NOAA Technical Memorandum NESDIS 46

HIRS/3 SCAN MIRROR MISALIGNMENT ONBOARD NOAA-16

Washington, D.C.
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NOAA Technical Memorandum NESDIS Series

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HIRS/3 Scan Mirror Misalignment Onboard NOAA-16

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1 BACKGROUND

The National Oceanic and Atmospheric Administration (NOAA)-16 earth orbiting satellite was deployed into polar orbit (ascending, equator, crossover at 1330 LST) on September 21, 2000. Evaluations of the Advanced Microwave Sounding Unit (AMSU) A and B data (Goodrum et al. 2000), received within a few days of orbital deployment indicated that these radiometers were functioning as designed. However, upon the completion of the outgasing of the High resolution Infrared Radiation Sounder (HIRS), marking the onset of routine availability of usable HIRS measurements to users which occurs about 3-weeks after launch, problems with the HIRS measurements began to be noticed. The following report summarizes the series of problems and corrective actions concerning the misalignment of the HIRS scan mirror onboard NOAA-16.

2 PROBLEM IDENTIFICATION

The first reports of problems for the NOAA-16, HIRS data were received from Dr. Pascal Brunel and his co-workers at Centre de Meteorologie Spatiale (CMS), Meteo-France, during November, 2000. Dr. Brunel reported "many troubles" with NOAA-16 HIRS data, "suspecting a (possible) shift of one HIRS spot in the measurements", as "if the instrument (were) not scanning in nominal geometry, or synchronization (was) not on time". The CMS staff suspected the "instrument or the on-board processing" as the source of these problems. The observations were made during routine processing at the CMS direct readout facility (in Lannion, France), using the Advanced-TIROS Operational Vertical Sounder (ATOVS) and Advanced Very High Resolution Radiometer (AVHRR) Processing Package (AAPP) available from EUMETSAT (Klaes et al. 1999).

Meanwhile, National Environmental Satellite, Data, and Information Service (NESDIS) efforts to validate and implement an operational sounding products system (Reale et al. 2000) for NOAA-16 had encountered unusual problems concerning the generation of limb adjustment coefficients (Wark 1993) for the HIRS. Since the HIRS is a cross-track scanner (Goodrum et al. 2000), the path of the atmospheric radiation reaching the HIRS instrument varies with the scan position. Measurements near the center of the scan are comprised of radiation which travel an essentially vertical path to the radiometer, while radiation from scan positions further away from nadir traverse a progressively longer "slant" path. This increase in path results in a gradual lifting of a given channel's vertical sensitivity, with scan positions further from nadir having peak sensitivities which are higher in the atmosphere than those closer to nadir. This is manifested as a systematic difference in the radiance measurements for a given channel across the scan, which is referred to as limb-effect. Typically, the limb effect is symmetric about nadir, since the instrument is designed with symmetric scanning angles with respect to nadir.

Limb effect is removed prior to the derivation of NESDIS operational sounding products through the generation and application of limb adjustment coefficients which normalize all the measurements to (look like) the nadir view (Wark 1993). Such adjustments are typically well-behaved (Goldberg 1999), with a high degree of symmetry in the coefficients applied on either side of nadir. However, for NOAA-16, a distinct lack of symmetry and large residual errors after limb adjustment were being observed for the HIRS, including a highly variable and scan dependent bias (which also changed sign) from one side of the scan to the other. These unusual results led to an initial series of actions by NESDIS to remove the symmetric constraints from the coefficient generation process, sometimes desirable, for example, if systematic differences due to microwave instrument side lobes are a concern. These results were slightly better than the original, but still inferior to results from previous satellites.

During the later part of November (one day after the receipt of CMS results), Dr. Thomas Kleespies of the NESDIS Office of Research and Applications (ORA) provided the first NOAA confirmation of an apparent data mislocation problem for HIRS onboard NOAA-16. These are presented in Figures 1 and 2 which display orbital segments of HIRS observation for channel 19, a surface sensitive channel, in the vicinity of Saudi Arabia and the Red Sea. Figure 1 shows hot, daytime observations corresponding to the ascending orbit node, and Figure 2 the relatively cold, nighttime observations corresponding to the descending orbit node. Geographical coastlines are appended over each image. Normally, these measurements contrast definitively along coastlines, which during the day (Figure 1) mark the boundary between the relatively hot land and cool ocean, and at night (Figure 2) the relatively cold land and warm ocean environments, respectively. As seen in both Figures, the data in the vicinity of coastlines appear to be misaligned by about one pixel to the left, relative to the direction of the satellite.

In early December, Mr. A. Reale of ORA provided additional NOAA results confirming asymmetry in the raw HIRS from NOAA-16. These are presented in the 4 panels of Figure 3 which show color enhanced, ascending (upper panels) and descending (lower panels) node orbit segments of calibrated HIRS measurements for the longwave channel 5 (upper panels), and shortwave channel 15 (lower panels) data from NOAA-16 (left panels) and NOAA-14 (right panels), respectively. Each panel corresponds to a remote, clear ocean region; the upper panels in the tropical Pacific west of South America, the lower panels in the tropical Atlantic west of Africa. The "limb effect" in these raw, calibrated measurements is seen as a darkening (cooling) from the center to outer portions of the scan, as expected for these mid-tropospheric sensitive channels. As seen for the NOAA-14 (right side panels), the limb darkening pattern is symmetric; that is, the same color shades appear on each side of the scan. The NOAA-16 measurements, however, are decidedly non-symmetric, with measurements on the right side (in the direction of the satellite) notably colder than on the left.

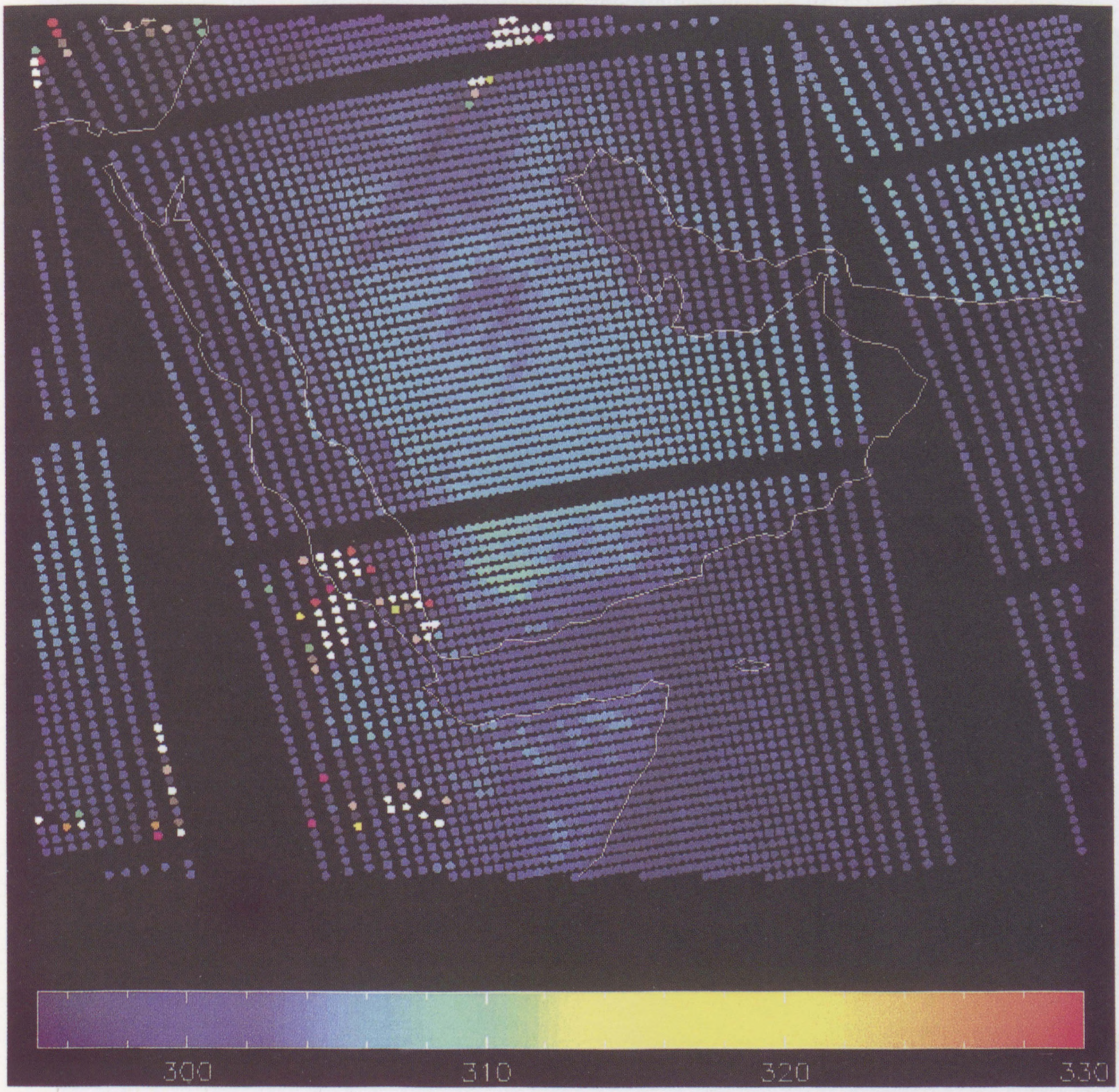

FIGURE 1: Original NOAA-16 measurements for HIRS channel 19 (sensitive at the surface) for an ascending node orbit segment (daytime) in the vicinity of the Red Sea, illustrating the approximately one pixel mislocation (to the left in the direction of the orbit track) along north/south coastal zones.

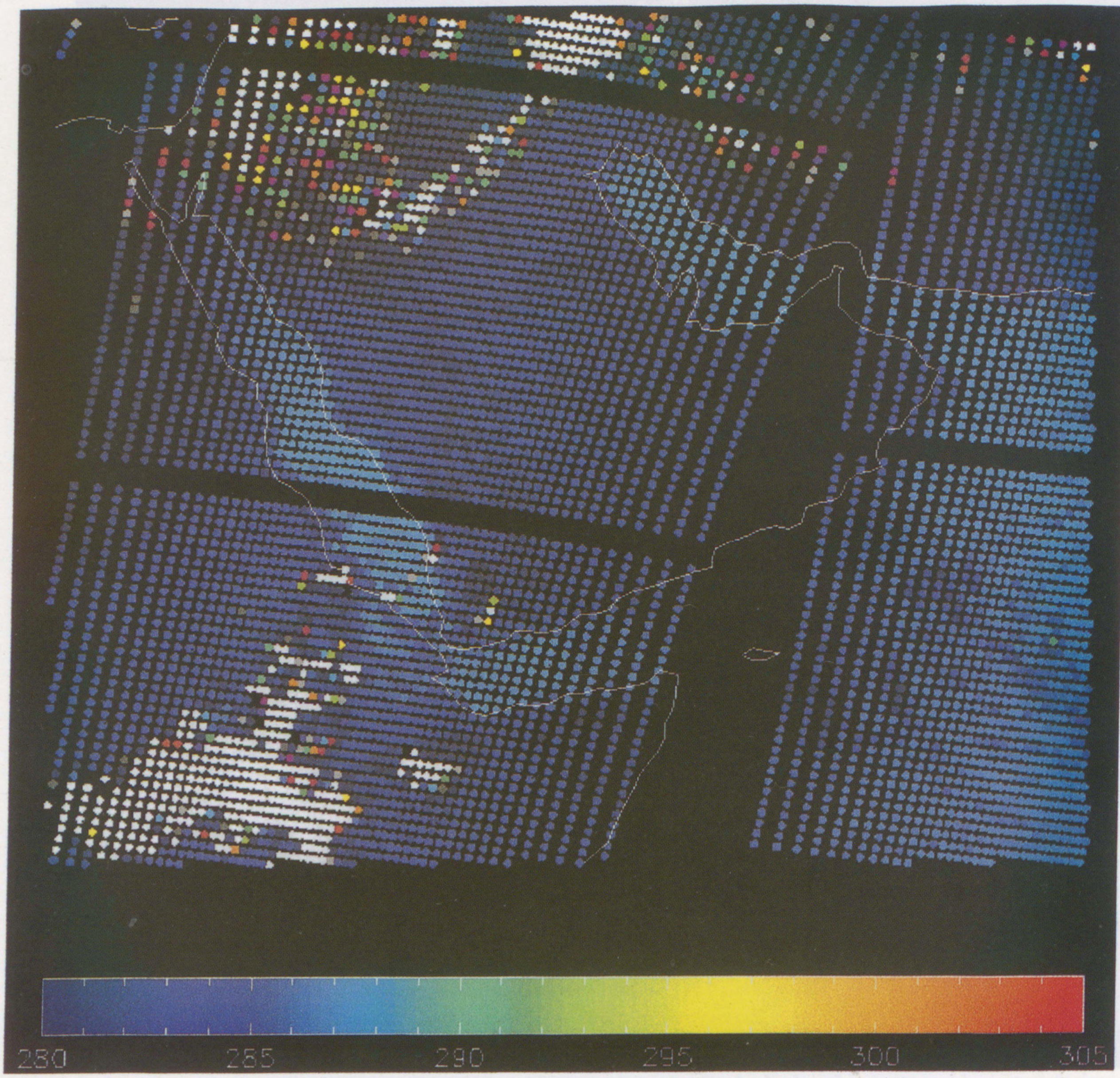

FIGURE 2: **Original NOAA-16 measurements for HIRS channel 19 (sensitive at the surface) for a descending node orbit segment (nighttime) in the vicinity of the Red Sea, illustrating the approximately one pixel mislocation (to the left in the direction of the orbit track) along north/south coastal zones.**

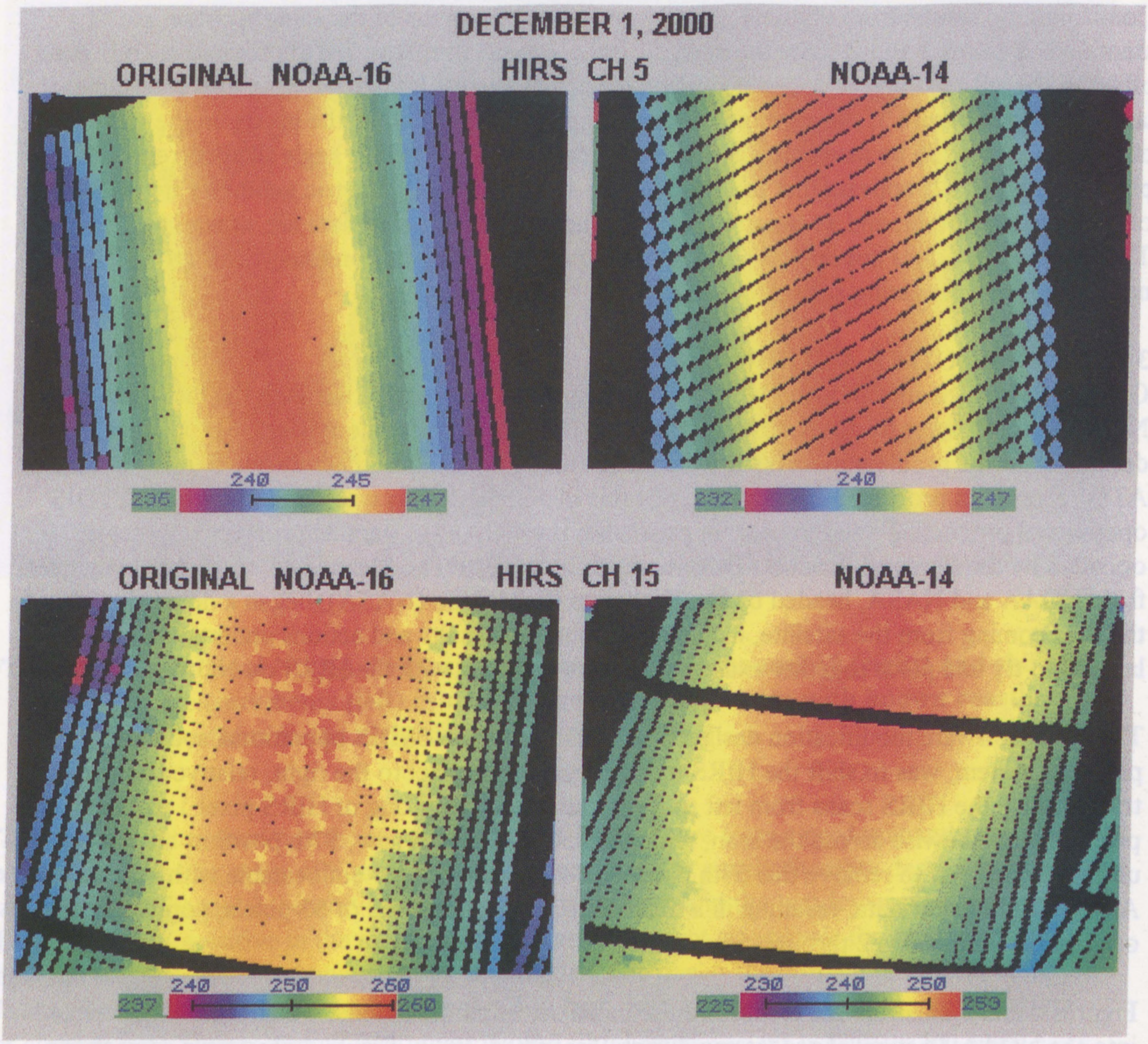

FIGURE 3: **Measurements for tropospheric HIRS channels 5 (upper panels) and 15 (lower panels) corresponding to original NOAA-16 (left side panels) and comparative NOAA-14 (right side panels) data for ascending (upper panels) and descending (lower panels) node orbit segments from remote, oceanic, predominantly clear regions, illustrating the asymmetry of the original NOAA-16 HIRS data.**

Combining the results from Figure 1, 2 and 3, two manifestations of the same problem are identified. Figures 1 and 2 show the navigational component; that is, the approximately one pixel offset to the left resulting in data mislocation measured against known geographical (coastline) landmarks, and Figure 3, the asymmetric scanning component, that is, the pixels on the right side of the scan appear to be measuring at a systematically higher scanning angle than corresponding pixels on the left. It appears that the HIRS is not scanning in a symmetric geometry from one side of the scan to another, and as reported by CMS, no other instrument data are similarly affected. The HIRS sensor does not appear to be operating as designed, nor consistent with ground navigation and processing software systems.

3 CORRECTIVE ACTION

Given the results from CMS and NOAA internal investigations, together with the fact that NESDIS front-end software is different than that used by direct readout users, Mr. Chalfant deduced that the problem must be instrument related. He then designed, developed and evaluated ATOVS product processing software to test this hypothesis. This was done using the NESDIS operational processing environment, in particular, the NOAA-16 parallel processing systems operated by the Forecast Products Development Team (FPDT). Meanwhile, instrument engineers from NOAA and NASA, headed by Dr. Katherine Richardson (NASA), began a detailed study of the data coming from the satellite, including ground test results and actions undertaken prior to launch, to try and piece together exactly what was going on with the HIRS on NOAA-16.

The initial software modification designed by FPDT for the NESDIS operational sounding products system, was to shift the HIRS measurements one pixel to the right, relative to the orbit track. Since the HIRS scans from left to right, this meant a shifting of HIRS pixel 1 to the pixel 2 position, and likewise across the scan, with pixel 56 shifted to a new, 57th position. It was ultimately decided to remove this 57th pixel, since it was no longer collocatable with other ATOVS radiometer data, resulting in a final shifted scan comprised of 55 pixels, populating the original pixel positions 2 through 56.

Figures 4 and 5 illustrate the result of these initial set of modifications, which were implemented into the NOAA-16 parallel processing during December, 2000. Figure 4 illustrates corrections with respect to data mislocation, and Figure 5 with respect to raw data asymmetry. Each Figure shows the original NOAA-16 HIRS measurements in the right side panels, and the corrected, shifted, measurements in the left side panels.

The orbit segments in each of the two (2) panels of Figure 4 are in the vicinity of the Persian Gulf, illustrating ascending node (daytime) measurements for HIRS channel 19. The gray pixels along the left side of the scan for the "shifted" measurements illustrate the original pixel position 1, which was shifted to the right (relative to the satellite track), leaving the original pixel-1 locations missing (gray). Notice how much better the boundary between the relatively cold ocean and warm land measurements (during the day) aligns with the coastline in the shifted measurements compared to the original data.

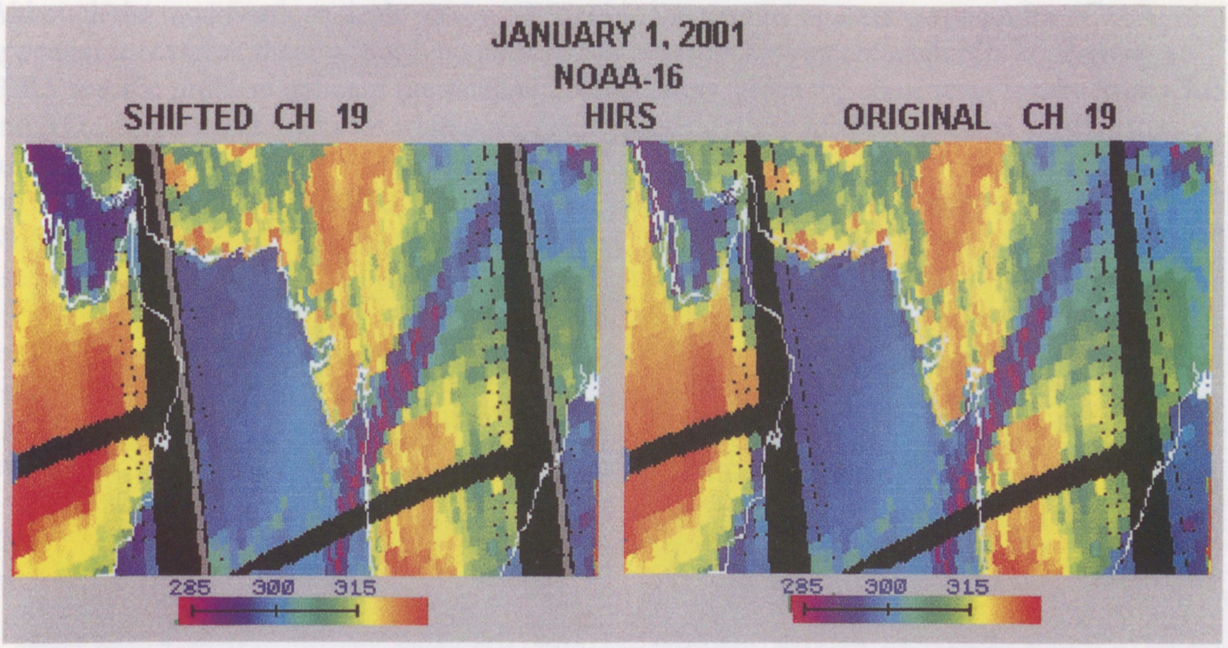

FIGURE 4: Original NOAA-16 measurements for HIRS channel 19 (right) and shifted measurements (left) exhibiting the better alignment with known coastline locations in the vicinity of the Persian Gulf.

The orbit segments shown in the four (4) panels of Figure 5 are from a predominantly clear region in the remote Pacific, west of South America. The two upper panels illustrate descending node data for HIRS channel 2, sensitive in the lower stratosphere, and the two lower panels show HIRS channel 5, sensitive in the middle troposphere. The right side panels for each channels show the original, unshifted observations, and the left side panels the corrected, shifted, data. Notice that the limb effect for each channel is different, with a limb-darkening (cooling) pattern for channel 5, and a brightening (warming) pattern for channel 2. This is as expected since temperature generally decreases with height in the troposphere (channel 5), but increases with height in the stratosphere (channel 2). The grey (missing) pixels which appear to be on the right are actually on the left side relative to the orbit track (similar to Figure 4). Notice the improved symmetry of the shifted versus unshifted limb effect.

A close inspection of the shifted data, however, still indicates a slight asymmetry in the shifted measurements. This is accounted for by the fact that after shifting, the rightmost (relative to the direction of the satellite, left in the picture) pixel (56) is offset by one scan position relative to the leftmost (non-missing), which is now in the pixel-2 position. Although the shifted data remain asymmetric, they are now being processed consistent with the actual path of the radiation through the atmosphere, with the expected symmetry among pixels 2 through 55. Properly accounting for this shift in the generation of limb correction coefficients resulted in a reduction of residual errors to expected levels (Allegrino et al 1999).

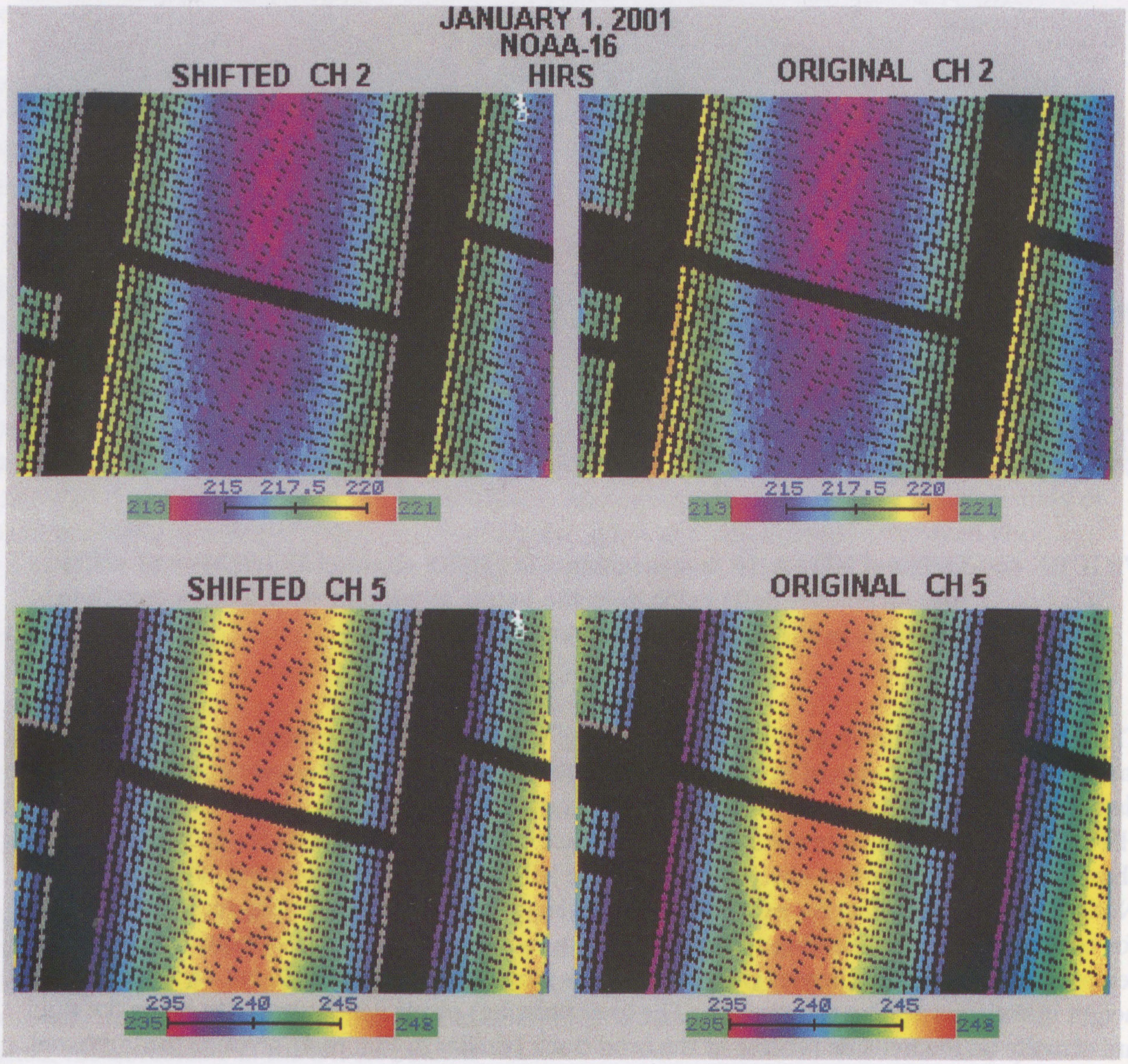

FIGURE 5: Original NOAA-16 measurements for tropospheric HIRS channels 5 (upper left) and 15 (lower left), and comparative NOAA-14 measurements (right) for ascending (upper) and descending (lower) node orbit sections from remote, ocean, predominantly clear regions illustrating the asymmetry of the NOAA-16 HIRS data.

Although the modifications deployed by NESDIS in the parallel operating system for NOAA-16 appeared successful, there was still no clear indication from instrument engineers concerning a HIRS specific problem onboard the satellite. Nonetheless, given the convincing results from CMS and NOAA, subsequent actions were undertaken by NESDIS to modify the earth location software for the NOAA-16 HIRS to include a one pixel offset to the right. This was done by introducing a "Roll" bias of +1.8 degrees (corresponding to a 1.0 pixel shift to the right) in the NESDIS front-end processing systems which generate the raw, level "1b" datasets distributed to users and archived by NOAA/National Climatic Data Center (Goodrum et al. 2000).[1] The result of this was an appropriate shift in the satellite zenith angle computed for each pixel and stored on the 1b-level file. These procedures were implemented by NESDIS for NOAA-16 processing on February 14, 2001. This action included tests at various pixel sub-increments, varying for 1.7 to 2.0 scan angle degrees, which indicated the best results at 1.8 degrees (equivalent to one pixel length).

The introduction of the roll bias as described above essentially reconfigured the HIRS pixels across the scan, so that:

- o pixel position 1 (the leftmost pixel) actually contains a satellite zenith angle that would normally be associated with position 2 (and similarly across the scan),
- o nadir remains between scan positions 27 and 28,
- o pixel position 55 contains a zenith angle normally associated with position 56 and with no symmetric counterpart on the left side of the scan, and
- o scan position 56 contains a zenith angle for scan angle "57", with no symmetric counterpart on the left[2].

4 USER CONFIRMATION

In early February, 2001, a series of results were received from the NOAA, Environmental Modeling Center which further confirmed asymmetry problems for the raw HIRS measurements from NOAA-16, with additional validation that a correction of one pixel length was optimal. Figure 6 provides two (2) plots which illustrate mean differences between HIRS measurements which were calculated (McMillin 1995) from NOAA, numerical weather prediction (NWP) forecast model data, and collocated NOAA-16 observations. Each plot illustrates unshifted (solid lines) and shifted (dashed lines) HIRS measurements, respectively, as a function of the scan position (horizontal axis). The shifted HIRS measurements simulated by EMC correspond to a one pixel shift to the right. The curves for each plot illustrate the variation in mean bias across the scan for HIRS channels 5 (left) and 15 (right).

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[1] However, direct readout users need to introduce a Roll bias to correctly account for the HIRS misalignment.

[2] This position is not processed operationally since it is only collocatable with Advanced Very High Resolution Radiometer (AVHRR), Local Area Coverage (LAC) data (Goodrum et al 2000).

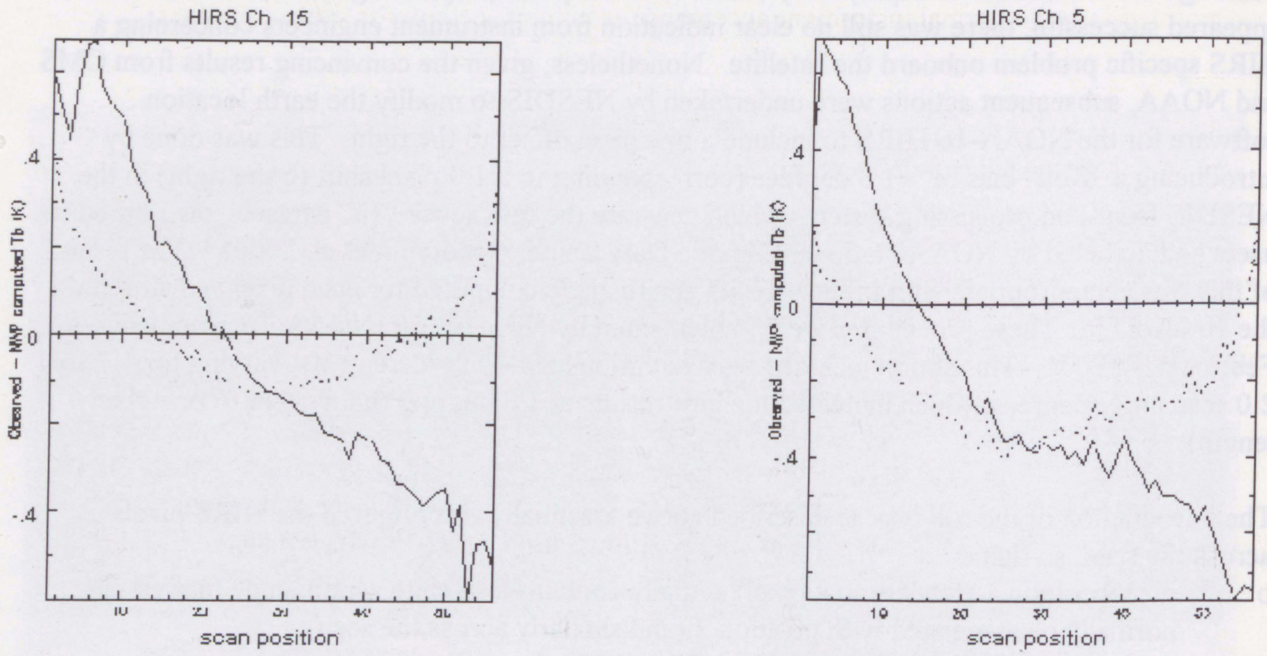

Figure 6: **Observed minus NWP-based simulated radiance temperature as a function of the satellite scan position (1-56) for original, non-shifted HIRS (solid), and HIRS observations shifted one pixel to the right (dashed) for channels 15 (left) and 5 (right onboard NOAA-16.**

As can be seen, the solid curves representing the original, non-shifted data show a more definitive bias which changes from positive to negative across the scan, whereas the dashed curves representing the shifted data show the expected symmetry about nadir. The magnitude of differences are not important since there are uncertainties in the nwp data and radiative transfer calculations used to compute HIRS measurements, the later varying per scan position as well. These results are conclusive since the nwp is not expected to exhibit systematic differences across the satellite scan.

5 ROOT SOURCE

Confirmation of a unique problem for HIRS onboard NOAA-16 was received in a report from the Lincoln Laboratory, Massachusetts Institute of Technology (MIT) on 16 February 2001, based on a study of a possible NOAA-16, HIRS misalignment with respect to AVHRR data (Meroth 2001). The report cites the most probable cause for a one-pixel shift as seen on-orbit to be a scan mirror shifting (or misalignment) on the motor shaft. A specific failure investigation found that after acceptance vibration testing, two set screws used to secure the scan mirror to the motor shaft were loose. The scan mirror was re-secured to the motor shaft and staked in place, however, it is likely that the mirror was not staked in the original alignment position. The report discusses the need to electronically verify the mechanical relationship between the scan mirror/motor and the NADIR cube mounted in the HIRS instrument on the alignment fixture;

insure that the electrical and mechanical nadir agree. Apparently, this was not done, but has been incorporated into the normal instrument acceptance testing procedure for future satellites.

The MIT report concluded a likely misalignment of the HIRS, and based on collocation studies with respect to the AVHRR, further concluded that the HIRS was misaligned by approximately 1.5 +/- .4 degrees, or .8 +/- .2 HIRS pixels.

Another inconsistency, this time concerning software documentation, was also identified during the HIRS misalignment and troubleshooting exercise, which at first appeared relevant, but later could only be interpreted as an interesting coincidence. It was determined that the HIRS/3 encoder positions for the earth views for NOAA-16 range from 0-55, which contradicts "NESS107", and the "Technical Description for the HIRS/3", VOL 1 (pg 28 and 50), which states that the earth views are 1-56. While this discrepancy is in the correct direction to explain the NOAA-16 shift, it does not explain why there is no apparent shift with NOAA-15 data. The level-1b data report delineating earth scene encoder positions for NOAA-15 and 16 also indicates a range of 0-55, which are out of sync by one position with NOAA-14 which indicates a (correct) range of 1-56.

6 SUMMARY

An international cooperative effort of European direct readout users (CMS) of NOAA polar orbiting data, NESDIS scientists responsible for the scientific integrity of measurements and derived products from polar satellite systems, and instrument engineers (NOAA and NASA) responsible for monitoring radiometer performance onboard the spacecraft, resulted in the timely identification of a misalignment problem impacting the HIRS/3 radiometer onboard NOAA-16. NESDIS modifications of operational front-end ground software systems to account for the misalignment when processing NOAA-16, HIRS/3 data, were deployed beginning in February, 2001. The importance of the post-launch validation process, particularly the feedback provided by the global user community (CMS, Lannion, France), to identify this problem that otherwise would have significantly compromised the use of these data in global weather and climate applications, is keenly illustrated. The diligence and cooperative spirit of the agencies involved is applauded. The primary benefit of Mr. Chalfant's incorporation of NOAA-16 unique software into the ATOVS product processing system in early December provided:

- the capability to check out changes to NESDIS' front-end "1B" processing related to HIRS unique scanning geometry as well as a calibration problem,
- the capability to generate and apply HIRS limb adjustment coefficients,
- the capability to check out a second geo-location problem associated with HIRS TIP frame time which produced an along track error, and
- the capability to check out the ATOVS temperature and moisture soundings as well as the HIRS atmospheric cloud, ozone and radiation products several months earlier than would have otherwise been possible.

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The National Oceanic and Atmospheric Administration was established as part of the Department of Commerce on October 3, 1970. The mission responsibilities of NOAA are to assess the socioeconomic impact of natural and technological changes in the environment and to monitor and predict the state of the solid Earth, the oceans and their living resources, the atmosphere, and the space environment of the Earth.

The major components of NOAA regularly produce various types of scientific and technical information in the following types of publications:

PROFESSIONAL PAPERS - Important definitive research results, major techniques, and special investigations.

CONTRACT AND GRANT REPORTS - Reports prepared by contractors or grantees under NOAA sponsorship.

ATLAS - Presentation of analyzed data generally in the form of maps showing distribution of rainfall, chemical and physical conditions of oceans and atmosphere, distribution of fishes and marine mammals, ionospheric conditions, etc.

TECHNICAL SERVICE PUBLICATIONS - Reports containing data, observations, instructions, etc. A partial listing includes data serials; prediction and outlook periodicals; technical manuals, training papers, planning reports, and information serials; and miscellaneous technical publications.

TECHNICAL REPORTS - Journal quality with extensive details, mathematical developments, or data listings.

TECHNICAL MEMORANDUMS - Reports of preliminary, partial, or negative research or technology results, interim instructions, and the like.

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