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# Fleet Numerical Oceanography Center and Tactical Environmental Support System Satellite Retrieval Methods For Scheduled Satellite Upgrades

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This report details the software requirements for scheduled Defense Meteorological Satellite Program (DMSP) and National Oceanic and Atmospheric Administration (NOAA) environmental satellite sensor upgrades for both the Fleet Numerical Oceanography Center(FNOC) and the Tactical Environmental Support System (TESS). The report describes current and future sensor packages flown on DMSP and NOAA polar orbiting platforms. Planned algorithm philosophies and options for both central site (FNOC) and tactical sites (TESS) are presented and recommendations are made. Hardware modifications required for acquisition of data from scheduled environmental satellite sensor upgrades are not presented in detail in this report.

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# FLEET NUMERICAL OCEANOGRAPHY CENTER AND TACTICAL ENVIRONMENTAL SUPPORT SYSTEM SATELLITE RETRIEVAL METHODS FOR SCHEDULED SATELLITE UPGRADES

## 1. INTRODUCTION AND BACKGROUND

### 1.1 Introduction

The purpose of this report is to detail the sensor characteristics and associated environmental retrieval methods in preparation for scheduled Defense Meteorological Satellite Program (DMSP) and National Oceanic and Atmospheric Administration (NOAA) environmental satellite sensor upgrades for both the Fleet Numerical Oceanography Center (FNOC) and the Tactical Environmental Support System (TESS). Algorithm philosophies and options for both central site (FNOC) and tactical sites (TESS) will be presented. Hardware modification requirements for acquisition of data from scheduled environmental satellite sensor upgrades will not be presented in detail in the current report.

### 1.2 Background

The U.S. Navy has requirements to process environmental satellite data at FNOC for central site products and at TESS sites for tactically oriented products. FNOC's Satellite Processing Center is responsible for receiving, processing, producing and distributing global environmental satellite products and has the distinct advantage of having access to the complete suite of real-time Navy Operational Global Atmospheric Prediction System (NOGAPS) products and fields (Hogan et al., 1991). TESS(3) has the responsibility of receiving and processing various environmental satellite data in support of on-scene tactical nowcasting (Phegley and Crosiar, 1991). With scheduled environmental satellite sensor upgrades, the Navy must be aware of the new sensors and decide which algorithm approach should be pursued in order to maintain current capabilities and to meet future enhanced operational requirements of FNOC and TESS.

## 2. CURRENT NAVY ENVIRONMENTAL SATELLITE PROCESSING

### 2.1 FNOC Environmental Satellite Processing

Environmental satellite processing at FNOC is designed to satisfy validated fleet requirements. These requirements include the providing of initial state data utilized by the Navy's Numerical Weather Prediction (NWP) models, including NOGAPS and the Navy Operational Regional Atmospheric Prediction System (NORAPS) and to provide near real-time satellite imagery and derived products to the operating forces of the U.S. Navy. Continued upgrades to NOGAPS/NORAPS must also include a continued effort in maintaining optimal satellite data assimilation methods. In order to realize the full potential of current and future environmental satellite derived products, and in turn meet the requirements of NWP forecasting skill, considerable efforts must be made in remaining at the forefront in assimilation of DMSP and NOAA satellite derived products.

A joint agreement exists between the Air Force, Navy and NOAA to share processing tasks and environmental product lines of mutual interest to all parties from DMSP, GOES, and TIROS. Data is exchanged between the Air Force Global Weather Central (AFGWC), the National Environmental Satellite, Data, and Information Service (NESDIS), the Naval Oceanography Center and FNOC via the Shared Processing Network (SPN). FNOC has been designated as the Center of Expertise (COE) for the processing of the DMSP Special Sensor Microwave/Imager (SSM/I).

### 2.2 TESS Environmental Satellite Processing

TESS is a modular, minicomputer based support system designed to provide Navy tactical commanders at selected shore commands and major ship combatants with secure and responsive environmental support. A Pre-Planned Product Improvement (P3I) program is underway to provide upgrades to both hardware and software systems of TESS(3). Richardson (1990) details many of the primary satellite sensor changes to occur during the TESS(3) preoperational development phase. Currently, TESS(3) has the capability to process the following environmental satellite data: DMSP data including OLS and SSM/I; NOAA TIROS; TOVS soundings; AVHRR; and GOES-WEFAX.

## 3. CURRENT DMSP AND NOAA POLAR ORBITING SATELLITE SENSORS

### 3.1 DMSP Sensors

The U.S. Air Force manages the DMSP, which is the Department of Defense (DoD) operational environmental satellite system designed to support worldwide military requirements. On-board sensors provide to FNOC and AFGWC, in stored mode format, global visible and infrared imagery, temperature and humidity soundings, auroral electron counts, and other specialized environmental data. DMSP also provides, in real mode format, direct readout (line of sight) visible and infrared data, as well as the special sensor data (sounder and imager) to TESS and worldwide tactical terminal sites.

The current DMSP Block 5D-2 satellite series is equipped with an Operational Linescan System (OLS), Special Sensor Microwave Temperature Profiler (SSM/T-1), Microwave Humidity Profiler (SSM/T-2), Microwave Imager (SSM/I), and other space environment sensors and instruments.

#### 3.1.1 Operational Linescan System (OLS)

The OLS is the primary data acquisition system on the DMSP Block 5D satellite. The system is designed to receive and transmit in real-time (real mode) or store multi-orbit (stored mode) day and night, visible (0.4 - 1.0 $\mu$m) and infrared (10.5 - 12.5 $\mu$m) spectrum data. These data, together with appropriate calibration, indexing, and other auxiliary signals, are provided to the spacecraft for transmission to ground stations. The OLS provides a near constant image resolution system in both visible (L-data) and thermal (T-data) modes. Fine resolution data (0.5 km resolution) is collected continuously by the infrared detector (TF-data) and during daylight for the visible detector (LF-data). Data smoothing permits global coverage in both the

TS and LS data modes resulting, but results in resolution degradation to 2.8 km. The OLS provides a swath width of 2963 km at a nominal altitude of 833 km.

### 3.1.2 Special Sensor Microwave Temperature Sounder (SSM/T-1)

In 1978, the SSM/T-1 became the first microwave sounder to be flown on a DMSP satellite. The objective of utilizing a microwave sensor was to overcome the limitations of infrared sounders by providing a better capability of temperature retrievals in cloudy atmospheres. The SSM/T-1 sensor system was designed to acquire microwave data simultaneously in seven channels. Table 1 describes the SSM/T-1 channel characteristics. Channel 1 (50.5 GHz) is a window channel responding to the earth's surface characteristics, dense clouds (high liquid water content), and rain. Background effect corrections to the other channels are made by means of channel 1. Polarization dependent surface characteristics are removed from the brightness temperatures, leaving only the atmospheric contribution which is polarization independent. Only channels 1-4 are affected by surface contributions, and therefore, must have the same polarization. Channels 5-7 are not affected by the surface, and do not have polarization constraints.

Table 1. DMSP Special Sensor Microwave Temperature Sounder (SSM/T-1)

| SSM/T-1 Channel No. | Center Frequency (MHz) | Maximum Bandwidth (MHz) | Beamwidth (Degrees) | NEΔT (K) |
|---|---|---|---|---|
| 1 | 50500 | 400 | 14.4 | 0.6 |
| 2 | 53200 | 400 | 14.4 | 0.4 |
| 3 | 54350 | 400 | 14.4 | 0.4 |
| 4 | 54900 | 400 | 14.4 | 0.4 |
| 5 | 58400 | 115 | 14.4 | 0.5 |
| 6 | 58825 | 400 | 14.4 | 0.4 |
| 7 | 59400 | 250 | 14.4 | 0.4 |

The SSM/T-1 instrument is a cross track dwell and step Dicke type microwave radiometer with a 32 second scan period. Microwave data are acquired at seven beam positions separated by 12 angular intervals with a 2.7 second integration time. Calibration is performed on each scan by means of cold and warm calibration targets. The cold target is a cold space reflector at 2.7 K; the warm calibration is a 300 K warm reference load. Synchronization, clock reference, system time and source power are supplied by the DMSP spacecraft.

### 3.1.3 Special Sensor Microwave Imager (SSM/I)

The first SSM/I was launched onboard the DMSP Block 5D-2 platform in June of 1987. The SSM/I, designed and built by Hughes Aircraft Company, is a scanning microwave radiometer system with four discreet frequencies at 19.35, 22.235, 37.0, and 85.5 GHz (Hollinger and Lo, 1983) designed to provide imagery and twelve environmental parameters. The brightness temperatures measured by the SSM/I are significantly affected by atmospheric attenuation and emission due to water vapor, clouds, precipitation, and the far wings of the oxygen band. The environmental parameters include: rain rates, water vapor and cloud liquid water over oceans, ocean surface wind speed, sea ice (age, concentration and edge location), snow water content, land surface type, land surface temperature, soil moisture, and cloud amount over land. Dual linear polarizations (horizontal and vertical) are available at each frequency except 22.235 GHz. Table 2 details the frequency characteristics of the SSM/I. The SSM/I instrument consists of an offset parabolic reflector, rotating at 31.6 rpm, which generates a conical scan pattern at 45° with the nadir, resulting in a 53.1° incidence angle with the earth's surface. Radiometric data are collected during 102 of the revolution with an integration time per sample of 7.95 ms (3.89 ms for the 85.5 GHz), resulting in a 1400 km swath width. The 85 GHz channels are sampled 128 times per scan (12.5 km scene spacing), while the lower frequencies are sampled 64 times per scan (25 km scene spacing). Due to the different size antenna footprints, the SSM/I 85 GHz channels are sampled every scan and the lower frequency channels are sampled every other scan, resulting in A and B scans. A complete set of housekeeping data requires four scans, resulting in an A, B, A', B' scan sequence.

### 3.1.4 Special Sensor Microwave Water Vapor Sounder (SSM/T-2)

The SSM/T-2 was the first microwave humidity profiler to be flown on a DMSP Block 5D-2 spacecraft. The first operational SSM/T-2 was onboard the F-11 spacecraft launched Thanksgiving Day, 1991. The SSM/T-2 was designed to work together with the SSM/T-1 in order to retrieve profiles of specific humidity, relative humidity and water vapor mass. The SSM/T-2 has three channels on the 183 GHz water vapor resonance line, a 150 GHz channel, and a 91 GHz channel. Similar to the SSM/T-1, the SSM/T-2 is a cross track dwell and step radiometer, but with an 8 second scan period. Radiometric data are acquired at 28 beam positions (3 angular increments), with four successive scans required to match the SSM/T-1 footprints. Figure 1 demonstrates the SSM/T-2 cross track scan geometry and relation to the SSM/T-1 footprints. Radiometric calibration is performed each scan via warm load and cold space calibration targets. The SSM/T-2 radiometric data has also shown value as imagery products, yielding multiple level structure to cloud and precipitation systems.

Table 2. DMSP Special Sensor Microwave Imager (SSM/I)

| SSM/I Channel No. | Center Frequency (MHz) | Maximum Bandwidth (MHz) | Polarization | Horizontal Resolution (Km) | NEΔT (K) |
|---|---|---|---|---|---|
| 1 | 19350 | 400 | H | 70 by 45 | 0.8 |
| 2 | 19350 | 400 | V | 70 by 45 | 0.8 |
| 3 | 22235 | 400 | V | 60 by 40 | 0.8 |
| 4 | 37000 | 400 | H | 38 by 30 | 0.6 |
| 5 | 37000 | 400 | V | 38 by 30 | 0.6 |
| 6 | 85500 | 350 | H | 16 by 14 | 1.1 |
| 7 | 85500 | 350 | V | 16 by 14 | 1.1 |

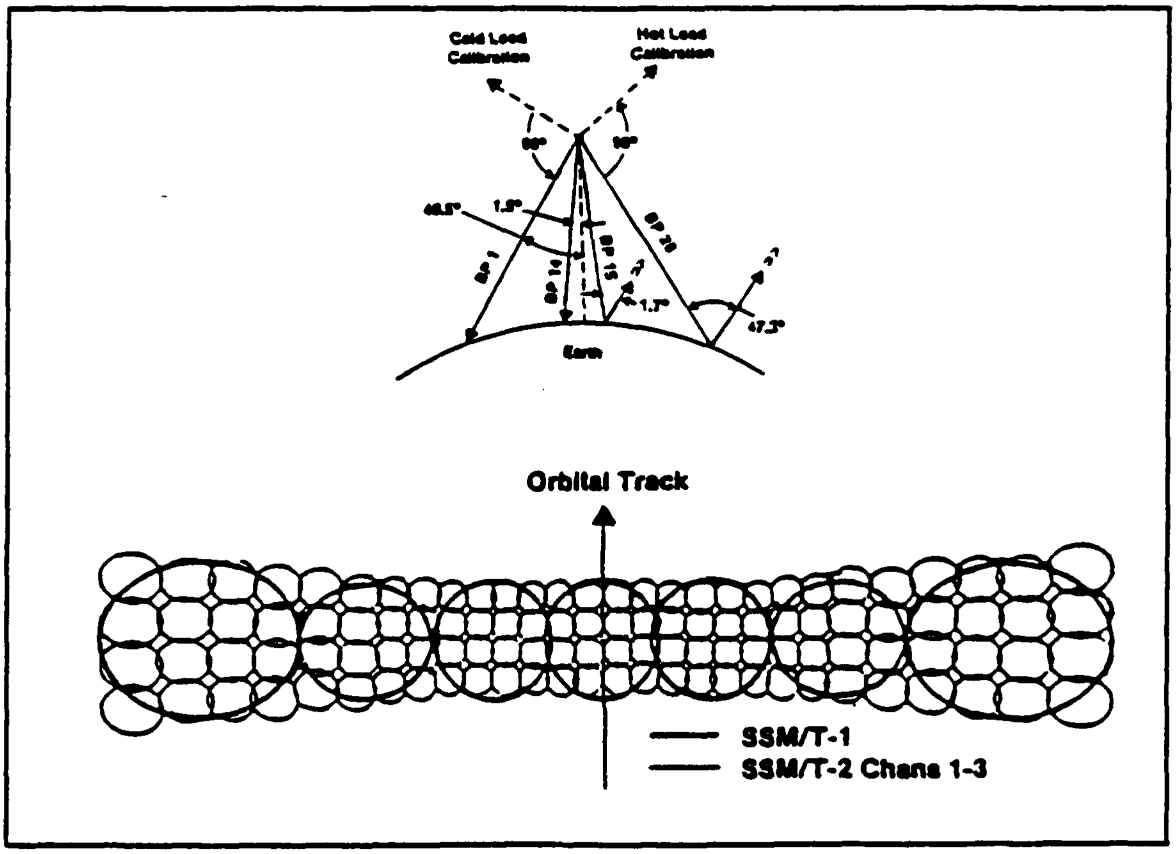


Figure 1. SSM/T-2 Scan Geometry and Coincidence with the SSM/T-1 Footprints (Courtesy of Aerojet Electronic Systems, Azusa, CA).

Table 3. DMSP Special Sensor Microwave Humidity Sounder (SSM/T-2)

| SSM/T-2 Channel No. | Center Frequency (MHz) | Maximum Bandwidth (MHz) | Beamwidth (Degrees) | Nadir Resolution (Km) | NEΔT (K) |
|---|---|---|---|---|---|
| 1 | 183310±3000 | 1000 | 3.3 | 48 | 0.6 |
| 2 | 183310±1000 | 500 | 3.3 | 48 | 0.8 |
| 3 | 183310±7000 | 1500 | 3.3 | 48 | 0.6 |
| 4 | 91655±1250 | 1500 | 5.75 | 84 | 0.6 |
| 5 | 150000±1250 | 1500 | 3.7 | 54 | 0.6 |

## 3.2 NOAA Sensors

The NOAA series of environmental polar orbiting satellites replaced the TIROS-N, NASA prototypes, with the launch of the first NOAA funded operational satellite in June 1979. Currently, the primary operational spacecraft are the NOAA-11 and NOAA-12. The NOAA series satellites carry four primary instrument systems. These include the Advanced Very High Resolution Radiometer (AVHRR/2), TIROS Operational Vertical Sounder (TOVS), Data Collection System (DCS), and the Space Environment Monitor (SEM).

### 3.2.1 Advanced Very High Resolution Radiometer (AVHRR/2)

The five channel AVHRR/2 became operational with the launch of NOAA-7, June 1981. The AVHRR/2 provides data for real time transmission to both Automatic Picture Transmission (APT) and High Resolution Picture Transmission (HRPT) users and for storage of global data on the spacecraft tape recorders. The APT data is analog and the HRPT is digital. AVHRR/2 data is available at 4 km resolution for direct readout APT stations and at 1.1 km resolution for direct readout HRPT stations. Global Area Coverage (GAC) at 4 km resolution is obtained from the onboard recorders at the NOAA central computer facility, Suitland, MD. The above resolutions represent the values for the nadir position. Table 4 describes the AVHRR/2 channel characteristics and primary functions.

Table 4. NOAA Advanced Very High Resolution Radiometer (AVHRR)

| AVHRR Channel No. | Wavelength ($\mu m$) | Primary Function |
|---|---|---|
| 1 | 0.55 - 0.9 | Daytime cloud/surface detection |
| 2 | 0.725 - 1.1 | Surface water discrimination, ice and snow melt |
| 3 | 3.55 - 3.93 | Nighttime sea surface temperature and cloud detection |
| 4 | 10.5 - 11.5 | Sea surface temperature and night cloud detection |
| 5 | 11.5 - 12.5 | Sea surface temperature and night cloud detection |

### 3.2.2 TIROS Operational Vertical Sounder (TOVS)

The TOVS system (Smith et al., 1979) combines data from several complementary sounding instruments onboard the spacecraft. These instruments are the twenty channel High Resolution Infrared Sounder (HIRS/2), the three channel Stratospheric Sounding Unit (SSU), and the four channel Microwave Sounding Unit (MSU).

#### 3.2.2.1 TOVS High Resolution Infrared Radiation Sounder (HIRS/2)

The TOVS HIRS/2 is the primary sensor for the retrieval of tropospheric data. The HIRS/2 is sensitive to energy from the visible to the carbon dioxide ($CO_2$) region of the infrared spectrum. Table 5 details the channel characteristics of the HIRS/2. The instrument is designed for the retrieval of temperature profiles from the surface to 10 mb, water vapor content in three vertical layers, and total ozone ($O_3$) content. The HIRS/2 instrument instantaneous field of view (IFOV) is 30 km at nadir and samples 56 IFOVs along each scan line of approximately 2250 km. The footprint is circular at nadir , but becomes increasingly elliptical with distance from nadir.

Table 5. NOAA High Resolution Infrared Radiation Sounder (HIRS/2)

| HIRS/2 Channel No. | Central Wave-number | Central Wave-length (μm) | Principal Absorbing Constituents | Level of Peak Energy |
|---|---|---|---|---|
| 1 | 668 | 15.00 | $CO_2$ | 30 mb |
| 2 | 679 | 14.70 | $CO_2$ | 60 mb |
| 3 | 671 | 14.50 | $CO_2$ | 100 mb |
| 4 | 704 | 14.20 | $CO_2$ | 400 mb |
| 5 | 716 | 14.00 | $CO_2$ | 600 mb |
| 6 | 732 | 13.70 | $CO_2$/$H_2O$ | 800 mb |
| 7 | 748 | 13.40 | $CO_2$/$H_2O$ | 900 mb |
| 8 | 898 | 11.10 | Window | Surface |
| 9 | 1028 | 9.70 | $O_2$ | 25 mb |
| 10 | 1217 | 8.30 | $H_2O$ | 900 mb |
| 11 | 1364 | 7.30 | $H_2O$ | 700 mb |
| 12 | 1484 | 6.70 | $H_2O$ | 500 mb |
| 13 | 2190 | 4.57 | $N_2O$ | 1000 mb |
| 14 | 2213 | 4.52 | $N_2O$ | 950 mb |
| 15 | 2240 | 4.46 | $CO_2$ /$N_2O$ | 700 mb |
| 16 | 2276 | 4.40 | $CO_2$ /$N_2O$ | 400 mb |
| 17 | 2361 | 4.24 | $CO_2$ | 5 mb |
| 18 | 2512 | 4.00 | Window | Surface |
| 19 | 2671 | 3.70 | Window | Surface |
| 20 | 14367 | 0.70 | Window | Cloud |

3.2.2.2 TOVS Microwave Sounding Unit (MSU)

The TOVS MSU is sensitive to energy in the oxygen absorption region of the microwave spectrum (50-58 GHz). The four channel MSU is used in conjunction with the HIRS/2 to permit temperature retrievals in moderately overcast conditions The MSU samples 11 IFOVs along the scan with a 110 km footprint at nadir. The TOVS MSU channel characteristics are shown in Table 6.

3.2.2.3 TOVS Stratospheric Sounding Unit (SSU)

The TOVS SSU is a Pressure Modulated Radiometer (PMR) sensitive to energy emitted by carbon dioxide ($CO_2$) at 15.0 $\mu$m. The PMR subsystem was provided by the British Meteorological Office. The SSU samples eight IFOVs along each scan of 1500 km extent. The SSU scan is not coincident with the outward edges of the HIRS/2 and MSU scans.

Table 6. NOAA Microwave Sounding Unit (MSU)

| MSU Channel No. | Frequency (GHz) | Principal Absorbing Constituent | Level of Peak Energy |
|---|---|---|---|
| 1 | 50.31 | Window | Surface |
| 2 | 53.73 | $O_2$ | 850 mb |
| 3 | 54.96 | $O_2$ | 500 mb |
| 4 | 57.95 | $O_2$ | 100 mb |

Table 7. NOAA Stratospheric Sounding Unit (SSU)

| SSU Channel No. | Wavelength ($\mu$m) | Principal Absorbing Constituent | Level of Peak Energy |
|---|---|---|---|
| 1 | 15.0 | $CO_2$ | 15.0 mb |
| 2 | 15.0 | $CO_2$ | 4.0 mb |
| 3 | 15.0 | $CO_2$ | 1.5 mb |

# 4. FUTURE DMSP AND NOAA POLAR ORBITING ENVIRONMENTAL SENSORS

## 4.1 Future DMSP Sensors

The next suite of DMSP satellites, the DMSP Block 5D-3 satellite series, is scheduled to be employed by the mid to late 1990s. The Block 5D-3 will again carry the OLS as the primary sensor. The combined functionality of the SSM/T-1, SSM/T-2 and SSM/I sensors will be combined into a single sensor package that surpasses the capabilities of the individual sensors.

<u>Special Sensor Microwave Imager/Sounder (SSMIS)</u>. The DMSP SSMIS is a millimeter/ microwave sensor that passively measures energy emitted, scattered and reflected from the earth's surface and atmosphere. The SSMIS uses an offset parabolic reflector, rotating at 31.6 rpm, which generates a conical scan at 45° with the nadir. This results in 53.1° angle of incidence with the earth's surface. Figure 2 depicts the SSMIS scan geometry. The SSMIS will provide lower atmosphere temperature and humidity profiles, upper atmosphere temperature profiles (10-0.03 mb), and twelve additional parameters similar to those of the current SSM/I parameters. The frequencies in which the SSMIS measures radiation were selected to increase the sharpness of some of the weighting functions and to improve the overall weighting function coverage of the atmosphere, compared to previous spaceborne microwave sensors (Swadley and Chandler, 1992). Table 8 details the DMSP SSMIS channel characteristics. However, the center frequencies of the upper air channels, SSMIS channels 19-24, represent the effective frequencies of a stationary sensor, and do not represent the actual center frequencies of the spaceborne sensor which are shifted by the hardware to annul the Doppler shifting due to spacecraft motion.

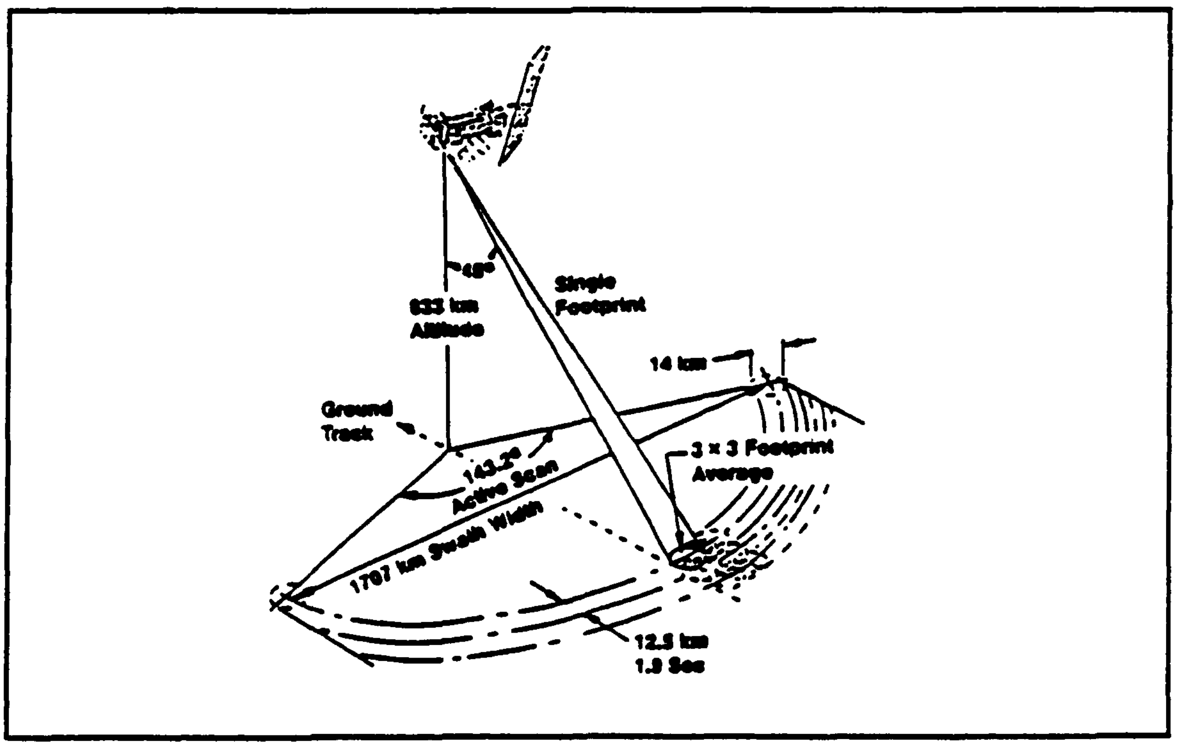

Figure 2. DMSP SSMIS Scan Geometry

Table 8. DMSP Special Sensor Microwave Imager Sounder (SSMIS)

| Channel No. | Center Frequency (MHz) | Frequency/ Stability (MHz) | Maximum Bandwidth (MHz) | Polarization | Horizontal Resolution (Km) | Scene Spacing (Km) | NEΔT (K) |
|---|---|---|---|---|---|---|---|
| 1 | 50300 | 10 | 400 | H | 39 by 38 | 38.0 | 0.4 |
| 2 | 52800 | 10 | 400 | H | 39 by 38 | 38.0 | 0.4 |
| 3 | 53956 | 10 | 400 | H | 39 by 38 | 38.0 | 0.4 |
| 4 | 54400 | 10 | 400 | H | 39 by 38 | 38.0 | 0.4 |
| 5 | 55500 | 10 | 400 | H | 39 by 38 | 38.0 | 0.4 |
| 6 | 57290 | 10 | 350 | V | 39 by 38 | 38.0 | 0.4 |
| 7 | 59400 | 10 | 250 | V | 39 by 38 | 38.0 | 0.5 |
| 8 | 15000 | 200 | 3000 | H | 15 by 13 | 12.5/38.0 | 0.7 |
| 9 | 183310±7000 | 200 | 3000 | H | 15 by 13 | 12.5/38.0 | 1.2 |
| 10 | 183310±3000 | 200 | 2000 | H | 15 by 13 | 12.5/38.0 | 1.0 |
| 11 | 183310±1000 | 200 | 1000 | H | 15 by 13 | 12.5/38.0 | 1.0 |
| 12 | 19350 | 75 | 500 | H | 74 by 45 | 25.0 | 0.7 |
| 13 | 19350 | 75 | 500 | V | 74 by 45 | 25.0 | 0.7 |
| 14 | 22235 | 75 | 500 | V | 74 by 45 | 25.0 | 0.7 |
| 15 | 37000 | 150 | 2000 | H | 45 by 31 | 25.0 | 0.5 |
| 16 | 37000 | 150 | 2000 | V | 45 by 31 | 25.0 | 0.5 |
| 17 | 91655 | 100 | 3000 | V | 15 by 13 | 12.5 | 0.9 |
| 18 | 91655 | 100 | 3000 | H | 15 by 13 | 12.5 | 0.9 |
| 19 | 63283.2±285.3 | 0.11 | 3.0 | H+V | 75 by 75 | 75.0 | 1.9 |
| 20 | 60792.7±357.9 | 0.11 | 3.0 | H+V | 75 by 75 | 75.0 | 1.9 |
| 22 | 60792.7±357.9±5.5 | 0.15 | 12.0 | H+V | 75 by 75 | 75.0 | 1.0 |
| 23 | 60792.7±357.9±16 | 0.5 | 32 | H+V | 75 by 75 | 75.0 | 0.6 |
| 24 | 60792.7±357.9±50 | 1.0 | 120 | H+V | 75 by 75 | 38.0/75.0 | 0.7 |

Scene spacing and NET values refer to scene averaged values used for retrievals of temperature and humidity.

## 4.2 Future NOAA Sensors

Some instruments now standard with the NOAA E-J block of satellites, will be changed beginning with the NOAA K. The NOAA K-M series of satellites will have an upgraded AVHRR and the Advanced Microwave Sounding Unit (AMSU). With the advent of AMSU, the HIRS instrument will become the supplementary sounder, and AMSU-A will be the primary temperature sounder and the AMSU-B will provide humidity profiles. The launch of NOAA-K is now estimated to be 1995. With the NOAA N-P series of satellites the AVHRR and HIRS/2 will be replaced by the Advanced Medium Range Imaging Radiometer (AMRIR).

### 4.2.1 Advanced Medium Resolution Imaging Radiometer (AMRIR)

The NOAA N-P series of satellites is scheduled to be deployed in the late 1990's, although budget cutbacks may delay and possibly eliminate the AMRIR. The AMRIR is an eleven channel visible/infrared radiometer designed for global measurements of cloud cover, sea surface temperature, snow and sea ice extent, as well as to provide temperature and humidity profiles at a resolution of 4 km. This AMRIR instrument will decrease the infrared spectral information content, as compared to HIRS/2, and in turn degrade the combined sounding system. This is compensated for by increased horizontal resolution and the improved sounding in partly cloudy scenes. The AMRIR sensor will have a horizontal resolution of 500 m, and a swath width of 2940 km. Table 9 details the AMRIR channel characteristics.

Table 9. NOAA Advanced Medium Resolution Imaging Radiometer (AMRIR) (Eyre, 1989).

| Number of Channels | Wavelengths ($\mu$m) | Primary Purpose |
|---|---|---|
| 1 | 13.55 | Temperature profile |
| 1 | 10.8 | (lower troposphere) |
| 1 | 12.0 | " |
| 2 | 4.4 - 4.6 | Surface temperature |
| 1 | 3.72 | Cloud parameters |
| 1 | 4.01 | " |
| 4 | 0.6 - 1.6 | Imagery for other applications |

4.2.2 Advanced Very High Resolution Radiometer (AVHRR/3)

The AVHRR/3 represents only slight modifications to the existing AVHRR/2. AVHRR/3 channel 1, 2 and 3 will no longer be linear; dark response is to be expanded, providing additional gray scales to enhance aerosol detection (Sparkman, 1989). All infrared channels are to be modified for a 335 K saturation to avoid hot region saturation. Table 10 details the AVHRR/3 channel characteristics.

Table 10. NOAA Advanced Very High Resolution Radiometer (AVHRR/3)

| AVHRR/3 Channel No. | Wavelength ($\mu$m) | Primary Function |
|---|---|---|
| 1 | 0.58 - 0.68 | Daytime cloud/surface detection |
| 2 | 0.84 - 0.87 | Surface water discrimination, ice and snow melt |
| 3A | 1.58 - 1.64 | Daytime cloud/snow discrimination, sea surface temperature |
| 3B | 3.55 - 3.93 | Nighttime sea surface temperature and cloud detection |
| 4 | 10.3 - 11.3 | Sea surface temperature and night cloud detection |
| 5 | 11.5 - 12.5 | Sea surface temperature and night cloud detection |

4.2.3 Advanced Microwave (Temperature) Sounding Unit (AMSU-A)

The AMSU-A is a 15 channel total power microwave radiometer designed and built by Aerojet Electronic Systems Division, and represents significant advancements in microwave radiometer technology. The AMSU-A passively measures microwave radiation from the oxygen absorption region (50.3 - 57.9 GHz) in 12 discreet frequencies, and at 23.8, 31.4, and 89.0 GHz. Table 11 details the AMSU-A channel characteristics. The 8 second cross track scan covers $\pm 50°$ from nadir, with 30 samples of a constant 3.3° antenna beamwidth. Figure 3 depicts the AMSU-A scan geometry. In-flight calibration is performed each scan by means of warm load and cold load targets. Several channels (5, 10 - 14) have multiple pass bands in order to improve the signal-to-noise ratio and match the narrow line widths at those frequencies.

Table 11. NOAA Advanced Microwave Sounding Unit (AMSU-A)

| AMSU Channel No. | Center Frequency (MHz) | Frequency/ Stability (MHz) | Maximum Bandwidth (MHz) | Beamwidth (Degrees) | NEΔT (K) |
|---|---|---|---|---|---|
| 1 | 23900 | 10.0 | 270 | 3.3 | 0.3 |
| 2 | 31400 | 10.0 | 180 | 3.3 | 0.3 |
| 3 | 50300 | 10.0 | 180 | 3.3 | 0.4 |
| 4 | 52800 | 5.0 | 400 | 3.3 | 0.25 |
| 5 | 53596±0.115 | 5.0 | 170 | 3.3 | 0.25 |
| 6 | 54400 | 5.0 | 400 | 3.3 | 0.25 |
| 7 | 54940 | 5.0 | 400 | 3.3 | 0.25 |
| 8 | 55500 | 10.0 | 330 | 3.3 | 0.25 |
| 9 | 57290 | 0.5 | 330 | 3.3 | 0.25 |
| 10 | 57290±217 | 0.5 | 78 | 3.3 | 0.4 |
| 11 | 57290±322±48 | 0.5 | 36 | 3.3 | 0.4 |
| 12 | 57290±322±22 | 0.5 | 16 | 3.3 | 0.6 |
| 13 | 57290±322±10 | 0.5 | 8 | 3.3 | 0.8 |
| 14 | 57290±322±4 | 0.5 | 3 | 3.3 | 1.2 |
| 15 | 89000 | 50.0 | 6000 | 3.3 | 0.5 |

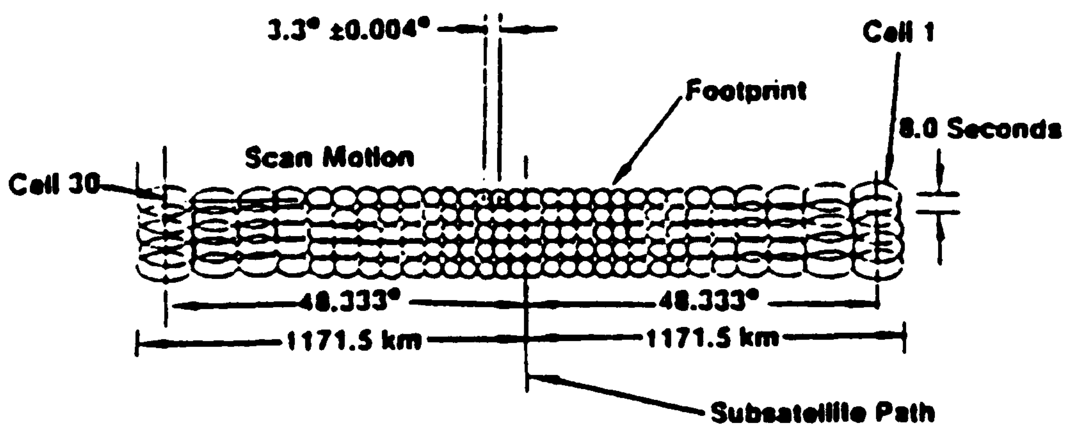


Figure 3. NOAA AMSU-A scan geometry (Patel, 1992).

### 4.2.4 Advanced Microwave Humidity Sounding Unit (AMSU-B)

The AMSU-B is the module of the AMSU designed to obtain profiles of atmospheric humidity from the surface up to 40 km with accuracies estimated to be 5 to 15 percent of saturation. The AMSU-B is a cross track total power microwave radiometer, measuring energy at 5 discreet frequencies. Table 12 details the AMSU-B channel characteristics. All channels have a 1.1° antenna beamwidth, translating to a 15 km footprint at nadir, with 90 samples per scan. The scan width is 2343 km, with a 2.67 second scan period.In-flight calibration is performed in the same manner as AMSU-A.

Table 12. NOAA Advanced Microwave Sounding Unit (AMSU-B)

| AMSU Channel No. | Center Frequency (MHz) | Frequency/ Stability (MHz) | Maximum Bandwidth (MHz) | Beamwidth (Degrees) | NE$\Delta$T (K) |
|---|---|---|---|---|---|
| 16 | 89000 | 50 | 6000 | 1.1 | 0.6 |
| 17 | 157000 | 50 | 4000 | 1.1 | 0.6 |
| 18 | 183310$\pm$1000 | 30 | 1000 | 1.1 | 0.8 |
| 19 | 183310$\pm$3000 | 30 | 2000 | 1.1 | 0.8 |
| 20 | 183310$\pm$7000 | 30 | 4000 | 1.1 | 0.8 |

Appendix A provides a tentative launch schedule of future DMSP and NOAA (polar orbiting and geosynchronous) satellite sensor platforms. Launch dates for NASA, US Navy, European Space Agency (ESA), National Space Development Agency of Japan (NASDA), People's Republic of China and France's satellite sensor platforms have also been included.

## 5. RETRIEVAL ALGORITHMS

Historically, the radiances measured by environmental satellite sensors have not been of direct geophysical interest. Significant efforts have been made to extract geophysical parameters from the radiances, such as with the AVHRR, TOVS, SSM/T-1 and SSM/I. For satellite sounding radiances, the common approach is to express the radiance integral as a convolution of the Planck function with the weighting function which represents the medium interaction. The temperature or humidity profile is obtained by solving the resulting Fredholm integral equation of the first kind. The solution of these integral equations is known as the retrieval or inverse problem, while the calculation of radiances from a given atmospheric state is known as the forward problem. The satellite radiance inversion problem is mathematically ill-posed. Solutions require additional constraints (a priori information) to select the optimal solution between the infinite atmospheric profiles satisfying the integral equation. Solutions to the inverse problem have been made via direct iterative methods of solving the Radiative Transfer Equation (RTE), i.e., physical retrievals, linearized statistical methods (D-matrix), and various filtering approaches. Although no general agreement has been made on retrieval methodology for satellite sounding products, there is a consensus that physical or physical statistical retrievals show the greatest potential, provided one desires a stand-alone satellite derived profile.

Two methods of satellite sounding verification exist, one being collocation of satellite retrievals with radiosondes. The verification process is routinely performed at the operational center generating the soundings and during algorithm comparison studies by other research centers. Results are difficult to interpret, as the radiosonde collocation method has complicating factors. For example the SSM/T-1 data may not be stratified according to beam position and the radiosonde data may be matched-up with differing space and time criteria. The other verification method is to calculate the radiances directly from an atmospheric state, i.e., to perform the forward problem calculation, to a degree of accuracy within the bounds that an NWP can predict the measurements, and compare the computed values with the satellite measured radiances. However, the inherent complexities of the forward calculations, limitations in spectroscopy and uncertainties in the amount and type of hydrometeors present within the sensor's IFOV, make this type of forward problem difficult and computationally intensive. It is for this reason that the radiosonde collocation method is the most widely utilized verification technique.

The spatial error characteristics of satellite soundings are not addressed by the above verification procedures. Correct specifications of the error characteristics are required for the optimum use of the satellite sounding data in statistical assimilation methods. These error characteristics vary with the retrieval method, sensor type, scan geometry, and the physical properties associated with the measurement, i.e., cloudiness and/or precipitation. Sienkiewicz (1993) details a methodology for utilizing forecast fields from an NWP system with satellite soundings to determine systematic errors in the satellite derived profiles. Results of this study showed significant biases accross a TOVS scan, which were not realizable via radiosonde collocation studies.

The current operational centers producing satellite soundings are NESDIS and AFGWC. NESDIS, the satellite sounding COE under the SPN, is responsible for producing and distributing both NOAA and DMSP temperature soundings, while AFGWC produces both DMSP SSM/T-1 and SSM/T-2 sounding products. Plans are for NESDIS to produce and distribute SSM/T-2 humidity profiles in the near future. Various organizations produce satellite soundings in research modes using developmental retrieval packages. Research retrieval methods for TOVS and SSM/T-1 include: NASA Goddard Laboratory for Atmospheres (GLA) physical retrieval method, University of Wisconsin Cooperative Institute for Meteorological Satellite Studies (CIMMS) simultaneous retrieval method and international TOVS processing package, Atmospheric Environmental Research (AER) unified retrieval method, University of Maryland singular value decomposition method (Thompson, 1992), Air Force Phillips Laboratory Geophysics Directorate differential inversion method (King et al., 1989), the Laboratoire de Meteorologique Dynamique (LMD) improved initialization inversion method, and the NESDIS minimum variance and classification methods.

For NWP applications, it is clear that the current utilization of satellite soundings is less than optimal, as demonstrated by recent negative impacts of satellite soundings on northern hemisphere forecasts (Baker et al., 1989). The accuracy of NWP 6 hour forecast fields have improved to the point where in certain regions the uncertainty in the satellite sounding retrievals are greater than the uncertainties in the forecast field. The simplistic approach of treating satellite soundings in a manner similar to radiosondes, but with larger error characteristic, will never fully utilize the information content of the satellite sounding radiances.

Recent developments under a joint NMC, NASA and NESDIS effort (Baker, 1992) have demonstrated that satellite sounding radiances may be directly assimilated by an NWP system. The system was designed to take advantage of the NESDIS operational system and the developmental approaches at both NASA GLA and NESDIS. The approach, known as "interactive soundings" (Susskind and Pfaendtner, 1989), utilizes the NWP model 6 hr forecast fields as the first guess for the retrieval scheme and relies on an accurate forward calculation of the radiances (Susskind et al., 1983). By-products to this retrieval scheme are estimates of surface temperature (land or sea), cloud height and amount, sea ice extent, snow cover, ocean surface roughness and other hydrologic parameters. The retrievals are then used in conjunction with other available data in the NMC model's spectral statistical interpolation (SSI) assimilation/initialization cycle (Parrish and Derber, 1991). The resulting "interactive" retrievals are also in balance with the wind and mass fields of the model, but can also contain the model's bias characteristics. To alleviate some of the latter problem, in areas where the model forecast may be of poor quality, i.e., where the satellite sounding radiances have large deviations from the model computed radiances, the classification retrieval procedure developed by McMillin (1986) is used. The GLA retrieval code has been ported to CRAY YMP at NMC and the technique is currently being evaluated on the T62 global spectral NWP model. Plans are to conduct a full resolution (T126) impact study including the classification procedure and NASA cloud clearing algorithms.

Eyre and Lorenc (1989) have developed the theoretical framework for the direct use of satellite sounding radiances in NWP which effectively utilizes more of the information content contained in the radiances. The direct assimilation of radiances is conceptually a mathematical equivalent to a conventional minimum variance retrieval. The NWP model field acts as the background for the inversion which is constrained by the field's expected error covariance. A linear version of the "forecast background" scheme has been applied to TOVS radiances at the U.K. Meteorological Office since 1987.

Variational inversion methods have been employed with the adjoint technique of data assimilation. Thepaut and Moll (1990) have developed tangent linear and adjoint operators of the International TOVS Processing Package (ITPP). Variational inversion consists of minimizing a cost function that measures the distance between the analyzed atmospheric state and available supporting observations. Two main terms included in the cost function are: 1) a measure of the departure of the observed radiances and the NWP model state radiances computed via a radiative transfer model, and 2) a term measuring the departure from a background atmospheric state, i.e., the first guess. The techniques used to minimize the cost function have included Newton's method (Eyre, 1989) and also conjugate gradient methods (Hoffman and Nehrkorn, 1989). The computational complexities of computing the first and second derivatives of the cost function require careful selection of the minimization technique.

### 5.1 DMSP SSM/T-1 Temperature Retrievals

AFGWC and NESDIS are the two operational centers processing the DMSP SSM/T-1 data and producing atmospheric temperature profiles. AFGWC utilizes software developed by Aerojet Electronic Systems (Rigone and Stogryn, 1977). The retrieval method is based upon a linear multiple regression technique, i.e., the so called "D-Matrix" approach. With this method, it is assumed that the deviation of the parameter vector, i.e., the retrieved temperatures and thicknesses, from the climatalogical mean can be expressed as a linear combination of the deviations of the measured data from its mean. The D matrix is obtained by the computing the matrix product of the parameter-data matrix and the inverse of the data-data covariance matrices and adding the radiometer noise covariance matrix. The data vector is collected from a large ensemble of radiosondes, and allows for updates of the D-matrices. The D-matrices also are statically stratified by geographical location and by SSM/T-1 beam position to include the effects of incidence angle. The D-matrix update process begins once a significant number of new radiosonde collocations have been collected and pairs of computed and measured radiances (data vectors) have been computed. A linear regression is performed between the measured and computed data vectors, with regression coefficients being computed on channel by channel basis. These coefficients are then used to update the a priori correlation matrices and expected data vector. Updates to the operational D-Matrices are performed only after the new or test D-Matrices have been verified to have lower retrieval error statistics. Advantages of the D-Matrix method are its computational efficiency and that the instrument noise variations in time are accounted for by the updating of the regression coefficients. Weaknesses include the lack of physical incorporation of the effects of various hydrometeors on the observed radiances and how the a priori statistical ensemble is representative of the current atmospheric temperature structure.

NOAA NESDIS utilizes a modified version of the original AFGWC code. The NMC SSM/T-1 retrieval is performed by a statistical process termed "synthetic regression" (Reale and Donahue, 1992). The departures from the AFGWC version are in the matrix update methodology, precipitation screening, and in the incorporation of the angle of incidence (beam position) and terrain influences. The "synthetic regression" is basically a weekly D-matrix update.

A physical, simultaneous retrieval algorithm, for SSM/T-1 radiances has been developed at CIMMS (Schreiner, 1990). The algorithm, which is designed to work with Level 1B radiance data (earth located brightness temperatures and/or radiances) available from NESDIS, consists of data preprocessing and the subsequent temperature retrieval. The preprocessing consists of "normalizing" the SSM/T-1 brightness temperatures to that of scenes without clouds or moisture and with unit emissivity via a statistical regression. The normalized SSM/T-1 antenna temperature is modeled via a special form of the RTE (Smith et al., 1985) and computed for each channel and beam position. The surface emissivity is retrieved using the SSM/T-1 surface channel and an independent estimate of the surface temperature. Ideally, this method would incorporate the SSM/I for real estimates of the cloud and water vapor effects. Using the

SSM/T-1 weighting functions as one basis set,and the spatial antenna pattern weighting functions in a 3 by 3 field of view as the other basis set, the temperature perturbation function coefficients can be specified and the RTE solved. The CIMMS SSM/T-1 physical retrieval package was developed under contract with the Naval Research Laboratory, Monterey, CA.

A unified physical statistical retrieval system has been developed for the potential use with SSM/T-1, SSM/T-2 and the SSM/I at AER (Isaacs, 1989). The technique was designed to process the DMSP sensor data in an integrated approach, rather than processing each sensor independent of each other. The statistical retrieval of SSM/T-1 temperature profiles, SSM/T-2 humidity profiles, and SSM/I parameters are performed via the operational D-Matrix approach to provide first guess profiles for the subsequent unified retrieval. The forward problem is accomplished via the RADTRAN simulation code (Falcone et al., 1982). Residuals between the observed and computed brightness temperatures are then computed and compared to the NET for that channel. If the residuals are not within tolerance, then the first guess profiles are adjusted by means of a simultaneous physical retrieval modeled after Susskind et al. (1984) and Smith et al. (1985). Cloud contamination screening is performed via the visible and infrared OLS data mapped into the various microwave channel footprints, while cloud liquid water estimates are made via the SSM/I over oceans. These parameters are utilized in the forwardproblem for the SSM/T-2 brightness temperatures. This method has shown marked improvements with water vapor retrievals in simulation studies but has not been utilized with actual SSM/T-2 data now available. This method is quite cumbersome from an operational software maintainability standpoint, which is a major concern.

## 5.2 DMSP SSM/T-2 Humidity Retrievals

AFGWC is the current operational center processing SSM/T-2 data and producing water vapor profiles. The operational software was developed by Aerojet Electronic Systems Division, and the retrieval products are being validated via radiosonde collocation (Boucher et al., 1993). The retrieval method is the statistical D-Matrix approach designed to decompose the non-linear retrieval problem into piecewise linear representation. The D-Matrix discriminants are based upon surface type, beam position, and air mass type. The dynamically based stratification is based upon air mass characteristics as defined by the total vapor mass and an estimate of the mean tropospheric temperature. The SSM/T-2 products include relative and specific humidities at 1000, 850, 700, 500, 400, and 300 mb. Water vapor masses from the surface to 1000, 1000-850, 850-700, 700-500, 500-400, 400-300, and above 300 mb are also retrieved. The SSM/T-2 brightness temperatures have also shown considerable promise when displaed in an image format. The preliminary retrieval results show RMS errors in the 20% range in RH for all sounding cases, but less than half that error for cloud free cases. The results are obtained using the initial a priori D-Matrices. RMS errors will be lowered and the biases removed when enough radiosonde collocations are obtained to perform the D-Matrix update.

5.3 DMSP SSM/I Parameter Retrievals

AFGWC and FNOC are the current operational centers processing SSM/I data and producing environmental parameters. FNOC is the designated COE under the SPN for the SSM/I. The FNOC SSM/I processing is performed on the Satellite Processing Center Upgrade (SPCU), and entails the production of Sensor Data Records (SDRs), Temperature Data Records (TDRs), Environmental Data Records (EDRs) and Quality Data Records (QDRs) for subsequent distribution to the operational Navy community, Naval Research Laboratory (NRL), Washington, D.C., and transmitted via the SPN. The original SSM/I Ground Processing Software (GPS), developed by the Hughes Aircraft Company, has incorporated the recommended changes to both the SDR and EDR processing suggested by the SSM/I Cal/Val reports (Hollinger, 1989, 1991). The earth located SDRs are utilized for imagery products and to produce the EDRs, which include the following parameters: ocean wind speed, sea ice concentration, ice age (first or multi-year) and ice edge, total precipitable water and cloud liquid water content over oceans, rain rates, soil moisture, surface type and temperature. The SSM/I GPS was originally designed to also compute cloud amount and liquid water content over land, but the accuracy of these products were not validated by the Cal/Val team and are no longer being computed (Colton, 1992).

Earth located TDRs are archived and also distributed via the SPN. TDRs allow for users to process SSM/I data with their own versions of corrections for antenna pattern and cross polarization effects. Variations exist between SSM/I sensors on the DMSP satellites, and these subtle differences must be accounted for when performing the TDR to SDR conversion. This results in differences in the input values to the parameter extraction algorithms, and subsequently different output products.

NESDIS is also producing SSM/I products in an effort to improve satellite sounding products. NESDIS has developed a set of algorithms for rain rates and snow/ice analysis (Grody, 1991, Grody and Ferraro, 1992, and Mitchell et al., 1992). However, these algorithms have been designed to operate on uncorrected TDRs. The resulting products are difficult to validate and compare with the FNOC operational SSM/I products.

NASA is currently sponsoring a five year program, WetNet, designed to examine the role of a remote interactive computer network for the earth sciences, and to promote interdisciplinary research in the atmospheric and related hydrologic sciences (Smith et al., 1992). WetNet's primary data is from the SSM/I. The SSM/I TDR data is acquired from NESDIS via FNOC, and processed by Remote Sensing Systems (RSS) with a proprietary environmental algorithm which performs quality control and produces modified antenna temperatures (Wentz, 1988). The SSM/I data are then sent to Marshall Space Flight Center (MSFC) and distributed to the WetNet scientists via magneto-optical cartridges for subsequent algorithm development studies. Again, the resulting SSM/I products are difficult to validate and compare with the FNOC operational SSM/I products.

Petty (1990) has developed a retrieval package for the SSM/I based upon the modeled results from a microwave radiative transfer model. A unified set of semi-physical algorithms for obtaining ocean wind speed, total precipitable water, cloud liquid water and precipitation are documented. Stand alone 37 GHz and 85 GHz algorithms for rain rate and cloud liquid water were also developed. The input SSM/I data for the study were provided by RSS.

## 5.4 DMSP SSMIS Temperature And Humidity Retrievals

Aerojet Electronic Systems Division is currently under contract to develop and deliver two operational Computer Software Configuration Items (CSCIs) for use at AFGWC and FNOC. The SSMIS GPS inputs raw sensor counts, calibration data and ephemeris data to produce SDRs, EDR, and TDRs. The SSMIS GPS also performs sensor health monitoring and the sounding verification and update processes.

The SSMIS will produce lower atmospheric temperature soundings to the 10 mb level, relative and specific humidity profiles up to 300 mb, water vapor mass between the mandatory pressure levels up to 300 mb, total vapor mass, along with estimates of tropopause pressure and temperature at a horizontal resolution of 38 km. The lower atmosphere temperature and humidity profiles will be computed via the linear statistical D-Matrix method with dynamic stratification (D-Matrix selection criteria) based upon air mass typing. The SSMIS lower atmospheric soundings will be earth located at the 11 km level along the beam propagation path.

Upper atmospheric soundings will be produced from 7 mb to 0.03 mb. The SSMIS upper atmosphere temperature retrieval method is significantly more complex than the lower atmosphere retrievals. The added complexity is due to the interaction of the earth's magnetic field with the magnetic dipole moment of the oxygen molecule. This causes "Zeeman splitting" of the oxygen absorption lines and produces significant changes in the weighting function behavior of the upper atmosphere (Stogryn, 1989). The earth's magnetic field at an altitude of 60 km is required input to the SSMIS GPS. The SSMIS upper atmospheric soundings will be earth located at the 60 km level along the beam propagation path.

All of the SSMIS temperature and humidity profile D-Matrices are updated on a channel by channel basis using operational radiosondes and rocketsondes. The update procedure insures that the SSMIS retrieval errors and biases are minimized.

The SSMIS GPS will also produce twelve additional parameters including: ocean wind speed, rain rates, sea ice concentration, ice age (first or multi-year), sea ice and snow edge, snow water content, land surface types and temperature, soil moisture, and cloud amount, cloud liquid water and total precipitable water over oceans.

## 5.5 NOAA TOVS Temperature Retrievals

NESDIS has the operational responsibility for producing TOVS retrievals. The statistical retrieval method of Smith and Woolf (1976), has been replaced by the new physical retrieval method known as the Minimum Variance Simultaneous (MVS) retrieval method (Fleming et al., 1988). The MVS retrieves profiles of atmospheric temperature and humidity, and surface temperature, simultaneously as a single solution vector. The first guess temperature and humidity profiles and corresponding radiance vector are obtained from an a priori library of coincident radiosondes and satellite observed radiance vectors. A search is performed to find the closest match between the observed radiance vector and those in the library. The 20 closest matching library radiance vectors, and associated temperature and humidity profiles, are then averaged to produce the first guess radiance vector and profiles. The operational retrievals utilize a linear version of the matrix operator involving the solution vector covariance matrix, weighting function matrix, and the instrument noise covariance matrix. The full blown operator is nonlinear because the solution vector covariance matrix involves the solution vector. The linear operator made applicable by using a single averaged solution vector covariance matrix from the library. The RTE then becomes a linear matrix equation and the solution vector is computed as a product of the averaged vector and matrices. The operator linearization removes much of the computational burdens (an order of magnitude less) involved in the full nonlinear VMS method (Fleming et al., 1986) with only a minor degradation in accuracy.

A physically based retrieval system for TOVS has been developed at the GLA (Chahine and Susskind, 1989). The system is based upon a relaxation method applied to the fully nonlinear RTE developed by Chahine (1982). The retrieval process begins with a computation of clear-column radiances and brightness temperatures from a first guess profile at both HIRS/2 and MSU frequencies. The surface emissivity at 50.3 GHz is determined for subsequent computation of the microwave brightness temperatures for the cloud filtering atmospheric channels. The clear-column radiances are then computed and the surface temperature is determined. The new profile is then computed and compared to the previous iteration profile. If a satisfactory residual is obtained, the iterative process ends and quality control of the profile is performed. The humidity and ozone profiles along with the cloud fields and other parameters can then be computed. The significant differences between the GLA retrieval method and the NESDIS operational algorithm are in the explicit use of physics in the GLA computations of the forward problem and the computation of the clear-column radiances.

The physical statistical retrieval method, 3I, developed at the LMD was designed to avoid the dependence upon a priori statistical ensembles, and include the advantages of numerically solving the RTE without the computational expense of computing radiances at each iteration (Chedin et al., 1985). The 3I method avoids the computational expense of a full physical retrieval through the use of the TOVS Initial Guess Retrieval (TIGR) data set. The TIGR data set was derived from a statistically optimal sampling of 1200 radiosonde reports depicting numerous atmospheric states. The TIGR data consists of TOVS radiances and brightness temperatures computed at various angles of incidence from the selected radiosonde reports. Once the observed radiances (clear-column) have been obtained, differences from the TIGR radiances are computed using a normalized least squares criterion. The matrix form of the RTE is expressed using a Bayesian-type estimator, and a linear model results using an appropriate quadrature formula. Results using the 3I retrieval method have shown that accurate solutions can be obtained from a single iteration and that the sounding quality control rejection rate is also lowered.

## 5.6 NOAA AMSU Temperature And Humidity Retrievals

NOAA/NESDIS is responsible for the development of retrieval algorithms and subsequent operational processing of the AMSU and HIRS/2, i.e., Advanced TOVS (ATOVS), combined sounding system. Several studies have been conducted in an effort to simulate the AMSU performance. Fleming and Kratz (1992) have used the SSM/T-1 as a proof of concept for a proposed AMSU-A temperature retrieval algorithm. The algorithm is based upon the MVS method for TOVS retrievals used operationally at NESDIS. Eyre (1990) has performed a simulation study where the expected ATOVS retrieval performance was assessed in terms of information content as quantified by the reduction in entropy of the appropriate probability density functions. A nonlinear simultaneous inversion approach (Eyre, 1989) was employed for the ATOVS simulation, with a new method for treating the frequency dependence of the microwave surface emissivity and also includes cloud liquid water in the solution vector. Results showed the value of retaining the combined microwave/infrared sensor system.

## 6. RECOMMENDED ALGORITHM STRATEGIES

Numerous algorithm packages are available for extracting quantitative geophysical parameters from existing satellite sensors. Algorithm packages are currently being designed, developed and tested for use with future DMSP and NOAA satellite sensors. The algorithm packages vary in their computational complexity and in the resulting accuracies of the products, as well as in the ease of software maintainability. Software maintainability is not usually factored into the tradeoff equation that weighs the operational constraints versus the required accuracy of the retrieved products.

### 6.1 Central Site Retrieval Algorithms

The current FNOC satellite processing is performed on a computer system that imposes a significant computational constraint on the algorithm packages. The ability to perform complex physical retrievals within operational timing constraints is unlikely. The current SSM/I processing on the SPCU, which is not computationally intensive, cannot effectively process all the existing DMSP satellite passes. However, the long term plans for a Distributed Processing System Replacement (DPSR) will, in all probability, be able to handle the computational burdens of the new DMSP Block 5D-2 and 5D-3 satellite data. FNOC is currently scheduled to produce DMSP Block 5D-3 SSMIS lower atmosphere temperature and humidity retrievals, upper atmosphere temperature retrievals, as well as the SSM/I type parameters. This will increase the computational load an order of magnitude when compared to the current SSM/I processing. Clearly, continued acquisition of new and more powerful computers/workstations is required, provided the processing of satellite temperature and humidity retrievals are to remain a separate entity from the NOGAPS/NORAPS suite of models.

The current trend at the global NWP processing centers (NMC, ECMWF, and U.K. Met Office) is that of direct assimilation of satellite radiances or, at a minimum, coupling the satellite retrieval software directly with the NWP model. Incorporating this trend at FNOC, would require a change in FNOC's satellite processing philosophy. Historically, satellite processing at FNOC has been done on systems separate from the computers hosting the NWP models. The computational complexity of the new retrieval methods along with the shear magnitude of data to be available with future sensors, requires the hosting of the interactive or direct retrieval methods on the same computer system that hosts the NOGAPS/NORAPS suite of models. Satellite sounding quality control and verification statistics can be readily compiled when hosted on the system used to host the NWP suite. Spatial error statistics could also be monitored and coupled with the MVOI analysis system resulting in more optimal assimilation of the satellite sounding data.

A decision must be made in regard to maintaining the position as leaders in global atmospheric prediction and satellite data assimilation, currently held by FNOC and NRL (Jensen and Hovermale, 1990). The development of an advanced coupled retrieval/assimilation system is mandatory for maintaining a leadership role. NESDIS/NMC has an active program addressing the issue of optimally assimilating NOAA sounding data. However, the development of such a system designed to optimize the assimilation of DMSP sounding products is not currently being pursued at NESDIS. By tackling the DMSP assimilation issue, the Navy has the oppurtunity to maintain its current role as the leader in DMSP assimilation strategies. The development of such a system requires a multi-year effort, but the payoff in terms of operational products and forecast accuracy is clear, provided the assimilation system passes the model information at scales the model can utilize. The Navy, by not transitioning to an advanced coupled retrieval/assimilation system, will be accepting the NMC/NESDIS interactive retrieval products, which also includes accepting the NMC NWP model biases and the associated information content at scales the NMC model can assimilate. Clearly, FNOC and NRL should make the effort to retain their combined roles as leaders in satellite data assimilation,and step forward to become the leader in DMSP assimilation strategies.

The ability of the assimilation system to utilize the full information content of the satellite radiances and/or derived temperature and moisture profiles, is an active area of research at NMC, GLA, ECMWF and the U.K.Met Office. Clearly, DoD must participate in such efforts, and specifically tailor their efforts towards the DMSP series. The utilization of non-standard satellite derived products such as rainrates and cloud liquid water in the initialization of the diabatic heating terms should also be explored. The recent DoD mandate to make FNOC the primary DoD global numerical weather prediction center and AFGWC the primary DoD meteorological satellite center, although perhaps politically correct, may hamper efforts to develop an advanced coupled retrieval/assimilation system. The communications hardware, and subsequent transmit/ receive capabilities between FNOC and AFGWC would have to be dramatically improved in order to provide all the satellite sounding and special sensor data in time to meet operational requirements. The costs of these hardware improvements would exceed the costs of maintaining the current capabilities and meeting future requirements of processing DMSP and NOAA polar orbiting data at FNOC. However, provided AFGWC can provide the special sensor and sounder data processed to Level 1B (or equivalent) format, and in a timely manner, the development of an advanced coupled retrieval/assimilation system can be realized.

### 6.2 Tactical Site Retrieval Algorithms

Tactical site satellite processing has greater computational constraints than does central site processing simply due to the limited space allowable for the computer hardware. However, computer workstation technology is progressing at such a rapid rate that many of the computational constraints will also be overcome. Software maintainability and robustness also carry more weight in the tradeoff equation that weighs the operational constraints versus the required accuracy of the retrieved products. Near term plans are to run a scaled down version of NORAPS on the tactical remote workstation. This would allow for a regional version of the combined retrieval/assimilation system. This option is even more attractive in times of crisis when stand alone capability becomes critical.

However, short term improvements to the tactical site satellite processing and generation of retrieval products can be realized. Nagle and Goroch, in a draft memo dated 13 July 1992, for the TESS(3) EDM Upgrade, presented several hardware configuration options designed to separate satellite data processing functions from all other TESS functions. Recent meetings between NRL and Naval Air Warfare Center (NAWC) personnel have addressed these issues and a tentative plan has been reached. The plan calls for enhancing the TESS(3) receiver/antenna system (AN/SMQ-11) processing capabilities and off loading virtually all of the satellite preprocessing to the SMQ-11 CPU. The SMQ-11 processor is planned to be equipped with high speed mainstream UNIX based CPU, 128 to 512 MBytes RAM, a 1280 by 1024 video board, an NAWC proprietary Universal Formatter board,and a VME interface to replace the existing IEEE-488 interface. This revised version of the SMQ-11 system is being called the Navy Enhanced Weather Tactical Terminal (NEWTT). The satellite preprocessing tasks to be performed by the NEWTT include: satellite pass scheduling, ephemeris data and orbit prediction, interface to Global Positioning System (GPS) time, frame synchronization, data decommutation, earth curvature correction, wow and flutter correction, panoramic distortion correction, sensor calibration, earth location, sensor data record (SDR) generation (level 1b format), and sensor health monitoring. A limited capability version of NEWTT and the Universal Formatter is scheduled for implementation by late 1995 in time for the Navy Geosat Follow-On (GFO) altimeter processing.

Short term software upgrades for TESS(3) satellite processing should include the development of support software to utilize the SSM/T-1 simultaneous physical retrieval software developed at CIMSS and SSM/T-2 ingest and humidity retrieval software. Near term software upgrades should include the development/porting of AMSU (ATOVS) processing code and SSMIS software to the TESS environment.Satellite applications for current and future geosynchronous platforms, such as GOES-NEXT, METEOSAT, and GMS, should also be developed. These applications include: cloud tracked wind generation, cloud advection modeling, and cloud analysis.

## 7. SUMMARY

The purpose of this report was to detail the sensor characteristics and associated environmental retrieval methods in preparation for scheduled Defense Meteorological Satellite Program (DMSP) and National Oceanic and Atmospheric Administration (NOAA) environmental satellite sensor upgrades for both the Fleet Numerical Oceanography Center (FNOC) and the Tactical Environmental Support System (TESS). Algorithm philosophies and options for both central site (FNOC) and tactical sites (TESS) were presented. Hardware modification requirements for acquisition of data from scheduled environmental satellite sensor upgrades also need to be investigated in the immediate future in order to meet the launch schedules.

## APPENDIX A. Scheduled Launch Dates for Environmental Satellites and Sensor Packages

| AGENCY | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | |
| DMSP | | *OLS* | *OLS* | | *OLS* | | | *OLS* | | |
| | | *SSM/T-1* | *SSM/T-1* | | *SSM/T-1* | | | *SSMIS* | | |
| | | *SSM/T-2* | *SSM/T-2* | | *SSM/T-2* | | | | | |
| | | *SSM/I* | *SSM/I* | | *SSM/I* | | | | | |
| | | | | | | | | | | |
| NOAA | *TOPEX* | | *NOAA-I* | *NOAA-J* | | *NOAA-K* | *NOAA-L* | | *NOAA-M* | |
| | | | *AVHRR-2* | *AVHRR/2* | | *AVHRR/3* | *AVHRR/3* | | *AVHRR/3* | |
| | | | *HIRS/2* | *HIRS/2* | | *AMSU* | *AMSU* | | *AMSU* | |
| | | | *MSU* | *MSU* | | *HIRS/2* | *HIRS/2* | | *HIRS/2* | |
| | | | | | | | | | | |
| | | | | *GOES-I* | | *GOES-J* | | *GOES-K* | | |
| | | | | | | | | | | |
| | | | | *SEAWIFS* | | | | | | |
| | | | | | | | | | | |
| NASA | *UARS* | | | | | *TRMM* | | *EOS-A* | | *EOS-B* |
| | | | | | | | | | | |
| US NAVY | | | | | | *GFO* | | | | |
| | | | | | | | | | | |
| ESA | | *METEOSAT-6* | | *MTS* | | *MSG* | | | | |
| | | | | | | | | | | |
| | | | | | | *EPS* | | | | |
| | | | | | | | | | | |
| NASDA (JAPAN) | | *JERS-1* | | *GMS-5* | *ADEOS* | *TRMM* | | *JPOP* | | |
| | | | | | | | | | | |
| CHINA | | | | | *FY-2* | | | | | |
| | | | | | | | | | | |
| FRANCE | *POSEIDON* | | *SPOT-3* | | *SPOT-4* | | | | | |
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## REFERENCES


Baker, W., 1992: Joint NESDIS/NASA/NMC Effort to Develop an Advanced Satellite Retrieval System. FirstNMC/NESDIS/DoD Conference on DMSP Retrieval Products. NOAA Science Center, Camp Springs, MD.

Baker, W., E. Kalnay, D. Deaven, G. DiMego, P. Julian, D. Esteva, R. Reynolds, T. Yu, H.-L. Pan, C. Dey, and K. Campana, 1989: Satellite Applications at NMC. ECMWF/EUMETSAT Workshop. The Use of Satellite Data in Operational Numerical Weather Prediction: 1989-1993. Volume I, pp. 271-300.

Boucher, D. J., B. H. Thomas and A. M. Kishi, 1993: Performance of the DMSP SSM/T-2Microwave Radiometer: A Comparison Between Sensor Derived, Model Analysed, and Radiosonde Measured Moisture Variables. Preprints Eighth Symposiom on Meteorological Observations and Instrumentation, Anaheim, CA.

Chahine, M.T., 1982: Remote Sensing of Cloud Parameters. J. Atmos. Sci., 31, pp. 744-757.

Chahine, M. T. and J. Susskind, 1989: Fundamentals of the GLA Physical Retrieval Method. ECMWF/EUMETSAT Workshop. The Use of Satellite Data in Operational Numerical Weather Prediction: 1989-1993. Volume I, pp. 271-300.

Chedin, A., N.A. Scott, C. Wahiche and P. Moulinier, 1985: The Improved Initialization Inversion Method: A High Resolution Physical Method for Temperature Retrievals from Satellites of the TIROS-N Series. J. Clim. and Appl. Meteorol., 24, pp. 128-143.

Colton, M. C., 1992: DMSP Special Sensor Microwave/Imager Processing at the Fleet Numerical Oceanography Center: Operational Status, Applications and Plans. Preprints Sixth Conference on Satellite Meteorology and Oceanography, Atlanta, GA.

DMSP SSM/I Calibration and Validation Report. Volume I, DMSP SSM/I Cal/Val Team, Hollinger, J. P. (Ed.), 1989, 174 pp.

DMSP SSM/I Calibration and Validation Report. Volume II, DMSP SSM/I Cal/Val Team, Hollinger, J. P. (Ed.), 1991, 260 pp.

ECMWF/EUMETSAT Workshop. The Use of Satellite Data in Operational Numerical Weather Prediction: 1989-1993. Volume I. European Center for Medium-Range Weather Forecasts, Shinfield Park, Reading RG2 9AX, U. K. 301 pp.

Eyre, J. R. and A. C. Lorenc, 1989: Direct Use of Satellite Sounding Radiances in Numerical Weather Prediction. Meteorol. Mag., 118, pp. 13-16.

Eyre, J. R., 1989: Inversion of Cloudy Satellite Sounding Radiances by Nonlinear Optimal Estimation: Theory and Simulation for TOVS. Quart. J. R Meteorol. Soc., 115, pp. 1001-1026.

Eyre, J. R. , 1990: The Information Content of Data from Satellite Sounding Systems: A Simulation Study. Quart. J. R. Meteor. Soc. , 116, pp. 401-434.

Falcone, V. J. , L. W. Abreu and E. P. Shettle, 1982: Atmospheric Attenuation in the 30-300 GHz Region using RADTRAN and MWTRAN. Proc. Soc. Photo Opt. Instrum. Eng., 337, pp. 62-66.

Fleming, H. E. , M. D. Goldberg, and D. S. Crosby, 1986: Minimum Variance Simultaneous Retrieval of Temperature and Water Vapor from Satellite radiance Measurements. Preprints of the Second Conference on Satellite Meteorology/Remote Sensing and Applications, Williamsburg, VA, pp. 20-23.

Fleming, H. E. , M. D. Goldberg, and D. S. Crosby, 1988: Operational Implementation of the Minimum Variance Simultaneous Retrieval Method. Preprints of the Third Conference on Satellite Meteorology and Oceanography, Anaheim, CA, pp. 16-19.

Grody, N. C. , 1991: Classification of Snow Cover and Precipitation using the Special Sensor Microwave Imager. J. Geophys. Res. , 96, pp. 7423-7435.

Grody, N. C. and R. R. Ferraro 1992: A Comparison of Passive Microwave Rainfall Retrieval Methods. Preprints Sixth Conference on Satellite Meteorology and Oceanography, Atlanta, GA, pp. 60-65.

Hoffman, R. N. and T. Nehrkorn, 1989: A Simulation Test of 3-D Temperature Retrievals. Mon. Wea. Rev. , 117, pp. 473-494.

Hogan, T. F. , T. E. Rosmond, R. Gelaro, 1991: The NOGAPS Forecast Model: A Technical Description. NOARL Report 13, 223 pp., Naval Research Laboratory, Monterey, CA.

Hollinger, J. P. and R. C. Lo, 1983: SSM/I Project Summary Report. NRL MR 5055, Naval Research Laboratory, 106 pp. , Washington, D. C.

Isaacs, R. G. , 1989: A Unified Retrieval Methodology for the DMSP Meteorological Sensors. Advances in Remote Sensing Retrieval Methods. A. Deepak, H. E. Fleming, and J. S. Theon (Eds. ). Deepak Publishing, pp. 203-214.

Jensen, J. J. and J. Hovermale, 1990: Numerical Air/Sea Environmental Prediction. Oceanus, 33, Winter 1990/91, pp. 40-48.

King, J. I. F. , R. G. Holhfeld and J. C. Kilian, 1989: Application and Evaluation of a Differential Inversion Technique for Remote Temperature Sensing. Meteor. Atmos. Physics, 41, pp. 115-116.

McMillin, L. M. , 1986: The Use of Classification Procedures to Improve the Accuracy of Satellite Soundings of Temperature and Moisture. Preprints Second Conference on Satellite Meteorology/Remote Sensing and Applications, Boston, MA.

McMillin, L. M. , 1991: Evaluation of a Classification Method for Retrieving Atmospheric Temperatures from Satellite Measurments. J. Appl. Meteor. , 30, pp. 432-446.

McMillin, L. M. , 1992: Classification Retrieval Approaches for DMSP. First NMC/ NESDIS/DoD Conference on DMSP Retrieval Products. NOAA Science Center, Camp Springs, MD.

Mitchell, K. E. , T. L. Black, F. Messinger and N. C. Grody, 1992: Impact of SSM/I Snow/Ice Analyses in the NMC ETA Model. Preprints Sixth Conference on Satellite Meteorology and Oceanography, Atlanta, GA, pp. 153-154.

NASA, 1987: HMMR High Resolution Multifrequency Microwave Radiometer. Earth Observing System, Volume IIe, Instrument Panel Report, 59 pp.

NOAA, 1985: ENVIROSAT-2000 Report Comparison of the Defense Meteorological Satellite Program (DMSP) and the NOAA Polar-orbiting Operational Environmental Satellite (POES) Program.

Parrish, D. F. and J. C. Derber, 1991: The NMC Variational Analysis System. Preprints of the Ninth Conference on Numerical Weather Prediction, Denver, CO, pp. 75-78.

Patel, P. K. , 1992: Advanced Microwave Sounding Unit-A (AMSU-A). Preprints Sixth Conference on Satellite Meteorology and Oceanography, Atlanta, GA.

Petty, G. W. , 1990: On the Response of the Special Sensor Microwave/Imager to the Marine Environment - Implications for Atmospheric Parameter Retrievals. Ph. D. Dissertation, University of Washington, 292 pp.

Phegley, L. and C. Crosiar, 1991: The Third Phase of TESS. Bull. Amer. Meteorol. Soc. , 72, pp. 954- 960.

Reale, T. L. and D. Donahue, 1992: NOAA/NESDIS SSM/T Algorithms and Evaluation. First NMC/NESDIS/DoD Conference on DMSP Retrieval Products. NOAA Science Center, Camp Springs, MD.

Richardson, K. A. , 1990: Satellites Upgrades During TESS(3) Preoperational Development. NOARL Technical Note 24, 38 pp., Naval Research Laboratory, Monterey, CA.

Rigone, J. L. and A. P. Stogryn, 1977: Data Processing for the DMSP Microwave Radiometer System. Proc. Eleventh International Symposium on Remote Sensing of the Environment, pp. 1599-1608.

Schreiner, A. J. , 1990: The Development and Study of a DMSP Retrieval Algorithm. A Final Report to Naval Atmospheric and Oceanic Research Laboratory. Contract No. N00014-86-C-0604, 24 pp.

Sienkiewicz, M. E. , 1993: Using Forecast Background Fields to Determine Systematic Errors in Satellite-Derived Profiles. Preprints Eighth Symposiom on Meteorological Observations and Instrumentation, Anaheim, CA.

Smith, M. R. , C. Vada LaFontaine, F. J. LaFontaine, D. D. Moss, B. M. Goodman, R. C. Dengel, J. T. Young and H. M. Goodman, 1992: WetNet: A Status Report. Eighth International Conference on Interactive Information Processing for Meteorology, Oceanography, and Hydrology, Atlanta, GA, pp. 63-66.

Smith W. L. and H. M. Woolf, 1987: The use of Eigenvectors of Statistical Covariance Matrices for Interpreting Satellite Sounding Radiometer Measurements. J. Atmos. Sci. , 33, pp. 1127-1140.

Smith W. L. , H. M. Woolf, C. M. Hayden, D. Q. Wark, L. M. McMillin, 1979: The TIROS-N Operational Vertical Sounder. Bull. Amer. Meteorol. Soc. , 60, pp. 1177-1187.

Smith, W. L. , H. M. Woolf and A. J. Schreiner, 1985: Simultaneous Retrieval of Surface and Atmospheric Parameters: A Physically and Analytically Direct Approach. Advances in Remote Sensing Retrieval Methods,A. Deepak, H. E. Fleming, and J. S. Theon (Eds. ). Deepak Publishing, pp. 221-230.

Sparkman, J. K. , 1989: NOAA Polar Orbiting Sensor Systems: Today and Tomorrow. Int. J. Remote Sens. , 10, pp. 609-612.

Stogryn, A. P. , 1989: The Magnetic Field Dependence of Brightness Temperatures at Frequencies Near the $O_2$ Absorption Lines. IEEE Trans. Geosci. Remote. Sens. , 27, pp. 279-289.

Susskind, J. and J. Pfaendtner, 1989: Impact of Interactive Retrievals on NWP. ECMWF/ EUMETSAT Workshop. The Use of Satellite Data in Operational Numerical Weather Prediction: 1989-1993. Volume I, pp. 271-300.

Susskind, J. , J. Rosenfield and D. Reuter, 1983: An Accurate Radiative Transfer Model for Use in the Direct Physical Inversion of HIRS2 and MSU Temperature Sounding Data. J. Geophys. Res. , 88, pp. 8550-8568.

Swadley, S. D. and J. Chandler, 1992: The Defense Meteorological Satellite Program's Special Sensor Microwave Imager/Sounder (SSMIS): Hardware and Retrieval Algorithms. Preprints Sixth Conference on Satellite Meteorology and Oceanography, Atlanta, GA.

Thepaut, J-N. and P. Moll, 1990: Variational Inversion of Simulated TOVS Radiances using the Adjoint Technique. Quart. J. R Meteorol. Soc. , 116, pp. 1425-1448.

Thompson, O. E. , 1992: Regularizing the Satellite Temperature-Retrieval Problem through Singular-Value Decomposition of the Radiative Transfer Physics. Mon. Wea. Rev. , 120, pp. 2314-2328.

Wentz, F. J , 1988: User's Manual, SSM/I Antenna Temperature Tapes, Remote Sensing Systems. RSS Technical Report 032588.

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