11.8 Post-Launch Verification/Validation During the NOAA KLM Satellite Era

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1. INTRODUCTION

The National Oceanic and Atmospheric Administration (NOAA) Polar Operational Environmental Satellites (POES) System is a series of five polar-orbiting satellites (K-15, L-16, M-17, N, N Prime (N')) with improved sounding and imaging capabilities that are intended to provide operational coverage for 10 years (1998 - 2008). The purpose of the POES is to make measurements of temperature and humidity in the Earth's atmosphere, surface temperature, cloud cover, water-ice boundaries, and proton and electron flux near the Earth. The system consists of a pair of satellites and a suite of instruments that continuously monitor the Earth and ensure that every part of the Earth is observed at least twice every 12 hours.

The data collected are entered into weather forecast models and are vital to medium and long-range forecasts. The data are used as an aid in responding to people who require rescue from hazardous situations. Users all around the world listen for and use this data to warn of catastrophic conditions. Data from the NOAA satellites are used by researchers within NASA's Earth Science Enterprise, a long-term research program designed to study Earth's land, oceans, atmosphere, ice, and life as a total integrated system.

2. ON-ORBIT VERIFICATION

Much effort is put into ensuring the operational performance of the satellites and the accuracy of the data. During the development and launch phases for each new POES satellite, the National Aeronautics and Space Administration (NASA) and NOAA engineers and scientists perform hundreds of pre-launch and on-orbit verification (OV) tests designed to check out each subsystem and instrument on the satellite.

The OV tests are performed by a team of spacecraft and instrument engineers from NASA and NOAA, their supporting contractors, operations personnel, the manufacturer, and instrument vendors. The resulting information provides NOAA with a database to support product development and performance monitoring during the operational phases of the mission. The same data provides NOAA with insight into the overall spacecraft subsystem and instrument interaction so that enhancements and/or ground system modifications may be applied to later satellites.

The OV testing is conducted in two phases. The 21-day activation phase is conducted by NASA and concludes with turnover of the spacecraft to NOAA to conduct the 45-day evaluation phase. The OV tests establish a satellite performance baseline designed to characterize all aspects of instrument and spacecraft operation. During this period, the NASA and NOAA engineers are supported by all entities of the POES Ground System, which, in addition to Control and Data Acquisition (CDA) stations, consists of the Satellite Operations Control Center (SOCC) and the Central Environmental Satellite Computer Center (CEMSCS) at Suitland, MD. Often the spacecraft manufacturer may become involved. Additionally, the instrument scientists and the data users provide invaluable support.

The NOAA satellite data are distributed to external users via the Level 1B (1B) data format. The Product Systems Branch (PSB) of the Information Processing Division (IPD) of the National Environmental Satellite, Data, and Information Service (NESDIS) is responsible for production, quality assurance, and distribution of the formatted 1B data sets. The OV team coordinates checkout activities with the scientists and product developers responsible for the integrity of the 1B data. Software support is often needed to check out anomalies encountered by the OV team.

3. KLM Era PROBLEMS

The KLM polar satellite series, known as the advanced TIROS-N (ATN) series, is the forerunner of the NOAA N/N' satellites and is an advanced version of the Television Infrared Observation Satellites (TIROS-N). The new KLM series presented its own set of challenges and required the effort of the entire community of engineers, software designers, users, and instrument scientists to resolve them. The resolution often resulted in a modification to the instrument preprocessor

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programs that produced the 1B data product. The following paragraphs describe some of the problems and resolutions implemented for the NOAA-K, L, and M spacecrafts during the OV period.

3.1 *NOAA-K/15*

The NOAA-K/15 Advanced Microwave Sounding Unit (AMSU) instruments, AMSU-A and AMSU-B, had two problems that will be addressed here: cross-wired channels and data interference. The users of the 1B data were instrumental in analyzing and finding solutions for both problems. Before discussing the problems, a general description of the instrument will be provided to promote a better understanding of how the problems were detected and resolved.

3.1.1 *AMSU Instruments*

The NOAA-K/15 AMSU instruments detect surface or atmospheric radiation in the microwave portion of the electromagnetic spectrum. The NOAA-15 AMSU-A (temperature sounder), a 15-channel passive radiometer, detects energy emitted by atmospheric molecular oxygen from the emission source through the atmosphere to the sensor that resides on the NOAA-15 satellite. Contributions to the upwelling terrestrial radiation sensed by the NOAA-K/15 AMSU-A are largely comprised of two terms – the earth's surface and the overlying atmosphere. Individual AMSU-A channels (frequency) are carefully chosen based on principles of radiative transfer theory. Each channel is radiatively selective in the sense that it detects microwave radiation from discrete layers of the Earth's atmosphere. Satellite meteorologists typically relate the radiation sensed in individual channels to specific atmospheric layers by use of a term called a weighting function. UW-CIMSS (2002)

3.1.2 *Cross-Wired AMSU-A Channels*

Members of the NESDIS/Office of Research and Applications Forecast Product Development Team (FPDT) detected anomalies in the Advanced Tiros Operational Vertical Sounder (ATOVS) system images. AMSU-A channels 7 and 15 appeared to be reversed. The AMSU-A channel 7 image showed atmospheric data, and the AMSU-A channel 15 image showed Earth data. An experienced user could immediately see that the imagery created by each channel was incorrect for that specific channel. The real problem was to find out why the images were incorrect and how to correct them. After running tests to verify the suspicion that AMSU-A channel 7 was switched with AMSU-A channel 15, the FPDT team contacted various ground systems entities that provided the data to determine whether one of them had a processing problem.

After ground system investigations provided assurance that there was no problem, the instrument itself became suspect. The manufacturer confirmed the channel mis-wiring problem. The NOAA-K/15 radiometric data for channels 7 and 15 were switched aboard the spacecraft. This meant that the Earth views and the calibration views for AMSU-A channels 7 and 15 were reversed. Channel 7 was wired to detect channel 15 data and channel 15 was wired to detect channel 7 data. Two of the 15 AMSU-A channels on the already-launched NOAA-K/15 satellite were rendered useless. A solution would have to be implemented on the ground.

The AMSU-A instrument preprocessor software was modified to reverse the data to simulate the correct channel switching. All the data was then usable, resolving a potentially catastrophic problem with the AMSU-A instrument.

3.1.3 *AMSU-B Data Interference - "Mystery Bias"*

The United Kingdom Meteorological Office (UK Met Office) AMSU-B instrument on the NOAA-K/15 satellite also had data problems. The L-band and S-band transmitting antennae (STX) on NOAA-K /15 satellite were causing interference in the AMSU-B instrument. As NESDIS was preparing to make the correction scheme for this "normal bias" operational, a new bias appeared in the data. The phenomenon was designated as the NOAA-K/15 AMSU-B "mystery bias." The anomaly was again reflected in the imagery produced from the AMSU-B data. It was apparent in the AMSU-B imagery that NESDIS routinely displays on the Web. All of the data -- earth-view counts, space-view counts, and target-view counts -- were affected. The cause was determined to be the degradation of the STX-1 antenna. Turning off the STX-1, which was used to transmit High Resolution Picture Transmission (HRPT) data, was not a viable option at that time. A method for correcting the bias had to be devised.

The UK Met Office, NASA, NOAA, and the Massachusetts Institute of Technology (MIT) all played a part in resolving this problem. The UK Met Office trended the bias behavior and devised a correction method. The method was integrated and tested in the AMSU-B instrument preprocessor providing bias correction coefficients in the AMSU-B 1B data for further analysis. NASA and NOAA conducted independent testing to support the UK Met Office conclusion. Finally, modifications were completed so the AMSU-B instrument preprocessor could detect the bias, flag and correct the calibration scans.

To support this operation, the UK Met Office routinely supplied corrections to be applied by the 1B user to the Earth views in a table. This table was incorporated in the "NOAA KLM Users' Guide" and can be found on the website, http://www2.ncdc.noaa.gov/docs/. Calibration views are corrected using the standard bias correction method. Corrections are made before calculating the polynomial coefficients a_0, a_1, a_2 that convert counts to radiance. The UK Met Office provides corrections to space view and target view counts in a table.

3.2 *NOAA-L/16*

NOAA-L/16 presented a new set of problems, one of which affected all instruments. The problem resolutions required a great deal of effort to analyze and characterize before a solution could be recommended. The major problem affected the High-Resolution Infrared Sounder (HIRS) instrument, and another affected the Advanced Very High Resolution Radiometer (AVHRR) instrument. Again engineers, scientists, and software developers were involved in the resolution of these problems, all of which could be seen in the imagery created from the HIRS and AVHRR data.

3.2.1 *HIRS Pixel Misalignment*

Soon after launch, problems were observed in the HIRS data. Personnel at the Centre de Meteorolgie Spatiale (CMS), Meteo-France, direct readout facility reported many problems with the HIRS data in November 2000. The CMS staff suspected a possible shift of one HIRS spot in the measurements and suspected the "instrument or the on-board processing" as the source of the problems. FPDT personnel produced imagery from the 1B soundings product, which seemed to confirm an apparent data mis-location problem. Geographical coastlines were appended over images created from orbital segments of HIRS observation for channel 19, a surface-sensitive channel. Normally, these measurements contrast definitively along coastlines. However, the NOAA-L/16 HIRS images appeared to be misaligned by about one pixel to the left, relative to the direction of the satellite. The imagery of raw HIRS data showed a "limb effect," which usually presents as a symmetric pattern. The NOAA-L/16 measurements were non-symmetrical. This, along with further testing, confirmed that the problem stemmed from the instrument or on-board processing and represented a possible shift of one HIRS spot in the measurements.

The HIRS instrument preprocessor software was thoroughly examined to ensure that there was no software problem contributing to the HIRS anomaly. After this was done, effort was concentrated on proving the pixel misalignment theory. Based on the results of these observations, it was deduced that the HIRS instrument was malfunctioning. Corrections would have to be made on the ground. NOAA and NASA engineers began a detailed study to determine what was going on with the instrument. FPDT personnel tested the misalignment hypothesis using the ATOVS product processing system in the NESDIS operational processing environment. The Level 1B HIRS Earth location data was adjusted to account for the misalignment as a 1.8 degree roll error. When using this data in the ATOVS system, an additional change was made to account for the asymmetry in the data and match the proper samples with the earth locations. Inspection of the imagery created by the shifted data showed such improved results that plans were made to incorporate changes into the HIRS 1B data product. Figures 1 and 2 depict the HIRS Channel 19 measurements minus the constant roll type attitude correction of 1.8 degrees and with the constant attitude corrections of 1.8 degrees, respectively.

3.2.2 *Clock Error and AVHRR Across-Track Error*

All NOAA-L/16 instruments exhibited an along-track error. The along-track error was suspected to be a clock error, but the possibility of a pitch attitude error had to be ruled out. A pitch correction of -0.44 degrees was tried and determined not to fit the behavior of the error. The pitch error was removed for NOAA-L/16 instrument data and replaced with a timing correction of 1 second for all instruments to fix the along-track error along with the normal SOCC-clock drift correction. For example: on May 16 at 0000Z, the clock error determined was +862 milliseconds (ms) (+1sec for along-track error and -138 ms for SOCC-clock drift error).

Almost a year after the NOAA-L/16 launch, the SOCC discovered the real cause of the apparent along-track error. While conducting frame-synch tests in preparation for ordering new frame synchs for the CDAs, SOCC discovered an additional delay in stamping Ground Receive Time (GRT) of approximately 900 milliseconds previously omitted when calculating the spacecraft clock error. It was stated in a message dated July 26, 2001 from Peter Phillips of the SOCC that "This will cause the

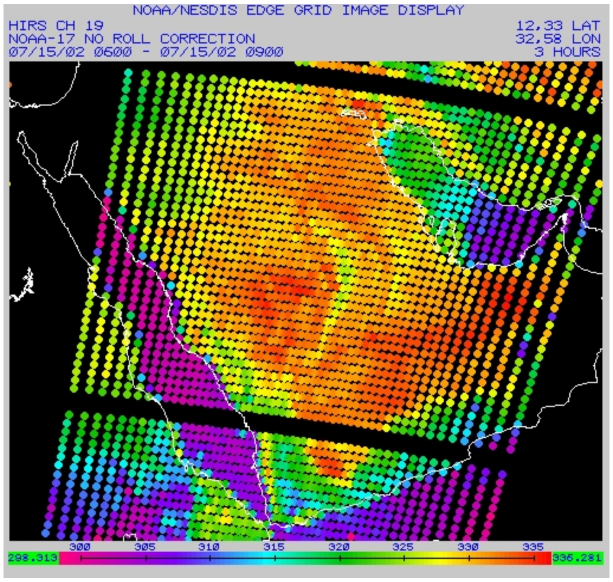

Figure 1. **HIRS Channel 19 Measurements Without 1.8 Degrees Roll Type Attitude Correction**

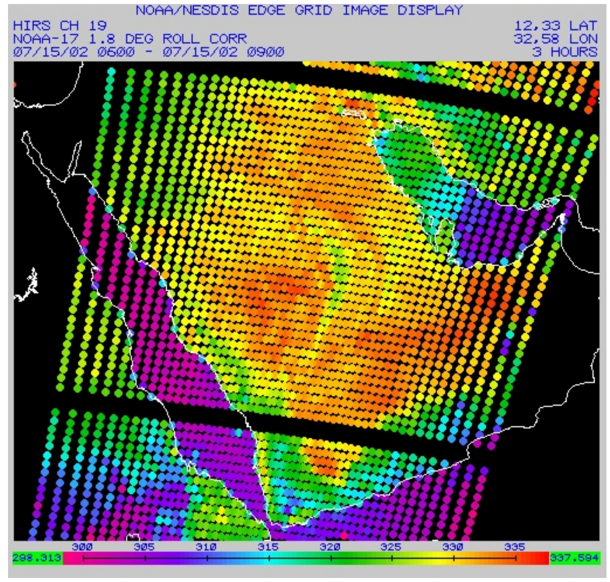

Figure 2. **HIRS Channel 19 Measurements With 1.8 Degrees Roll Type Attitude Correction**

reported spacecraft error to be 900 milliseconds less than the true value for KLM spacecraft. Because the spacecraft clock error is used as the basis for setting the spacecraft clock, the net effect of this discrepancy will be that the spacecraft clock will be set 900 milliseconds ahead of the true value. This, in turn, would cause the AVHRR imagery to appear to be lagging the calculated spacecraft position by nearly 1 second, which is the problem users have seen on both the NOAA-15 and 16 spacecraft." After conclusive tests were performed by SOCC engineers, the frame-synch blocking factor was adjusted and the spacecraft clocks were corrected by -900 milliseconds or whatever amount was needed to bring the "true" error to 0.

The AVHRR imagery also demonstrated an across-track error. NESDIS navigation personnel spent many hours examining AVHRR imagery in order to characterize the problem and develop a correction. The error could not be treated as a typical roll error, since the error was in opposite directions on opposite sides of the sub-track with no error around the nadir point. The AVHRR across- track error was corrected by using a scan angle of +/-55.25 degrees (stepping angle of 0.05398143624 degrees) instead of the normal +/-55.37(stepping angle 0.05409868099 degrees). The true cause of this error was never determined. Figures 3 and 4 depict images produced by HRPT data, which show the uncorrected across-track and along-track errors and the corrected across-track and along-track errors, respectively.

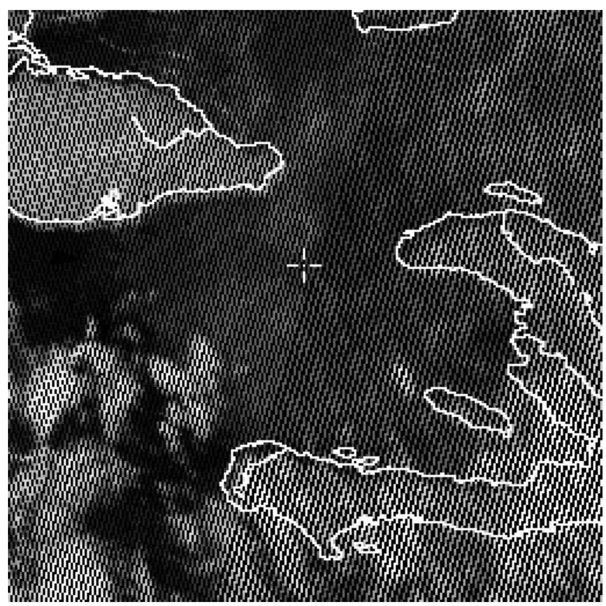

Figure 3. **HRPT Image Depicting the Along-Track and Across-Track Errors**

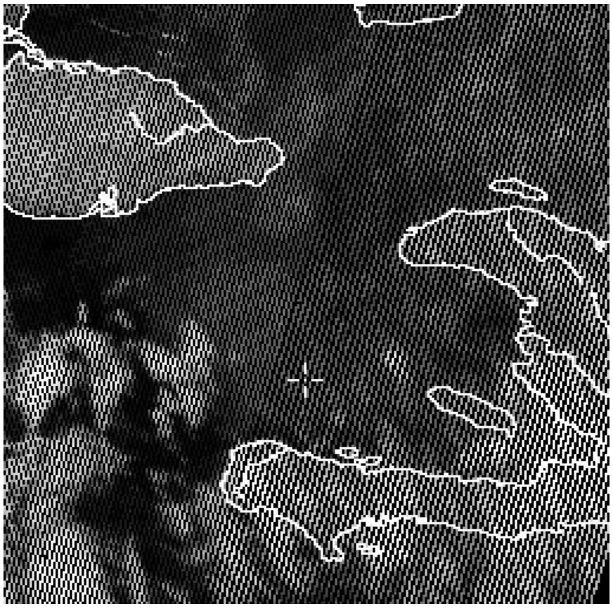

Figure 4. **HRPT Image Corrected for Along-Track and Across-Track Errors**

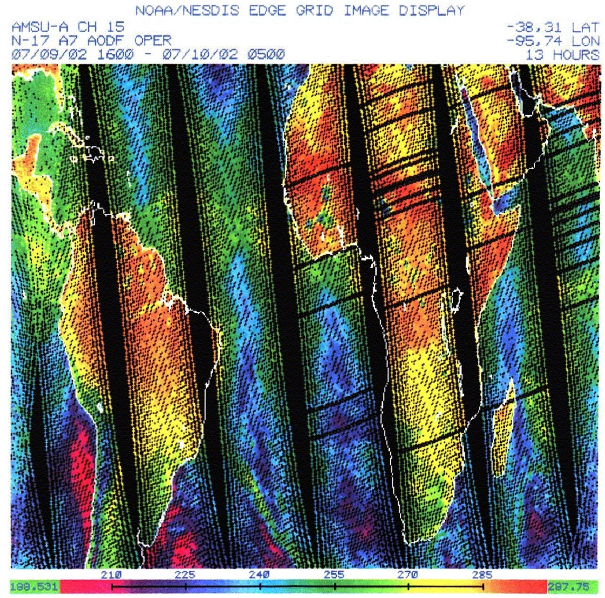

Figure 5. **AMSU-A Image Depicting Channel 15 Data With (On The Right) and Without (On The Left) The AMSU-A Data Dropout Anomaly**

3.3 *NOAA-M*/17

NOAA-M/17 was launched June 2002, and instrument data products were made operational in record time when compared to that of the two previous satellites in the series. As expected, lessons were learned from the earlier launches. It was recognized immediately by NESDIS FPDT personnel that the NOAA-M/17 HIRS instrument imagery looked like that of NOAA-L/16 and the same adjustment for the HIRS pixel misalignment was applied.

The AMSU-A instrument developed an anomaly characterized by data dropouts when the satellite was in the dark part of the orbit. Personnel from NOAA, NASA, Lockheed, Northrop Grumman and Lincoln Laboratory, MIT met to resolve the problem. J. Philip Green reported in the Polar Weekly Status Report, July 10 -16, that "The cause was thought to be marginal data handling synchronization of the timing associated with either the instrument or the S/C. A series of recovery tests were recommended and approved. The first, an instrument reinitialization test involved commanding the instrument off, then on again. Five days of data were reviewed after the recovery test which confirmed the fix." Figure 5 depicts AMSU-A channel 15 measurements with the AMSU-A data dropout anomaly (right) and the AMSU-A measurements minus (left) the data dropout anomaly.

On-orbit verification is almost complete and the instrument 1B data product is being produced with one Earth location adjustment for the HIRS instrument and no clock-error adjustments. AMSU-B RFI "mystery bias" corrections were only needed for the NOAA-K spacecraft. Instrument manufacturers were able to correct the antenna problems before the launch of successive satellites. Users, software developers, engineers, and scientists will continue to study and recommend improvements to the products delivered to the user community.

4. LESSONS LEARNED

Testing and verification/validation begin long before the launch of a satellite. It begins with the planning of each new series and continues through each phase of development.

The instrument preprocessor software that generates the 1B data product is often the first suspect when a problem is encountered in the product. Though the solution is often implemented via a Level 1B input or software modification, the problem can be anywhere in the vast collection of components that compose a satellite system. It could be anywhere from the satellite to the ground system. Thus extensive on-orbit verification (OV) is needed. A successful OV period requires and is achieved regularly via the cooperation, dedication, commitment, knowledge, and expertise of the many organizations involved. Much work precedes the implementation of a solution to a problem. Analysis, trending, and testing are accomplished, often within a short period of time.

These activities do not end once the OV period ends and a satellite and its data products are made operational. It is an on-going process that continues for the life of the satellite.

5. CONCLUSION

The KLM satellites and lessons learned during on-orbit verification have provided a baseline for future NOAA satellites. The National Polar-Orbiting Environmental Satellite System (NPOESS) is the next series of NOAA satellites after MetOp, NOAA-N, and N'. MetOp is a joint venture with the European Organization for the Exploitation of Meteorological Satellites (EUMETSAT) where N and N' will fulfil the afternoon mission, while EUMETSAT satellites fulfil the morning mission. Modifications have already been made to NOAA-N/N' satellites. The AMSU-B instrument has been replaced with the Microwave Humidity Sounder (MHS) instrument and the HIRS instrument has been modified. NPOESS instrumentation will benefit from the analysis of current data and lessons learned during prior OV verification, ensuring that a new threshold will be reached in the quality of data provided to users around the world.

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