta})\right]^T \mathbf{R}^{-1}\left[\mathbf{y} - \tilde{H}(\mathbf{x_b},\boldsymbol{\beta})\right] \\ &+ \frac{1}{2}\left(\boldsymbol{\beta} - \boldsymbol{\beta}_\mathbf{b}\right)^T \mathbf{B}_{\boldsymbol{\beta}}^{-1}\left(\boldsymbol{\beta} - \boldsymbol{\beta}_\mathbf{b}\right)\end{aligned} \quad (3)$$

where $\mathbf{x_b}$ and $\boldsymbol{\beta}_\mathbf{b}$ are from the background.

A variant of the VarBC method is being tested at NRL for use in NAVDAS-AR 4DVAR system (Xu, 2008). The VarBC formulation results in the minimization of the following cost function:

$$\begin{aligned}\mathbf{J}(\mathbf{x},\boldsymbol{\beta}) = &\tfrac{1}{2}\left[(\mathbf{x_b} - \mathbf{x})^T \mathbf{B}^{-1}(\mathbf{x_b} - \mathbf{x})\right] + \\ &\tfrac{1}{2}\left[(\boldsymbol{\beta}_\mathbf{b} - \boldsymbol{\beta})^T \mathbf{B}_{\boldsymbol{\beta}}^{-1}(\boldsymbol{\beta}_\mathbf{b} - \boldsymbol{\beta})\right] + \\ &\tfrac{1}{2}\left[\mathbf{y} - \tilde{H}(\mathbf{x},\boldsymbol{\beta})\right]^T \mathbf{R}^{-1}\left[\mathbf{y} - \tilde{H}(\mathbf{x},\boldsymbol{\beta})\right]\end{aligned} \quad (4)$$

where $\mathbf{B}$ and $\mathbf{R}$ are the model background and observational error covariance matrices, respectively. The NRL Static BC scheme updates coefficients after each analysis cycle, while for VarBC, the coefficients are updated within the analysis step.

### 4. RADIANCE MONITORING TOOLS

NRL and other NWP centers performing radiance assimilation have developed numerous graphical radiance monitoring tools to assess the status of sensor radiances, raw and bias corrected departures, the bias corrections and coefficients, and the assimilated/rejected observation counts by sensor and channel both assimilated and rejected. Passive monitoring of a sensor or select channels is also possible, and proves to be a valuable tool to characterize channel error statistic, systematic biases, calibration biases and uncertainties, bias corrections, and other parameters, all of which is required information before undergoing radiance assimilation trials. Both spatial and temporal aspects of the above parameters are also examined. Figure 1 shows the typical spatial distribution of both raw and bias corrected departures for AMSU-A channel 6 from NOAA-15, 16, and 18 for a 6-hour analysis window. Additional examples of routinely produced radiance monitoring graphical tools are shown in Figures 2-5.

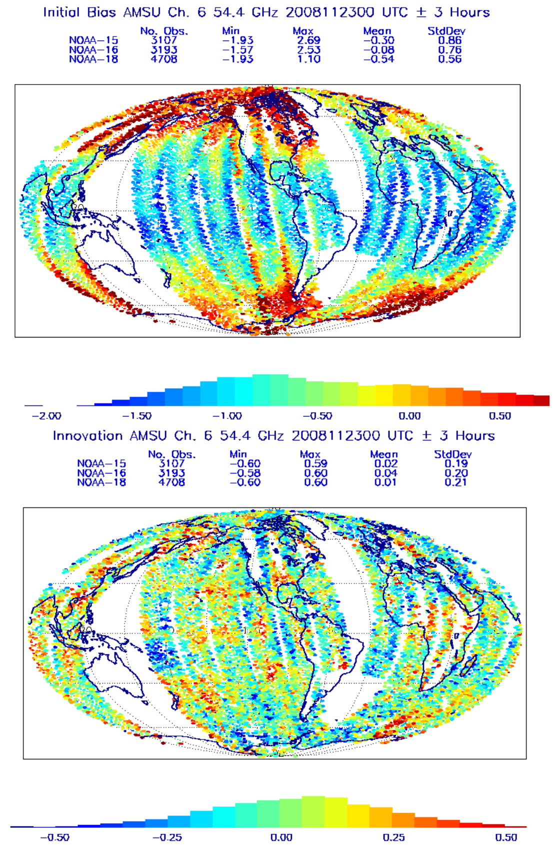



Figure 1. Raw (uncorrected) and bias-corrected departures for AMSU-A Channel 6 (54.4 GHz) from NOAA-15, 17 and 18

### 5. THE SSMIS CAL/VAL EXPERIENCE

The first SSMIS was launched aboard the F-16 spacecraft from Vandenberg Air Force Base (VAFB), CA, on 18 October 2004 using the last in the series of Titan II launch vehicles. The F-16 was place in a circular sun-synchronous near-polar orbit at a mean altitude near 850 km, orbital inclination of 98.9°, and a local time of the ascending node (LTAN) of 19:54.The second SSMIS was launched from VAFB on 4 November 2006 aboard the F-17 spacecraft utilizing a Delta IV rocket, and placed into a circular sun-synchronous near-polar orbit at a mean altitude near 850 km, orbital inclination of 98.9°, and a local time of the ascending node (LTAN) of 17:30, i.e. the terminator orbit.

After the launch of the F-16 a comprehensive Calibration and Validation (Cal/Val) program was performed to evaluate the sensor performance and noise characteristics, geolocation accuracy, and validate the retrieved products (Kunkee, 2008). The analysis of the OB-BK departure patterns proved to be of vital importance in detecting and understanding the physical mechanisms responsible for the observed departures and their relationship to the calibration anomalies (Swadley, 2008b). The European Centre for Medium Range Weather Forecasts (ECMWF) provided global analyses from the surface to 0.01 hPa to the SSMIS Cal/Val team.

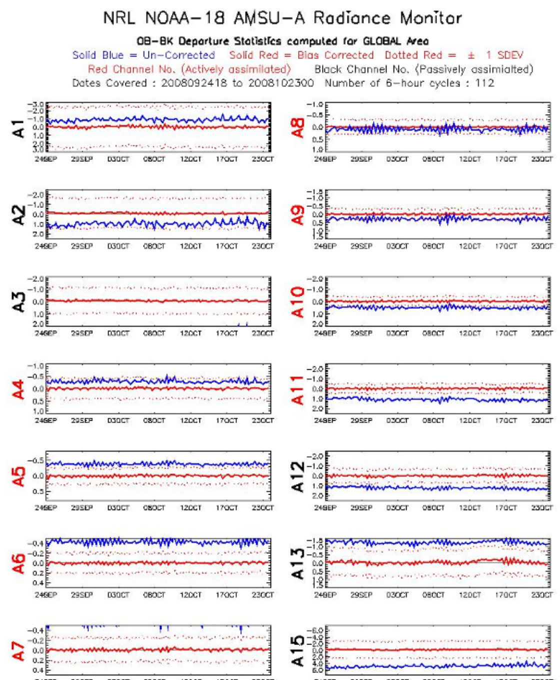



Figure 2. NOAA-18 AMSU-A "Radgram" depicting 30 day time series of global mean raw and bias corrected departures and standard deviation

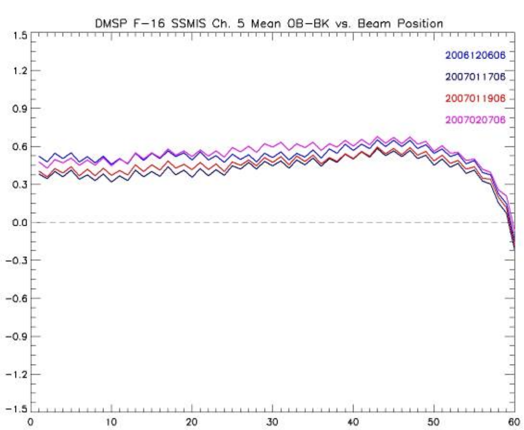



Figure 3. Scan bias plots for DMSP F-16 SSMIS channel 5 for 4 select dates depicting pattern is stable in time.

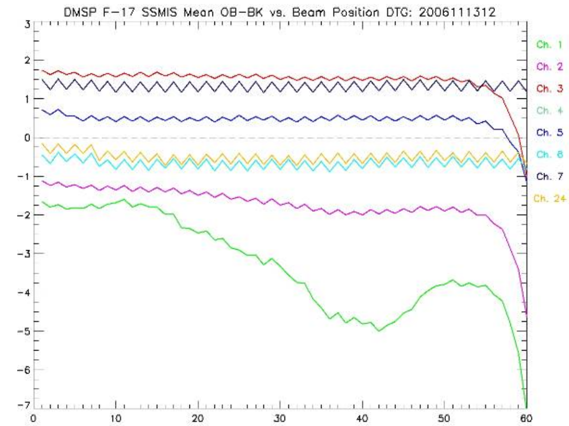
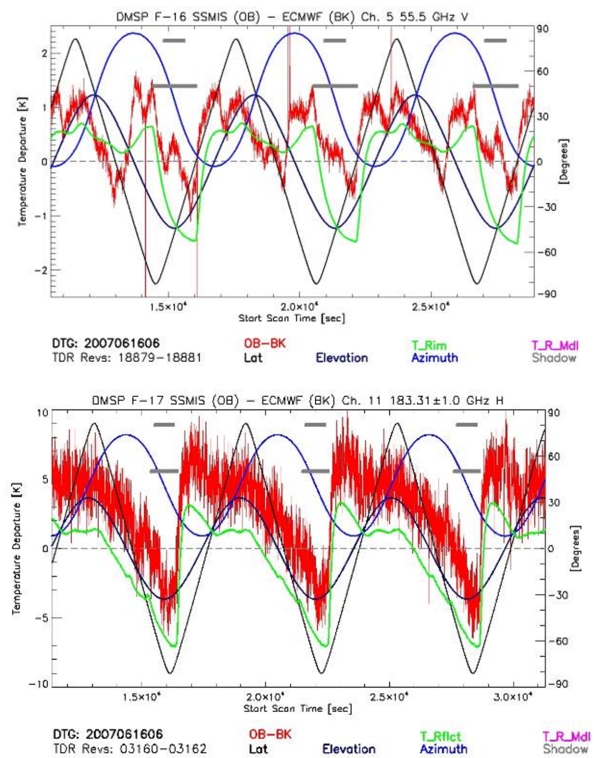



Figure 4. Scan bias plots for DMSP F-16 SSMIS channels 1-7 and 24, depicting pattern is channel dependent.




$$\Delta T_{Emis} = T_{Obsvd} - T_{Scene} = \varepsilon(\nu)_{Rflct}\left(T_{Rflct} - T_{Scene}\right)$$

Figure 5. Time series of scan averaged uncorrected departures (RED) for SSMIS channel 5 (top), and channel 11 (bottom), 55.5 and 183 GHz, respectively depicting the frequency dependence of the reflector emissivity and resulting emission bias. The reflector temperature is in GREEN

During the F-16 Cal/Val program, several types of radiometric calibration anomalies were discovered (Swadley, 2006). Similar, yet different calibration anomalies were also discovered during the subsequent F-17 Cal/Val program. The SSMIS data are affected by the following calibration anomalies: 1) reflector emission; 2) solar warm load intrusions; 3) field-of-view (FOV) obstructions; 4) moon intrusions into the cold sky reflector; 5) random noise spikes; and 6) specific to the F-17 SSMIS, a residual Doppler scan bias and increased calibration noise.

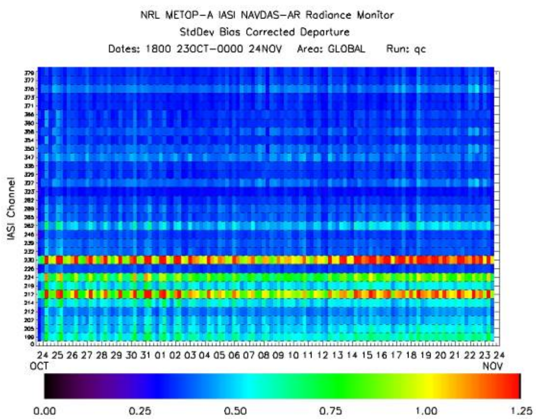



Figure 6. METOP-A IASI Hovmoeller or “DNA” plot for the standard deviation of the global bias corrected departures for the assimilated channels.

The SSMIS radiometric anomalies were difficult to detect with the traditional calibration and validation approach of comparing observed brightness temperatures with those computed at collocated radiosondes available from the global observation network. The geographic locations of these anomalies dramatically change throughout the year. and the global OB-BK departures proved to be an invaluable tool in describing the time evolution of the calibration anomaly patterns. Utilizing OB-BK departure patterns in conjunction with the DMSP Graphic Simulator (DGS) developed by the Aerospace Corporation allowed for quantification of the physical mechanisms causing the observed calibration anomalies. Figure 7 depicts a typical F-16 OB-BK departure pattern for SSMIS channel 4 and a coincident DGS view of the SSMIS from the Sun.

## *6. RADIANCE PREPROCESSING FOR NWP*

There are three main drivers for operational radiance assimilation systems:

1) Sufficient number of channels to sense both the surface and the full extent of the NWP model atmosphere
2) Low noise in relationship to the dynamical scales and background uncertainties being simulated
    a. Temperature gradients are larger scale than moisture gradients
    b. Spatial averaging can be used to lower noise in temperature sensitive channels
3) Spatial resolution adequate to resolve the fine scale moisture features

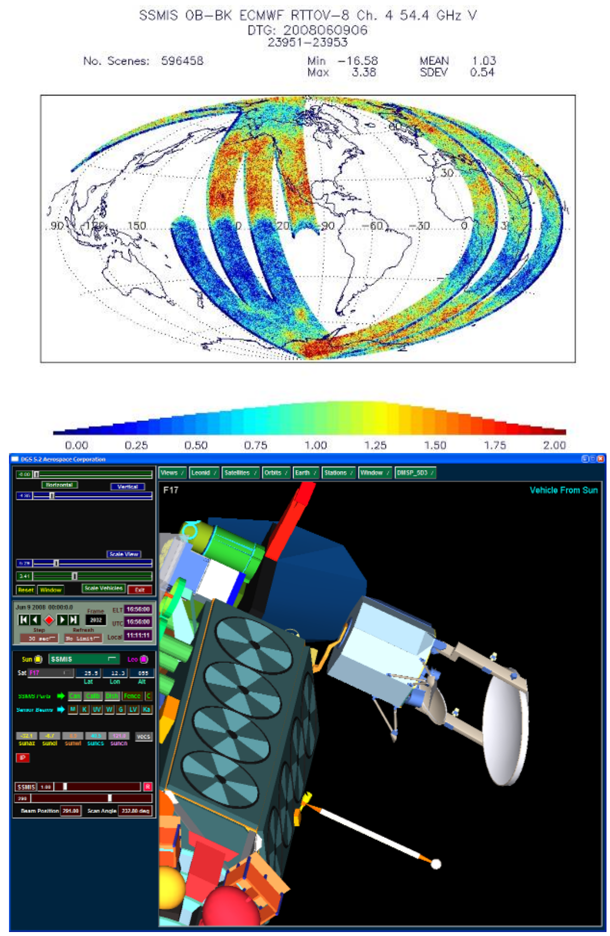



Figure 7. OB-BK departure pattern for SSMIS channel 4 for the 6 hour analysis window for 09 June 2008 at 0600 UTC, and a DGS view of the SSMIS from the Sun at sub satellite location: 25.3 S and 12.3 E.

The accuracy requirements for radiances in today’s operational DAS are quite demanding for the temperature sensitive channels in the troposphere and lower stratosphere. The bias corrected OB-BK uncertainties for DAS for global NWP require values less than 0.25 K in the atmospheric temperature sensitive channels. Accuracy requirements are less demanding in the upper stratosphere and mesosphere (40 – 100 km) and for the humidity sensitive channels. Figure 8 illustrates the accuracy requirements for the SSMIS channel suite in terms of the analysis quantity $\mathbf{HBH}^{\mathbf{T}}$ where $\mathbf{B}$ is the background covariance matrix, and $\mathbf{H}$ is the Jacobian matrix of the brightness temperatures, $\partial T_B / \partial \mathbf{x}$.

The NWP accuracy requirement is often at or below the sensor system noise values, so that additional processing must be performed in order to bring the uncertainties to levels acceptable to NWP DAS. The preprocessing requirement for NWP DAS involves removing scan biases, footprint matching, Backus-Gilbert re-sampling, scene and/or calibration averaging for noise reduction, channel thinning, and in the case of the SSMIS sensor anomalies, mitigating the biases identified by the SSMIS Cal/Val efforts prior to assimilation. This NWP preprocessing requirement will continue to be important for the NPOESS era sensors and the NWP community will need to perform these functions in conjunction with the sensor developers as part of the Cal/Val efforts.

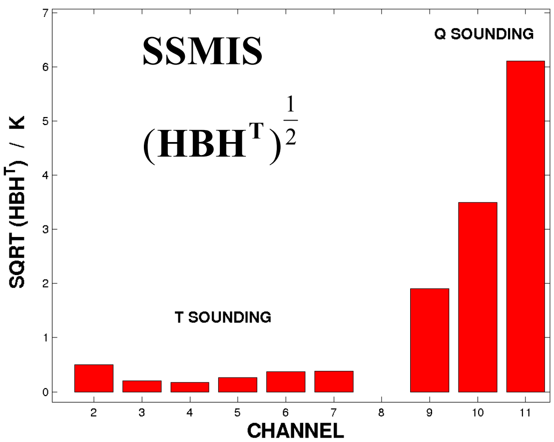



Figure 8. The $HBH^T$ analysis term for the select channels of the F-16 SSMIS

## 7. PATH FORWARD FOR FUTURE SENSOR SYSTEMS

Prior to adding a new sensor to the operational data stream at NWP centers, several weeks or months of passive radiance monitoring is performed, where the departures are monitored using the DAS but not assimilated into the operational analysis. NWP trial forecasts using the new sensor radiances are also performed and bias correction schemes are developed as needed to support the assimilation of the new sensor data of as part of the pre-operational sensor checkout. Several components need to be in place for the rapid transition of new NPOESS/NPP sensor data into operational DAS. These include:

1) Access to the NPP CrIS and ATMS data with the necessary processing infrastructure (data flow plumbing) in place
2) CrIS/ATMS TDR/SDR readers and sample data sets available at least 6 months prior to launch
3) Pre-processing strategy established
4) Detailed sensor specifications adequate for Line-by-Line radiative transfer model development and validation
5) Validated fast forward radiative transfer models with the adjoint and/or Jacobian computation capability

The day-one capability of the NWP centers to monitor global patterns of the OB-BK sensor departures is already part of the routine preparation for assimilating new sensor data. The Operational NWP centers have the radiance monitoring tools, processing infrastructure and experience in place to perform the necessary sensor checkout. These assets should be heavily relied upon in order to transition the sensor data into operations as rapidly as possible. In this way, NWP and DAS have and will continue to play an important role in the Cal/Val efforts for future satellite sensor systems.

## 8. ACKNOWLEDGEMENTS

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