NOAA Technical Report NESDIS 77

NOAA POLAR SATELLITE CALIBRATION: A SYSTEM DESCRIPTION

Washington, D.C.
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U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Environmental Satellite, Data, and Information Service

NOAA TECHNICAL REPORTS

National Environmental Satellite, Data, and Information Service

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Cecil A. Paris
Office of Satellite Data Processing and Distribution
Information Processing Division
Ingest Systems Branch

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PREFACE

This report is intended to represent an instructional guideline to calibration. Its purpose is to familiarize the readers, users, and managers of satellite acquired environmental data or data systems - with the basic operational technology, terminology and status of the somewhat neglected technology of total system calibration. It should be pointed out that the procedures, algorithms, and instrument operations contained in this document are those used through the launch of NOAA-I. Improvements and changes to instruments will necessitate revisions to algorithms and procedures.

It is characteristic of any area of investigation that a user of data or information must understand the quality of his/her data before attempting to derive conclusions from an analysis thereof. The level of confidence in the quality determines the commitment to the analysis. Few technological areas have produced, in their entire histories, masses of data comparable to the technology of environmental satellites. The mere volume of this type of data has helped to create a whole new sub-technology dedicated solely to the retention, extraction and distribution of these data. The interpretation of such data is currently the focus of thousands of researchers who are trying to unravel some of the mysteries of the Earth and its thermal engine.

Environmental satellites represent hundreds and sometimes thousands of man-years of effort in both pre-launch and post-launch activities. On board these satellites are environmental sensors that collect information through an environment that is not a part of the satellite operational system design. Consequently, factors pertinent to calibration (linearity of response, slopes, intercepts, etc.) of environmental sensing devices may not directly relate to measurement of physical properties of the environment.

The assurance of quality acquired by sensors which are located hundreds (or even thousands) of miles away, and are accessible only after radio transmission and various other electronic or other manipulations, should not readily be taken for granted. The integration of information from multiple sources, some citing accuracies of thermal properties to a few tenths of degrees, and others to a few whole degrees, demands close scrutiny.

ACKNOWLEDGEMENTS

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CONTENTS

1. EXECUTIVE SUMMARY

The operational processing of polar satellite data has undergone many evolutionary changes since the launch of TIROS-N in 1978. These changes have resulted in both functional and organizational changes within NESDIS. In general, corporate knowledge of the detailed steps involved in processing satellite data has been greatly diminished. The following describes several factors contributing to our current situation:

-- Decreasing staff/budget and non-replacement of key positions, prompting centralization of many separate functions into one functional element.

-- Re-hosting of applications software from the original TIROS-N satellite processing subsystem to an IBM mainframe system. All capabilities inherent to the current system were not transferred in totality to the new system.

-- The lack of properly documented software, procedures, and methodologies associated with detailed, step-by-step processing of satellite data, i.e. pre-launch, early orbit support, in-flight calibration, etc.

In efforts to mitigate any further erosion of our knowledge base of operational satellite data processing with respect to calibration, this report is intended to document the instructional guidelines for processing of pre-launch and in-flight calibration data for instruments aboard the NOAA Polar-orbiting Operational Environmental Satellites (POES). Its purpose is to familiarize the reader--the user and managers of satellite acquired environmental data or data systems--with the basic operational technology, terminology and status of the NOAA polar satellite calibration system. Thus, a very brief description of calibration, radiometry, POES instrumentation, and procedures for pre-launch, early-orbit, in-flight, and post-launch support have been included as these subjects pertain to operational calibration.

2. BACKGROUND

The term "calibration" is defined as the process of determining or marking the capacity or the graduations of, or to rectify the graduations of, any measuring instrument that provides quantitative data. A more specific definition for satellite calibration is the process of quantitatively defining the system response to known controlled signal inputs. In the calibration of environmental satellites, accuracy and frequency in calibration are essential, but usually at odds with each other, and with acquisition of data. One must calibrate frequently enough so that signal changes from unwanted effects are as close to zero as possible, or at worse linear. One of the elements of accuracy usually requires a sufficiently long "look" at the calibration source. Along with the requirement for data in the sensing cycle, there must be enough time to view the calibration source.

From an operational perspective, the primary purpose of calibration is to measure the quantitative data provided by the POES satellite, and to maintain upper and lower limits on these measurements (reproducibility). However, there are other areas of major significance in the overall processes. These include:

- Providing data users with requested information on calibrated parameters for a user-specified period that may require retrieval from archived data tapes.

- Interfacing with instrument manufacturer's scientist, NASA technical officers, research (ORA) instrument scientist, calibration oversight panel, and various contractor personnel to establish procedures and algorithms for pre-launch evaluations and post-launch data ingesting.

- As user requirements change so does the satellite and instruments. This necessitates changing and/or updating the software to accommodate these revisions. Calibration provides for a better understanding of the functioning of the instrument and offers useful insights on software development for future spacecraft data processing.

3. RADIOMETRY

The bulk of the energy received by the planet Earth is in the form of solar electromagnetic radiation. Part of the incident solar energy is scattered and absorbed by the earth's atmosphere, and the remainder is transmitted to the earth's surface. Of the latter, a part is scattered outward and the remainder is absorbed. According to thermodynamic principles, absorption of electromagnetic energy by a medium is a transformation into thermal energy, which is accompanied by a rise in the thermometric temperature of the material. The reverse process, that of "thermal" emission, serves to create a balance between absorbed solar radiation and radiation emitted by the earth's surface and its atmosphere. The term "radiometry" means the measurement of incoherent radiant electromagnetic energy. All material media (gases, liquids, solids, and plasma) radiate (emit) electromagnetic energy. Planck's 1st law of physics states " radiant energy arising from processes within atoms or molecules is emitted in finite quanta each of which is equal to the product of the radiation frequency by a universal constant "$\hbar$".

The function of a radiometer is to measure the antenna radiometric temperature T_A, which represents the radiation power delivered by the antenna to the receiver. The measurement process is characterized by two important attributes: (1) accuracy (2) precision. Accuracy referring to the design of the radiometric system to measure the input/output functions of the radiometer; precision defined as the "radiometric sensitivity" that can detect the smallest change in T_A.

The general goals of pre-launch spacecraft calibration activities include the determination of linearity of response, sensitivity of the system, stability of the system, output in voltage or digital counts per quantity of radiation, and a check-out of the electronics. The accuracy of in-flight calibration depends in part on the quality, stability, and accuracy of internal calibration sources, which normally should be calibrated prior to launch by reference to appropriate standards.

In general, a radiometer is exposed to a source at one or more predetermined positions under normal atmospheric conditions or in a vacuum. Sources for thermal infrared radiation range from simple blackened surfaces to complex cavities, where their temperatures are more or less accurately measured. These in turn are usually calibrated against primary or secondary standards and a relationship is determined between the output of the radiometer and the radiance. Calibration of sources takes place via various transfer agents such as a thermophile. For visible and near infrared radiation the source may be the sun or a calibrated lamp, viewed through an integrating sphere, a diffuse plate, or some other arrangement to assure uniform illumination of the detector to as great a degree as possible. These sources are generally calibrated against primary or secondary standards through transfer agents. For microwaves the source is either a black body similar to that used for thermal infrared calibration of a "noise generator" that simulates a black body at a given brightness temperature (brightness temperature referring to a radiance count vs the usual kinetic temperature), or a grooved plate.

4. INSTRUMENTS

NOAA operates the polar satellites which provide data used to generate output products that are utilized in meeting some of the NOAA responsibilities. These products are used for meteorological prediction and warning, oceanographic and hydrologic services, and space environment monitoring and prediction. For the purpose of this report the instrumentation will be confined to the Polar Orbiting Environmental Satellites (POES).

The primary environmental sensors for these satellites are:

1. A TIROS Operational Vertical Sounder (TOVS). The TOVS is a three instrument system consisting of:

    a. High Resolution Infrared Radiation Sounder (HIRS/2)
    b. Stratospheric Sounding Unit (SSU)
    c. Microwave Sounding Unit (MSU)

2. Advanced Very High Resolution Radiometer (AVHRR)

The above instruments, being the primary instruments of concern for this report, will be discussed in detail below. (For further information on the polar satellite system refer to **NOAA Technical Memoranda NESS 95 and 116**).

Deep space is the only source that is relatively uniform, fills the FOV, and has an accurately known radiance (i.e.,close to 0). It is presumed unchanging during a mission, and is always "on". A space "look" is generally considered vital for absolute radiometric calibration of most detectors, though its use is more as a noise estimator rather than as a calibrator.

The sensor commonly views space by means of a scanning mirror or antenna. Usually a view of space is part of the scan sequence for each scan line with scanning radiometers. Each instrument aboard the NOAA Polar Orbiter has a unique "viewing" and scanning sequence.

Therefore, it would be appropriate to review the sequence of each instrument.

4.1 AVHRR

The AVHRR is a cross-track scanning system. The scanning rate is 360 scans per minute. The time within each scan line of data represents an IFOV of 1.39 milliradians. The analog data output from the sensors is digitized on board the satellite at a rate of 39,936 samples per second per channel. Each sample step corresponds to an angle of scanner rotation of 0.95 milliradians.

At this sampling rate, there are 1.362 samples per IFOV. A total of 2048 samples will be obtained per channel per Earth scan. As a result of the design of the AVHRR scanning system the normal operating mode of the satellite calls for direct transmission to Earth [continuously in real-time (High Resolution Picture Transmission/HRPT)].

4.2 HIRS/2

The IFOV of the HIRS/2 channels are stepped across the satellite track by the use of a rotating mirror. This cross track scan, combined with the satellite motion in orbit, will provide coverage of a major portion of the Earth's surface. The width of the cross track scan is 99° or 2240 km and consists of 56 steps. The mirror is stepped from home position in 55 steps of 1.8°. At the end of the scan (at position 56) the mirror rapidly returns to the home position and repeats the scanning pattern. Each scan takes 6.4 seconds to complete (100 milliseconds per step), and there are 42 km between IFOVs along the sub-orbital track.

HIRS/2 can be commanded to automatically enter a calibration mode every 256 seconds. When the instrument is in the calibration mode, the mirror (starting from the beginning of a scan line) rapidly slews to a space view and samples all channels for the equivalent time of one complete scan line of 56 scan steps. Next, the mirror is moved to a position where it views a cold calibration target and data is taken for the equivalent of 56 scan steps. The mirror is then taken to view an internal warm target for another 56 scan steps.

Upon completion of the calibration mode, the mirror continues its motion to the home position where it begins normal Earth scan. The total calibration sequence is equivalent to three scan lines (no Earth data are obtained during this period). The analog data output from the HIRS/2 sensor is digitized on-board the satellite at a rate of 2880 bits per second. At this rate, there are 288 bits per step (step time = 100 milliseconds) which includes all 20 channels.

4.3 MSU

MSU is a passive scanning microwave spectrometer (passive meaning measuring the signal received from the source, versus the usual radar/active technique of sending out a signal, exciting the source and measuring the signal received). The sensors consist of two four-inch diameter antennas, each having an IFOV of 7.5°.
The antennas are step-scanned through eleven individual 1.84-second Earth viewing steps and require a total of 25.6 seconds to complete. The 124-kilometer IFOV resolution at the sub-point creates an underlay of approximately 115 km between adjacent scan lines. The data output represents an apparent brightness temperature after a 1.84-second integration period per step. Unlike the HIRS/2 and SSU instruments, the MSU has no special calibration sequence that interrupts normal scanning. The calibration data are included in a scan line of data. From the last Earth view position, the reflector rapidly moves 4 steps to view space, 10 additional steps to view the housing, and then returns to the home position to begin another scan line. Since each scan line requires 25.6 seconds, synchronization of MSU within the other two TOVS instruments occurs every 128 seconds (5 scan lines).

4.4 SSU

The SSU is a step-scanned far-infrared spectrometer with three channnels in the 15 micrometer carbon dioxide absorption band. It makes use of the pressure modulation technique to measure radiation emitted from carbon dioxide at the top of the Earth's atmosphere. The three SSU channels have the same frequency, but different cell pressures.

The instrument consists of a single primary telescope with a 10° IFOV which is step-scanned perpendicular to the satellite subpoint track. Each scan line is composed of eight individual 4.0 second steps and requires a total of 32 seconds, including time for the mirror retrace. The 10° IFOV gives a resolution of 147 km at the satellite subpoint and the stepping produces an underlap between adjacent scan lines of approximately 62 km at nadir. A calibratioin sequence is initiated every 256 seconds (8 scans) during which the radiometer is in turn, stepped to a position to view unobstructed space and an internal blackbody at a known temperature. This calibration mode is synchronized with the HIRS/2 instrument. Data is sampled at the rate of 40 samples per second, and is digitized to 12-bit precision. Therefore, the SSU data rate is 480 bits per second.

The instrument is provided by the United Kingdom. All pre-launch processing of data is done by the UK. A chart is generated containing all final evaluatioins and sent to ISB for placement in the APPENDIX B file. Therefore, it is only necessary to receive the figures from the (UK) and place them in the file along with the other instruments data.

5. TARGETS

The target can be interpreted to be the source of the radiation being collected. It may be a cavity, a plate, a cloud, the earth's land or sea surface, or even an emitting layer of the atmosphere surrounding the sensor.

Pre-launch calibrations of the infrared and microwave channels are carried out in a thermal/vacuum chamber to minimize absorption of radiation in the path between the source and the radiometer and to simulate conditions in space. The radiometer sequentially views the warm calibrated laboratory blackbody (in place of the earth "target"), a blackbody cooled to 77 degrees Kelvin (cold space view), and its own internal blackbodies. Temperatures of all blackbodies are sensed with thermistors or platinum resistance thermometers (PRT's).

NOTE: By definition a blackbody is an ideal body or surface that absorbs completely all radiant energy of any wavelength falling upon it with no reflection of energy.

6. PRE-LAUNCH PROCESSES

Data are collected as the laboratory blackbody is cycled through a sequence of temperature plateaus approximately 10 degrees K apart between 175 and 320 degrees K, which spans the entire range of earth target temperatures. The entire procedure is carried out independently for several instrument operating temperatures (e.g.10, 15, and 20 degrees C for the AVHRR and 5, 10, 15 and 20 degrees C for the HIRS/2) that bracket the range of operating temperatures encountered in orbit. The operating temperature is represented by the temperature of the instrument's baseplate, which is also approximately the same as the temperature of its internal warm blackbody.

The instrument manufacturers and NESDIS technical personnel independently analyze the data from the pre-launch tests to determine operating characteristics of the instrument such as their signal-to-noise ratios, stability, linearity of response, and sensitivity (output in digital counts per unit incident radiance). However, one cannot expect those characteristics to be the same in orbit as they were before launch. One reason is that the thermal environment varies with position in the orbit, causing output in digital counts to vary. Also, instrument components age in the several years that usually elapse between the time of the pre-launch tests and launch, and the aging process continues during the two or more years the instrument typically operates in orbit. Therefore, the TIROS/NOAA radiometers have been designed to view cold space and one or more internal warm blackbodies as part of their normal scan sequences in orbit. This provides data in the microwave and infrared channels for determining signal-to-noise and radiometric slopes and intercepts. There are no on-board calibration sources for the visible region; in the visible channels, the calibration determined before launch is used.

There are other coefficients necessary for in-orbit calibration that must be derived from pre-launch test data. These include the coefficients to account for the non-linearity in the AVHRR's response, which will be described under the topic"AVHRR" later in this document, and the coefficients for calibrating the temperature sensors in the internal blackbodies of the AVHRR and the HIRS/2, described here.

The HIRS/2 has two internal blackbodies. The temperature of each are measured with four thermistors. The AVHRR has a single internal blackbody, whose temperature is measured with four PRT's. The MSU has two internal blackbodies, one for each of the two antennas. The temperature of each blackbody is sensed with two PRT's.

Polynomials are used to convert the outputs of each thermistor or PRT to temperature, i.e,

$$T = \sum_{j=0}^{4} a_j X^j \qquad \text{(nn)}$$

Where X is the thermistor or PRT output in digital counts, T is temperature in degrees Kelvin, and a_j are coefficients that are specific to each thermistor or PRT. A set of coefficients for each thermistor or PRT, determined by calibration against a thermometric standard, is provided by the instrument manufacturers.

However, if the in-orbit calibration is to be traceable to the laboratory blackbody and thence to the NIST standard, those coefficients should relate brightness temperature (not kinetic temperature) to counts. For the TIROS/NOAA instruments, this is achieved by using the instrument itself to transfer the calibration of the laboratory blackbody to the PRT's. This process utilizes data from the pre-launch tests. The data are analyzed by ITT and by NESDIS for the HIRS/2 and the AVHRR'S as follows:

1. The radiometer calibration, i.e., the relationship between target radiance and output of the AVHRR or HIRS/2, in digital counts, is derived from data collected when the radiometer viewed the calibrated laboratory blackbody.

2. The radiometer's outputs on viewing its internal blackbody are

now converted from counts to radiances and then to equivalent brightness temperatures. The radiometer itself measures the brightness temperatures of its internal blackbody. (See NOAA Technical Memorandum NESS 107- rev.1 Appendix A for discussion of formula to convert radiances to temperature). A data set of internal target brightness temperatures vs the outputs, in digital counts, of the internal blackbody's PRT's is thereby assembled. The number of samples is determined by the number of laboratory blackbody temperature plateaus and the number of instrument operating temperature plateaus.

3. A polynomial relating brightness temperature of the internal blackbody to PRT output, in counts, is fitted to the data by regression. The coefficients are the a_j for Eq. (nn).

The coefficients for the AVHRR and HIRS/2 are produced in this way. Similar steps are used by Jet Propulsion Laboratories (JPL) for coefficients for MSU, only different algorithms used for conversions (these algorithms will be discussed under MSU). The coefficients that are used for the AVHRR, HIRS/2, and MSU are tabulated in the file APPENDIX B. (APPENDIX B is a user output file that contains the calculated values from the pre-launch processing).

6.1 AVHRR INFORMATION

The AVHRR instrument is manufactured by the International Telephone and Telegraph Corporation (ITT) of Fort Wayne, Indiana. Upon completion of the thermal vacuum testing, ITT will send a tape with the necessary pre-launch data for processing. This tape contains the instrument temperature calibration data, and a 10, 15, 20, and 25 degree celsius base plate temperature. Also an ITT alignment and calibration data book containing tables of data equations to be used in the calibration processes will be included.

AVHRR responds to radiation reflected or incident from the earth within five specific intervals of the electromagnetic spectrum.

CHANNEL 1: records visible radiation with wavelengths of .58 to .68 microns. This channel used for the detection of cloud cover, snow cover, sea/lake ice, pollution, and tropical storms.

CHANNEL 2: records near infra-red radiation, with wavelengths of .73 to 1.0 microns and is used primarily to discern clouds. Since liquid water absorbs near infra-red radiation more strongly than visible radiation this channel is used for land-water boundaries. Can be used with channel 1 to locate areas of snow and ice melt. The NOAA AVHRR split channel allows comparison of the visible and near IR signals which aid interpretation of the data.

CHANNEL 3: records near infra-red radiation, with wavelengths of 3.55 to 3.93 microns and responds to emitted IR and reflected solar energy. Channel 3 is very sensitive to high energy sources, and can be used to detect hot spots, such as gas flares, forest fires, volcanoes, and smoke stacks. Because of its warm temperature capability and low attenuation by water vapor, Channel 3 is excellent for thermal mapping of clouds and surface temperatures in the tropics, where high moisture content often degrades longer wavelength channels.

CHANNEL 4: records IR with wavelengths of 10.3 to 11.1 microns. Used for mid-latitude ocean currents, fronts, thermal studies, and cirrus cloud coverage. Degraded in tropics (significantly) by moisture.

CHANNEL 5: records IR radiation with wavelengths 11.5 to 12.5 microns. Designed to account for effect of water vapor attenuation and to enhance determination of SST in tropics.

SENSOR MECHANICS: AVHRR sensors are mounted so that they are always oriented toward the earth. The key is the scanning mirror, which rotates 360 rpm. When pointed at the earth (each rotation) imagery sampling occurs and permits receipt of earth scene radiation at specified times during the scan. The radiation is then reflected from the scanning mirror to the secondary optics which separates it into discrete spectral bands. Visual and IR imagery are produced from the earth scene simultaneously; visual by silicon detectors, and IR by metal segment detectors. They (Vis and IR images) are then digitized and transmitted to earth via S-band frequencies.

6.1.1 AVHRR CALIBRATION

The pre-launch calibration relates the AVHRR's output, in digital counts, to the radiance of the scene. (In pre-launch tests, the scene is represented by the laboratory blackbody). The calibration relationship is a function of channel and baseplate temperature. For channel 3, which uses an InSb (indium antimonide) detector, the calibration is highly linear. However, as channel 4 and 5 use HgCdTe (mercury cadmium teluride) detectors, their calibrations are slightly nonlinear.

To characterize the calibration when the AVHRR is in orbit, the only data available are those acquired when the AVHRR views space and the internal blackbody. This gives two points on the calibration curve, sufficient to determine only a straight-line approximation to the calibration.The linear approximation is what is applied to determine scene radiances. Scene brightness Temperatures are then derived via the temperature-to-nonlinearity look-up table.

To calculate the internal blackbody radiance, it is first necessary to compute the target temperature. The conversion of PRT mean counts to temperature uses the following:

$$T_i\,(K) = \sum_{j=0}^{4} a_{ij}\, X_i^j$$

where X_i is the mean count for PRT_i where $i = 0,1,2,3,4$; a_{ij} are coefficients of the conversion algorithm; and T_i is the temperature of the internal blackbody calculated from PRT_i .

The coefficients a_{ij} are supplied in Appendix B. The average temperature of the internal target is computed by

$$T = \sum_{i=0}^{4} b_i T_i$$

where T_i is the average of the internal blackbody temperatures (K) and b_i is the weighing factor of each PRT (supplied in Appendix B)

The non-linearity in the calibration is accounted for through the addition of a correction term to the brightness temperature of the scene. The appropriate correction term is determined by interpolation in a table of correction terms versus scene brightness temperatures specified at 10 degree intervals between approximately 200 and 320K. The corrections, also functions of the AVHRR's internal blackbody, are temperatures of 10, 15, and 20C for each channel. The appropriate correction is determined by interpolation on the internal blackbody temperature.

VISIBLE CHANNEL CALIBRATION

There are no calibrated sources of visible radiation within the AVHRR instrument, so that the user must either rely on pre-launch calibration information for AVHRR channels 1 (500 to 700nm) and 2 (710 to 1000nm), or rely on the results of ground-based experimental techniques for deriving the calibration equations for these channels on the orbiting AVHRR. The target albedo (A) expressed as a percentage of that for a perfectly reflecting Lambertian surface illuminated by an overhead sun is linearly related to the count level (X):

$$A = MX + I.$$

Values of the associated slope (M) and intercept (I) deduced from pre-launch calibration data are given in Appendix B.

6.1.2 AVHRR
DATA

This is a description of the data sets used for AVHRR pre-launch processing:

The data sets generated are named by the user according to standard Fortran, e.g FT01F001 xxx.xxxxxxxx.DATA (name).

JCL

1. ASPLINE - Generates response curves for the AVHRR IR channels.

2. AVHENGF - Generates temperature to radiance table.

3. ATAPE - Reads and evaluates the ITT thermal vacuum tape.

6.1.3 AVHRR
SOURCE

1. AVHSF - Generates spline curves for IR channels.

2. ASPLINEF - contains starting wavenumber and normalized response functions.

3. AVHENG - inputs spline fit data;outputs temporary/permanent disk for temperature to radiance table of 180 to 350 degrees kelvin.

4. AVHRAVCF - updates telemetry coefficient files.

5. ENERGY - inputs spline fit data

6.1.4 AVHRR
PROCEDURES

1. Receive instrument temperature calibration tape from ITT. (AVHRR THERMAL VACUUM TEST TAPE):

   10 15 20 25 degree celsius base plate temperature. Duplicate the tapes and store as backup; Determine how many samples of Space, Ramp, Target, and Blackbodies there are per scan. Determine how many scans to process (100 or 360) Observe the PRT ranges for each PRT Observe if doric values are missing. Determine what plateau temperatures were used.

2. Generate spline curves for IR channels
   a. source code AVHSF pgm creates spline curve

   b. JCL(ASPLINE) executes AVHSF pgm

      JCL and SOURCE modules per spacecraft:

JCL	SOURCE
ASPLINEF	ASPLINEF
ASPLINEG	ASPLINEG
ASPLI203	ASPLI203
ASPLI204	ASPLINEH (204)
ASPLI205	ASPLI205

   c. Job input:
      1. Channel and number of points

      2. Wavelength vs normal response from ITT alignment and calibration data book Table 4.4 "Data measured Response". (rearrange in NESDIS channel order; switch ITT 3 & 4 table values to give NESDIS order!).

d. Job output: AVHRR Spline Curves
   1. Starting wave number
   2. Normalized Response Functions (spline curves)

   FT06F001 - Printout and temporary/permanent disk (appx-B)
   FT08F001 - SOURCE (ASPLINEX) (CPIDs).

3. Generate energy table (temperature to radiance conversion) [AVHENGX].

   a. SOURCE(AVHENX)
   b. JCL(AVHENX)

   c. Job input:
      1. Spline curves from 2.d - FT08F001 (NESDIS CHANNEL ORDER).
      2. Start temperature (180 degs K) - FT05F001

   d. Job output:
      1. Printout and temporary/permanent disk of the temperature to radiance table of 180° K to 350° K.

4. Update Telemetry coefficients file
   a. Job input:
      1. ITT Alignment and calibration data book Table 3.3.1-1 (use same calibration equations table to compute CPIDs PRT coefficients).
      2. Calibration equations

   b. Job output:
      The actual values are contained in a disk data set SOURCE(AVHRAVCF) [this is needed as input to the job in the next step @ job step name STEPTWO].

5. A two step program procedure:
   ITT AVHRR Thermal Vacuum Test Tape read and evaluation;

INTERIM:

1. Run pgm ITTTEST to determine how many samples of space, ramp, target, and BB exist per scan.

2. Check data statement in F$INIT to match FT05F001 input. F$INIT is a subroutine that has a given number of sample values of space, ramp target, and BB per scan. When this subroutine is called the data is matched with the correct spacecraft by data statement FT05F001.

a. JCL(ATAPE)..
Modules per spacecraft - refer to section on AVHRR SOURCE for appropriate module.

b. STEPONE: SOURCE(ENERGY)
Input:
1. FT05F001 - spline curves from 2.d (must be in ITT channel order for PGM energy and sub SWTCH).

Output:
1. FT01F001 - temperatures
2. FT02F001 - responses followed by radiances

c. STEPTWO: SOURCE(AVHRR)

Input:
FT01F001 - Temperatures
FT02F001 - Responses and Radiances
FT03F001 - AVHRR temperature coefficients from 4.b, calibration equations.
SYSIN - AVHRR Temperature Coefficients from 4.b...* Calibration equations needs to be modified to concatenate the card image input and data file of the Calibration Equation.
IN TAPE - The ITT AVHRR Thermal Vacuum Test Tape

Output: Printout containing the following:

Baseplate temperature target level, target temperatures, telemetry data, noise analysis and histograms for space, target,

& BB, BB PRT Temperatures and counts, BB Space, Target temperature and counts. Baseplates are at 10, 15,20 degrees centigrade. IR target temp. taken from external target PRT 2 (1 of 8) **** current method is to take the average of the four external BB PRTs***

6. This portion semi-automated using a HP - 9836 computer, 9-track temperature to radiance tape, and HPL (modified BASIC LANGUAGE).

   + ATAPE the job is run three times to get the three outputs for the Baseplate temperatures of 10, 15, and 20 degrees celsius.

   + Run program COPYIT to copy the data onto 1600 BPI 9-track tape. In ASCII format for the HP system.

   + Run program DUMPIT to verify the data copied to tape.

Input: ITT ATAPE printout 10 15 20 deg C copied to tape for Hp system process. 9-track 1600 BPI temp to radiance tape NESDIS channel order.

Output: Baseplate data work sheets Non-linearity work sheets - (all the computations were done by the computer)

NOTE: In the future we desire to fully automate this effort by modifying the ATAPE program to extract the target values and compute the non-linearity correction tables on the main frame system.

METHOD: For the temperature range, 205 to 320 deg Kelvin

- Compute the C constants by running the X (target counts) and Y (target radiance) through the least square fit algorithm.

- Utilize energy table (temp to radiance conversion table) to find temperatures. Calculate the delta T's.

- Determine average radiance for the BB from the least square coefficients and average BB space counts.

- Determine slope and intercept from average space counts and radiances, and average BB counts and radiances.

- Determine RL from (target counts * slope + intercept).

- Determine Diff TEMP from Target Temp - TL.

6.2 HIRS/2 INFORMATION

The High Resolution Infrared Radiation Sounder (HIRS/2) - a 20 channel instrument making measurements primarily in the infrared region of the spectrum. The instrument is designed to provide data that will permit calculation of a temperature profile from the surface to 10 mb; water vapor content in three layers in the atmosphere; and total ozone content. The design is based on the HIRS instrument flown on the NIMBUS satellite. Built by the Aerospace/Optical Division of ITT, HIRS measures incident radiation in 20 spectral regions of the IR spectrum, including both longwave (15 micrometers) and shortwave (4.3 micrometers) regions.

In orbit, the instrument output is locked to the spacecraft clock. The scan mirror synchronizes its stepping to this clock. The instrument can be commanded to automatically enter a calibration mode every 256 seconds. Upon receipt of the calibrate command, it enters the calibrate mode. Starting from the beginning of a scan line, the mirror rapidly slews (equivalent to the time for 8 scan elements) to a space view where it stops for the length of time necessary to complete one line (equivalent to 48 scan elements). All channels of the instrument are sampled during this period. The mirror is next moved to a position where it views a cold calibration target. Data are taken for the equivalent of 56 scan steps at which time the scan mirror is stepped to view the internal warm target. After another 56 samples, the mirror continues its motion to the start of scan (home) position, where it begins normal Earth scan. The total calibration sequence is equivalent in time to three scan lines. No Earth data are obtained during this period.

6.2.1 HIRS CALIBRATION

During normal operation, calibration of the HIRS/2 instrument is performed once every 256 seconds (40 lines). Calibration is provided by viewing two internal targets and space. The temperature of both internal targets, a warm target (IWT) around 290 K and a cold target (ICT) ranging from 260 K to 270 K, are determined from four thermistors embedded in each target. Because of large temperature gradients induced by solar effects throughout the orbit the temperature of the ICT cannot be reliably determined with sufficient accuracy to improve the calibration. Therefore, only the IWT and space-view data are used for calculating calibration coefficients.

Element 58 of each HIRS/2 line contains five samples of each of the four thermistors used to determine the temperature of the IWT. The output of each thermistor is converted to temperature K by:

$$T = \sum_{j=0}^{4} a_i \bar{X}^j$$

where T is the temperature indicated by the thermistor, $\bar{X}$ is the average of 200 samples for that thermistor (40 lines times 5 samples per line) and a_j are the conversion coefficients supplied in appendix B. The temperature of the IWT (T_{IWT}) is determined by averaging the temperatures derived from the four thermistors. The T_{IWT} is converted into radiance (N). The computation of calibration coefficients requires that for each channel an average value of the space and internal warm target view data be computed. For that line containing space-view data, there are 56 samples per channel. Samples 1 through 8 contain data while the scan mirror is moving to the space target and are therefore not usable. For that line containing IWT view data, all 56 samples per channel are usable. The channel slopes are computed by:

$$M = \frac{(N_{SP} - N_{IWT})}{(\bar{X}_{SP} - \bar{X}_{IWT})}$$

where: M is the slope for each channel

N_{SP} and N_{IWT} are the radiance of space and the internal warm target

$\bar{X}_{SP}$ is the mean space value (in counts) of the 48 usable space data samples

$\bar{X}_{IWP}$ is the mean IWT value (in counts) of the 56 usable IWT data samples.

The channel intercepts are computed from the equation

$$I = N_{SP} - M\bar{X}_{SP}$$

6.2.2 HIRS
PROCEDURES

Because of the uniqueness of the HIRS data, and processing brevity (compared to MSU and AVHRR) it is better only to consider the steps in the procedures and neglect the JCL, DATA, and SOURCE categories:

For launches up through NOAA/J it is necessary to digitize the data received from ITT for HIRS processing. This required a twenty eight step process before going into the next step of pre-launch processing. However, digitizing for NOAA/J has already been done and the KLM series will be done by the manufacturer, ITT. Therefore the HIRS data is prepared according to the following steps.

1. Receive tapes from ITT
2. Receive spectral response and optical graphs
3. Give to SIB for generation of one hundred spline points. 4. Receive one hundred point HIRS spline from SIB

   A. Floppy up load to mainframe (FILTNEWX)
   B. Extract band correction coefficients for Appendix (30 points).

4. Run JCL(HIRSFX)
   Input: (FILTNEWX)
   Output: (SPL1ICPX)- CPID order 30 points (SPL1IXBX)- APPENDIX B

5. Use ITT Alignment & Calibration data book to extract pertinent data for CIPDS file & APPENDIX B

   A. Process Electronic Calibration (15 deg C BPT), Utilizing Table 3.4-1, (Gain Grouping). Reference Green book for details. ***By running JCL(HIRSPGM)

      Input: ECFM1I-(OUTPUT FROM HIRSFX -15 deg slope/intercept data).

Output: HULSTV-CPIDS data (Gain Grouping)

B. Digital A Telemetry Conversion

1. Transfer data from Alignment and Calibration data book [Table 4.1-1), 5 terms (A-E) to CPIDS.

2. Compute Electronic Calibration Data (See explanation in Table 4.1-1...) Verify how preprocessing software uses this value.

6.3 MSU INFORMATION

Information on the MSU instrument is initially received in either of three ways: tapes, tables, or manuals. The Jet Propulsion Laboratories of Pasadena, California is the manufacturer of the MSU unit. It is from them (JPL) that the tapes containing the thermal vacuum data are obtained. Usually two tapes are received to be read for data therein. In addition to the two tapes from JPL, a set of tables and documents is sent from NASA (NASA MSU technical officer). This will include the gray code binary to digital value conversion tables, Rosemount tables, and AUX MUX P.R.T. Assignments.

Gray code binary: The gray code is a scale that ranges from 0 to 255 according to brightness. Zero being the least and 255 the brightest. In measuring radiance a brightness value is assigned. To make this value useful for calibration purposes the digital value must be known to determine a count. This table provides these conversions to digital values according to brightness.

Rosemount table: This table lists the different sensors by their respective launch model serial numbers. The table contains a resistance value for each sensor at a given temperature. The temperature range is from 180 degrees celsius to 80 degrees celsius.

AUX MUX ASSIGNMENTS: A table with PRT assignments.

NASA\JPL PRT's: Contains the calculated PRT coefficients as determined by NASA and JPL.

6.3.1 MSU CALIBRATION

Parameters necessary for calibrating are provided with each scan line. Each scan line containing only one sample for each parameter. An average of these data from several scan lines is used for the calculation of calibration coefficients.

The relationship between input radiance and instrument output counts is non-linear in the MSU channel. Only linear relationships between radiance and instrument output counts can be derived from in-flight data, therefore, a non-linearity correction must be applied. The algorithm is:

$$C' = \sum_{i=0}^{2} d_i C^i$$

where: C_i is the radiometric count output
d_i is the non-linearity correction coefficient
C' is the modified count value to be used in the linear algorithm.

NOTE: PRT's provide count output by determining target temperature.

The conversion of each PRT count output to temperature (K) requires the use of two algorithms, the first to convert counts to resistance (R) and second to convert resistance to temperature (K).

The first algorithm is:

$$R_A = K_0 + K_1 \frac{C_A - T_A \text{ CAL LO}}{T_A \text{ CAL HI} - T_A \text{ CAL LO}} \qquad \text{for PRT 1A and 2A}$$

or

$$R_B = K_0 + K_1 \frac{C_B - T_B \text{ CAL LO}}{T_B \text{ CAL HI} - T_B \text{ CAL LO}} \qquad \text{for PRT 1B and 2B}$$

where:

R_A is the resistance of PRT 1A or 2A; R_B is the resistance of PRT 1B or 2B; C_A is the count value of PRT 1A or 2A; C_B is the count value value of PRT 1B or 2B; K_0 and K_1 are the resistance conversion coefficients supplied in appendix B.
T_A CAL HI and T_A CAL LO and T_B CAL HI and T_B CAL LO are the high and low calibration reference points for electronic systems A and B respectively.
The second algorithm, converting R to temperature is:

$$T = \sum_{i=0}^{2} e_i R^i$$

where T is the temperature Kelvin of the internal target as derived from the resistance ($R = R_A$ or R_B) and e_i are the temperature conversion coefficients for each PRT. The coefficients e_i are supplied in appendix B.

(Note the similarity between the second algorithm and equation [nn] from the Pre-launch Processes discussion).

6.3.2 MSU
(DATA SETS)

The following is a list of output data sets generated in the procedure for MSU pre-launch processing. In most instances these data sets will be used as input data for the next step in the MSU senario. Therefore it is important to understand what takes place at each step in order to make an accurate verification of the data.

1. DATA(MPRTKFXX) - Gives PRTs in degrees kelvin for CPIDS AND APPENDIX B.

2. JCL(MPRTCFXX) - Degrees celsius PRT values. Used as input for MSUSS.

3. DATA(MFITCFX) - A separate output of PRT coefficients as needed by MSUSS.

4. DATA(MAVPLFMX) - the averaging of 22 values every 10 scan lines of output data from all 20 sensors.

5. DATA(MNLCPFXX) - contains the plateaus are the operating range of the values from (MAVPLFMX).

6. The final output is the data to be entered into the CPIDS AND APPENDIX B (ULTIMATE OUTPUT).

6.3.3 MSU
(JCL)

The following is a JCL list that actually executes programs to generate the various data sets and outputs necessary for the final information to be entered in CIPIDS AND APPENDIX B.

1. JCL(MROSEFMX) - reads the resistance values entered from the Rosemount table, and utilizing different temperatures (range from -50 to 50 deg C), and two check point

temperatures outputs data files. These files will become apparent in procedures.

2. JCL(MSUSS) - outputs earth, space, xtal, dicke, etc values (22 values per scan line). A very large file (MAVPLFXX).

3. JCL(MJPLPLAT) - searches the JPL tape, uses MSUSS program output data(MAVPLFXX) to find the plateau range for use in MSUNLC.

6.3.4 MSU

PROCEDURES

The following steps describes the senario by which the final data are obtained for the MSU instrument. After becoming familiar with the programs (JCL, source, data) it will become apparent that this procedure was organized in an effort to make pre-launch processing as straight-forward as possible.

1. Action #1 ....(DATA VIEW)
   A. Receive tape from JPL (normally two tapes).

   B. Run SOURCE(MSUCOPY)
      1. Reads the MSU JPL Tape
      2. Dumps 152 words of a few records.
      3. Gets internal serial number
      4. Determines number of records

After copying tape it may prove useful to allocated data to disk. This precludes having to mount a tape each time data have to be accessed. Use ISPF to allocate space, and IEBEGENER to copy data.

2. Receive from NASA MSU technical officer (JPL documents, tables, etc.).
   1. Gray code binary to digital value conversion tables

(CPIDS INPUT).
2. Rosemount tables (MROSE INPUT)
3. AUX MUX PRT Assignments (PRTFIT & MSUSS INPUT)
4. NASA/JPL PRT coefficients. (MSUNLC INPUT)

3. Job # 1 - JCL (MROSEFXX)
   A. Input: FT05F001
      1. Number of PRT's followed by blocks of 3:
      2. Number of counts, Number PRT, label
      3. Curve resistance values at, - 50° thru +50° C
      4. Two check points: +10°, +40° C

   B. Output:
      1. FT06F001 - DATA(MPRTKFXX)
         degrees Kelvin values - for CPIDS & APPENDIX B
         A. CPIDS
         B. APPENDIX B [cal 1A & 1B] [cal 2A & 2B]

      2. FT09F001 - JCL(MPRTCFXX)
         degrees celsius values - for input into MSUSS.

      3. FT08F001 - SYSOUT = T
         temperature checks for each of the 24 PRTs.

4. Run JCL(PRTFIT) on cold and hot target PRTs (-180 to 80 degrees). MSUSS uses the data generated here as input. PRTFIT was modified to generate 4th order coefficients from PRT Rosemount data (AUXMUX PRT's) PRT assignment table - cold and hot external target Input - AUX MUX PRT DATA.

The program was redesigned to read all the resistance and temperatures for each of twenty thermistors (14 earth, and 6 space). The code is designed to make the appropriate target selections from a master logical unit list via data (a FORTRAN data statement set-up - data statement dictates order).

Output - FT06F001 - Coefficients in degrees celsius.

1. A listing showing the actual data input of the twenty coefficients, and ordinate differences.

- FT09F001 - DATA (MFITCXX)

2. A separate output of just the coefficients as needed by MSUSS.

5. RUN JCL (MSUSS)
Input - JCL(MPRTCFXX) - PRT values in degrees celsius in specific order (pgm logic)

FT05F001 - DATA(MFITCFXX) coefficients from PRTFIT program output. Remember - the FM serial number and the weighing factor have to be determined.

JPL TAPE DATA
Output - EARTH, SPACE, XTAL, DICKE, etc.

1. FT10F001 - All 22 values of data per scan (large) (MAVPLFM4,MAVPLFM5,MAVPLF11,MAVPLF10...)
The averaging of 22 values every ten scans. Download into LOTUS to view the graphic display of points and compare against the output of MSUNDX. Include labels on the printout. Also save printout of all the averaged 22 parameters of information uniquely formatted for LOTUS activity.

2. FT13F001

3. FT11F001 - SYSOUT=T (large output).
A special extraction to view the external earth and space target temperatures & TCAL high and low values. These are used to determine the weighing factors for the MSUSS input.

4. FT14F001 - SYSOUT=T
Download to PC, Run LOTUS to analyze EARTH VIEW, BB, SPACEVIEW to detect and delete any bad points.

6. SOURCE(MSUNDX) (Data View)
MSUNDX - the program MSUNDX extracts the necessary information from the MSUSSND created data set (MAVPLFXX) for determining the 100 & 300 degree points and the plateau range for computing the MSU NLCs.

Input: NSS.DIATAICA.DATA(MAVPLFXX)
Output: Outlist of ET1,ET2,DKE,BT1,BT2, & SP. (Download for graphic display).

7. JCL (MJPLPLAT)

A program to search the JPL tape, MSUSS program output data (MAVPLFXX) to find the plateau range for MSUNLC. Uses the 100 and 300 degree points and selects the plateau range determined by MSUNDX.

Input: FT11F001 - DATA (MAVPLFXX) [MSUSS OUTPUT]

Output: FT08F001 - Replica of FT09 (verification)
FT09F001 - DATA (MNLCPFXX), the Plateaus [input for MSUNLC].

8. JCL (MSUNLC)

Input: DATA(MJPLCFM4) JPL coefficients.
DATA(MNLCPFXX) THE PLATEAUS.

Output: INFORMATION FOR APPENDIX-B & CPIDS.

7.0 ACTIVATION/EVALUATION

When a satellite is launched there is a period following that is referred to as Activation/Evaluation. This period usually last for 30 to 60 days. During this time there are special processing requirements for each instrument. The following lists the requirements as requested by NASA.

<u>AVHRR</u> A 10 second 1b print for turn-on at rev 001 FBK and then once per day for the first five days. A scanner jitter plot for each orbit on the first day and once daily thereafter throughout the A/E period.

Long History prints for rev's 1, 2, and 3, and for the first 3 rev's following the IR turn on at new 242 FBK.

Short History prints for each orbit for the first day and once daily thereafter throughout the A/E period.

<u>HIRS</u> A 15 minute 1b print after electronics turn-on and after IR turn on.

Long History Print required for rev's 1, 2, 3 FBK and twice daily for the 3 rev's following IR turn-on. These are to be taken simultaneously with AVHRR.

Short History Prints for each rev 1-5 and then daily throughout the A/E period. These are to be taken simultaneously with AVHRR.

<u>MSU</u> 15 minute 1b for the instrument turn-on from rev 44-49 FBK and then weekly throughout the A/E period.

Long History Print required for each rev 44 through 46 FBK.

Short History Print for each orbit from turn-on at rev 44 to 49 and daily throughout the A/E period.

SSU 15 minute 1b print after turn-on at rev 18 FBK and at rev 46 to 51 (scanner turn-on) and once per week throughout the A/E period.

Long History Print for rev 46 to 48 FBK.

Short History Print for each orbit from turn-on at rev 18 to rev 20 and at rev 46 to 51.

Both special processing and the routine processing of the satellite data are done by operating the program DFER. DFER is a program that processes the data into two distinct files; (1) level 1b - which is raw data that have been quality controlled, assembled into discrete data sets, and to which Earth location and calibration information have been appended (but not applied). (2) A calibration file that contains the calibration information according to the unique calibration periods for each instrument (see instrument descriptions under Sensors for details on calibration periods).

The program HISPRINT accesses the calibration file for required information. It (HISPRINT) can provide a Short History Print or a Long History Print. A Short History Print gives an average of the calibration parameter on a per orbit basis. The Long History Print gives the value of the parameter per calibration period, hence this can be a very long file.

7.1 IN FLIGHT

The NOAA CEMSCS computer processes the satellite data on a daily basis. The calibration parameters are plotted and checked for outliers using a trigger of six sigma. These plots are the Ingest Systems Branch's (ISB) Daily and Orbital Average Plots that are of two types (1) Long-Term Trending and (2) Short-Term Trending. Long Term Trending shows one average point per day, for the last 61 days of a given instrument parameter; each plot point represents an average of 14 orbits per 24 hours. Short-Term Trending shows one average point per orbit for the last 61 orbits of a given instrument parameter. Each plot point represents an average of its calibration summaries for that orbit (calibration summaries are the short history prints referred to in the section Activation/Evaluation).

On each page of the plotted data is a description of the type of plot, the date and julian day of the most recent orbit, and the name of the satellite. At the bottom of each graph appears a parameter number, the name of the instrument, and the parameter name.

The programs that execute the daily calibration processes are scheduled to run automatically. This involves the utilization of numerous programs and subroutines as well as archiving (considering that with each instrument and their channels approximately 1000 parameters are handled). The general operational programs are:

1. CALMONNH - Autoscheduled job submission that provides the names and slot numbers (PB) of the currently available data sets (HFLIST).

2. GRABDAY - scans the names to determine what should be submitted as input to HISPRT2.

3. IPD.SKELETON.JCL(PLOT#ND)-calls and executes several programs for plotting and checking the data:

   a. HISPTR2 - checks any errors in data and plotting components and gives error messages. It processes data from history files for all the instruments and transfers the information on the various parameters and their respective values to the calibration event file.
   b. CHECK - checks for data which is too far off the mean. By using yesterday's limits, checks most recent points for being outside the limits, and reports these points.

   c. PLOT - plots the average orbital value of the parameters that have failed the hard limit and soft limit tests.

   d. THRESHOL - transfers the values of the parameters to a QC file.

e. SORT - checks and prevents duplication of datasets so that the data sets collected will be new for the day.

By accessing the NOAA CEMSCS computer, these Trending Plots along with many others can be reviewed. They are updated every Monday morning by 7 am.

7.2 QUARTERLY CALIBRATION

Each quarter (3 mos) SOCC will request a special calibration for the MSU instrument. This is accomplished by SOCC notifying ISB of the exact date and time. This calibration involves a five minute continuous space view that allows for instrument stability and noise checkouts. Most of the actual calibration commands are controlled by SOCC and ISB's responsibility is to send to them (SOCC) a 1B listing of the responses during the period.

APPENDIX A

ACRONYMS

A/E	ACTIVATION/EVALUATION
AVHRR	ADVANCED VERY HIGH RESOLUTION RADIOMETER
CEMSCS	CENTRAL ENVIRONMENTAL SATELLITE COMPUTER SYSTEM
FBK	FAIRBANKS, ALASKA
FOV	FIELD OF VIEW
HIRS	HIGH RESOLUTION INFRA-RED RADIATION SOUNDER
ICT	INTERNAL COLD TARGET
IR	INFRA-RED
ISB	INGEST SYSTEMS BRANCH
ITT	INTERNATIONAL TELEPHONE & TELEGRAPH (CORP)
IWT	INTERNAL WARM TARGET
JCL	JOB CONTROL LANGUAGE
JPL	JET PROPULSION LABORATORIES
MSU	MICROWAVE SOUNDING UNIT
NASA	NATIONAL AERONAUTICAL AND SPACE ADMINISTRATION
NOAA	NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
POES	POLAR ORBITING ENVIRONMENTAL SATELLITE

PRT	PLATINUM RESISTANCE THERMISTOR
SIB	SATELLITE IMPLEMENTATION BRANCH
SOCC	SATELLITE OPERATIONS CONTROL CENTER
SSU	STRATOSPHERIC SOUNDING UNIT
TIROS	TELEVISION INFRA-RED OBSERVATIONAL SATELLITE
TOVS	TIROS OPERATIONAL VERTICAL SOUNDER
VIS	VISIBLE

APPENDIX B

Amendments to NOAA Technical Memorandum 107
Appendix-B for NOAA-I/13

A separate Appendix-B to NOAA Technical Memorandum 107 is prepared in advance of each new NOAA polar satellite launch. This Appendix-B contains coefficients necessary for the proper calibration of satellite data from the TIROS-N/NOAA radiometers, and is used primarily by High Resolution Picture Transmission (HRPT) and Direct Sounder Broadcast (DSB) service users. The Automatic Picture Transmission (APT) users who digitize the APT data may find some of these coefficients useful.

APPENDIX-B
NOAA-I/13 COEFFICIENTS

I. AVHRR FM-206 (SECTION 5.1)

A. VISIBLE COEFFICIENTS

CHANNEL	G	I
1	0.1076	-3.9747
2	0.1035	-3.8280

B. Related Information

The following table lists equivalent widths, integrated solar irradiances, and effective central wavelengths for the AVHRR FM-206:

	W	F	λ
Ch.1	0.121	194.09	0.641
Ch.2	0.243	249.42	0.843

Glossary:

G: Slope (% albedo/count)

I: Intercept (% albedo)

W: Equivalent width (μm)

F: In-band solar irradiance (Wm^{-2})

λ: Effective wavelength(μm)

The slope (G) and intercept (I) values are based on the November 1992 calibration of the AVHRR and the October 1992 calibration of the 40" integrating sphere performed at ITT (Reference: "AVHRR/2 FM-206 Visible calibration Data Package: November 1992, Report" submitted by ITT to NASA/GSFC on Task 15, Contract NAS5-30887). The normalized response functions given in "The ITT Alignment and Calibration Data Book" for this instrument have been used in the calculation of W, F, and λ; further, the 1984 Neckel and Labs solar spectral irradiance values have been used in the calculations of F.

NOAA-I/13 AVHRR FM-206 Calibration

PRT	a_0	a_1	a_2	a_3	a_4
1	276.597	0.051275	1.363E-06	0.0	0.0
2	276.597	0.051275	1.363E-06	0.0	0.0
3	276.597	0.051275	1.363E-06	0.0	0.0
4	276.597	0.051275	1.363E-06	0.0	0.0

b_I - PRT WEIGHTING FACTORS

b_1	b_2	b_3	b_4
0.25	0.25	0.25	0.25

CENTRAL WAVE NUMBERS, AVHRR FM-206

WHEN USED BY THE INVERSE PLANCK FUNCTION THESE CENTRAL WAVE NUMBERS GIVE THE MINIMUM ERROR FOR THE SPECIFIED TEMPERATURE BANDS. THE THIRD BAND MAY BE USEFUL FOR SEA SURFACE TEMPERATURES.

TEMP	CHANNEL 3	CHANNEL 4	CHANNEL 5
190 - 230	2636.124	924.0114	836.1164
230 - 270	2640.147	924.5165	836.4339
270 - 310	2643.153	924.9732	836.7651
290 - 330	2644.382	925.2164	836.9520

AVHRR CHANNEL 3
STARTING WAVE # 2439.02393
INCREMENT 9.41466
NUMBER OF POINTS 60

0.70987E-04	0.75658E-04	0.79814E-04	0.93517E-04	0.14134E-03
0.25731E-03	0.51168E-03	0.10443E-02	0.18303E-02	0.26639E-02
0.32382E-02	0.33804E-02	0.33377E-02	0.33039E-02	0.33312E-02
0.34008E-02	0.34656E-02	0.35141E-02	0.35435E-02	0.35476E-02
0.35277E-02	0.34953E-02	0.34641E-02	0.34478E-02	0.34484E-02
0.34596E-02	0.34647E-02	0.34488E-02	0.34288E-02	0.34245E-02
0.34288E-02	0.34286E-02	0.34129E-02	0.33948E-02	0.34647E-02
0.35928E-02	0.32841E-02	0.22153E-02	0.10875E-02	0.62718E-03
0.56816E-03	0.43822E-03	0.23721E-03	0.12460E-03	0.10527E-03
0.10527E-03	0.97071E-04	0.90372E-04	0.89954E-04	0.92967E-04
0.96603E-04	0.99287E-04	0.10000E-03	0.99557E-04	0.99218E-04
0.99283E-04	0.99416E-04	0.99433E-04	0.99382E-04	0.00000E+00

AVHRR CHANNEL 4
STARTING WAVE # 847.45752
INCREMENT 2.80419
NUMBER OF POINTS 60

0.12461E-03	0.14668E-03	0.17603E-03	0.21993E-03	0.28661E-03
0.38542E-03	0.53025E-03	0.76897E-03	0.11652E-02	0.17865E-02
0.27118E-02	0.40173E-02	0.56046E-02	0.71460E-02	0.83191E-02
0.90831E-02	0.95988E-02	0.10016E-01	0.10374E-01	0.10664E-01
0.10881E-01	0.11030E-01	0.11117E-01	0.11156E-01	0.11185E-01
0.11244E-01	0.11361E-01	0.11523E-01	0.11704E-01	0.11883E-01
0.12049E-01	0.12191E-01	0.12302E-01	0.12386E-01	0.12449E-01
0.12492E-01	0.12450E-01	0.12229E-01	0.11739E-01	0.10929E-01
0.97820E-02	0.82829E-02	0.65187E-02	0.47412E-02	0.32172E-02
0.21482E-02	0.14661E-02	0.10333E-02	0.71669E-03	0.45967E-03
0.26485E-03	0.13644E-03	0.72416E-04	0.53760E-04	0.58657E-04
0.66145E-04	0.68086E-04	0.66162E-04	0.62306E-04	0.00000E+00

AVHRR CHANNEL 5
STARTING WAVE # 787.40137
INCREMENT 2.09809
NUMBER OF POINTS 60

0.27353E-03	0.41552E-04	0.35772E-04	0.48247E-03	0.15468E-02
0.31645E-02	0.52183E-02	0.75385E-02	0.97459E-02	0.11408E-01
0.12205E-01	0.12384E-01	0.12375E-01	0.12560E-01	0.12966E-01
0.13460E-01	0.13917E-01	0.14310E-01	0.14687E-01	0.15098E-01
0.15531E-01	0.15892E-01	0.16083E-01	0.16060E-01	0.15934E-01
0.15848E-01	0.15919E-01	0.16075E-01	0.16153E-01	0.15992E-01
0.15571E-01	0.15060E-01	0.14648E-01	0.14460E-01	0.14325E-01
0.13976E-01	0.13152E-01	0.11766E-01	0.99539E-02	0.78664E-02
0.56610E-02	0.35503E-02	0.17683E-02	0.54862E-03	0.00000E+00
0.00000E+00	0.33479E-04	0.16708E-03	0.20187E-03	0.17369E-03
0.12404E-03	0.90998E-04	0.81621E-04	0.86421E-04	0.95755E-04
0.10136E-03	0.10233E-03	0.10021E-03	0.96540E-04	0.00000E+00

Non-Linear Correction Procedures for AVHRR FM-206

The response of the AVHRR channels 4 and 5 in counts is slightly non-linear and can be expressed as a quadratic function of scene radiance. With previous instruments the non-linear corrections have been given as the difference between the actual scene temperature, which is measured before launch in the laboratory, and the temperature derived from a two-point linear calibration using a radiance of space of zero (the in-flight measurement). Knowing the in-flight temperature measurement and the internal target temperature, the user could find the non-linear temperature corrections by interpolating within a two dimensional table which was provided by NESDIS.

Beginning with the AVHRR FM-206 instrument a new non-linear correction procedure is being implemented at NESDIS. As was the case previously, gain and intercept calibration coefficients (G and I) are imbedded in the 1B data stream, which allows the user to perform a linear calibration. However these coefficients are now derived using a negative radiance of space (RSP), which is a constant and which makes the non-linear corrections independent of the internal target temperature. The gain and intercept coefficients were derived from the following equations:

$$G = (RT - RSP)/(CT - CSP); \quad I = RSP - G * CSP,$$

where RT is the radiance of the internal calibration target, and CT and CSP are the counts from the views of the internal calibration target and space, respectively.

These coefficients provide a linear radiance from the instrument response in counts: $RLIN = G * C + I$. A further description of the linear calibration procedures is provided in the main text of NOAA Technical Memorandum NESS 107. The following discussion updates the description of the non-linear corrections given in the main text.

For the first time, users will have the choice of computing non-linear corrections in radiance units or in temperature units. The following equation provides a corrected radiance which is a function only of the linear radiance described above:

$$RAD = a * RLIN + b * RLIN * RLIN + c$$

With the energy tables or by using the inverse of the Planck function with the appropriate central wave numbers, this radiance can be converted to temperature. No additional temperature correction should be applied. The coefficients to apply this equation for channels 4 and 5 of FM-206 are as follows:

	Channel 4	Channel 5
Coefficient a :	0.91159	0.94784
Coefficient b :	0.0003820	0.0002057
Coefficient c :	5.01	3.24
Space Radiance RSP:	-5.31	-3.28

Some users may wish to make a temperature correction rather than a radiance correction. This may be done by first computing the linear radiance , RLIN, as described above and then converting that radiance to a measured scene temperature either by use of the energy tables or by using the inverse of the Planck function with the appropriate central wave numbers which are specified subsequently. A non-linear correction to this measured scene temperature is obtained by interpolating in the following table:

Temperature Correction Table For FM-206

Measured Scene Temperature	Temperature Corrections Channel 4	Temperature Corrections Channel 5
205.00	9.42	3.96
215.00	5.93	3.02
225.00	4.53	2.27
235.00	3.32	1.43
245.00	2.14	1.05
255.00	1.47	0.70
265.00	0.87	0.40
275.00	0.24	0.13
285.00	0.07	0.01
295.00	-0.00	0.01
305.00	-0.09	-0.06
310.00	-0.01	-0.02
315.00	0.07	0.03
320.00	0.25	0.20

It must be emphasized that these temperature corrections only apply if the linear radiance is computed using the negative radiance of space values specified previously.

II. MSU FM-09, NOAA-I/13 (SECTION 5.2)
NON-LINEARITY CORRECTION COEFFICIENTS

CHANNEL	d_0 (count)	d_1 (#)	d_2 (count^{-1})
1	53.616052	0.954298	8.92931E-6
2	36.999525	0.965759	7.10821E-6
3	42.426744	0.955055	1.02059E-5
4	35.257497	0.959981	9.23400E-6

(# d_1 is dimensionless)

PRT COUNT TO RESISTANCE COEFFICIENTS

K_0 (Ohm) 495.6

K_1 (Ohm) 107.8

Internal Warm Target PRT Resistance to Temperature (K) Coefficients:

PRT	e_0 (K)	e_1 (K/Ohm)	e_2 (K/Ohm^2)
1A	28.74552	0.4278088	3.056633E-05
2A	28.86749	0.4263018	3.083285E-05
1B	28.73856	0.4335265	3.147607E-05
2B	28.67430	0.4282688	3.054580E-05

MSU, FM-09, NOAA-I/13

Centroid of Spectral Response Functions:

CHANNEL	$v_c (cm^{-1})$
1	1.6779
2	1.7927
3	1.8334
4	1.9331

N_{SP} - RADIANCE OF SPACE

CHANNEL	N_{SP} (mW/[m^2-sr-cm^{-1}])
1	0.000086
2	0.000096
3	0.000084
4	0.000092

III. SSU, FM-7, NOAA-I/13 (SECTION 5.3)

a_j - PRT COUNT-TO-TEMPERATURE COEFFICIENTS

a_0	a_1	a_2
284.125	4.819×10^{-3}	8.75×10^{-9}

THERMISTOR TO TEMPERATURE COEFFICIENTS

b_0	b_1	b_2	b_3
375.969	-203.161	179.13	-85.16

c_0	c_1	c_2	c_3	
375.969	-203.161		179.13	-85.16

NORMALIZED RESPONSE FUNCTION

CHANNEL	CENTRAL WAVE (CM^{-1})
1	669.988
2	669.628
3	669.357

IV. HIRS/2I, FM-2I, NOAA-I/13 (SECTION 5.4)

IWT PRT COUNT-TO-TEMPERATURE COEFFICIENTS

a_0	a_1	a_2	a_3	a_4
301.37210	6.52057E-03	9.05197E-08	4.73741E-11	8.29062E-16
301.37560	6.52283E-03	9.13565E-08	4.73871E-11	7.86019E-16
301.41250	6.51819E-03	9.18444E-08	4.75139E-11	7.30508E-16
301.37420	6.51875E-03	9.04524E-08	4.72894E-11	8.06020E-16

HIRS/2I FM-2I VISIBLE COEFFICIENTS

CHANNEL	G (% ALBEDO/COUNT)	I (% ALBEDO)
20	0.02798	96.927

HIRS/2I FM-2I BAND CORRECTION COEFFICIENTS

CHANNEL	v_c	b	c
1	668.81	-0.077	1.00019
2	679.59	0.020	0.99992
3	690.18	0.016	0.99993
4	703.02	0.018	0.99991
5	715.96	0.040	0.99986
6	732.98	0.028	0.99987
7	749.34	-0.034	1.00000
8	902.39	0.544	0.99916
9	1028.77	0.062	0.99979
10	792.82	-0.005	0.99994
11	1359.95	0.090	0.99972
12	1479.90	0.292	0.99931
13	2189.06	0.022	0.99997
14	2212.55	0.021	0.99997
15	2231.68	0.029	0.99993
16	2267.04	0.022	0.99999
17	2418.31	0.025	0.99992
18	2516.80	0.058	0.99970
19	2653.33	0.264	0.99927

HIRS/2I FM-2I TYPICAL RADIOMETRIC PERFORMANCE (bp=15°C).

Channel	Slope	Output Noise (Counts)	Calculated NE ΔN	Specified NE ΔN
1	.3070508	2.11	.646	3.00
2	.1732523	0.86	.148	0.67
3	.1294716	0.91	.118	0.50
4	.0600071	0.91	.055	0.31
5	.0538439	0.93	.050	0.21
6	.0571450	1.03	.059	0.24
7	.0328884	0.96	.032	0.20
8	.0551080	0.45	.025	0.10
9	.0677353	0.34	.023	0.15
10	.0387282	0.92	.036	0.20
11	.0359972	0.95	.034	0.20
12	.0377320	0:92	.035	0.19
13	.0009931	1.00	.0009	0.006
14	.0011266	1.02	.0011	0.003
15	.0009784	0.99	.0009	0.004
16	.0006535	1.23	.0007	0.002
17	.0020032	0.46	.0009	0.002
18	.0009856	0.49	.0004	0.002
19	.0004590	0.49	.0002	0.001
20	.02692898	0.35	.009%	.1%

NOTE: Slope is mW/m^2 ster cm^{-1} per count (except channel 20 which is % albedo per count).
Noise is the counts, standard deviation from 4480 samples in each channel.

NORMALIZED RESPONSE FUNCTIONS (FROM 30-POINT SPLINE FIT)
HIRS/2I, FM-2I, NOAA-I/13

CHANNEL 1
STARTING WAVE # 0.65741E+03
INCREMENT 0.89862E+00
NUMBER OF POINTS 30

0.00000E+00	0.95119E-03	0.18285E-02	0.26421E-02	0.34792E-02
0.41578E-02	0.53232E-02	0.10528E-01	0.22165E-01	0.42956E-01
0.73857E-01	0.12259E+00	0.18774E+00	0.19917E+00	0.16597E+00
0.10640E+00	0.60611E-01	0.35472E-01	0.21101E-01	0.12581E-01
0.76335E-02	0.48522E-02	0.50691E-02	0.51278E-02	0.44333E-02
0.34589E-02	0.22803E-02	0.65961E-03	0.00000E+00	0.00000E+00

CHANNEL 2
STARTING WAVE # 0.66046E+03
INCREMENT 0.13497E+01
NUMBER OF POINTS 30

0.00000E+00	0.41925E-03	0.89170E-03	0.82879E-03	0.87767E-03
0.11920E-02	0.36109E-02	0.83087E-02	0.18555E-01	0.34771E-01
0.50469E-01	0.60258E-01	0.65837E-01	0.69401E-01	0.72030E-01
0.73981E-01	0.75699E-01	0.74049E-01	0.60040E-01	0.37045E-01
0.16760E-01	0.73536E-02	0.32478E-02	0.15859E-02	0.13937E-02
0.11077E-02	0.78120E-03	0.41411E-03	0.46593E-04	0.14669E-08

CHANNEL 3
STARTING WAVE # 0.66549E+03
INCREMENT 0.16921E+01
NUMBER OF POINTS 30

0.00000E+00	0.16050E-11	0.00000E+00	0.30538E-04	0.26797E-03
0.52910E-03	0.69761E-03	0.16125E-02	0.45751E-02	0.12009E-01
0.25721E-01	0.40498E-01	0.55442E-01	0.69382E-01	0.78400E-01
0.77331E-01	0.71258E-01	0.63586E-01	0.47478E-01	0.23191E-01
0.94550E-02	0.37628E-02	0.17400E-02	0.14150E-02	0.99220E-03
0.75665E-03	0.31206E-03	0.29803E-03	0.31239E-03	0.19875E-06

CHANNEL 4
STARTING WAVE # 0.68186E+03
INCREMENT 0.16155E+01
NUMBER OF POINTS 30

0.00000E+00	0.13431E-03	0.35993E-03	0.80011E-03	0.16333E-02
0.37091E-02	0.81738E-02	0.18148E-01	0.32996E-01	0.46599E-01
0.52598E-01	0.54132E-01	0.55099E-01	0.56365E-01	0.57749E-01
0.57620E-01	0.54048E-01	0.45428E-01	0.32808E-01	0.19206E-01
0.10168E-01	0.52492E-02	0.28703E-02	0.15801E-02	0.84042E-03
0.57548E-03	0.97217E-04	0.17979E-04	0.96420E-05	0.31857E-08

CHANNEL 5

STARTING WAVE # 0.67576E+03

INCREMENT 0.26938E+01

NUMBER OF POINTS 30

0.00000E+00	0.65092E-12	0.00000E+00	0.19818E-08	0.10010E-06
0.40203E-04	0.17247E-03	0.35861E-03	0.55066E-03	0.12542E-02
0.42775E-02	0.14774E-01	0.34844E-01	0.49947E-01	0.57239E-01
0.59415E-01	0.56200E-01	0.46313E-01	0.27101E-01	0.11542E-01
0.37914E-02	0.11748E-02	0.81256E-03	0.56870E-03	0.39392E-03
0.16246E-03	0.91760E-04	0.10593E-03	0.12144E-03	0.50821E-07

CHANNEL 6

STARTING WAVE # 0.69880E+03

INCREMENT 0.23621E+01

NUMBER OF POINTS 30

0.00000E+00	0.16267E-04	0.79955E-04	0.26343E-03	0.46148E-03
0.69217E-03	0.85638E-03	0.18513E-02	0.42426E-02	0.96175E-02
0.18611E-01	0.30705E-01	0.41099E-01	0.50483E-01	0.54543E-01
0.52881E-01	0.49635E-01	0.43958E-01	0.31397E-01	0.16207E-01
0.68657E-02	0.30349E-02	0.15168E-02	0.11794E-02	0.94464E-03
0.80191E-03	0.60098E-03	0.49006E-03	0.32562E-03	0.36649E-07

CHANNEL 7

STARTING WAVE # 0.70117E+03

INCREMENT 0.33738E+01

NUMBER OF POINTS 30

0.00000E+00	0.19100E-04	0.15503E-04	0.11577E-04	0.23800E-04
0.12686E-03	0.20091E-03	0.31126E-03	0.39319E-03	0.74094E-03
0.29168E-02	0.13091E-01	0.38072E-01	0.48079E-01	0.50071E-01
0.52410E-01	0.48469E-01	0.27417E-01	0.90765E-02	0.25147E-02
0.76194E-03	0.70192E-03	0.51472E-03	0.31326E-03	0.11631E-03
0.13957E-04	0.10704E-04	0.74844E-05	0.42397E-05	0.54034E-09

CHANNEL 8

STARTING WAVE # 0.85117E+03

INCREMENT 0.29976E+01

NUMBER OF POINTS 30

0.00000E+00	0.51345E-08	0.00000E+00	0.40410E-04	0.16097E-03
0.21520E-03	0.38994E-03	0.91420E-03	0.17384E-02	0.44183E-02
0.10230E-01	0.18675E-01	0.23944E-01	0.26296E-01	0.28676E-01
0.30887E-01	0.30999E-01	0.29099E-01	0.27236E-01	0.27657E-01
0.30008E-01	0.25194E-01	0.11350E-01	0.34872E-02	0.10204E-02
0.35952E-03	0.29284E-03	0.22206E-03	0.94810E-04	0.69754E-08

CHANNEL 9
STARTING WAVE # 0.98054E+03
INCREMENT 0.33952E+01
NUMBER OF POINTS 30

0.00000E+00	0.14468E-04	0.13005E-03	0.23114E-03	0.33374E-03
0.47217E-03	0.10638E-02	0.18840E-02	0.41756E-02	0.90987E-02
0.17293E-01	0.25518E-01	0.30263E-01	0.31660E-01	0.31628E-01
0.31867E-01	0.33530E-01	0.33543E-01	0.23332E-01	0.10643E-01
0.41635E-02	0.16225E-02	0.78903E-03	0.47227E-03	0.34061E-03
0.24446E-03	0.16207E-03	0.66849E-04	0.74272E-05	0.81459E-09

CHANNEL 10
STARTING WAVE # 0.75978E+03
INCREMENT 0.22772E+01
NUMBER OF POINTS 30

0.00000E+00	0.49558E-06	0.44548E-05	0.79173E-05	0.11431E-04
0.16173E-04	0.36439E-04	0.64534E-04	0.14303E-03	0.31166E-03
0.59235E-03	0.87408E-03	0.10366E-02	0.10844E-02	0.10834E-02
0.10915E-02	0.11485E-02	0.11489E-02	0.79919E-03	0.36457E-03
0.14261E-03	0.55574E-04	0.27027E-04	0.16177E-04	0.11667E-04
0.83736E-05	0.55513E-05	0.22898E-05	0.25440E-06	0.27902E-10

CHANNEL 11
STARTING WAVE # 0.12907E+04
INCREMENT 0.47207E+01
NUMBER OF POINTS 30

0.00000E+00	0.13528E-03	0.13612E-03	0.13757E-03	0.12417E-03
0.13106E-03	0.24266E-03	0.55865E-03	0.11906E-02	0.32481E-02
0.85970E-02	0.18262E-01	0.24218E-01	0.23633E-01	0.21982E-01
0.21426E-01	0.21720E-01	0.21968E-01	0.20292E-01	0.14269E-01
0.63976E-02	0.20395E-02	0.69574E-03	0.29148E-03	0.11302E-03
0.36796E-04	0.00000E+00	0.00000E+00	0.38798E-10	0.00000E+00

CHANNEL 12
STARTING WAVE # 0.13855E+04
INCREMENT 0.67414E+01
NUMBER OF POINTS 30

0.00000E+00	0.84234E-06	0.97108E-06	0.52040E-04	0.12417E-03
0.20506E-03	0.31037E-03	0.11711E-02	0.53534E-02	0.12026E-01
0.13327E-01	0.12841E-01	0.12974E-01	0.12630E-01	0.11851E-01
0.12109E-01	0.11289E-01	0.10703E-01	0.99887E-02	0.81774E-02
0.66938E-02	0.41683E-02	0.17157E-02	0.43195E-03	0.11223E-03
0.63421E-04	0.21745E-04	0.76421E-06	0.28188E-06	0.18228E-10

CHANNEL 13
STARTING WAVE # 0.21461E+04
INCREMENT 0.30345E+01
NUMBER OF POINTS 30

0.00000E+00	0.56205E-05	0.25806E-05	0.44786E-04	0.15438E-03
0.28348E-03	0.42069E-03	0.55881E-03	0.16105E-02	0.46661E-02
0.18325E-01	0.37195E-01	0.40099E-01	0.35591E-01	0.36629E-01
0.41438E-01	0.42311E-01	0.34601E-01	0.21127E-01	0.91064E-02
0.32581E-02	0.84612E-03	0.62084E-03	0.40057E-03	0.21572E-03
0.22971E-05	0.15543E-04	0.15726E-04	0.90622E-05	0.12405E-08

CHANNEL 14
STARTING WAVE # 0.21758E+04
INCREMENT 0.27034E+01
NUMBER OF POINTS 30

0.00000E+00	0.13963E-06	0.61772E-04	0.29614E-03	0.46379E-03
0.66161E-03	0.87130E-03	0.24524E-02	0.66104E-02	0.15987E-01
0.27746E-01	0.37140E-01	0.42385E-01	0.45854E-01	0.47110E-01
0.44781E-01	0.38148E-01	0.27438E-01	0.17034E-01	0.79153E-02
0.35104E-02	0.14752E-02	0.84715E-03	0.62514E-03	0.35468E-03
0.14198E-03	0.00000E+00	0.00000E+00	0.58714E-10	0.00000E+00

CHANNEL 15
STARTING WAVE # 0.21906E+04
INCREMENT 0.30517E+01
NUMBER OF POINTS 30

0.00000E+00	0.11702E-03	0.25515E-03	0.41401E-03	0.52588E-03
0.83331E-03	0.18000E-02	0.43999E-02	0.91005E-02	0.16084E-01
0.24008E-01	0.31454E-01	0.36783E-01	0.38401E-01	0.37207E-01
0.35201E-01	0.32290E-01	0.26438E-01	0.17604E-01	0.88693E-02
0.31208E-02	0.13862E-02	0.66927E-03	0.48403E-03	0.21365E-03
0.46777E-04	0.82745E-06	0.75906E-06	0.42737E-06	0.59953E-10

CHANNEL 16
STARTING WAVE # 0.22207E+04
INCREMENT 0.33897E+01
NUMBER OF POINTS 30

0.00000E+00	0.29477E-04	0.24339E-04	0.20804E-04	0.17586E-03
0.30890E-03	0.43665E-03	0.57632E-03	0.13547E-02	0.48542E-02
0.15901E-01	0.31974E-01	0.42399E-01	0.44842E-01	0.43995E-01
0.41787E-01	0.34903E-01	0.19806E-01	0.73467E-02	0.18798E-02
0.60498E-03	0.60294E-03	0.45669E-03	0.28440E-03	0.17626E-03
0.78956E-04	0.71410E-04	0.65512E-04	0.59801E-04	0.16971E-07

CHANNEL 17

STARTING WAVE # 0.23807E+04

INCREMENT 0.27069E+01

NUMBER OF POINTS 30

0.00000E+00	0.49123E-03	0.56009E-04	0.74611E-04	0.57702E-03
0.10005E-02	0.17514E-02	0.32947E-02	0.78090E-02	0.21903E-01
0.37760E-01	0.37003E-01	0.29958E-01	0.28258E-01	0.30412E-01
0.34413E-01	0.36738E-01	0.34603E-01	0.26802E-01	0.16272E-01
0.85769E-02	0.43458E-02	0.30137E-02	0.15597E-02	0.38863E-03
0.95292E-03	0.44940E-03	0.58509E-03	0.39320E-03	0.00000E+00

CHANNEL 18

STARTING WAVE # 0.24315E+04

INCREMENT 0.57552E+01

NUMBER OF POINTS 30

0.00000E+00	0.37052E-05	0.69777E-04	0.11337E-03	0.13441E-03
0.19548E-03	0.24436E-03	0.43705E-03	0.10292E-02	0.24281E-02
0.57647E-02	0.10213E-01	0.15350E-01	0.18555E-01	0.20888E-01
0.22129E-01	0.21614E-01	0.19332E-01	0.15765E-01	0.98820E-02
0.51885E-02	0.23122E-02	0.99010E-03	0.47972E-03	0.24534E-03
0.19733E-03	0.11662E-03	0.76397E-04	0.42582E-05	0.23110E-10

CHANNEL 19

STARTING WAVE # 0.25037E+04

INCREMENT 0.11769E+02

NUMBER OF POINTS 30

0.00000E+00	0.95791E-08	0.10033E-04	0.55274E-04	0.10701E-03
0.14156E-03	0.47403E-03	0.11655E-02	0.27314E-02	0.60835E-02
0.89646E-02	0.10067E-01	0.10085E-01	0.92837E-02	0.86678E-02
0.90217E-02	0.97985E-02	0.54453E-02	0.17813E-02	0.57509E-03
0.19564E-03	0.10708E-03	0.85435E-04	0.61255E-04	0.33690E-04
0.15718E-04	0.64077E-05	0.42495E-05	0.21152E-05	0.44513E-10

APPENDIX C

ELECTROMAGNETISM SPECTRUM

A copy of the electromagnetic spectrum has been included for a handy reference. This should aid in the appreciation of the frequency ranges (channels) of each instrument.

ELECTROMAGNETIC SPECTRUM

SW=SHORT WAVE
LW=LONG WAVE

METEOROLOGY
SW LW
.2μm 4μm 50μm

REMOTE SENSING (Active)
Radar
3.5, 10 cm

COMMUNICATIONS
FM
106-88 MC
TV
Microwave Channels SW AM LW
m-bands m-bands
1600 - 550 KC
Wx Radio

STANDARD DESCRIPTION
Gamma rays X-rays Ultraviolet Visible Infrared Microwave Radio "Acoustic" Waves

10^{-12} 10^{-10} 10^{-8} 10^{-6} 10^{-4} 10^{-2} 10^{0} 10^{2} 10^{4} 10^{6}
WAVELENGTH (meters)

SUBSET WAVELENGTH DIMENSIONS
Micronmeters (μm) 10^{-2} 10^{0} 10^{2}
Angstroms
Å 10^{0} 10^{2} 10^{4}

FREQUENCY DIMENSION
Hertz (Hz) $3*10^{18}$ $3*10^{16}$ $3*10^{14}$ $3*10^{12}$ $3*10^{10}$ $3*10^{8}$ $3*10^{6}$ $3*10^{4}$ $3*10^{2}$
SUBSETS
Kilocycles (KC) $3*10^{5}$ $3*10^{3}$ $3*10^{1}$
Megacycles (MC) $3*10^{4}$ $3*10^{2}$ $3*10^{0}$
Gigahertz (GHZ) $3*10^{5}$ $3*10^{3}$ $3*10^{1}$

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