NASA Technical Memorandum 104576

Interim Status Report on Results From the U.S./Russian Meteor-3/ Total Ozone Mapping Spectrometer

August 15, 1991 to June 1, 1992

ORIGINAL CONTAINS
COLOR ILLUSTRATIONS

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ABSTRACT

The development of Meteor-3/TOMS (Total Ozone Mapping Spectrometer) was a joint project of the United States and Russia to fly a U.S. ozone measuring instrument (TOMS) on board a Russian spacecraft (Meteor-3) and rocket (Cyclone), launched from Plesetsk, Russia. The Meteor-3/TOMS (M3TOMS) was launched into a 1202 km high near-polar orbit on August 15, 1991, where it can obtain complete global coverage for most of each year. Both the US and Russian sides have successfully received and processed data into ozone amounts from August 25, 1991 to June 1, 1992, and expect to continue for the life of the instrument and spacecraft. The successful development of the instrument hardware, spacecraft interface, data memory, telemetry systems, and software are described. Descriptions are given of the U.S. and Russian ground stations for receiving M3TOMS data. In addition, the data reduction software was independently developed by the U.S. and by the Russians, and is shown to agree to better than the precision of the measurements.

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1.0 INTRODUCTION

Section Contributors:

Jay R. Herman
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Ongoing monitoring of the Earth's ozone layer has long been recognized as an essential activity of the space program. For the past 13 years NASA/GSFC has had an extremely effective program in place based on the TOMS (Total Ozone Mapping Spectrometer) and the SBUV (Solar Backscatter Ultraviolet Spectrometer) launched on board the Nimbus satellite in October 1978. The two most important forms of ozone data obtained are the long-term ozone trends and the day-to-day complete pictures of the ozone amounts over the entire globe. The first has enabled NASA scientists to unequivocally determine the global (-2.6% per decade) local zonal average (up to -8% per decade) rates of ozone decrease. The second has enabled us to monitor the year-to-year development of the Antarctic ozone hole, the effects of volcanic eruptions on the ozone layer, the influence of weather patterns (winds and pressure changes) on ozone amount, and to acquire an understanding of the relationship between atmospheric dynamics (temperatures and winds) and the local ozone amounts. An unexpected side benefit has been the development of a method to determine stratospheric aerosol properties after major volcanic events (Mt.Pinatubo, June 1991) from the 35 cross orbital track ozone measurements.

The determination of long-term trends in ozone amount requires that there be substantial overlap in time between the old data set (Nimbus/TOMS) and a new ozone monitoring instrument. The Meteor/TOMS program was conceived to accomplish this task and to foster scientific cooperation between the Soviet Union and the United States. After several years of combined effort, a refurbished version of the original TOMS engineering instrument was launched on board a Soviet Meteor class spacecraft and Cyclone rocket from Plesetsk, USSR on August 15, 1991.

To date the joint effort has been entirely successful. The integration and launch of the Meteor-3/TOMS mission represented a major forward in cooperative space projects with the former Soviet Union. TOMS is the first NASA instrument to be integrated and flown on a Soviet satellite. The lessons learned, in both a technical and cultural sense, will prove invaluable for both countries (United States and Russia) in the years to come.

The activity was truly a team exercise. The Meteor-3/TOMS project was large and complex, with additional difficulties caused by language, cultural differences, limited communication capabilities, and the requirement for frequent travel. The project was precedent setting, in that no guidelines or previous experience existed to aid the team through the various stages of development and testing. Under these conditions, total teamwork and cooperation was required to plan and execute the various phases of the program. These included design, development, and testing of the TOMS instrument and the interface to the Meteor spacecraft. During this phase of the project there were 9 formal Joint Working Group meetings, 6 meetings between technical specialists from both countries, 4 Joint Data Group meetings, 3 spacecraft testing and integration sequences, and a joint operation for the final integration, launch, and mission operations. These activities frequently required extended residence of many U.S. team members in the Soviet Union. The cooperation between both countries, and between government and industry, was outstanding during the development and launch phase of the program. This cooperation is continuing during the satellite operation and ozone data reduction portion of the program.

The spacecraft and TOMS instrument have performed to design specifications. Data acquisition and exchange, mission operations, and scientific cooperation with our Russian colleagues has been excellent. The data returned from the Meteor-3/TOMS mission is starting to yield scientifically useful results that will increase our understanding of atmospheric ozone, radiative transfer, aerosol detection, and improve our abilities to analyze remote sensing data for this and future missions.

2.0 MISSION DESCRIPTION

Section Contributors:

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Eve Abrams	Arlin Krueger
Michael Forman	Thomas Riley
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2.1 OVERVIEW

The Meteor-3/TOMS mission is based on a US Total Ozone Mapping Spectrometer (TOMS) instrument, including associated interface and data storage equipment, integrated on a USSR Meteor-3 spacecraft. In July 1990, NASA Headquarters and the USSR State Committee for Hydrometeorology (Hydromet) signed the Meteor-3/TOMS Implementing Agreement, delineating the activities and responsibilities of NASA and Hydromet for the Meteor-3/TOMS mission. Meteor-3/TOMS was launched on August 15, 1992 from the Plesetsk Kosmodrome Complex, Plesetsk, USSR, into a polar orbit on a USSR Cyclone launch vehicle for a planned two year mission with the probability of an extended lifetime.

The TOMS instrument is designed to produce a global map of the spatial distribution of total ozone on a daily basis. The scientific and technological goals of the Meteor-3/TOMS instrument are to gather global total ozone data of environmental importance, and to improve the quality of satellite measurements of ozone through comparison of coincident data. The programmatic objective is to establish avenues of communication between the countries at both scientific and technical levels to help resolve the question of global ozone modification. The larger goal is to acquire the knowledge for the improvement of the quality of life for all of earth's citizens.

TOMS is designed to map the spatial distribution of total ozone by measuring the atmospheric albedo of the sunlit earth at six selected wavelengths in the ultraviolet region of the spectrum. The field-of-view of the instrument is swept across the spacecraft ground track. This produces a swath of observations bridging the region between adjacent orbits to produce spatially continuous global coverage. The Meteor-3/TOMS provides a high resolution map of the global total ozone on a daily basis.

The primary science objective of TOMS is to continue observations of important ozone changes. The scientific priorities for this mission are briefly described below.

1. Continue the precise global total ozone climate data base of Nimbus-7 TOMS in order to monitor the change due to man's activities and natural changes.

2. Maximize possible coverage of ozone amount at Antarctic latitudes during the months of September and October to monitor the development of the Antarctic ozone hole.

3. Maximize possible coverage of the ozone at Arctic latitudes during the month of February, augmented with coverage during January and March to determine whether related ozone depletions occur in the Arctic.

Normal operating command sequences are prepared by NASA and sent to Hydromet. The command sequences cover a period of 14 days. TOMS science data is recorded for 13 orbits (approximately 1 day of data) and then is downlinked to the USSR and US ground stations. Normal operations sample TOMS and Meteor housekeeping data one orbit every two weeks.

2.2 DATA PROCESSING AND DATA PRODUCTS

The TOMS data is downlinked separately twice each day in the USSR and twice each day in the US. The second downlink is to assure good data transmission, and is not processed if the first transmission is acceptable. The US receiving station is the Wallops Orbital Tracking Station located at the GSFC/Wallops Flight Facility and the main USSR receiving station is at Obninsk. If either the NASA or Hydromet ground station misses a pass of the spacecraft, raw scientific ozone data for the time period missed is exchanged between NASA and Hydromet.

Both NASA and Hydromet receive and process the TOMS flight data. NASA processes the raw flight data through the TOMS algorithm to produce total ozone data in the current Nimbus-7 TOMS format. Hydromet provides general spacecraft parameters for use in data reduction algorithms. Hydromet also provides precise time, location, and periodic spacecraft attitude information. This information, along with TOMS service telemetry, is delivered by Hydromet to the NASA data processing center as an individual set of data. The total ozone data computed from all algorithms developed independently by NASA and Hydromet are compared with each other and with other data sources (Dobson, Lidar, ozonesondes, and with available scientific data from US and Soviet spacecraft and ground stations).

There are four data levels for the Meteor-3/TOMS mission. They are:

Level 0	TOMS data converted to counts in major frame format
Level 1	Raw counts, scan angle, zenith angle, day number, etc.
Level 2	Analyzed ozone data versus latitude, longitude, day number, etc.
Level 3	Analyzed ozone data: maps, grids, plots, etc.

Data handling responsibilities between NASA and Hydromet are divided as follows.

NASA:

- Generation of TOMS command sequences
- Production of Level 0/1/2/3 data products for use by NASA
- TOMS instrument status monitoring
- Declaration of emergencies
- Generation of TOMS calibration data sets which will be transmitted to Hydromet

Hydromet:

- Spacecraft operations
- Production of Level 0/1/2/3 data products
- Uplinking of TOMS command messages
- TOMS housekeeping data monitoring
- TOMS telemetry monitoring
- Periodic spacecraft attitude telemetry sampling
- Spacecraft orbit element determination

Joint NASA/Hydromet:

- Operational communications
- Scientific analysis of TOMS data

Representatives of NASA and Hydromet meet periodically to review the status of the instrument and the ozone data. An initial joint publication will be produced in an agreed upon journal. The initial publication will describe the instrument and its calibration and provide a sample of the ozone data obtained by Meteor-3/TOMS. Subsequent publications may be prepared jointly or separately.

NASA and Hydromet are each entitled to receive all raw flight data from TOMS and may reproduce, use and disclose it for any purpose at their discretion. It is the intention of both NASA and Hydromet that the raw, processed, and analyzed data will be made available to the international scientific community through publication or other appropriate means. Both NASA and Hydromet will deliver TOMS Level 2 and Level 3 archival ozone data tapes to the National Space Science Data Center (NSSDC).

2.3 KEY PERSONNEL

US PERSONNEL

Samuel W. Keller	Associate Deputy Administrator	Code ADA NASA Headquarters
George F. Esenwein	Program Manager	Code SEF NASA Headquarters,
Jefferson S. Hofgard	Acting Chief, International Programs	Code SEF NASA Headquarters
Charles E. Cote	Project Manager	Laboratory for Atmospheres, Code 910 NASA/Goddard Space Flight Center
Stanley H. Way	Deputy Project Manager	Atmospheric Experiment Branch, Code 915 NASA/Goddard Space Flight Center
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Holland T. Bell	Head, Data Acquisition Branch	Data Acquisition Branch, Code 833 NASA/Goddard Space Flight Center
Arnold G. Oakes	Data Processing Manager	Information Systems Development Facility, Code 936 NASA/Goddard Space Flight Center
Eve M. Abrams	Contamination Engineer	Thermal Engineering Branch, Code 732 NASA/Goddard Space Flight Center

USSR PERSONNEL

N. Petrov	Deputy Head of Main Department of the USSR State Committee for Hydrometeorology (Hydromet)
V. Adasko	Director of All-Union Research Institute for Electromechanics (VNIIEM)
V. Khattatov	Deputy Head, Central Aerological Observatory
B. Morozov	Head of Space Systems Agency, Ministry of Defense
S. Konyukhov	General Designer of "YUZHNOYE" Design Bureau
O. Federov	Responsible Member of the USSR Council of Ministers
H. Makarov	Head of FVNIIEM Subsidiary of All-Union Research Institute for Electromechanics
Yu. Trifonov	Deputy Director of All-Union Research Institute for Electromechanics (VNIIEM)
Yu. Kazakov	Deputy Head, International Department of USSR GOSHYDROMET

R. Salikhov	Deputy Head, FVNIIEM
A. Volkov	Deputy Head, "Planeta" Scientific Industrial Association
V. Mistshyuk	Deputy Director of TV Scientific Research Institute
V. Mekscha	Head of Space Systems Division, Ministry of Defense
G. Petrenko	Head of Department, FVNIIEM
A. Vladimirov	Head of Department, FVNIIEM
A. Korotkov	Head of Department, FVNIIEM
G. Tolmachev	Head of Laboratory, FVNIIEM
A. Danilov	Interpreter, Central Aerological Observatory

SUPPORTING ORGANIZATIONS

Center for Flight Control (TSUPP)

FVNIIEM

Head of Space Systems Agency, DOD

Intercosmos

"Planeta" Scientific Industrial Association

TV Scientific Research Institute

"YUZHNOYE" Design Bureau

USSR Council of Ministers

VNIIEM

SUPPORTING CONTRACTORS

Bendix Field Engineering Corporation

Computer Sciences Corporation

Design Dynamics, Inc.

G.E. International Services Corporation

International Development and Energy Associates, Inc.

McDonnell Douglas Space Systems Company

NSI Tech Services Corporation

Perkin Elmer

Hughes/STX

Swales and Associates

Symbiotics Technologies, Inc.

UNISYS

University of Maryland

2.4 FLIGHT COMPONENTS

2.4.1 Instrument Description

The flight components consist of the TOMS Instrument Assembly, the Interface Adapter Module (IAM), and the Meteor-3 spacecraft. NASA provided the TOMS Instrument Assembly and IAM. The USSR provided flight hardware including the Meteor-3 spacecraft, the Cyclone launch vehicle, and all on-board facilities required to operate the

TOMS and IAM, (e.g., power, timing, and commanding of instrument modes by stored and real time commands).

The TOMS instrument consists of a single Ebert-Fastie monochromator with a fixed grating and an array of exit slits. Functionally, TOMS measures the radiance backscattered by the atmosphere in six ultraviolet bands (312 to 330 nm) during the daylight portion of the orbit. Once per day, as the spacecraft crosses over the day-to-night polar terminator, reflected sunlight from a diffuser plate is viewed by the instrument for solar irradiance calibration. The stability and characterization of the diffuser plate is a major aspect of the system calibration.

In addition to various housekeeping sensors for monitoring the well-being of the system, TOMS is also provided with in-flight wavelength and electronic calibration modes for periodic assessment of radiometric performance. In-flight calibrations are designed to check stability of the monochromator wavelengths in radiance and irradiance modes, and the gain stability of the signal processing electronics.

2.4.2 Instrument Heritage

The Nimbus-7/TOMS Flight Model 1 (FM-1) engineering model was refurbished to flight status, becoming Meteor-3/TOMS (FM-2). Meteor-3/TOMS is intended as an extension of the Nimbus/TOMS program. Nimbus-7/TOMS was launched in October 1978 and has operated continuously since that time. Improvements and changes incorporated into FM-2 include:

1. Bake-out of all materials that mechanically support optical elements
2. Mounting of the Optics Module and Electronics Module to a baseplate
3. Replacement of some electronics components
4. Replacement of some optical components
5. Addition of a three-plate Diffuser Module
6. The required interface between the TOMS and the Meteor-3 spacecraft, an Interface Adapter Module (IAM).
7. Addition of flight interconnection cables.

2.4.3 Hardware Description

The TOMS instrument, illustrated in Figure 2.4.3-1, includes the following assemblies:

1. TOMS FM-2 Instrument Assembly
2. Interface Adapter Module (IAM)
3. Interconnecting flight cables

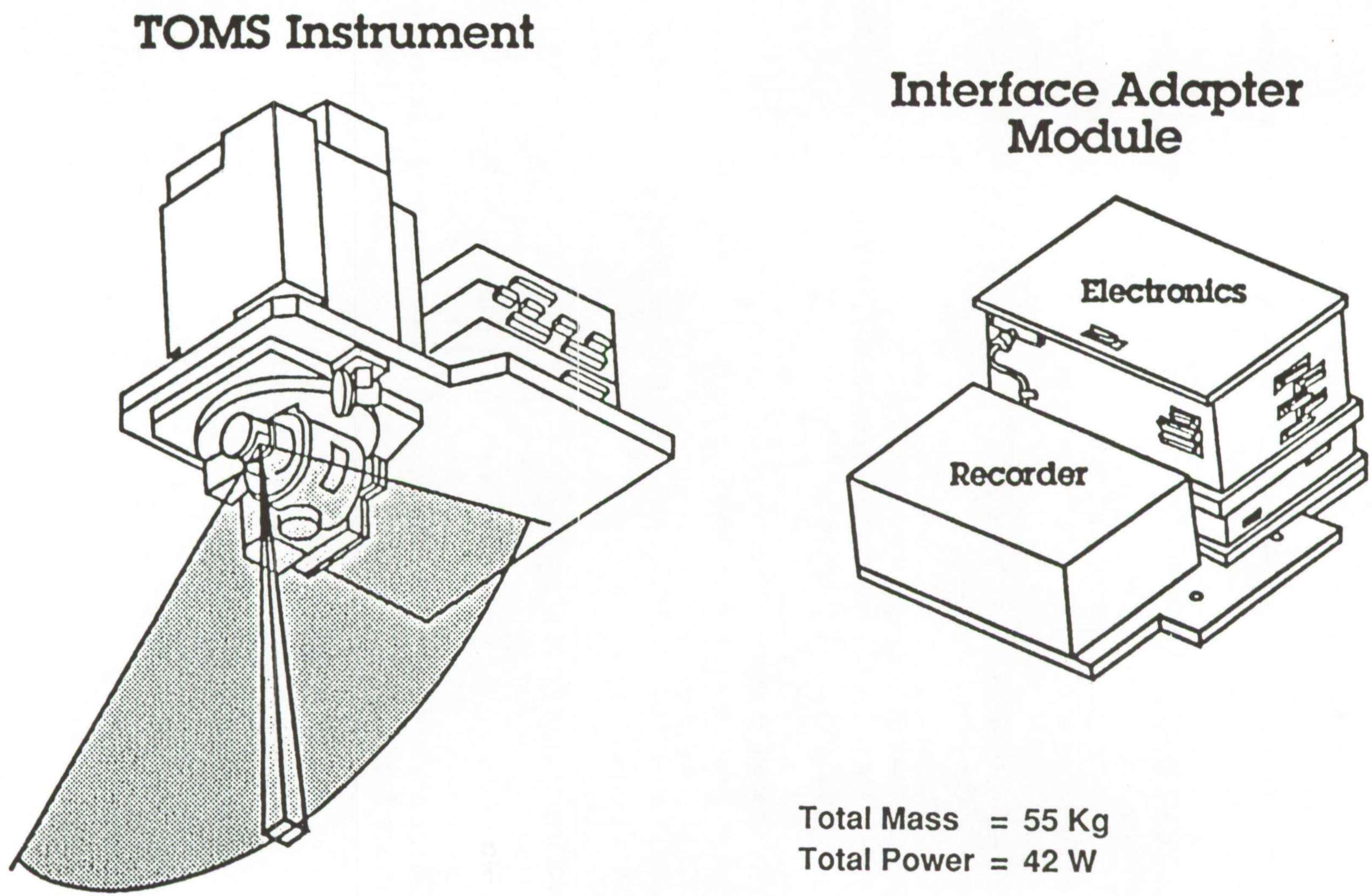


Figure 2.4.3-1 TOMS instrument assembly diagram

The FM-2 Instrument Assembly includes the Optics Module (OPM), Electronic Logic Module (ELM), Diffuser Module, and baseplate. The IAM consists of the interface electronics, data recorder, and baseplate. The Instrument Assembly and IAM each has a mass of 28kg.

2.4.3.1 TOMS Optical System

The TOMS optical system is shown schematically in Figure 2.4.3.1-1. The major TOMS optical subsystems are:

- Diffuser Module
- Cross-Track Scanner
- Depolarizer
- Objective Lens
- Slit Assembly and Chopper/Wavelength Selector
- Monochromator Optics
- Exit Lens
- Photomultiplier Tube
- Mercury Calibration Lamp

The above items, with the exception of the Diffuser Module, comprise the Optics Module.

2.4.3.2 Electronic Logic Module (ELM)

The signal processing electronics in the ELM are identical to the Nimbus-7 TOMS. In data recording, the chopped optical signal from the exit slit generates a current in the photomultiplier tube (PMT). This current drives four electrometer amplifiers in parallel. Each amplifier employs a different gain to span the input energy range. A summing node at each electrometer input accepts either the PMT output (during normal data acquisition modes), or a precise signal pulse (during Electronic Calibration Mode). Each electrometer drives a dedicated voltage-to-frequency counter (VFC) that performs analog-to-digital conversion on each of the four parallel gain stages. The four VFCs output to four accumulators which are controlled and synchronized to the optical chopper. The accumulators count up when light is admitted to the PMT and count down when the chopper blocks light to the PMT. In this manner, the resultant value represents the actual input signal minus the dark current and other currents not synchronous with the chopper. The accumulator thus operates as an integrator and synchronous demodulator, rejecting any DC components in the signal. Other functions provided by the ELM include: analog housekeeping data; calibration lamp control; and chopper servo control.

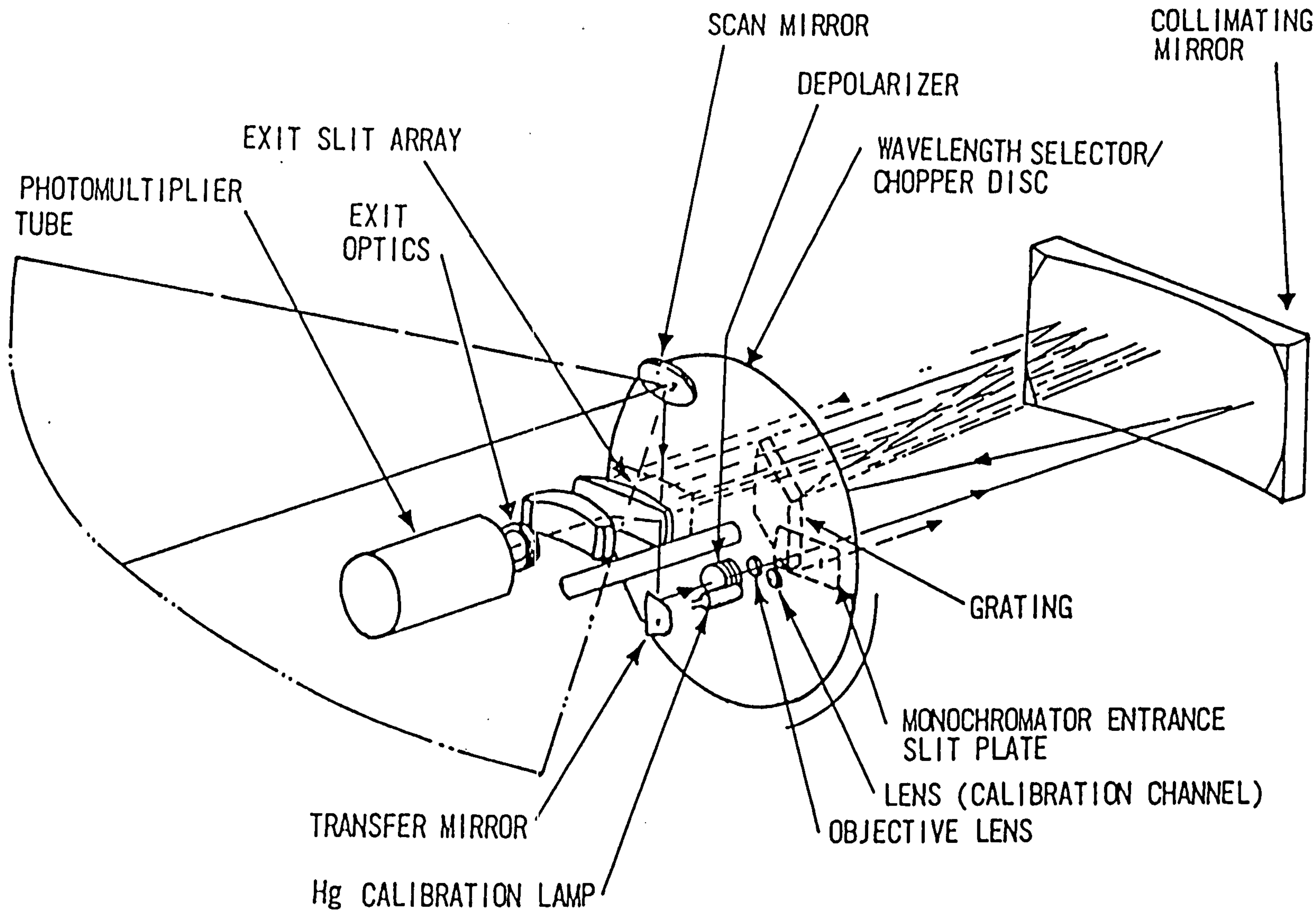


Figure 2.4.3.1-1 Meteor-3/TOMS optical system.

2.4.3.3 Interface Adapter Module (IAM)

The IAM effectively integrates the TOMS instrument as part of the Meteor-3 spacecraft and is designed for compatibility while imposing no adverse effects on either system. The IAM contains the electronics to interface TOMS to Meteor-3, the DC/DC converter, and the data recorder. The IAM converts the Meteor-3 power, commands, clock, telemetry, and data interfaces into a compatible system for TOMS. Power is provided to the TOMS, diffuser module, data recorder, and the IAM's own circuits. TOMS total power consumption ranges 17 to 39 Watts. The IAM satisfies the Meteor-3 requirements for a single-block access to inputs, outputs, and autonomous testing without removing TOMS from the spacecraft.

2.4.3.4 Data Recorder

The data recorder is an on-board storage system that is provided as part of the IAM to record measurements at the instrument sample rate through useable portions of the orbit. The TOMS science data are only meaningful during daytime portions of the orbit. Measurements are stored on-board for approximately 13 orbits. The same stored data is transmitted daily to NASA and USSR receiving stations.

2.4.3.5 Baseplates

All the TOMS assemblies were mounted on two baseplates which were attached to the Meteor-3 spacecraft instrument platform in mutually agreed upon locations. The baseplates were designed for thermal and mechanical compatibility with the instrument platform. The TOMS Instrument Assembly requires definite orientation of its axes in relation to the spacecraft axes and has a bolt pattern in its baseplate that guarantees unequivocal installation of all assemblies into the seating places of the spacecraft. This alignment is critical to the mission science.

2.4.3.6 Interconnecting Flight Cables

Interconnecting flight cables include cables, flight quality connectors, and connector labels. NASA provided Hydromet with mating connectors for the IAM-to-spacecraft cables.

2.4.4 Calibration

TOMS calibration consists of both prelaunch and in-flight efforts. The radiometric response of TOMS is established using standard reference sources. Responses of the various in-flight calibration systems are characterized over the range of anticipated operating conditions. This is performed prior to launch. Once in orbit, the instrument is evaluated and the various in-flight calibration systems are used to provide the correlation to ground calibration.

2.4.4.1 Prelaunch Calibration

The prelaunch radiometric calibration of the TOMS instrument was composed of three parts: 1. radiance calibration, 2. irradiance calibration, and 3. system linearity calibration. The TOMS instrument measures the UV solar irradiance above the earth's atmosphere, and the earth radiance from illumination of the atmosphere by the sun. The irradiance measuring mode of TOMS uses a diffuser plate in the instrument's optical path. The objective of the prelaunch radiance and irradiance calibrations was the determination of the instrument response to a known UV illumination source.

2.4.4.2 In-Flight Calibration

The ground calibration is transferred to the TOMS operating environment after launch. This is accomplished by using the ground calibration as a base and correcting calibration constants using housekeeping data and in-flight calibration data. Housekeeping sensors monitor the various voltages, currents, and temperature parameters which impact the TOMS performance. The in-flight calibrations (solar calibration, wavelength calibration, and electronic calibration) monitor system spectral and radiometric responses.

A solar calibration cycle measures solar irradiance for calculating earth albedos. In-flight wavelength calibration is used to detect sub-Angstrom wavelength shifts in the monochromator due to shock, vibration, or thermo-mechanical distortions. During electronic calibration the gain stability of the signal processing electronics is checked by injecting precise simulated chopped signals into the input of each electrometer amplifier. Data are accumulated as in radiance measurements. Eight different input levels are automatically sequenced to test the full range of the amplifiers.

2.4.5 Meteor-3 Spacecraft

2.4.5.1 Attitude Control Subsystem

Figure 2.4.5.1-1 illustrates the Meteor-3 spacecraft and the locations of the TOMS Instrument Assembly and IAM. The Meteor-3 spacecraft utilizes a three-axis stabilization system to provide a nadir-pointing/fixed-yaw attitude. Attitude is sensed using a combination of gyros and a horizon sensor. The Meteor-3 horizon sensor is unique compared to US earth sensors. It employs a single nadir pointing optical sensor, a single

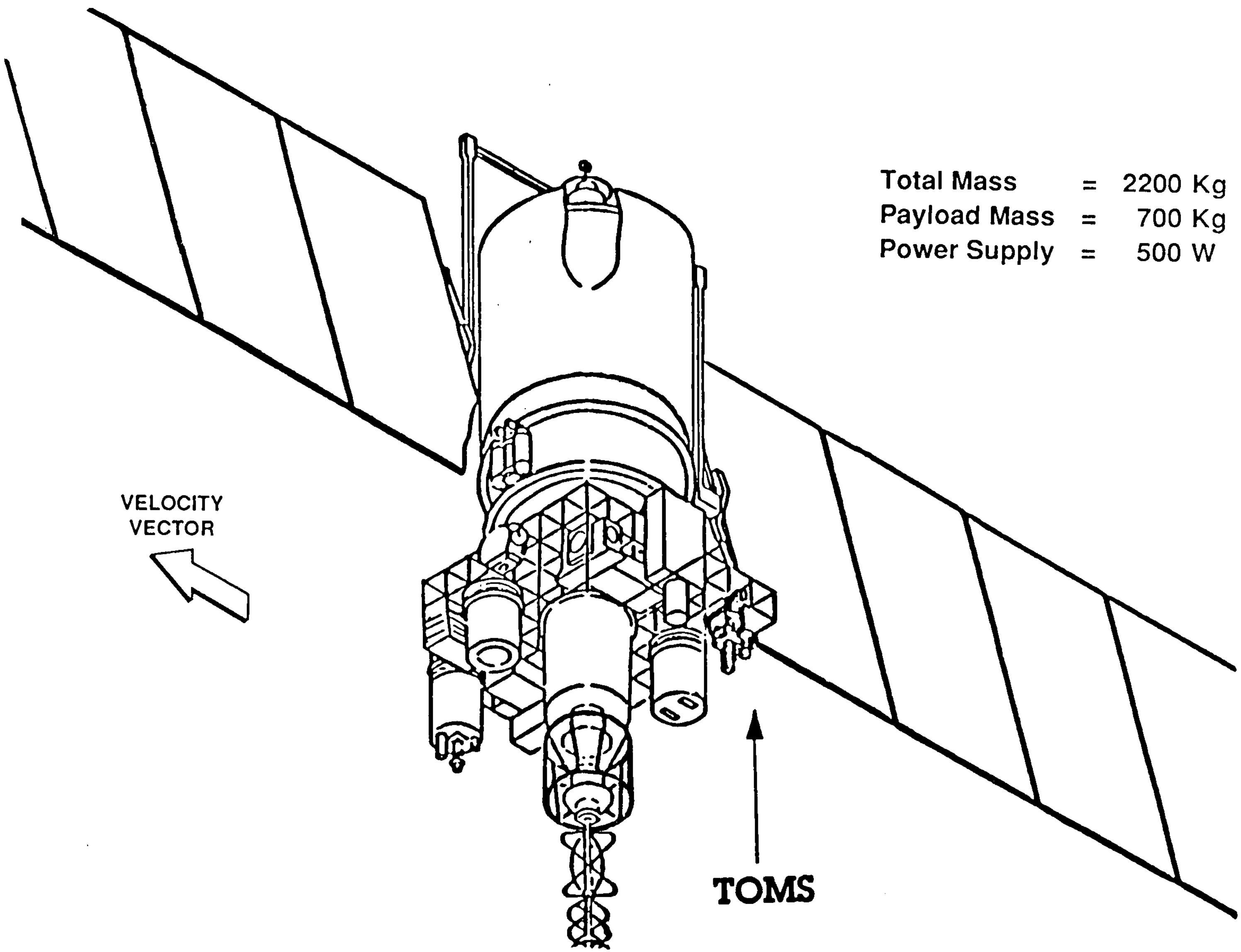


Figure 2.4.5.1-1 Locations of the TOMS Instrument Assembly and IAM

scan mirror rotating about the yaw axis, and eight fixed mirrors arranged such that the sensor is provided earth limb crossing views eight times per rotation of the scan mirror.

Attitude is controlled using momentum wheels. On previous flights, hydrazine thrusters were used to unload residual spacecraft momentum. The thrusters were removed and replaced with magnetic torquer bars for this mission because of concerns of potential contamination of the TOMS instrument.

2.4.5.2 Electrical Power Subsystem

Meteor-3 is powered by solar charged nickel-cadmium batteries. Primary power is provided at -24 to -34 volts unregulated, -27 volts nominal, and is not connected to the spacecraft chassis. Two independent battery modules are used for reliability, with one set being charged while the other is driving the load. The power supply provides a total of 500 Watts, with power available at all times after launch except during emergencies.

2.4.5.3 Command and Telemetry Subsystem

Both programmed and real time command capabilities are available. Because of operational constraints, real time capability is normally used only for emergencies. Satellite uplink commanding is controlled by Hydromet. Nominal uplink commands are at 10 to 15 day intervals. Stored commands operate the satellite systems during these intervals.

A 23 bit time code has been provided to TOMS. The code is formatted days (6 bits): hours (5 bits): minutes (6 bits): seconds (6 bits) of Moscow Standard Time. The Soviets provide a time correction for which accuracy is better than 100 milliseconds. The IAM generates sub-second time code for use by the TOMS.

2.4.6 Mission Orbit Description

Meteor-3 was launched from the Plesetsk Cosmodrome (Russia) on August 15, 1991 into a nearly circular non sun synchronous orbit at an altitude of 1202 km. The main characteristics of the orbit and the TOMS instrument are summarized in Table 2-1.

Table 2-1
Meteor-3/TOMS Characteristics

Altitude	1202 km
Inclination	82.5^{o}
Orbital Period	109 min
Orbital Eccentricity	$< 2 \times 10^{-3}$
Orbital Precession Period	212 days
Launch date and Time	Aug 15, 1991 at 12:15 pm Moscow Standard Time
First Ozone Data	August 22, 1991
Number of Orbits/Day	13.210
Instantaneous Field of View	$3^{o} \times 3^{o} \pm 0.1^{o}$
Wavelength Calibration	Mercury Line at 296.7 nm
Discrete Wavelength Range	312.5 - 380 nm
Wavelength Channels	312.35, 317.4, 331.13, 339.73, 359.0, and 380.16 nm
Spectrometer Bandwidth	1.1 nm
Cross Track Scan Angle	$\pm 51^{o}$
Number of Scenes/Scan	35
Ground Size of Nadir View	64 x 64 km
3-Plate Diffuser Exposure	Daily, 1-Week, 15-Weeks
Expected Spacecraft Lifetime	3 years

The complexity of the Meteor orbit arises from its precession period of 212 days and its orbital inclination of 82.5°. The first Meteor-3/TOMS data was obtained on August 22, 1991 with the spacecraft moving from south to north (ascending orbit) and crossing above the equator at about 10:30 in the morning. Approximately 212 days later, on March 21, 1992, the spacecraft will again cross the equator at 10:30 am on its ascending orbit. By March 22, 1992 the ascending portion of the orbit will have moved from 10:30 am to the sunrise terminator ($\approx$6 am), precess through the night, emerge at the sunset terminator ($\approx$6 pm), cross noon, and be again at 10:30 am.

Unfortunately, the orbital inclination of 82.5° prevents the 212 day precession period from truly being a cycle. For example, for the first sunrise terminator crossing, the Meteor orbit is nearly parallel to the night-day line. For the second crossing, the orbit is at an angle ($\approx$15°) to the terminator line. Subsequent crossings will be at different angles until the 212 day precession period is a multiple of the 365 day rotation period of the earth around the sun. The changing angles arise from the change in the earth's inclination angle toward the sun during the year ($\pm$23.5°).

The precessing orbit introduces complexities (large changes in zenith and azimuth angles) into the data reduction for obtaining ozone amounts from measured albedos. The difficulties are especially evident whenever the spacecraft orbit gets near the terminator. Under this condition, all of the data are obtained for high solar zenith angle (the sun low on the horizon relative to the point on the earth's surface where the spacecraft is looking). Until now, our experience with the Nimbus—7/TOMS has not required analysis of data at such large zenith angles (except for extreme polar region data). This has stimulated an extensive radiative transfer research effort to understand the new conditions. The result should be an improved ability to reduce the Meteor-3/TOMS data, and to improve the accuracy of all of the TOMS instruments in the geophysically important polar regions. A significant benefit of the Meteor-3 orbital parameters is increased ability to detect the presence of atmospheric aerosols and to obtain their properties.

2.4.7 Contamination Control

The optical components of TOMS are sensitive to contamination by both particulates and hydrocarbons. Of particular concern is the diffuser module. A change in its reflectivity directly effects the accuracy of the ozone measurements. Although contamination by particulates is to be avoided, the major source of concern is contamination by hydrocarbons which can be polymerized by UV solar radiation.

To minimize contamination of the instrument during test and integration in the USSR, a set of procedures which specified the handling of TOMS was defined in a Contamination Control Plan. This document was provided by NASA prior to first integration. In addition, several meetings were held with the Soviets to discuss contamination control in general and the specifics of contamination control relative to TOMS.

NASA personnel monitored contamination control procedures whenever the instrument was out of its shipping container to assure that the instrument was kept clean and took appropriate action to remedy any areas of concern. The NASA Contamination Control Engineer also worked with the Soviets in establishing their cleanroom facilities and in monitoring the cleanliness of the spacecraft.

2.4.8 Ground Support Equipment

NASA provided Ground Support Equipment (GSE) adequate to perform the tests called for in the Integration and Test Plan. The GSE consisted of a Bench Checkout Unit (BCU), assorted test cables, cable break-out boxes, and hand-held meters. The BCU included components to perform the functions of the Bench Test Equipment, Nimbus-7 spacecraft interface simulator, Meteor-3 spacecraft simulator, source illuminator, and external power supply. The BCU was also able to test all functions of TOMS used in flight.

2.4.9 Storage and Transportation

The TOMS Instrument Assembly and IAM were delivered to Hydromet fully assembled. Special handling fixtures were installed to provide support and a means of lifting without touching the Instrument Assembly or IAM. TOMS was shipped to the USSR by air and within the Soviet Union by air or truck. Special containers were used for shipping and storage that provided protection from contamination and excessive vibration and shock loads. The TOMS and IAM were sealed in dry nitrogen-purged bags. Accelerometers mounted on the instrument handling fixtures documented the maximum shock load to which they were exposed.

Hydromet provided initial documentation and relevant paperwork to the USSR Customs Office in order to minimize the USSR customs clearance procedures and time required for the TOMS instrument to clear USSR customs. NASA personnel accompanied the TOMS Instrument Assembly and IAM through customs and during all transportation in the USSR. Special arrangements were made with Pan Am to assure NASA presence on the tarmac during loading and unloading from the plane. The TOMS Instrument Assembly and IAM were always loaded, transported, handled, and unloaded under the supervision of a representative from NASA. In accordance with the Implementing

Agreement between NASA and Hydromet, the TOMS shipping containers were not opened for any reason, including customs inspection, except in a cleanroom environment of Class 100,000 or better and while accompanied by NASA personnel.

2.5 GROUND COMPONENTS

2.5.1 Tracking and Communication Facilities

The NASA satellite downlink telemetry system is supported by the Wallops Orbital Tracking Station located at the GSFC/Wallops Flight Facility, Wallops Island, Virginia. An RF receiving system was installed to support the 466.5 MHz downlink. Since the downlink frequency is very near public communication channels, it was necessary to use narrow band filters to minimize rf interference. The receive only antenna system was assembled using an existing pedestal and a new 8 meter dish. The system does not have autotrack capability. Instead, computer generated program tracking is used successfully for data collection. A backup receiving system was also implemented using an existing UHF radar system in the receive mode.

The initial reception problems due to the frequency drift of the Soviet spacecraft transmitter were compensated for by adjusting the ground station receiving parameters. There have been no other serious problems with data reception. Wallops Island Orbital Tracking Support (WOTS) consists of approximately 10 contacts per week (nearly daily) lasting about 13 minutes each. Of the 13 minutes the actual data downlink lasts about 7 to 8 minutes. To date, WOTS has supported about 470 successful data contacts. The data is transmitted in real time form WOTS to TIOCC via NASCOM. For backup purposes, the data is also recorded at WOTS and archived for a short period of time.

The main USSR receiving station is located approximately 100 km southwest of Moscow at Obninsk. Figure 2.5-1 illustrates the flow of telemetry and commands in the Meteor-3/TOMS mission.

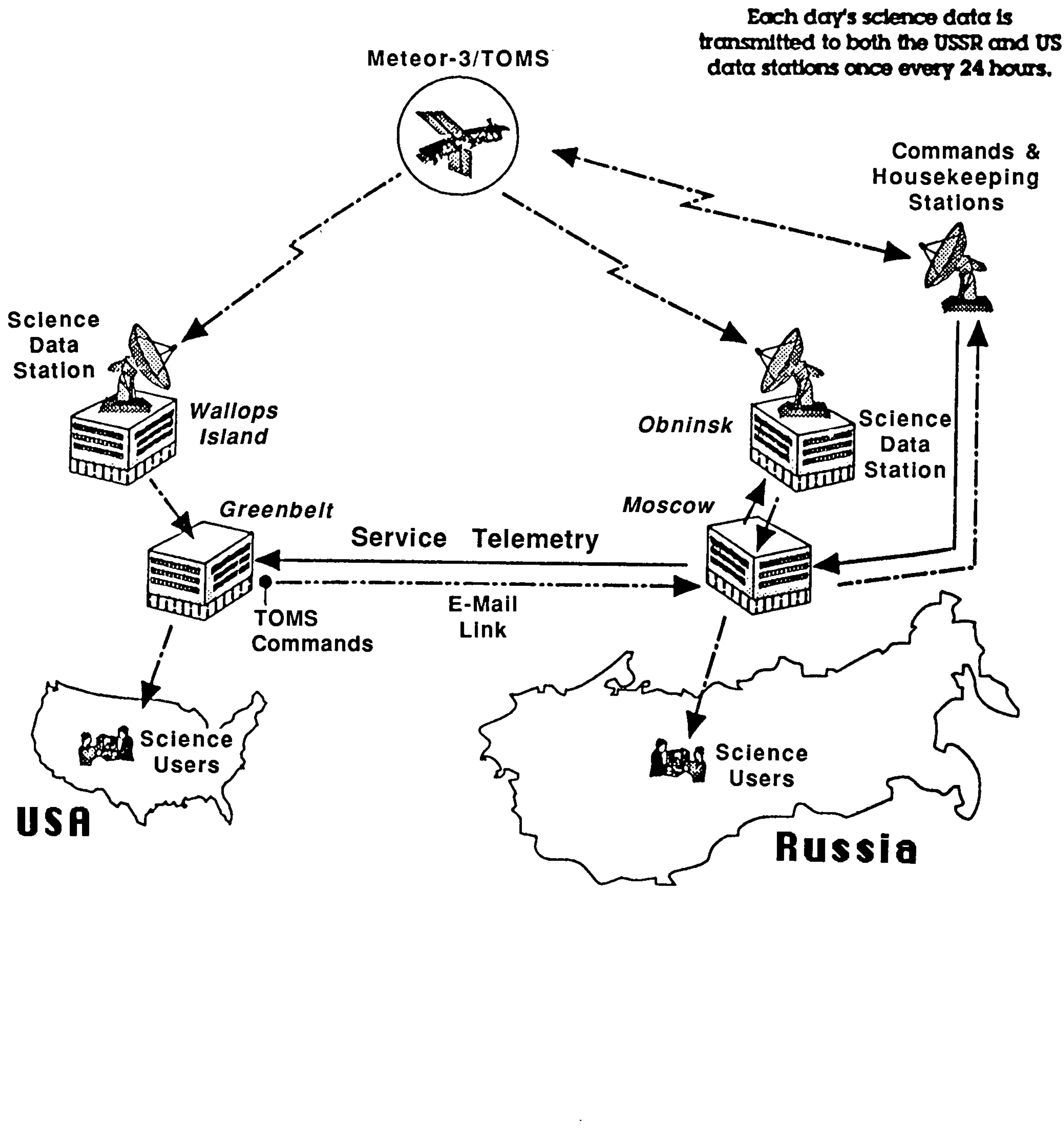


Figure 2.5-1 Meteor-3/TOMS telemetry and command flow diagram

2.5.2 Mission Operations

2.5.2.1 Launch and Activation

The NASA team was present on August 15, 1991 for the launch of Meteor-3/TOMS from Plesetsk. Power was turned on during the first orbit (approximately three hours after launch) upon a pass over a Hydromet ground station equipped to command the TOMS functions. This allowed for transmission of housekeeping data, insured that TOMS was in a safe-holding state, and warmed the instrument and diffusers. NASA and Hydromet began monitoring TOMS Housekeeping data during the first week TOMS was turned on. NASA personnel evaluated the instrument performance and determined to continue operation of the instrument.

TOMS was allowed to outgas for a seven day period and full activation (high voltage on) occurred on August 22, 1991. At this point, the science data was activated. As soon as the sun was within the diffuser field-of-view as specified by NASA, a solar irradiance measurement was performed.

2.5.2.2 Operations

TOMS is normally controlled using on-board stored commands. Real time commands were used for initial turn on and in the future will only be used for special operations and emergencies. Normal operating command sequences in the form of lists of programmed commands are prepared by NASA and sent via electronic mail to Hydromet on a regular basis. These commands cover a period of 14 days. Hydromet provides NASA the spacecraft orbit elements via electronic mail in order for NASA to produce these Two Week Command Lists for the next period. The Two Week Command Lists include orbit number, time, and corresponding Programmed Commands. Hydromet is responsible for transmission of commands to the Meteor-3 spacecraft.

Both sides have developed a joint operation plan of data exchange needed for operations and ozone fields calculations. The joint operation plan specifies agreed upon formats, data rates, schedules, and coordinated operating procedures. Spacecraft status reporting is provided by Hydromet and monitored by NASA and Hydromet. Emergency procedures have been developed to handle critical out-of-limit conditions and were provided to Hydromet six months prior to launch.

TOMS will be left on unless emergency conditions require turn-off. The NASA Mission Operations Manager will be notified at once of any power interruptions or any other Meteor-3 actions that might affect TOMS.

2.6 Launch and Orbit Activation

The on-orbit start-up sequence originally had six stages:

STAGE 1 - HEATER POWER ON
STAGE 2 - INITIALIZATION
STAGE 3 - ELECTRONICS CALIBRATIONS
STAGE 4 - HIGH VOLTAGE VERIFICATION
STAGE 5 - HIGH VOLTAGE FULL-TIME / SOLAR CALIBRATIONS
STAGE 6 - LAMBDA CALIBRATION (FULL ORBIT)

Stage 1 occurred on orbit #2 after launch (launch was on August 15, 1991 at 12:15.6 hours Moscow time). Stage 2 occurred on orbit #3 after launch. Stage 3 was to begin on orbit 66 after launch (this was the fifth orbit on day 6).

On August 18, 1991, three days after Meteor-3/TOMS launch, civil problems in the Soviet Union forced the NASA representatives to leave Moscow prior to stages 3 through 6 activation. It was decided that stage 4 (HIGH VOLTAGE VERIFICATION) S/C orbit 92 (equivalent to Day 8, Orbit 5) would be deleted. In other words, the high voltage verification would not be performed, but the high voltage would be turned on (on orbit 93, Day 8 orbit 6) and remain on without verifying whether the data was verified as good. More detail about all stages is presented below. Figure 2.6-1 shows, in graphic form, the stages for the TOMS FM-2 start-up sequence. A listing of all commands sent during start-up is in the Technical Description and Operations Manual, Meteor-3/TOMS, NASA/Goddard Space Flight Center, Greenbelt, Maryland, July, 1991.

Below is a description of all stages:

The first stage is POWER-B (HEATER POWER) ON. This single command is transmitted on S/C Orbit 2 (Day 1, Orbit 6).

The second stage is initialization. Initialization is accomplished on S/C Orbit 3 (Day 1, Orbit 7) using a sequence of 11 realtime commands and the initial PCS program load. The realtime commands will put the TOMS instrument into a 'Safe Hold' state with High Voltage OFF, Scanner OFF and Diffuser STOWED. The stored PCS programs will initiate regular recorder swaps and data transmissions starting on S/C Orbit 11 (Day 2, Orbit 2).

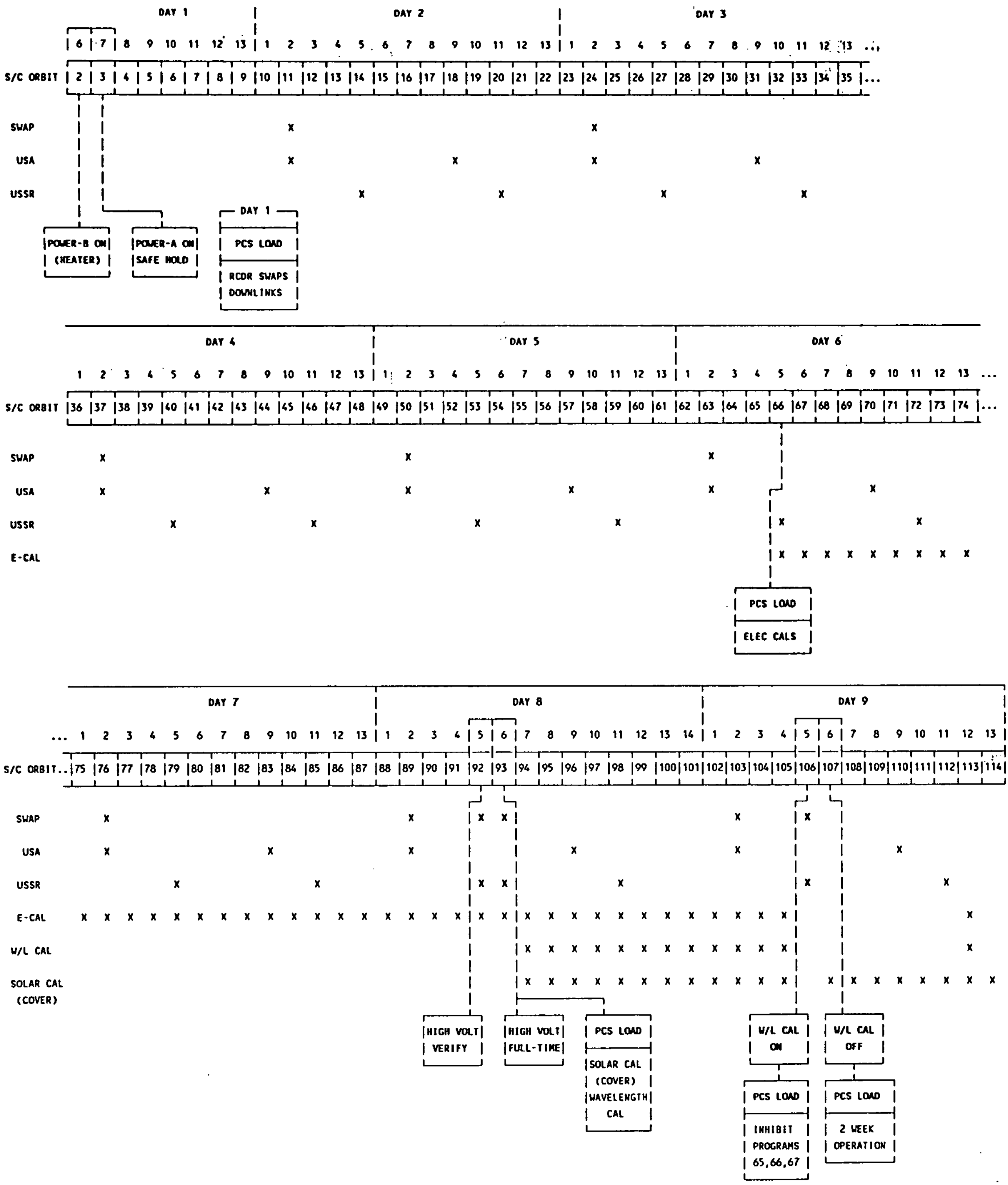


Figure 2.6-1 TOMS FM-2 start-up sequence

The third stage consists of Electronic Calibrations to be performed every orbit followinga PCS load on Orbit 66 (Day 6, Orbit 5), and continue through the end of the start-up sequence.

The fourth stage is verification of the High Voltage system. On S/C Orbit 92 (Day 8, Orbit 5), High Voltage will be commanded ON for 66 seconds. The recorded data will be immediately transmitted and analyzed. One orbit after good verification, High Voltage will be commanded ON (full-time).

The fifth stage of the start-up sequence, commanding the High Voltage ON full-time, is scheduled for S/C Orbit 93 (Day 8, Orbit 6) or the contingency S/C Orbit 94 (Day 8, Orbit 7), depending on time of good verification. In either case, the realtime command for High Voltage Power ON, and a PCS load for the recycling of Program 65 - Solar Cal (Cover), and Program 66 - Wavelength Cal, is required. Depending on which orbit is used, the recorder will be swapped and downlinked in realtime (Orbit 93), or the PCS load will include those Program commands to execute on Orbit 96 (Day 8, Orbit 9).

The sixth stage of the start-up sequence commands the Hg Lamp ON and the Lambda Calibration ON for one full orbit. This final stage requires a spacecraft interrogation on 2 successive orbits. On the first of these 2 orbits, S/C Orbit 106 (Day 9, Orbit 5), the recorder will be swapped, data transmitted, and the Hg Lamp and Lambda Cal Mode commanded ON. Also during this pass, the PCS will be loaded to inhibit the execution of the Wavelength Cal (Program 66), Electronics Cal (Program 67), and Solar Cal (Program 65) during the one-orbit Wavelength Cal. On S/C Orbit 107 (Day 9, Orbit 6), the Hg Lamp and Lambda Cal Mode will commanded OFF. The Scanner will then be commanded to SCAN. The PCS will be loaded on this pass with the first 2 week operational command load.

3.0 TESTING AND INTEGRATION

Section Contributor:

John Loiacono

The TOMS FM-2 and Interface Adapter Module (IAM) integration and testing phases took place at both the NASA contractor and S/C "vendor" facilities; the S/C vendor for the Meteor-3 is located in the Soviet Union, and the NASA contractor, Perkin Elmer, is located at Pomona, CA.

Integrating the TOMS FM-2 and IAM with the Meteor-3 occurred in three (3) phases:

(1) The TOMS FM-2 was almost to flight status and IAM was a nominal engineering model for the first integration with the Meteor-3: 1st integration took place in Istra, USSR on October 3-27, 1990.

(2) TOMS FM-2 and IAM were returned to Perkin Elmer where they were brought up to flight model status for the 2nd integration with Meteor-3: 2nd integration occurred in Istra, USSR on May 6 to June 5, 1991.

(3) The TOMS FM-2 and IAM remained in the USSR from June 5, 1991 until August 1, 1991.

(4) The instruments were then flown to the launch site where a 3rd integration and testing of the TOMS FM-2 and IAM took place: 3rd integration occurred in Plesetsk, USSR on August 3 to August 15, 1991.

(5) Launch occurred on August 15, 1991 from Plesetsk at 12:14.60 Moscow time.

The TOMS FM-2 and IAM were brought up to flight status at Perkin Elmer by upgrading parts, materials and the structure of the TOMS FM-2 and IAM. Additionally, environmental and calibration testing were performed. Below is a description of the instrument integration and testing at Perkin Elmer, Istra and Plesetsk, USSR for the TOMS FM-2 and IAM flight models.

3.1 Perkin Elmer

The testing schedule for the TOMS FM-2 and IAM at Perkin Elmer is attached (see Figure 3.1-1). The environmental testing for the IAM is presented in the Verification Plan for TOMS IAM, prepared by Perkin Elmer Corporation, #74-0020, Revision B, 2/1/91. The environmental testing for the TOMS FM-2 is presented in the Verification Plan for TOMS FM-2, prepared by Perkin Elmer Corporation, #74-0015, Revision D, 3/27/91. The Verification Plan for TOMS IAM and the Verification Plan for TOMS FM-2 are part of the TOMS FM-2 Final Report, Appendix B1.

The verification tests (or calibration tests) of TOMS FM-2 were made to demonstrate compliance with the requirements of the instrument specification (GSFC Specification 610-TOMS, 1988). Table 3-1 lists the system requirements and the test procedures used to verify compliance with the requirements. These parameters are identical to the Nimbus-7/TOMS instrument. Below is a summary of the results.

(1) Polarization Sensitivity

The TOMS instrument requirement for residual polarization sensitivity to the incident radiation is less than 5 percent over the operational range of angles and wavelengths. Data are shown in Appendix A1 of the TOMS FM-2 Final Report.

(2) Wavelength Coverage

The TOMS instrument meets the requirement for operation from 312.5 to 380 nm. Data are shown in Appendix A2 of the TOMS FM-2 Final Report.

(3) Spectral Bandpass

The TOMS instrument meets the requirement for discrete spectral bands with center wavelengths of 380, 360, 339.8, 331.2, 317.5, 312.5 nm. Data are shown in Appendix A2 of the TOMS FM-2 Final Report.

(4) Spectral Resolution

The TOMS instrument meets the requirement for a full half width, half maximum spectral bandpass equal to or less than 1.0 +0.3/-0.0 nm for all bands over the wavelength range. Data are shown in Appendix A3 of the TOMS FM-2 Final Report.

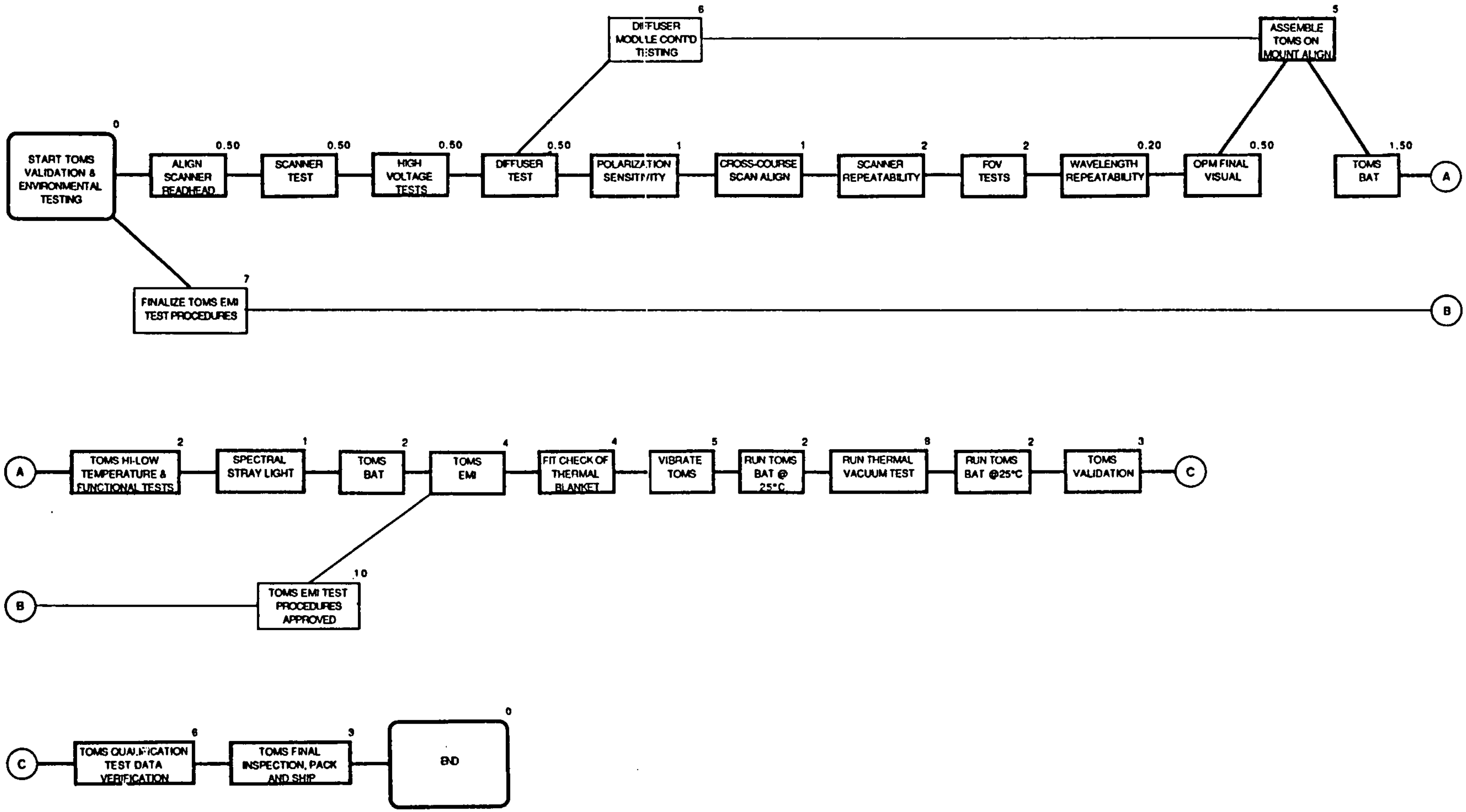


Figure 3.1-1 Testing schedule for the TOMS FM-2 and IAM

Table 3-1

SYSTEM REQUIREMENT COMPLIANCE VERIFICATION

Ref No.	Parameter or Characteristics	Performance Test Procedure	Specification Requirement	Results	610-TOMS-001 Paragraph
1	Polarization Sensitivity	552961	<5%		3.4.2.4
2	Wavelength Range	552960	312-380 nm		3.4.3.1
3	Spectral Bandpass	552960	1-380,2-360,3-340,4-331,5-318,6-312 nm		3.4.3.2
4	Spectral Resolution	552960	1.0 +0.3/-0.0 nm		3.4.2.5
5	Wavelength Accuracy	552960	0.15 nm for <340nm 0.25 nm for >340nm		3.4.3.3
6	Spectral Stray Light	552962	<.1%		3.4.3.9
7	IFOV	552963	3°x3° $^{+}$ .1°		3.4.2.2
8	IFOV Registration	552963	0.3°		3.4.2.3
9	FOV Uniformity	552963	error will not accumulate beyond width of an IFOV element for 10^8 line scans		3.4.2.4
10	Wavelength Repeatability	552965	+0.02 nm of nom.		3.4.3.4
11	In-Flight Wavelength Calib.	552965	0.02 nm		3.4.3.3

Table 3-1 Cont'd

12	Dynamic Range	552967	1000/1 (.32 to 320 ergs/ cm^2-sr-nm-sec)		3.4.3.6
13	Signal-to Noise Ratio	552967	>30		3.4.3.8
14	Measurement Stability	552967	+/-1%		3.4.3.7
15	Radiometric Linearity	552967	+/-1%		3.4.37
16	Cross-Course Scan Accuracy	552966	lateral image displacement,< 5% of IFOV between adjacent scan lines.		3.4.2.3
17	Cross-Course-Repeatability	552966	+/-0.3%		3.4.2.3
18	Cross-Course Scan Alignment	552968	+/-0.5°		3.4.2.1
19	Sensor Alignment	530075	+/-0.5°		3.5.1
20	Operating Modes	552970			3.3
21	Nimbus Pwr Source Charact.	552970			
22	Nimbus Pwr Transients	552970			
23	S/C Command Inputs	552970			
24	VIP Digital A Format	552970			

Table 3-1 Cont'd

25	VIP Digital B Format	552970			
26	VIP Analog T/M	552970			
IAM TEST					
REF NO	SIGNAL FUNCTION	IAM TO MET.-3 ICD 358701	IAM ATP TP80-0528	B.A.T. TP80-0558	
1	CONTINUTIY & ISOLATION		8.0	Appendix B	
2	Quiescent Voltages & Currents	3.2.1	9.2.9.3	8.2, 8.3.3	
3	TOMS Commands & Digital Status	3.2.5	9.4	8.6, 8.3.1	
4	IAM Sequencer Commands & Digital Status	3.2.5	9.4	8.4.8	
5	Analog Signals	3.2.6	9.5	8.3.2	
6	Clock Signals	3.2.3.1	9.6		
7	Housekeeping & Digital Status	3.2.4, 4.0	9.7.9.1, 9.7.9.2	8.4.1	
8	Time Code	3.2.3	9.7.9.3	8.6	
9	ECAL, Recorder & PDSK	4.1.3, 3.2.2	9.7.3, 9.7.9.4	8.6, 8.4.2	
10	Wavelength Calibration	4.1.2	9.7.4	8.6, 8.4.3	
11	Solar Calibration A	4.1.3	9.7.7	8.6, 8.4.4	
12	Solar Calibration A		9.7.5	8.6, 8.4.5	

Table 3-1 Cont'd

13	Solar Calibration B		9.7.6	8.6, 8.4.6	
14	Area Scan		9.7.9	8.4.7	
15	EMI-EMI test per PE document TP80-0570				

(5) Wavelength Accuracy

The TOMS instrument meets the requirement for each spectral band beeping within +0.15 nm of the specified wavelength for wavelengths less than 340.0 nm and +0.25 nm for wavelengths greater than or equal to 340.0 nm over a temperature range of 25 +/-10°C. Data are shown in Appendix A2 of the TOMS FM-2 Final Report.

(6) Stray Light Rejection

The TOMS instrument meets the requirement of unwanted contribution by all unwanted wavelengths to the signal produced by radiation defined by the bandwidth of any TOMS spectral band being less than one (1) part in one thousand (1,000). Data are shown in Appendix A4 of the TOMS FM-2 Final Report.

(7) IFOV

The TOMS instrument meets the requirement of having an instantaneous half power field of view of $(3.0 +/- 0.1^{\circ})^2$ for all spectral bands. Data are shown in Appendix A5 of the TOMS FM-2 Final Report.

(8) IFOV Registration

The TOMS instrument meets the requirement of having an accuracy of the step scan being such that lateral image displacement does not exceed 5% of the effective width of an IFOV element at any point along adjacent lines. Data are shown in Appendix A5 of the TOMS FM-2 Final Report.

(9) FOV Uniformity

The TOMS instrument meets the requirement relating to FOV Uniformity. Data are shown in Appendix A5 of the TOMS FM-2 Final Report.

(10) Wavelength Repeatability

The TOMS instrument meets the requirement of having a repeatability of the centers of each spectral band within +0.02 nm of the nominal wavelength. Data are shown in Appendix A5 of the TOMS FM-2 Final Report.

(11) In-flight Wavelength Calibration

The TOMS instrument meets the requirement of having an in-flight wavelength calibration which has a measurement accuracy of 0.02 nm. Data are shown in Appendix A5 of the TOMS FM-2 Final Report.

(12) Dynamic Range

The TOMS instrument meets the requirement of having a dynamic range of 1000:1 (0.32 to 320 ergs*cm^2/sr*nm*sec). Data are shown in Appendix A5 of the TOMS FM-2 Final Report.

(13) Signal to Noise Ratio

The TOMS instrument meets the requirement of having a signal to noise ratio of greater than 30. Data are shown in Appendix A6 of the TOMS FM-2 Final Report.

(14) Measurement Stability

The TOMS instrument meets the requirement of having a measurement stability of better than +/- 1% while viewing the same source under the same conditions but separated in time by at least 24 hours. Data are shown in Appendix A7 of the TOMS FM-2 Final Report.

(15) Cross-Course Scan Accuracy

The TOMS instrument meets the requirement of having a cross-course scan accuracy of the step scan such that the lateral image displacement does not exceed 5% of the effective width of an IFOV element at any point along adjacent lines and that an error does not accumulate beyond the effective width of an IFOV element over 10,000 consecutive line scans. Data are shown in Appendix A8 of the TOMS FM-2 Final Report.

(16) Cross-Course Scan Repeatability

The TOMS instrument meets the requirement of having a cross-course scan repeatability defined by the centers of the nominal thirty-five (35) IFOVs and an X-axis alignment target of the TOMS within +/-0.3°. Data are shown in Appendix A8 of the TOMS FM-2 Final Report.

(17) Cross-Course Scan Alignment

The TOMS instrument meets the requirement of having a cross-course scan alignment of +/-0.5°. Data are shown in Appendix A8 of the TOMS FM-2 Final Report.

(18) Sensor Alignment

The TOMS instrument meets the requirement of providing alignment references such that the orientation of the optical axis of the sensor is in alignment with respect to the spacecraft X, Y, and Z axis to within +/- 0.5° and known to within +/- 0.1°. Data are shown in Appendix A5 of the TOMS FM-2 Final Report.

3.2 Soviet Union Testing

The integration testing flow of TOMS in the Soviet Union is shown in Figure 3.2-1, Overall Meteor-3/TOMS Integration Flow Chart.

(1) Istra, USSR

The first integration took place in Istra, USSR about 40 Km west of Moscow. The TOMS FM-2 was almost to flight status and IAM was a nominal engineering model for the first integration with the Meteor-3: 1st integration took place in Istra, USSR on October 3-27, 1990. The integration testing flow is shown in Figure 3.2-2, First Integration. The test data from this integration is available in the NASA/GSFC Code 910 TOMS FM-2 Project Office. Upon completion of first integration the TOMS was returned to the USA.

(2) Istra, USSR

The second integration took place in Istra, USSR. The TOMS FM-2 and IAM were flight ready. The integration lasted from May 6 to June 5, 1991. The integration flow is shown in Figure 3.2-3, Second Integration. The test data from this integration is available in the NASA/GSFC Code 910 TOMS FM-2 Project Office. Upon completion of second integration the TOMS FM-2 was stored in Istra, while the IAM was stored in the US Embassy in Moscow, USSR. The instruments were stored until August 3, 1991, and were shipped to the launch site by a Soviet military freight plane.

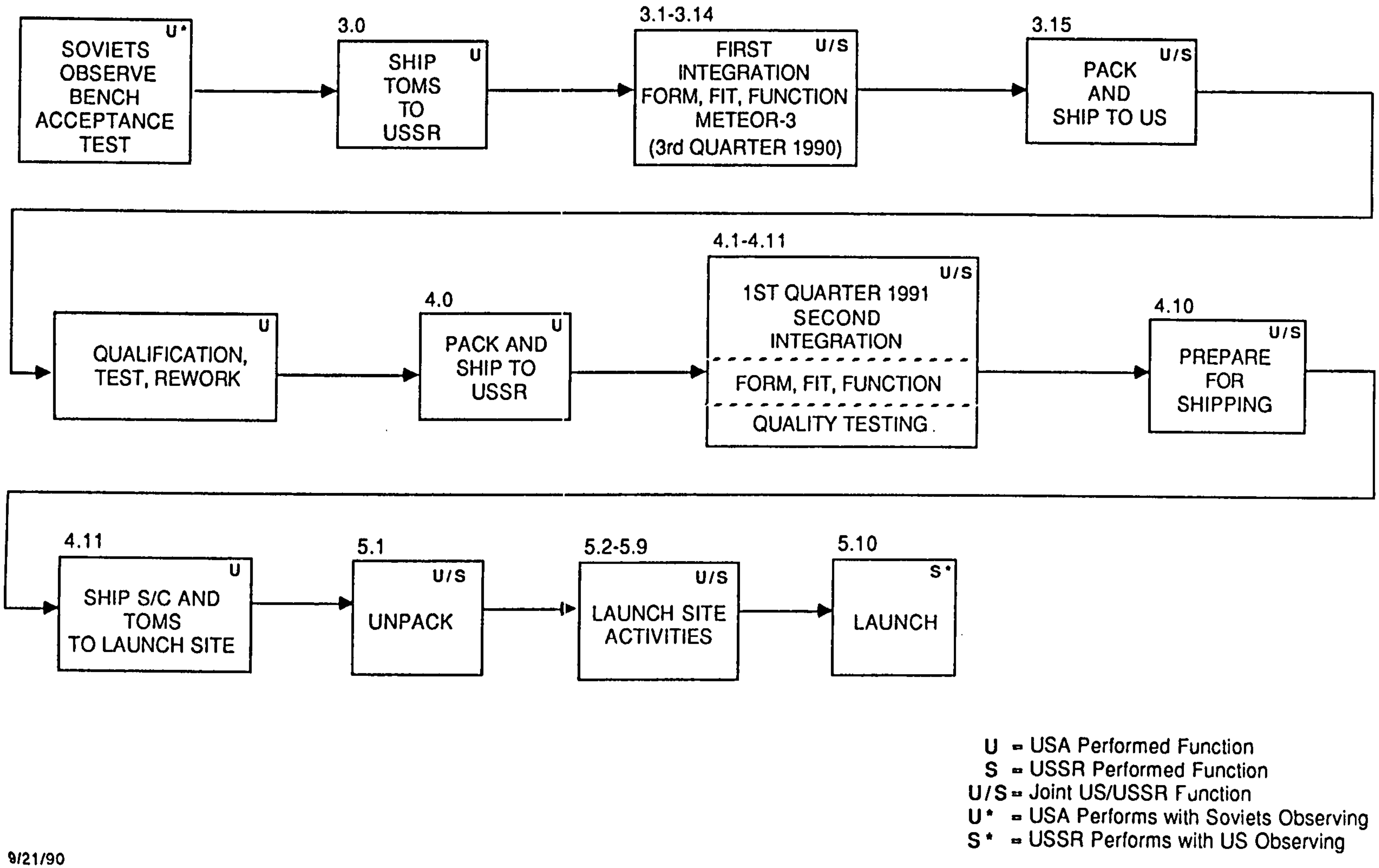


Figure 3.2-1 Overall integration flow diagram of Meteor-3/TOMS

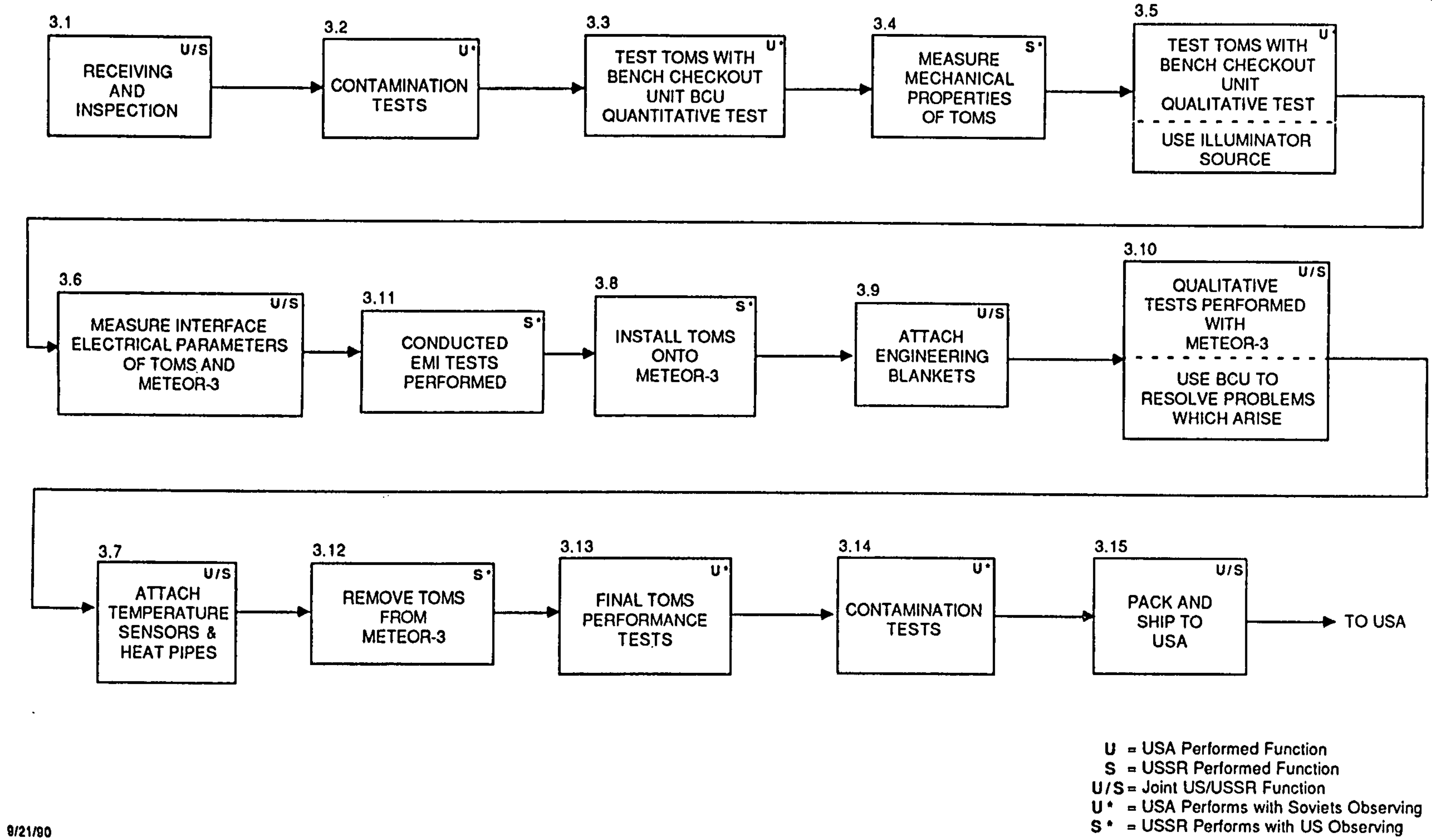
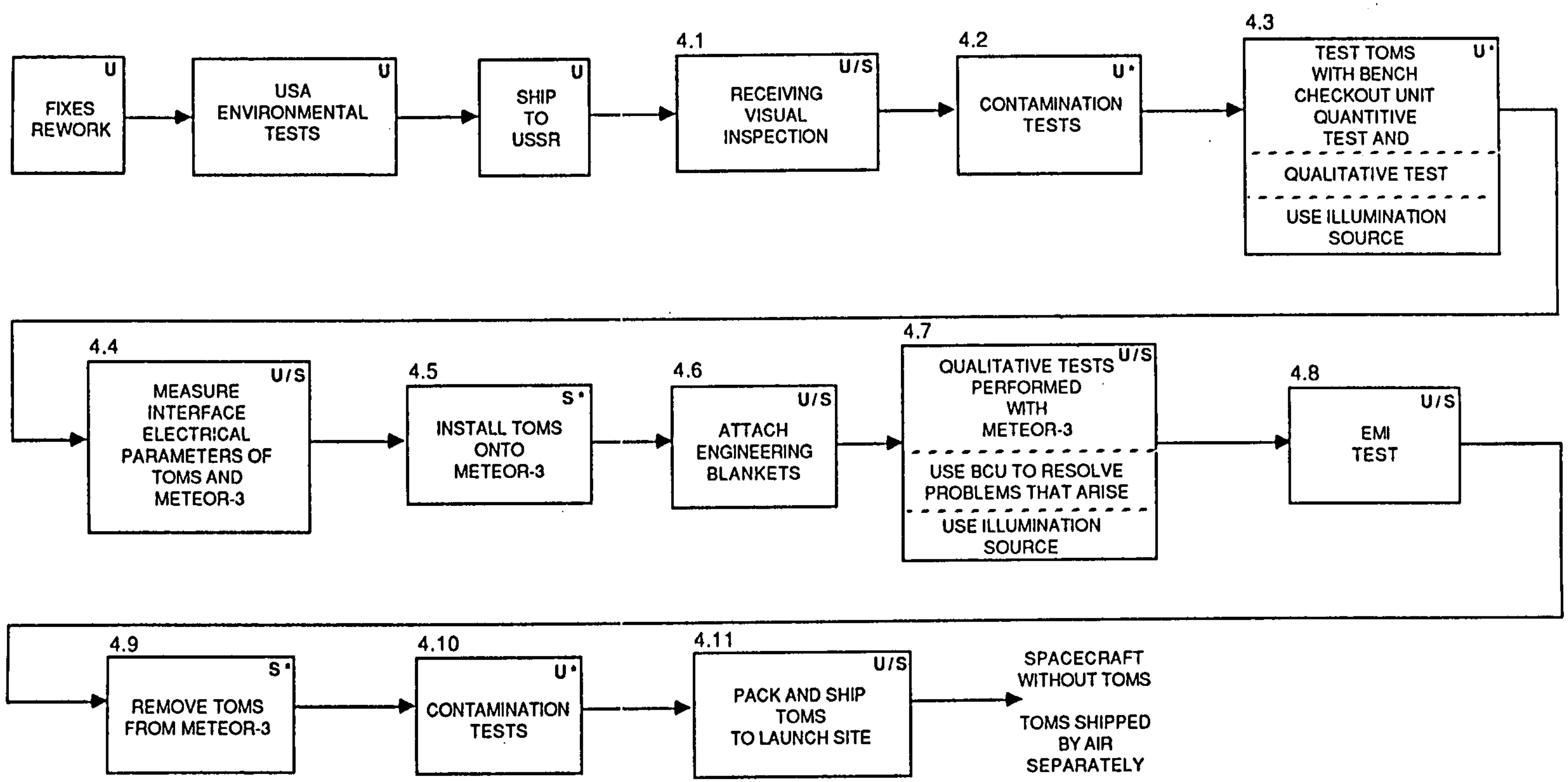


Figure 3.2-2 1st integration testing flow diagram



U = USA Performed Function
S = USSR Performed Function
U/S = Joint US/USSR Function
U* = USA Performs with Soviets Observing
S* = USSR Performs with US Observing

Figure 3.2-3 2nd integration testing flow diagram

(3) Plesetsk, USSR

The Third integration took place in Plesetsk, USSR. The TOMS FM-2 and IAM were bolted onto the Meteor-3 and integrated testing was performed for the last time. The integration testing flow is shown in Figure 3.2-4, Launch Site Activities. The integration lasted from August 3, 1991 to August 11, 1991. The test data from this integration is available in the NASA/GSFC Code 910 TOMS FM-2 Project Office. On August 11, the Meteor-3, with TOMS FM-2 and IAM attached, was shipped to the booster mating facility; the Meteor-3 arrived at the booster mating facility on the morning of August 12. On August 13, 1991, the Meteor-3 spacecraft was mated with the "Cyclone" launch vehicle. Launch occurred on August 15, 1991 at 12:15.6 hours Moscow time.

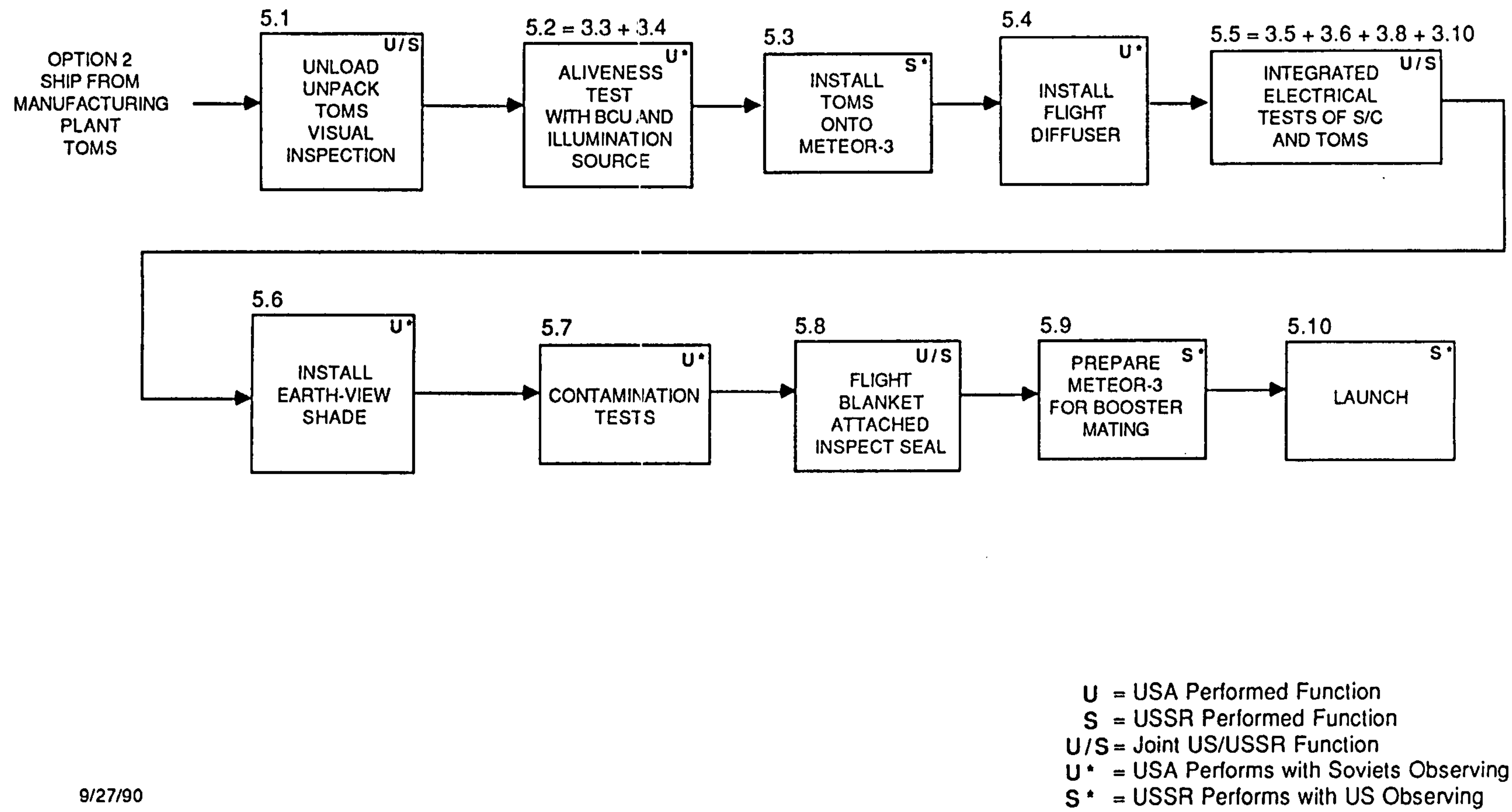


Figure 3.2-4 Launch Site Activities

4.0 METEOR-3/TOMS INTERFACE ADAPTER MODULE

4.1 DESCRIPTION OF OPERATION

Section Contributors:

John Loiacono
Stanley Way

4.1.1 Introduction

The Meteor-3/TOMS mission is a joint US/USSR scientific experiment in which a US Total Ozone Mapping Spectrometer (TOMS) instrument and an Interface Adapter Module (IAM) are integrated on a USSR Meteor-3 Spacecraft and launched into a polar orbit. The Interface Adapter Module provides the adaptation of the Meteor-3 Spacecraft characteristics to those required by the TOMS instrument. Since the TOMS FM-2 (Flight Model-2) is a refurbishment of the TOMS engineering model, the instrument interface is designed to mate with a Nimbus-7 spacecraft. Therefore, the IAM duplicates those functions of the Nimbus-7 spacecraft used by TOMS.

The IAM contains a state-of-the-art solid state recorder (SSR) for recording the science and engineering data from the TOMS and IAM. This is the first NASA mission to place an SSR into orbit as the main recording device for an instrument. The SSR is expected to last at least 2 years, barring any catastrophes. Engineering telemetry from the SSR is received every 24 hours.

The control of the SSR by the IAM and the internal functioning of the data storage, and error detection and correction techniques in the SSR is described below. A summary of the SSR's current operation is given.

4.1.2 IAM System Description

The following paragraphs summarize the functions of the IAM.

There are six major functions of the IAM which include power conditioning, command processing, timing, data acquisition and formatting, data storage, and data output.

Power conditioning involves receiving the 27 VDC spacecraft power from Meteor-3 and converting it to well regulated -24.5 VDC primary power for TOMS and switched telemetry power. The IAM also converts spacecraft power to the secondary voltages necessary for the IAM internal circuits and the SSR. Diffuser heater power is routed directly from the EMI filters to the TOMS instrument connector.

The IAM receives commands from Meteor-3 that are interpreted and distributed to TOMS, IAM and SSR. The Meteor-3 provides 7 discrete commands to IAM. Due to the limitation in the total number of discrete commands that are allocated for TOMS by Meteor-3, the IAM takes a discrete (single) spacecraft command and converts it to a sequence of commands. The sequence of commands are stored in a read only memory (ROM): the timing for each command in the sequence is controlled by the IAM and has been preset in the IAM ROM before launch. The ROM contains command sequences for TOMS and the IAM, including commands that direct SSR functions: DATA TRANSMISSION USA, DATA TRANSMISSION USSR, and IAM RESET.

Three areas of timing are performed by the IAM. The first involves receiving the Meteor-3 Time Code and appending it to the TOMS science data telemetry (Meteor-3 provides the IAM with a 16 Khz clock which is used to generate sub-second time for the TOMS data). The second is the generation of all timing signals needed by TOMS. The IAM provides TOMS with several high frequency clocks including the TOMS data readout clocks. The third major timing area is the data input and output clocks for the SSR. The IAM provides the SSR a clock for synchronizing the input and output of data. Data is stored by bursting data into the SSR at 10 Khz bursts. The information rate of the data readout is 160 Kbits/Second.

4.1.3 IAM Formatter

Data acquisition, formatting and storing are major functions of the IAM. The IAM receives all science and engineering data from TOMS. All of the TOMS science data and some of the TOMS engineering data (analog and digital) are stored in the SSR. All the TOMS digital engineering data and some of the TOMS analog data are forwarded to the Meteor-3 for storage. The engineering digital data from the IAM are stored in the SSR. All the engineering analog and digital data from the IAM are presented to the Meteor-3 on a parallel bus: each analog or digital data point is contained on a single wire from the IAM to the Meteor-3. The Meteor-3 records the digital engineering data and the engineering analog data; the Meteor-3 converts the analog data with an 8 bit Analog to digital converter before storage.

TOMS provides the IAM with 424 bits/second of science and engineering data serially and TOMS continuously makes parallel engineering analog and digital data available to the IAM. The IAM samples the parallel (analog and digital) interface every 8 seconds since the TOMS operating period (one scan of the earth) is 8 seconds. The TOMS serial (science and engineering) data is sent to the IAM, where the data is formatted and merged with IAM and SSR engineering data, then stored in the SSR for later playback. Twenty four (24) hours worth of data are recorded on the SSR before playback.

The formatted data consisting of 8 second operating periods are known as TOMS minor frames. Two sequential 8 second minor frames make up a major frame (16 seconds). Notice that the minor frame counter is either FF or 00. After receiving the data on the ground, the data processing algorithm uses the minor frame counter to distinguish between the 1st and 2nd minor frames within a major frame.

The IAM formatter inserts data from the IAM into each minor frame. Also, the IAM formatter circuitry places a header and trailer onto each minor frame. Each 8 second data block, consisting of IAM and TOMS data, is preceded with a synchronization pattern, minor frame #, and time code.

The IAM appends a 16 bit cyclic redundancy code onto each 8 second data block. The purpose of the 16 bit field is to provide the capability to detect errors which may have been introduced into the frame during the data handling process. The generator polynomial used to create the 16 bit cyclic redundancy code is: $g(x) = x^{16} + x^{12} + x^5 + 1$. In addition to the cyclic redundancy code appended to the TOMS data by the IAM, the SSR attaches its own 8 bit modified Hamming code (similar to a cyclic redundancy code) to every 64 bits of TOMS data.

4.1.4 IAM Commanding of SSR

The Meteor-3 sends commands to the IAM. The Meteor-3 commands for controlling the SSR are:

1. DATA TRANSMISSION USA
2. DATA TRANSMISSION USSR
3. RECORDER SWAP
4. IAM RESET
5. SPARE
6. SPARE

The Meteor-3 commands the IAM to playback data from the SSR 4 times each day; twice over the USA and twice over the USSR. The same data is transmitted to each country twice a day. The reason for transmitting the same data 4 times is: (1) the list of commands for TOMS are generated in the USA one (1) month prior to the actual use of the commands; (2) the same data is transmitted twice to each country's ground station because ground station maintenance and outages can be unforeseen one (1) month in advance.

The SSR can perform simultaneous record and playback by using two independent buffers. The Meteor-3 commands the IAM to playback the data when the spacecraft passes over a ground station. The IAM sends sequence of commands to the SSR to playback the data in the playback buffer. When the same data has been transmitted twice to the USA and twice to USSR, the Meteor-3 sends the IAM the RECORDER SWAP command: which copies the data from the record buffer to the playback buffer. The record buffer is now free to accept new data from the IAM and TOMS.

A recorder reset command is sent to the SSR when Meteor-3 sends the IAM RESET command. The IAM RESET command resets the IAM sequencer and loses all data in the SSR.

4.1.5 SSR System Operation Description

The SSR is an integral part of the IAM. No direct connection exists from the IAM external connectors to the SSR. The SSR stores data into the SSR's 128 Megabit memory array. Commands to the SSR and data from the SSR are first handled by the IAM. The SSR has many features that were not needed for the Meteor-3/TOMS mission, such as: different input and output data rates; larger memory capacity; and different record modes. These features are fixed for the Meteor-3/TOMS mission and cannot be changed from the ground.

A two minute initialization (or boot-up) of the recorder occurs when power is applied to the SSR; at which time the commands stored in the SSR ROM are sent to the SSR. During initialization, all memory pages will be verified for error free operation with the SSR's Built In Test (BIT) and the Error Detection And Correction (EDAC) circuits exercised to validate correct detection and correction. At the end of initialization, the SSR is ready to accept data without additional commanding. The initialization leaves the recorder in the power up configuration.

The power up initialization configures the SSR to operate in the channel/buffer mode and to use external clocks for the input and output of data. The SSR can implement three different recorder modes of operation: FIFO, tape recorder, and channel/buffer. The channel/buffer mode is commanded from the SSR ROM commands during initialization. The IAM cannot command the SSR into any other record mode nor can the IAM command the SSR to use its internal clock.

The channel/buffer mode was selected for the Meteor-3/TOMS mission because: (1) the channel/buffer mode can record data at all times; (2) the channel/buffer mode required only one Input/Output interface, thus relieving the IAM of additional burden of switching between I/O interfaces; (3) the FIFO and tape recorder mode could not record data at all times with one I/O interface.

4.1.6 Memory Array

The SSR records serial data from the IAM at 10 Khz bursts. The SSR recording functions are, for the most part, independent from the IAM. Although the IAM supplies the clock to record and playback data, the SSR controls the data segmentation and storage. The SSR records the data by fanning out the serial input data stream into a parallel array of memory devices. The SSR has an internal 72 bit data bus separated into a 64 bit data field and an 8 bit cyclic redundancy code field created by a modified Hamming code generator. The modified Hamming code is independent and separate from the cyclic redundancy code appended to TOMS data by the IAM formatter described earlier.

Physically, the SSR memory array is divided into 2 Printed Circuit cards, each with 64 Megabits of user memory. Each memory card contains an additional 8 Megabits of transparent memory reserved for the modified Hamming code. Therefore, the SSR memory cards have a total of 72 Megabits per card.

As stated earlier, the Meteor-3/TOMS SSR operates in the channel/buffer mode, and contains two (2) virtual buffers. The buffers are named channel 0 and channel 1. Channel 0 is always used to store input data (called the recording buffer) and channel 1 is always used to output data (called the playback buffer). After the Meteor-3 has commanded the IAM to playback SSR data 4 times in one day (by issuing DATA TRANSMISSION USA or DATA TRANSMISSION USSR), the Meteor-3 sends a RECORDER SWAP command to the IAM. Issuing the RECORDER SWAP command to the IAM causes a sequence of commands to the SSR that: (1) stops recording on the channel 0; (2) copies the data from channel 0 to channel 1; (3) starts recording on channel 0. Henceforth, the purpose of each channel, channel 0 is always the record buffer and channel 1 is always the playback buffer, is intact.

4.1.7 Internal Memory Verification

The SSR interrogates the entire (used and free) memory for bit errors. The interrogation is intended primarily to improve system bit error rates by correcting "soft" errors in the stored data, but the interrogation also enhances the component reliability by compensating for memory device failures (true hardware errors) where such failures do not affect multiple bits in the same word (72 bits). Single bits corrected and multiple bits detected are logged into the SINGLE ERROR COUNTER and sent in the telemetry.

Two methods are used to detect and correct bit errors and make up the error management plan. The error management plan is a combination of: (1) hardware implemented error detection and correction coding (EDAC) for single bit error correct and multiple error detect using the modified Hamming code suffix on each data word, and; (2) firmware controlled data patterns that read/write/verify to locate permanent failures that would compromise data storage.

The error detection and correction (EDAC) technique uses a modified Hamming code of 8 bits which is added to each 64 bits of input data while recording. On playback, this coding technique has the strength to detect two errors anywhere in the 72 bit data field and correct any single error. Single errors are logged in the SINGLE ERROR COUNTER.

The EDAC method is in itself not sufficient to meet the bit error rate and probability of success specifications. This is due to the nontrivial possibility of memory faults occurring in areas of memory not yet accessed by user data and also due to the fact that the EDAC algorithm is not capable of 100 percent detection of memory failures involving more than two bits on a memory word with a 72 bit field.

The built in test (BIT) feature compensates for EDAC's shortfallings by operating in background and interrogates used and unused contents of memory with two methods. The entire memory is tested with both methods every 16 seconds in background.

The first method is called memory refresh (or memory scrub). Memory refresh periodically reads and writes to all stored data (i.e. memory "in use"), verifying integrity. The second method used by the BIT is pattern testing. Pattern testing is done periodically on unused portions of memory.

4.1.8 Error Detection Methods; Corrections

Comments on the single bit error correction (counter):

1: The entire memory is checked frequently. Any data transmitted from the SSR with incorrect bits (multiple bit errors) will be caught and flagged by examining the cyclic redundancy code appended to the data by the IAM data formatter.

2: To calculate a precise "Single Event Upset" rate, it would be necessary to know how many pages of memory (or number of RAMS) were "in use" for each SINGLE ERROR COUNT.

3. The IAM reads the SINGLE ERROR COUNTER once every 128 seconds. Therefore, the uncertainty of 128 seconds exists in the number of devices or pages in use at a single telemetry reading. The uncertainty corresponds to a total of 54,272 bits at the TOMS data rate of 424 bits/sec.

4.2 POSTLAUNCH SOLID STATE RECORDER OPERATIONS

The TOMS Solid State Recorder (128 Megabits - 64 pages) has been utilized continuously since the initial turn-on of the TOMS instrument in August 1991. Data retrieval from the recorder has been flawless. The recorder is divided into two sections, one for recording and the other for playback. Basic operation of the recorder modes is by stored commands issued every two weeks from the Meteor-3 command system in the U.S.S.R./C.I.S. Four times a day, twice to Wallops Flight Facility (WFF) and twice to C.I.S. (various ground stations), the recorder contents for the previous day are downloaded. At the end of each day the recorders are swapped to enable playback of the previous days data by recorder #1 and recording by recorder #2. There have been no problems sending commands to the U.S.S.R./C.I.S. (a GSFC/TIOCC function) and uplinking them to the Meteor-3 by the U.S.S.R./C.I.S. control center.

4.2.1 Single Bit Corrections

Single bit errors can be caused by a hardware deficiency or by radiation induced bit flips in the memory chips (i.e."Single Event Upsets"). The recorder was flown with three known problem bits that exhibited their error characteristics as a function of temperature. One memory chip has a known problem below +20° C, one below +13° C and the other below -12° C. Since the bit errors were all correctable, it was decided not to repair them. Some "hardware" bit errors are observed in flight, and it is likely that they are directly related to these known bit problems. In addition, radiation induced "Single Event Upsets" (SEUs) have been observed in large numbers, primarily within the South Atlantic Anomaly. These SEUs are thought to be caused primarily by trapped high energy protons and they are observed to produce a fairly constant SEU rate of 300-400 events per day. More analysis is required and comparison of predicted radiation to measured radiation from Meteor-3 radiation monitors has been suggested to the Meteor-3 C.I.S. team.

The attached plots, Figures 4.2-1 to 4.2-4, are Single Bit Corrections for the period from Day 234 through Day 365. A single anomalous event occurred on Day 289 and Day 290 when then number of counts reached approximately 600,000. At this time, there is no explanation for this event. Data for Day 252 is missing from the data file utilized.

4.2.2 SSR Status Word Readback

Other status words indicate nominal operation of the recorder. One very useful status word is a readback of the latest command sent to the SSR. This has been an excellent means of verifying proper timing of the SSR commands.

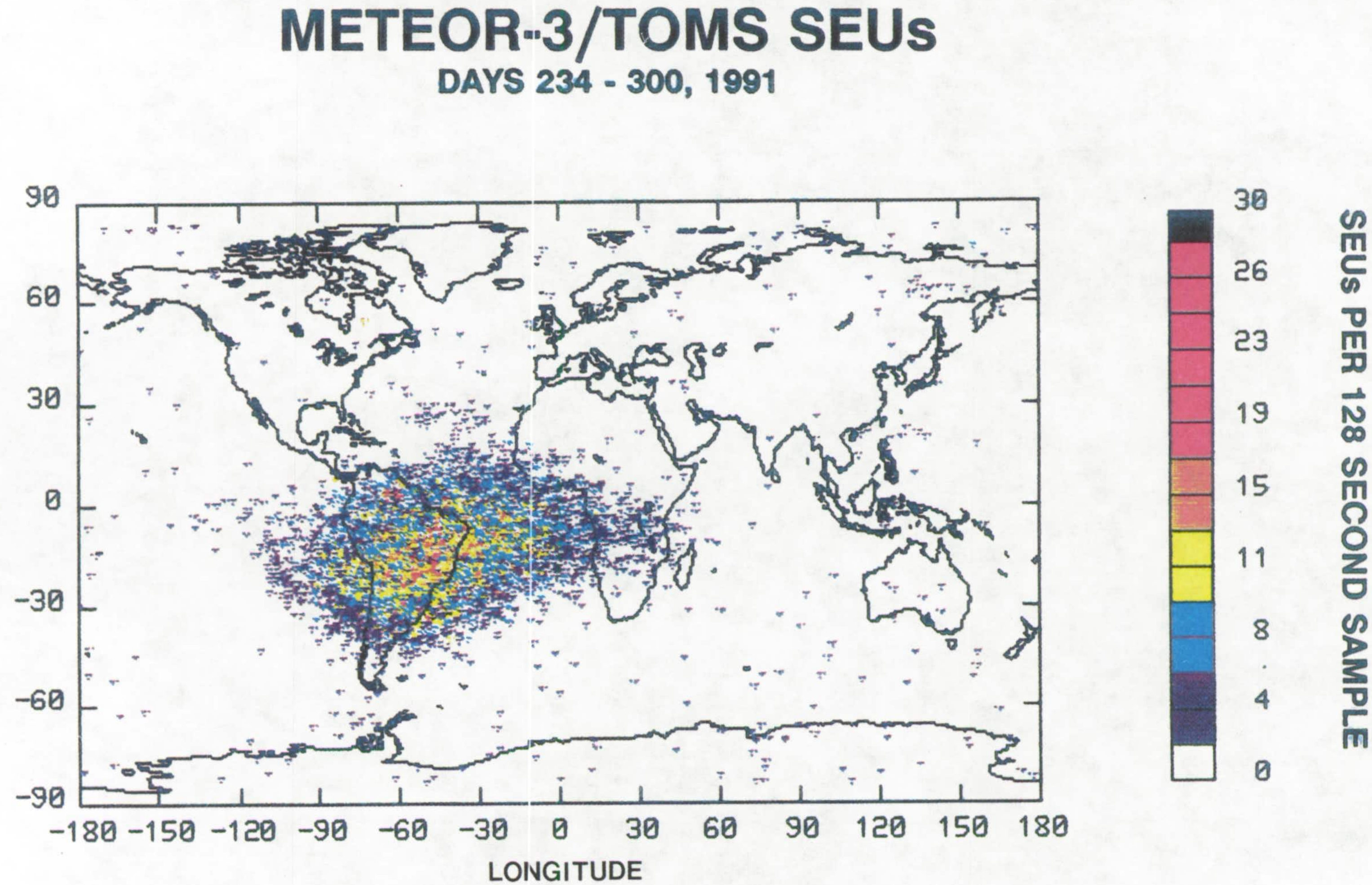


Figure 4.2-1 Single Event Upsets for Days 234-300 (Hardware SBCs removed).

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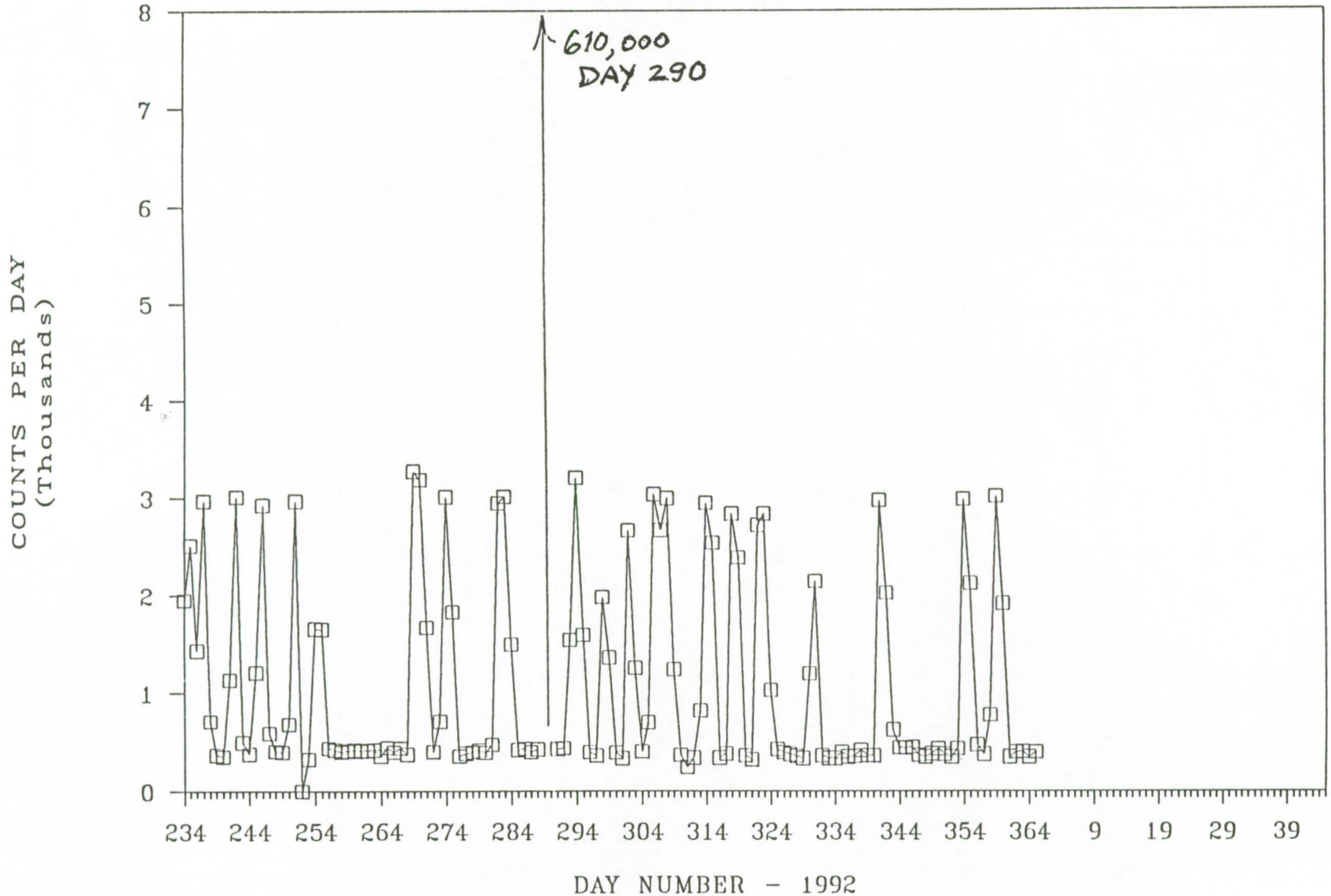

Figure 4.2-2 Plot of Single Bit Corrections for Days 234-365.

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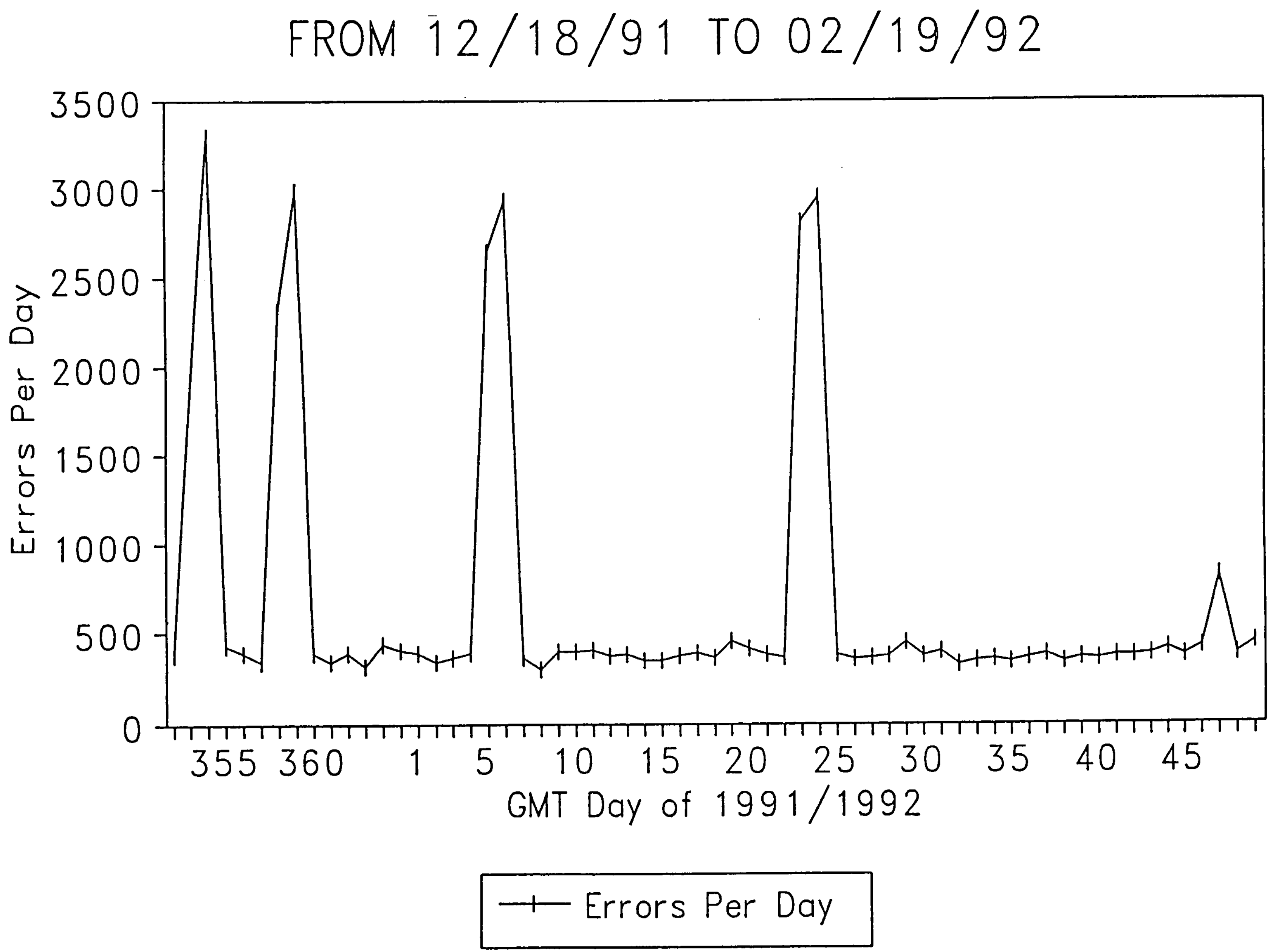

Figure 4.2-3 Plot of Single Bit Corrections for Days 353-050

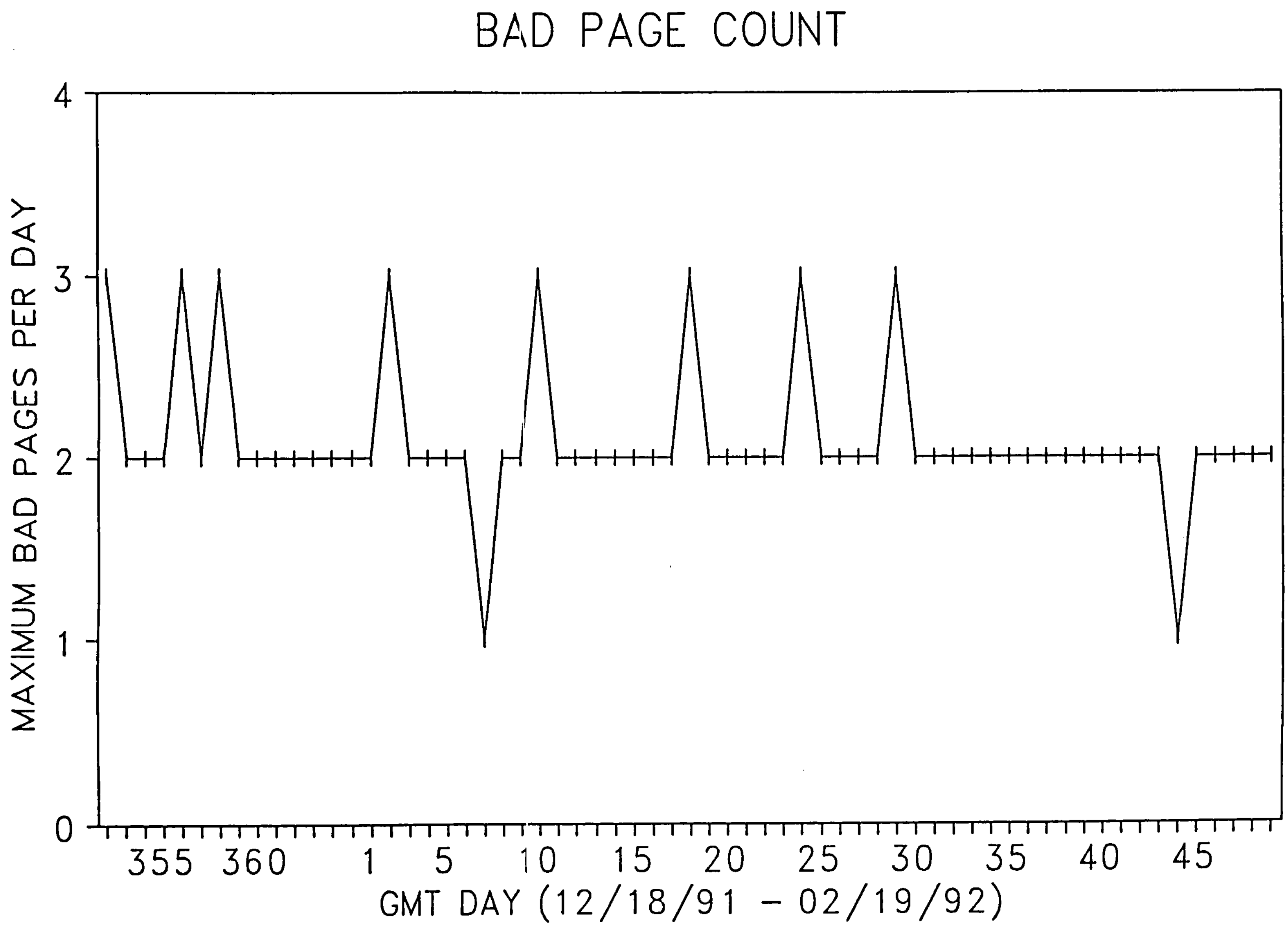

Figure 4.2-4 Plot of Single Bit Corrections

5.0 MISSION OPERATIONS

Section Contributors:

John Sissala
Michael Forman

5.1 General

TOMS operations on the Meteor-3 spacecraft have been nominal. The instrument and recorder have performed as expected. The electronic mail system between Moscow and Goddard has operated and has been used daily. Instrument command loads have been successfully transmitted to Moscow every two weeks. We have had extremely professional and cooperative support from the Wallops data capture site. All data to date has been received and processed to level zero. Tapes have been sent daily to the Science Processing Facility for Science processing. No instrument or processing anomalies have affected the data quality. All onboard instrument calibrations have been executed as requested by the project.

In summary, spacecraft operations to date have been a smooth-running operation with all parts of the daily operation working together to gather a complete data set of ozone observations for science processing.

5.2 Instrument Performance

The instrument performance has been nominal since launch. The instrument turn on and activation process was implemented without problem. The chopper motor has been in sync since turn-on. The high voltage has been on since orbit 93 without problem. With the exception of the electronics calibration, all calibrations have executed as programmed and planned.

Instrument temperatures have varied from a low of approximately 16 degrees Celsius at launch to a high of almost 32 degrees C. These fluctuations are shown on the attached graph. Our nominal operating range for most functions is between 10 and 35 degrees C. The variations have had no discernible affect on the data quality or instrument operations.

On December 31 the chopper motor current began dropping from its normal 8 milliamp (mA) operating range to a low of 3.95 mA on January 29. It subsequently increased to the 5 mA range by mid February. This fluctuation, also, had no discernible affect on the data quality. (A similar range of chopper motor currents had been observed on Nimbus 7). At no time has the chopper motor current gone outside of the design ranges.

5.3 Solid State Recorder Performance

The Solid State Recorder (SSR) has reliably recorded and transmitted all data. Onboard self testing of memory shows a consistent one "bad page count" (2 or more single-bit errors on a two Megabit page of memory) with a maximum of three bad pages. Single bit memory errors occur more frequently with the great majority happening in the South Atlantic Anomaly area of high charged proton activity at spacecraft altitudes.

5.4 Moscow-to-Goddard Communication Link

The San Francisco/Moscow Teleport electronic mail communication link has provided a reliable method to transfer information between the Central Aerological Observatory (CAERO) in Moscow and the TIOCC here at Goddard. The TIOCC transmits a daily report of telemetry status, and a bi-weekly set of TOMS operating commands. CAERO, in turn, provides a bi-weekly set of Meteor-3 state vectors and the ground-clock-to-spacecraft-clock time difference. The link is also used for routine administrative messages.

5.5 Data Transmission and Acquisition

The Flight Dynamics Facility at Goddard generates ground trace reports for TIOCC command generation, and acquisition vectors for the Wallops Flight Facility. This interface has worked smoothly.

The Meteor-3 transmits a 24-hour SSR load twice each day to the Russians and twice to the USA. Acquisitions at the Wallops Flight Facility have been nearly flawless. With the exception of a five-minute segment of data, all data has been acquired. The second, redundant, spacecraft dump is only acquired if we believe we can improve the quality of the data. Wallops has always acquired on the first pass of each day.

Between September 8 and September 30 the Meteor-3 transmitter frequency drifted from a nominal 466.5 MHz to 467.5 MHz. This drift caused a minor increase in bad quality data. This problem, however, accounts for over 88 percent of the total bad quality frames. Since September 30 there has been no further drift in transmit frequency and Wallops now acquires all data at the 467.5 MHz frequency.

5.6 Data Processing

TIOCC has received all dumps acquired by Wallops. These files have been stripped into Raw Data Tape files and archived locally on optical disk. All raw data has been processed to level 0. Of the greater than 1.7 million frames of data processed, only 215 are of bad quality. As previously discussed, 191 of these bad frames occurred during September when the transmit frequency was unstable. The percentage of good minor frames processed and passed on for science processing is 99.99 percent!

5.7 Calibrations

Calibrations have been scheduled and executed on a regular basis since launch. Each calibration is scheduled when the solar angles are appropriate. When the angles are correct, a cover diffuser calibration is performed each orbit, a working diffuser calibration is performed weekly, and a reference diffuser solar calibration is performed twice each 212 days when the diffuser has a normal incidence to the sun vector. Wavelength calibrations always occur during earth night, and occur during satellite night if possible. Electronic calibrations were scheduled and executed once per orbit up until November 20. The electronics calibration was inhibited, however, on that day due to an anomalous 60 volt voltage spike occurring in the middle of the calibration. The cause is still under investigation.

5.8 Reports

The TIOCC has prepared and published its first quarterly report covering operations from August 15th (launch) through October 31. The second quarterly report (November 1, 1991 through January 31, 1992) was written and distributed before February 28.

6.0 SCIENTIFIC RESULTS

Section Contributors:

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6.1 DATA PROCESSING FOR LEVELS 1 TO 3

Overview

The Meteor-3/TOMS data is telemetered from the satellite to the Wallops ground station along with instrument housekeeping data for health and safety of TOMS. The data stream is not mixed with any other instrument. Data relating to the spacecraft is supplied by the Russians at 2 week intervals (e.g., orbital vectors, temperatures,etc.) via E-mail. After the instrument data is received at the Wallops ground station, the data stream is recorded and sent to GSFC via NASCOM. The NASCOM data stream is received at the Code 513 TIOCC, the TOMS Instrument Operations Control Center, (see Figure 6.1-1).

LEVEL 0: The GSFC Code 513 TIOCC checks the quality of the transmission from the ground station, requests retransmission if needed, breaks the NASCOM data blocks into "major-frames" as defined by the project documentation. Header information is inserted (e.g., orbit number), flags are set to indicate data quality, grey code conversion, and necessary formatting are performed prior to transmission to the scientific data reduction facility, SDRF (Code 916 and the Meteor-3/TOMS data reduction contractor).

Transmission from TIOCC to SDRF is by ETHERNET directly to the mainframe data reduction computer (currently an IBM 9021 in Code 930 and by mid-summer, 1992, to the Code 916 Vax 6410).

The new SDRF consists of a DEC Model 6410 VAX computer clustered with VAX 3000 and MicroVAX II computers. Large data storage facilities are included: 5 Gbytes of on-line magnetic disk storage, 90 Gbytes of read-write optical storage with removable media, 9-track 6250 tape drives, and cartridge (200 Mbyte) tape drives. The appropriate software for compilers, file management and documentation, and graphics are available for the SDRF. The change will improve access to the ozone data by scientists and contractors for the purpose of data analysis and quality control.

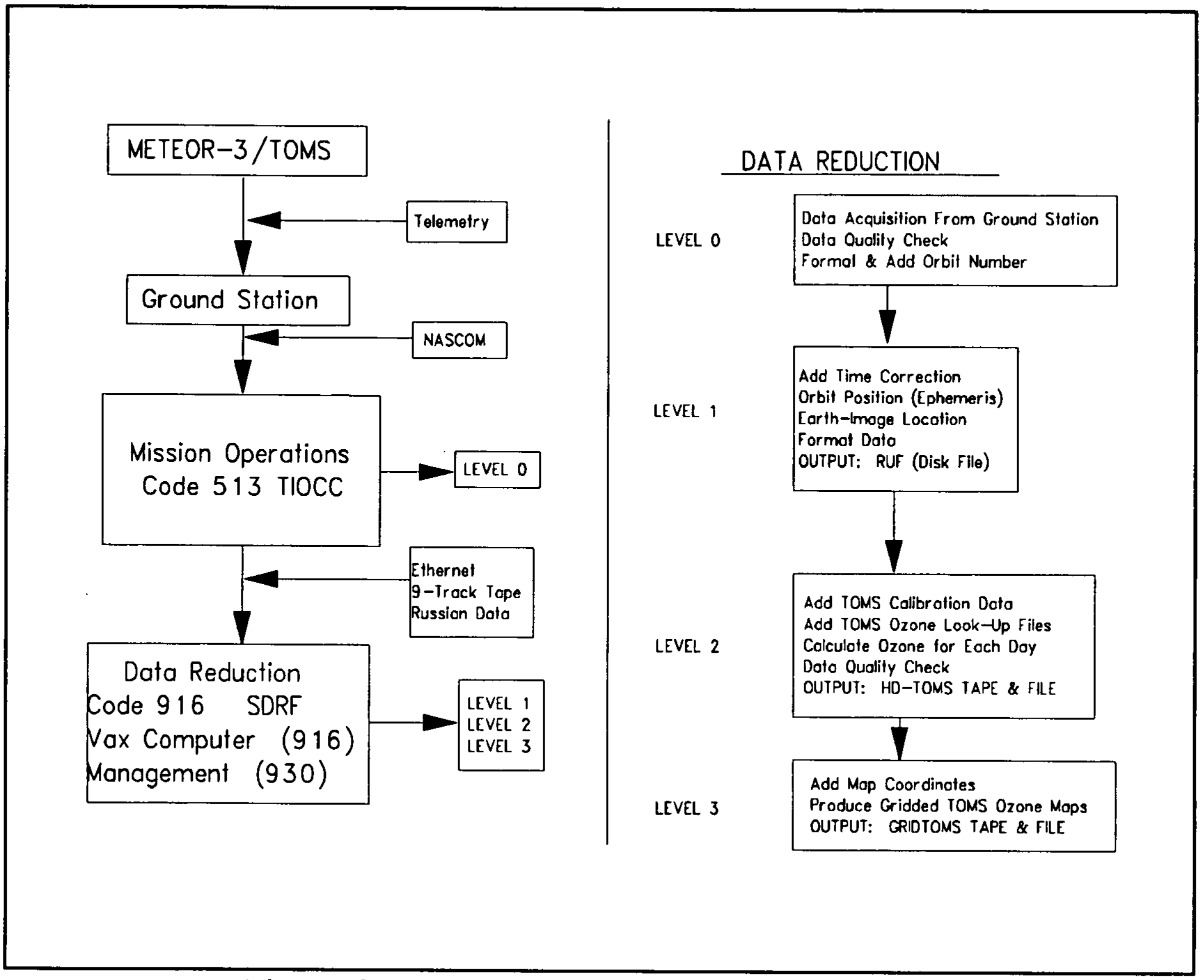


Figure 6.1-1 METEOR-3/TOMS DATA FLOW

Data reduction of the science data will be accomplished on the Code 916 VAX using Civil Service and contract personnel managed by Code 930. The science data processing is divided into three distinct stages indicated by Levels 1, 2, and 3 as shown in Figure 6.1-1.

LEVEL 1: Level 1 processing reads the data output from level 0, formats the data into the agreed format for producing the Raw Units File, or RUF, (tape or optical disk data file), adds time correction data, adds satellite orbital information data from the Flight Dynamics Facility, calculates image location data for each of the scan positions, adds satellite attitude data, adds data quality flags, and finally produces the RUF. Since it is planned to use optical disk data storage in place of tapes, the name RUT (Raw Unit Tape from Nimbus-7/TOMS) will be changed to RUF (Raw Unit File). The RUF data will be archived to IBM style cartridge tape cassettes (200 Mbytes). The RUF data forms the input to Level 2 processing.

LEVEL 2: Level 2 processing reads the RUF data from level 1, adds several precomputed data products, and produces the ozone data in the form of a disk file (HDTOMS, High Density TOMS) used as the basic data set for scientific ozone studies. In order to produce the HDTOMS data set, the following additional information is needed (supplied as part of level 1 RUF data):

a. The TOMS instrument calibration data (diffuser plate goiniometry, diffuser plate reflectivity, electronic gain, wavelength calibration, etc.) from a combination of laboratory and in-flight sources.
b. Snow-ice ground cover data to help determine ground reflectivity or cloud height and reflectivity.
c. Terrain-height data.

The output from level 2 processing (HDTOMS) contains the total ozone calculated from four wavelength pairs. These are the A-, B-, and C-pairs currently used on Nimbus/TOMS and Meteor-3/TOMS. The HDTOMS also contains the lower boundary reflectivity, terrain height, the measured calibrated and corrected radiances for each wavelength channel, the time of the measurement, and the ground location of the measurement. These data are given for each of the 35 cross-track scan positions along each orbital track. There are additional data provided in each record, as specified in the Nimbus-7/TOMS User's Guide, to aid the investigator's understanding of the Meteor-3/TOMS ozone data product. Processing times are estimated in Table 6-1.

Table 6-1

SOFTWARE LEVEL	INPUT SIZE	PROCESSING TIME	OUTPUT SIZE	PRODUCT
1	12 Mbytes/day	0.5 Hour/day	15 Mbytes/day	RUF
2	15 Mbytes/day	0.2 Hours/day	11 Mbytes/day	HDTOMS
3	11 Mbytes/day	0.1 Hours/day	0.14 Mbytes/day	GRIDTOMS

Note: Processing times are in VAX 6410 cpu + I/O units of time.

6.1.1 Level 1

Spacecraft science data has been received from Level 0 processing by TIOCC without interruption since instrument turn-on, August 25, after launch on August 15, 1991. Based on schedules negotiated with our Russian counterparts, we have received regular updates of the spacecraft position data every two weeks. These data have been reviewed by the Goddard Flight Dynamics Facility (FDF) to check that the accuracy is within the specifications for obtaining good ozone values. The FDF calculated that the requirement has been met for locating the position of the viewed image on the surface of the earth be located to within 20 km. The Russian data has been routinely converted into the spacecraft ephemeris and merged with the Level 0 data for processing into Level 1 radiance/irradiance used for obtaining ozone (Level 2). Consistency checks have been run on the orbital determination for Meteor looking for deviations from a smooth progression of coordinates. The results were satisfactory except for one short period in October that showed an unexpected amount of variance. An updated set of spacecraft vectors were obtained from the Russians, and the analysis is being rerun with the new data.

Aside from the negligible loss of a few frames of data scattered throughout the record, the Meteor-3/TOMS data record is complete for the entire period since launch. Data processing has been completed up to the end of January with the normal 2-week delay from calendar time.

There are no problems to date with the Level 1 processing. Plans are underway to move the Levels 1 and 2 processing from the IBM 3081 to the Code 916 Vax 6000. Disk and tape drives have been purchased and installed for this purpose. The software has been converted from IBM to VAX Fortran, and testing is nearly completed. A complete reprocessing of the Meteor-3/TOMS data on the new system is scheduled for July 1992 to incorporate the latest in-flight instrument calibration.

6.1.2 Level 2

Using the input data from Level 1, Level 2 software performs the conversion of measured albedos in 6 wavelength channels, surface reflectivities, and solar irradiance to ozone amount as a function of orbital latitude, longitude, time, and scan position.

In addition to the data contained in Level 1, some external data are required. These are, TOMS calibration constants, TOMS albedo vs ozone tables, and a set of initial ozone profiles as a function of latitude and season. For Meteor-3/TOMS, the calibration constants and ozone tables require special attention. Because of the drifting Meteor orbit relative to the sun-angles (azimuth and zenith angles), there are new (largely resolved) problems with the radiative transfer programs when used at high solar zenith angles ($\Theta_o > 75°$).

The problems show up in the calculation of surface reflectivity as the Meteor orbit precesses near the terminator. Over wide swaths of the earth's surface, the calculated reflectivities are either very high when looking towards the sun (200%), or very low when looking away from the sun (-140%). The extreme values in effective calculated reflectivity arise from two basic sources. First, there is a built-in assumption that the reflecting surface is lambertian. At high solar zenith angles the reflectivity deviates strongly from Lambertian conditions, and can produce apparently over-large values. Second, the reflectivities are calculated by subtracting the Rayleigh scattering portion of the atmosphere from the measured radiance. An error in the Rayleigh scattering atmospheric model can lead to negative reflectivities (e.g., presence of clouds, high altitude haze). Recent results have conclusively determined that most of the problems originate from the presence of large amounts of atmospheric aerosols injected by the Mt. Pinatubo eruption during June 1991.

A possible contributor to both of these conditions is the likely presence of spacecraft attitude errors. The Russians provide only one spacecraft attitude estimate every two weeks. Errors in attitude (roll, pitch, and yaw) can produce significant errors in zenith and azimuth angles that are most important at high solar zenith angles (when the spacecraft is near the terminator) and under conditions of atmospheric aerosol contamination. This combination of problems is under intensive investigation for both Meteor and the original Nimbus-7/TOMS instruments (the Nimbus orbit is now drifting to an hour-angle where these problems are more important).

Possible attitude errors can also effect the earth image location for each of the scan positions, and the effective solar zenith and azimuth angles used in the ozone vs albedo lookup tables. The result will be a systematic error in measured ozone amounts that affects both the daily ozone maps and the calculation of long-term ozone trends. Comparison of reflectivity data with known geographical boundaries in Iceland and Antarctica have not shown large attitude errors.

6.1.3 Level 3

Level 3 processing involves the production of data sets suitable for producing global maps of ozone for each day. The same software can also produce maps of surface reflectivity and solar zenith angles that can be used for both science and diagnostic purposes. This processing is up to date for Meteor-3/TOMS.

Level 3 processing output has enabled the Ozone Processing Team (OPT) to become aware of dramatic changes in the earth's atmosphere as well as to detect processing errors. The first indication of the Pinatubo volcanic eruption effects on the ozone amount was first seen in the Meteor-3/TOMS data during the November joint data meeting with the Russians. This showed up as a scalloping effect in the equatorial ozone maps with the extreme scans 1 and 35 positions showing much higher ozone amounts than the nadir scan position 17. This has been subsequently shown to arise from the Mie scattering effect of aerosols produced by conversion of the injected SO_2 gases into the stratosphere. A paper is in preparation explaining this effect and the apparent and real reduction of ozone in the equatorial region due to the Pinatubo eruption.

6.1.4 Comparison With Nimbus-7/TOMS

The ozone data from Nimbus-7/TOMS and Meteor-3/TOMS have been compared for the same period of time (August 25, 1991 to February 29, 1992). The comparison was performed in terms of zonal averages in 10° latitude bands. A sample of the data is shown in Figure 6.1.4-1 for the latitude bands ±60°, ±30°, and the equator. The two data sets agree to within 5% except for the period between days 260 and 290 when the Meteor spacecraft orbit was near the terminator. At the present time, we do not know what is responsible for the systematic differences between the data sets. At the equator, the offset between Meteor and Nimbus has reversed since launch (hour angle ≈ 10 am ascending orbit) and Day 330 (hour angle ≈ 12 noon descending orbit). Other latitudes show different but systematically changing offsets. Aside from differences in the Day 1 absolute calibration (which should produce a constant offset between the two data sets), the combination of problems with the orbital drift, spacecraft attitude, and use of an interim calibration probably cause the differences. Each of these items is under intensive study as detailed in the next section.

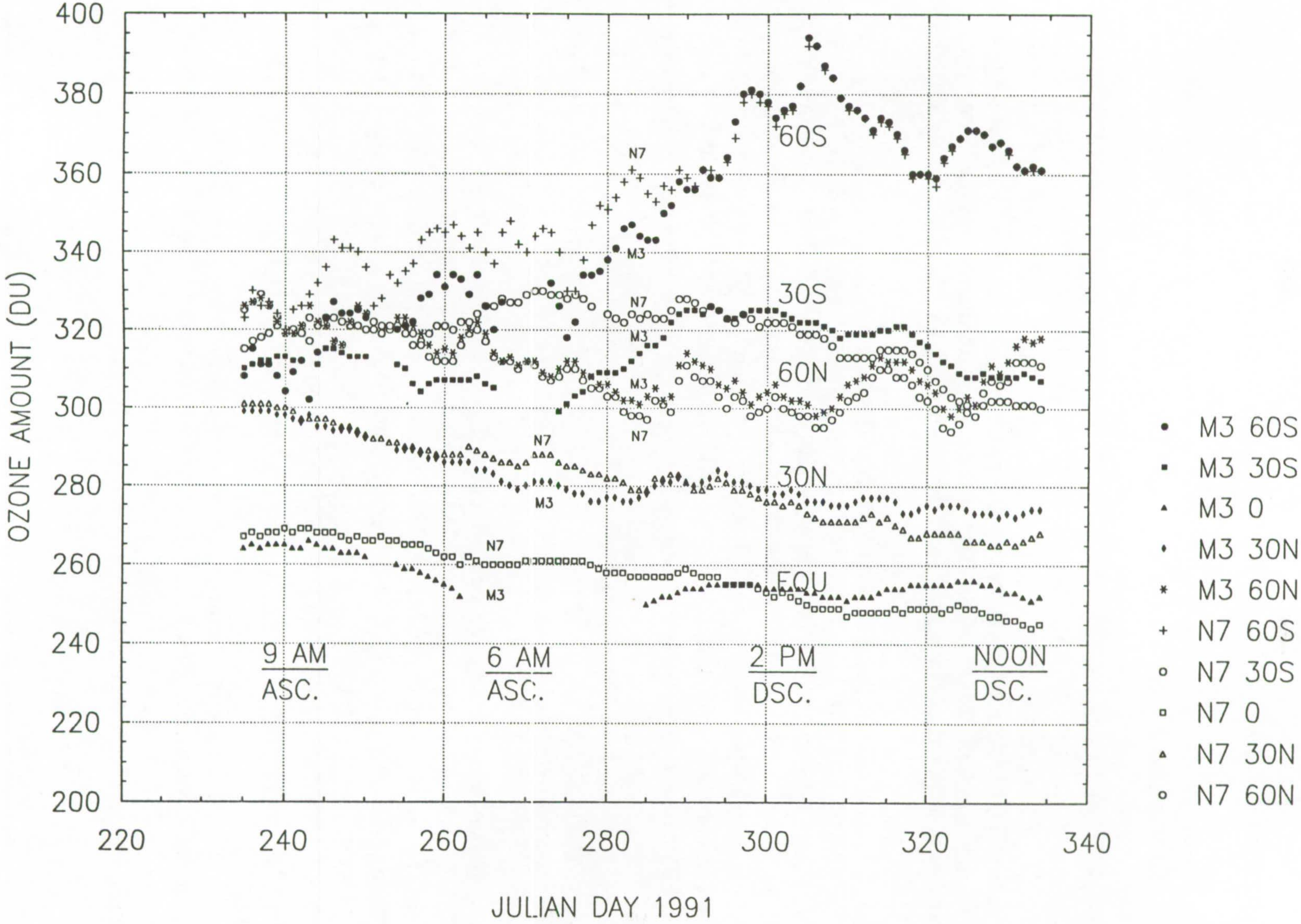


Figure 6.1.4-1 Meteor-3/TOMS and Nimbus-7/TOMS ozone amounts

6.2 STUDY AREAS

6.2.1 Validation of Data

During the validation of the first hundred day's Meteor-3/TOMS data the derived effective surface reflectivity from the Meteor-3/TOMS was found to vary from -140% to 200%. This unexpectedly large range of reflectivity values had not been seen on the preceding TOMS spacecraft (Nimbus-7). Since the derived reflectivity is used as part of the ozone retrieval algorithm, we have attempted to define the physical conditions for the occurrence of the large observed reflectivity range.

6.2.1.1 Symptoms of the "Reflectivity Anomaly"

(1) The percentage of processed samples with derived effective surface reflectivity outside of a predefined range (where the range is -5% to 105%) varies with the satellite's local equator crossing time (LECT). At around noon LECT, the number of samples with out-of-range reflectivities is fewer than 1%, but rises to as high as 20% at near 6 a.m. LECT (when the orbit plane is nearly parallel to the terminator). (see Figure 6.2.1-1)

(2) Maps of these derived effective reflectivities show that, at around noon LECT, there is no orbit dependent pattern on the maps. They begin to appear, however, as the orbit precesses to near 6 a.m. LECT.

(3) When the orbit is at near 6 a.m. LECT, the reflectivity derived from the measurements at off nadir scan positions begin to show anomalously high or low values. Typically, high values (as high as 200%) are obtained at the scan positions toward the sun and low values (as low as -140%) are obtained at the scan positions toward the terminator. There is a reflectivity slope across each scan, and the shape of the pattern is closely related to the solar zenith angle distribution and the azimuth angle of the scanning plane with respect to the sun (see Figures 6.2.1-2 to 6.2.1-5).

(4) These anomalous reflectivity values affect the ozone measurements. One indication is that the comparison of the gridded ozone data from Meteor-3/TOMS with that of Nimbus-7/TOMS shows a difference that clearly correlates with the bad reflectivity sample occurrence curve (see Figure 6.2.1-6).

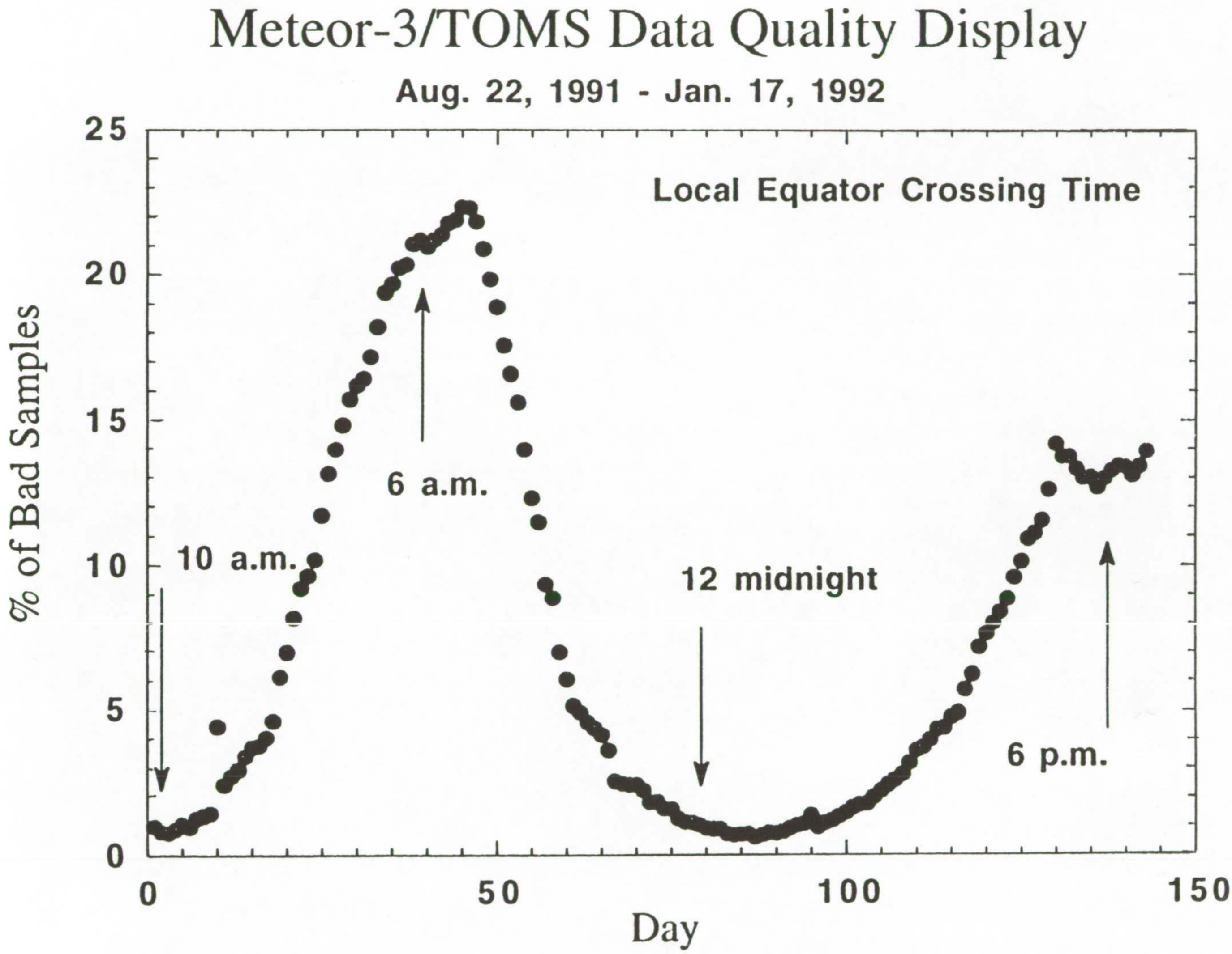


Figure 6.2.1-1 Meteor-3/TOMS reflectivity data

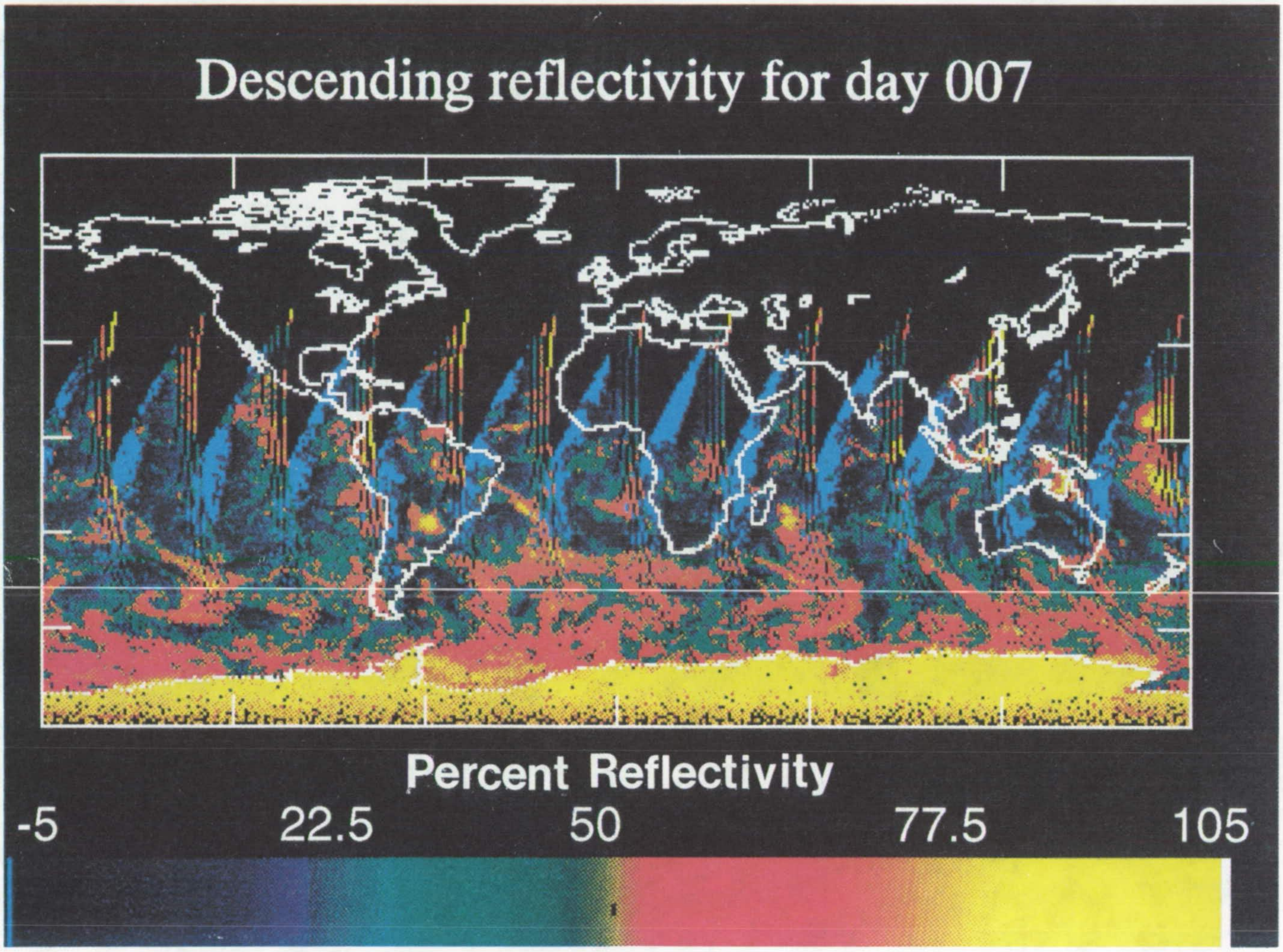


Figure 6.2.1-2 Meteor-3/TOMS reflectivity data

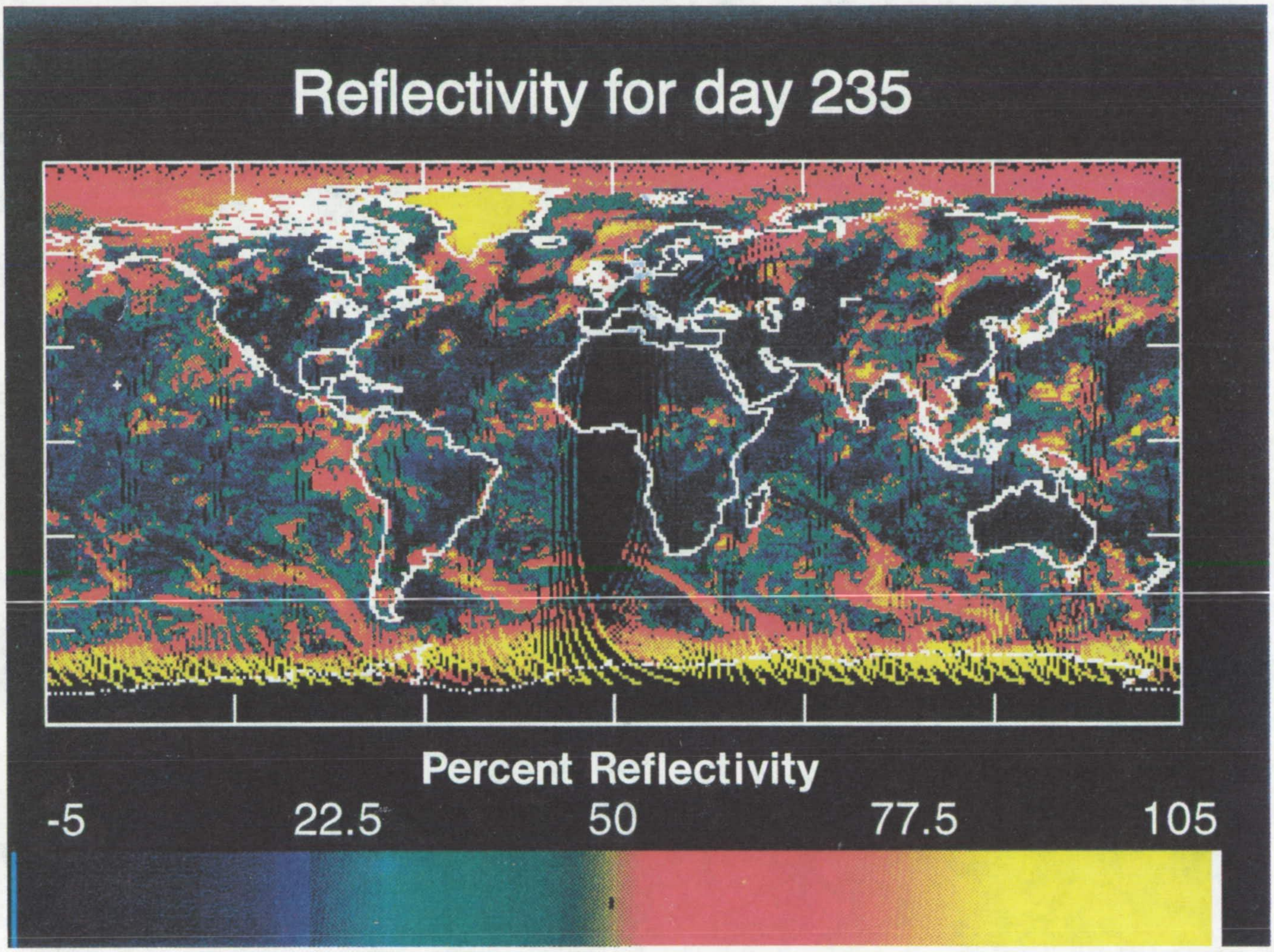


Figure 6.2.1-3 Meteor-3/TOMS reflectivity data

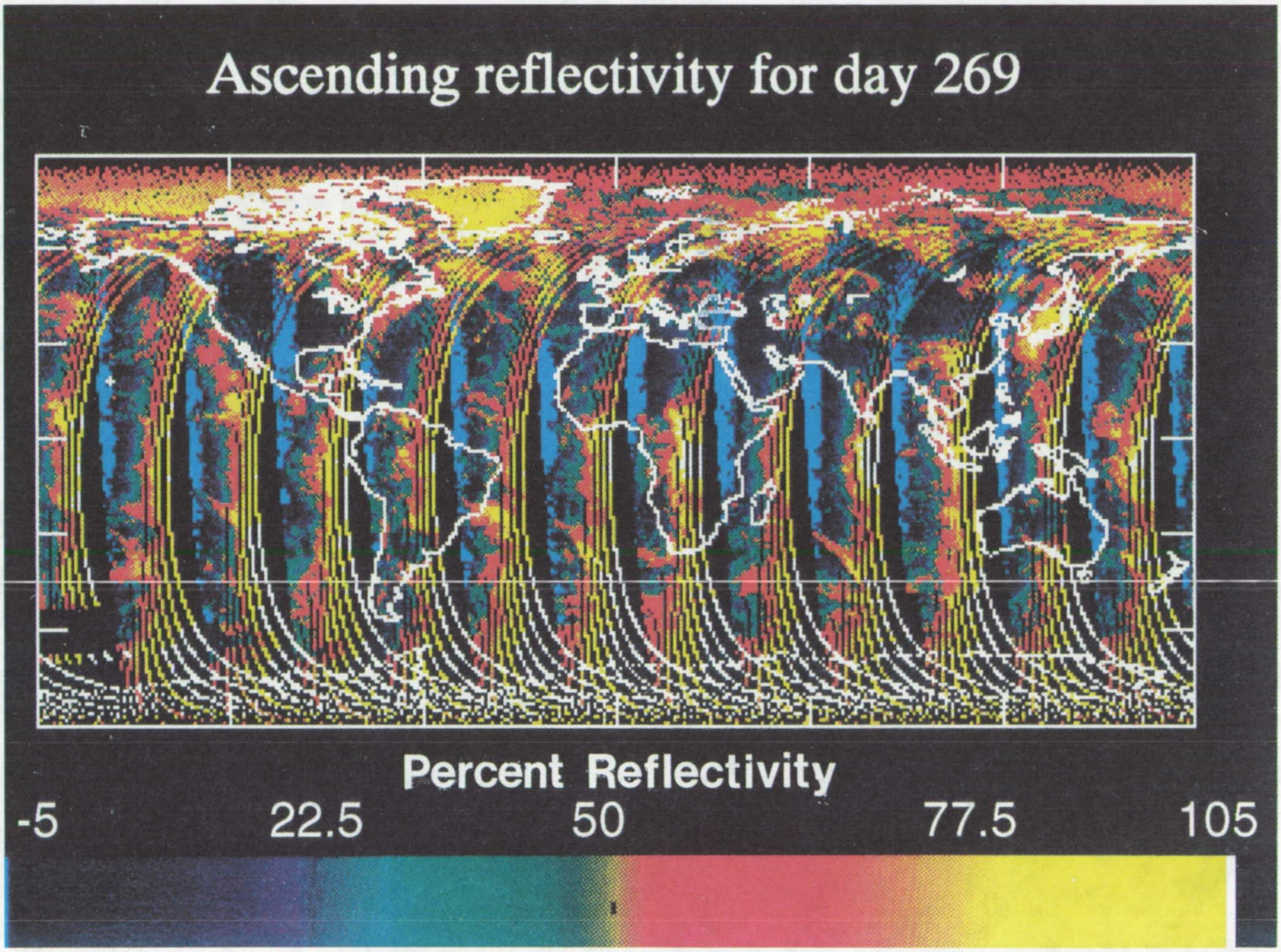


Figure 6.2.1-4 Meteor-3/TOMS reflectivity data

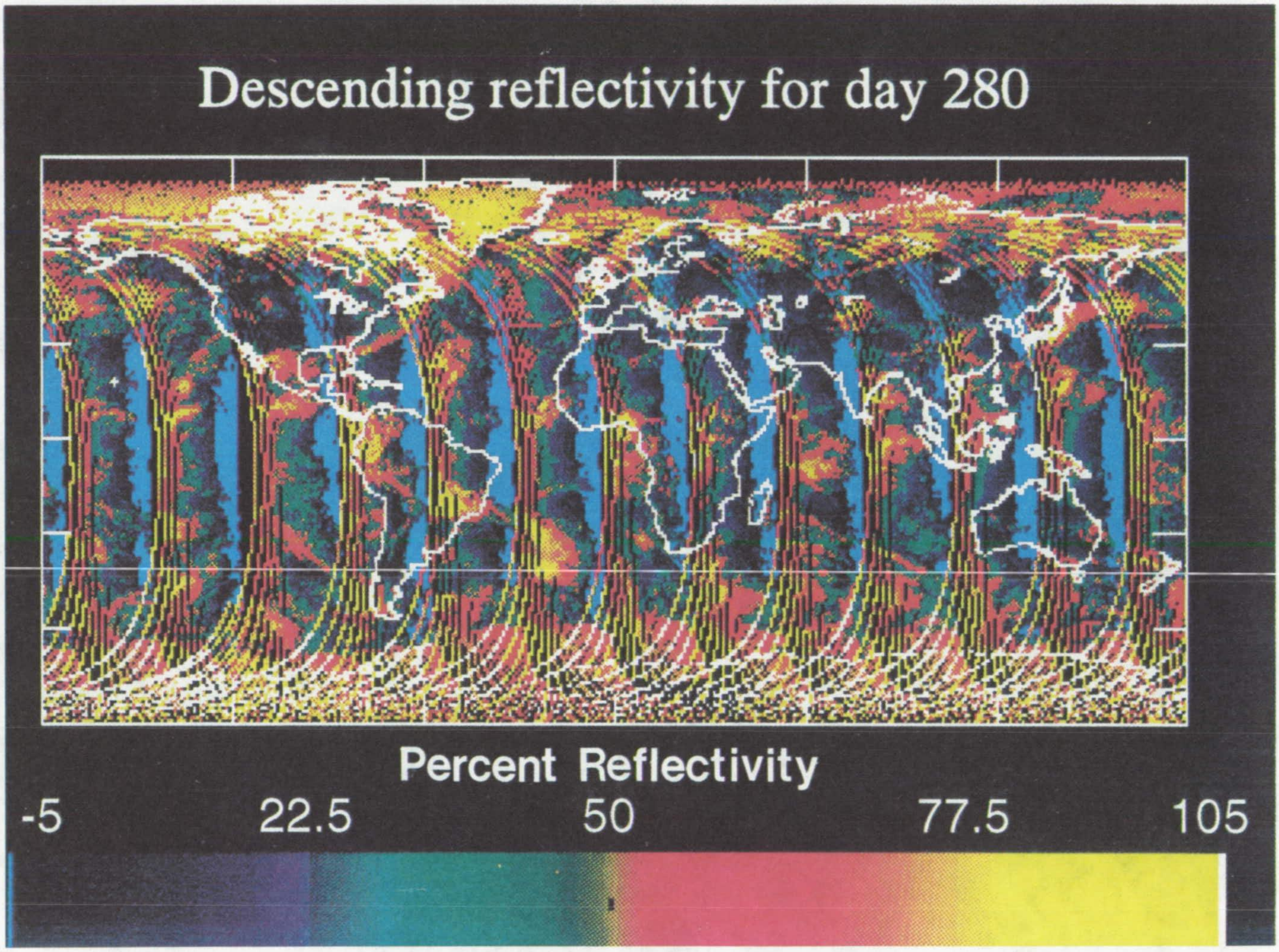
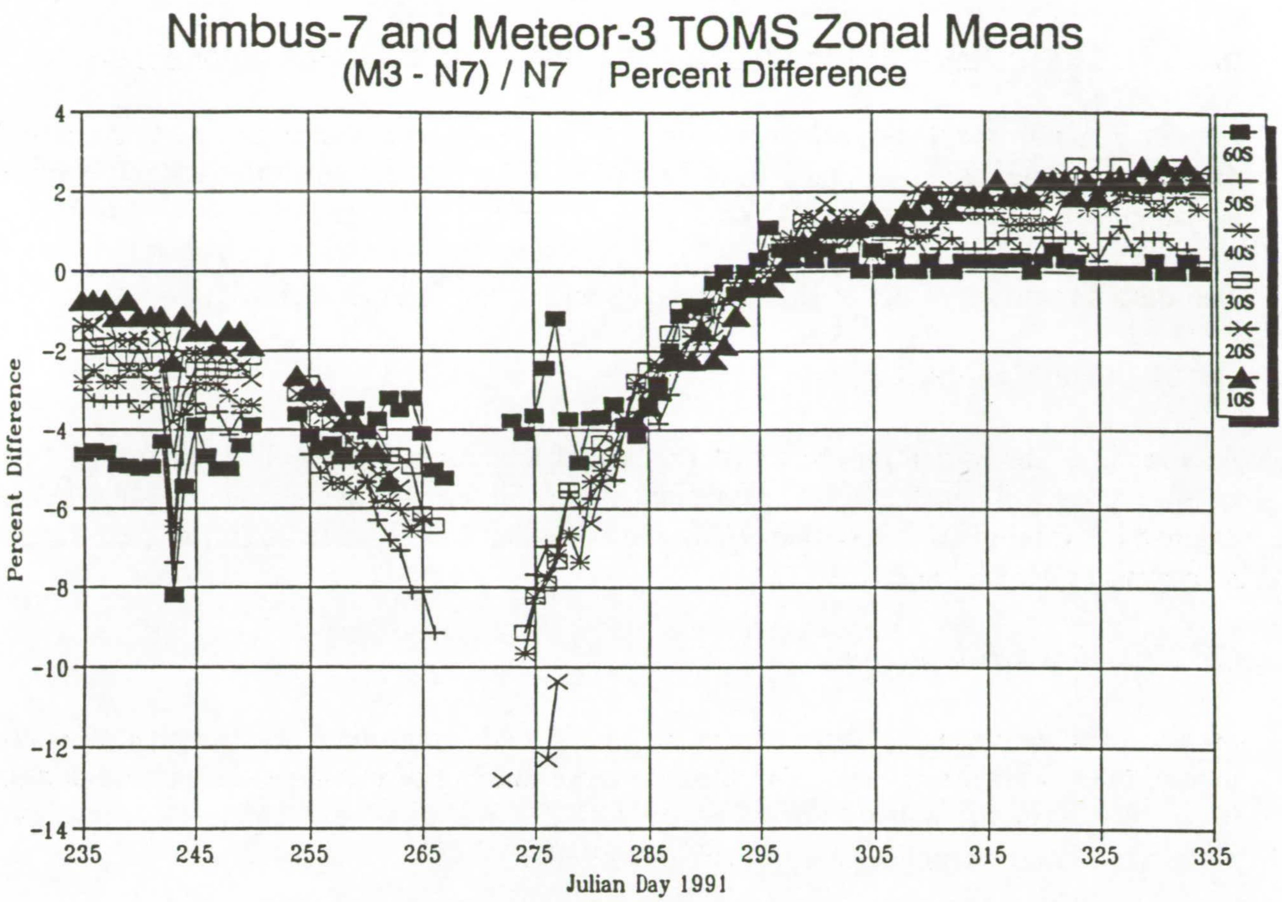


Figure 6.2.1-5 Meteor-3/TOMS reflectivity data



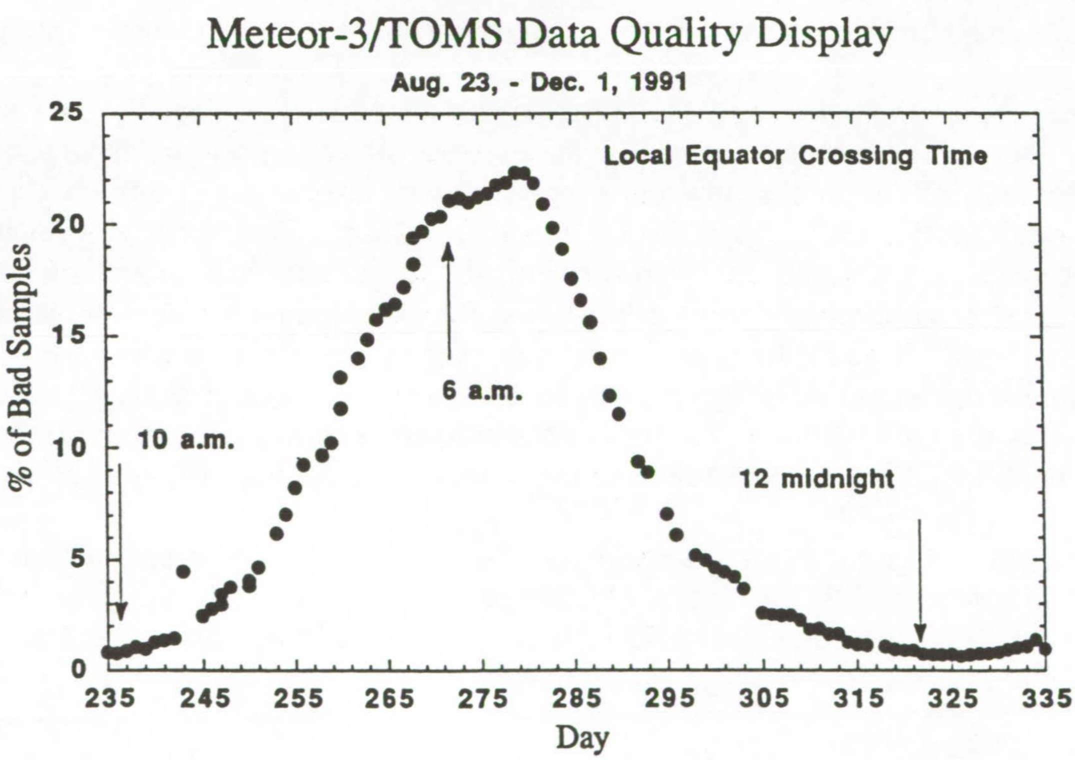


Figure 6.2.1-6 Reflectivity comparisons with Nimbus-7/TOMS

6.2.1.2 Orbit Characteristics of Meteor-3 and Related Measurement Geometry

Meteor-3 is not in a sun-synchronous orbit. The orbital precession period is about 212 days for a whole cycle (around 7 minutes a day). The inclination angle is 82.5°, and the average orbit height around 1200 km.

The most important effect of this precessing and higher altitude orbit is:

(1) High solar zenith angles

As a result of the orbital precession, there is a large amount of data obtained at high solar zenith angles. When the LECT is around noon, the rate of occurrence of solar zenith angles higher then 75° is less than 10%, but when the LECT shifts to 6 a.m., the rate of occurrence becomes nearly 100%.

(2) Changing azimuth angle

As the orbit shifts away from the noon LECT, the instrument scanning plane shifts toward the solar-zenith plane. Therefore, a large number of measurements are done near 0° or 180° azimuth angles. For Nimbus-7/TOMS, the solar-zenith plane and scanning plane are almost perpendicular to each other (90°).

(3) Decreased accuracy for the measurements at the extreme off nadir scan positions

Meteor-3's orbit altitude is about 200 km higher than that of Nimbus-7. As a result, the view angle at the scenes measured by the extreme off nadir positions is larger than that for Nimbus-7/TOMS (the view angle for scenes measured at scan positions 1 and 35 for Nimbus/TOMS is 63.3°, but 67.5° for Meteor-3/TOMS). This larger view angle results in decreased accuracy in the measurement: the larger the view angle, the larger the covered area on the surface of the Earth, and therefore the larger the nonlinearity in the measurement. This factor is less problematic when the orbit is at around noon LECT, because the adjacent orbits have some overlaps and the measurements at extreme scan positions are not really used. It becomes a problem, however, for the morning and the afternoon LECT orbits, when the extreme samples are required to cover the Earth.

Displayed in Figures 6.2.1.2-1 and 6.2.1.2-2 are the azimuth angles and solar zenith angles for Meteor-3/TOMS at day 235, where the LECT is near 10 a.m. and the viewing geometry is fairly close to that of Nimbus-7/TOMS, and at day 269, where the LECT is near 6 a.m. and the viewing geometry is very different from that of Nimbus-7/TOMS.

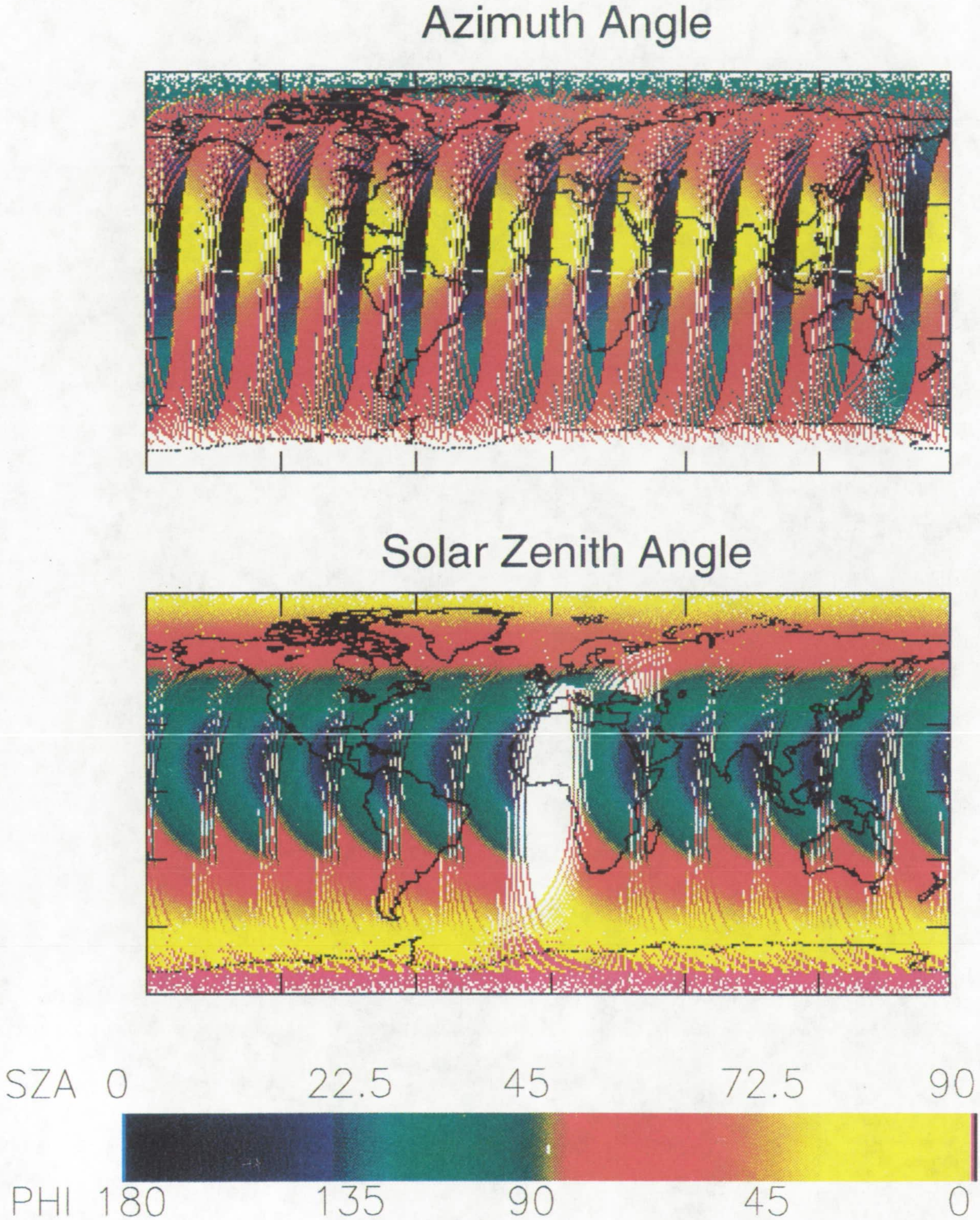


Figure 6.2.1.2-1 Azimuth angles and solar zenith angles at day 235

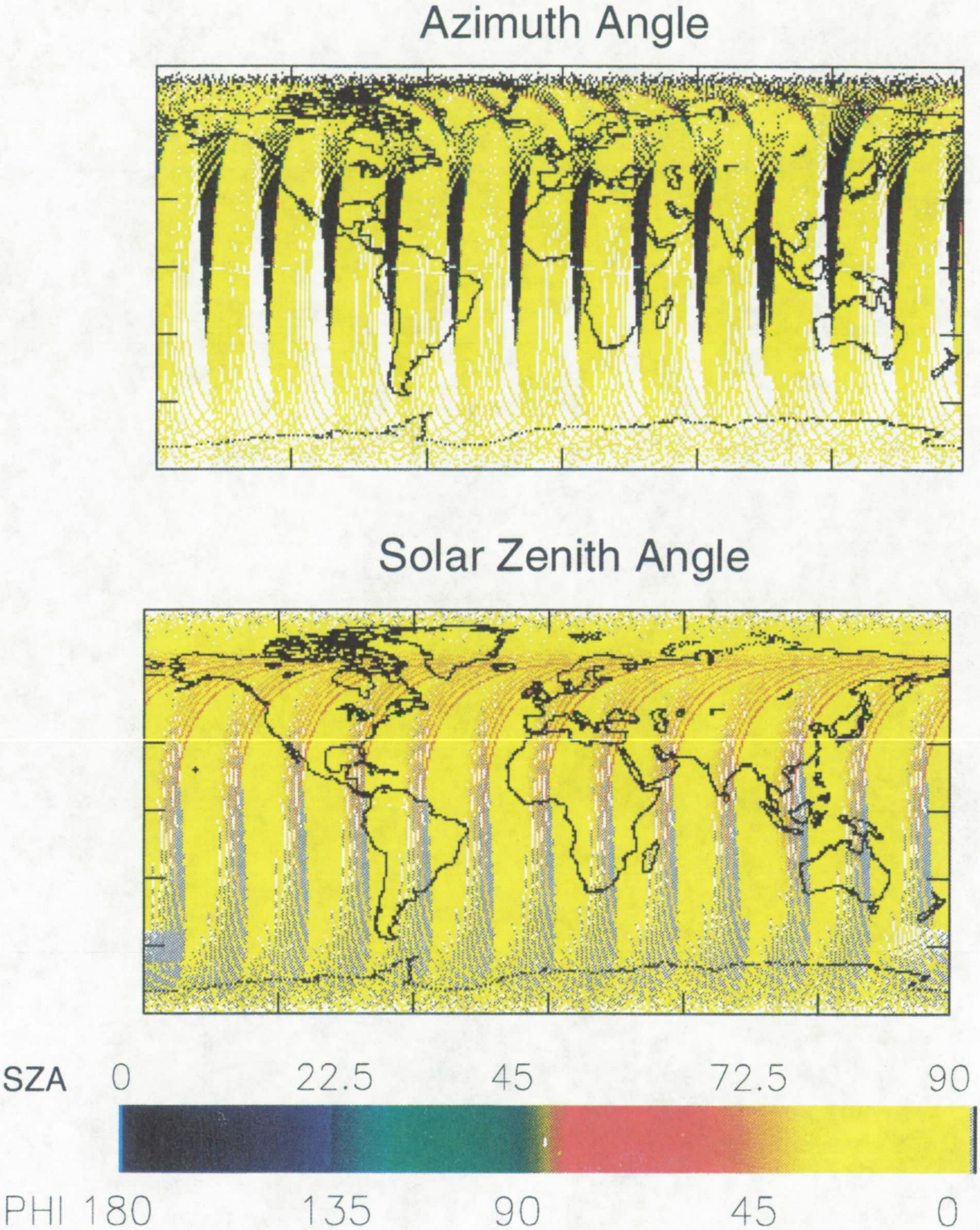


Figure 6.2.1.2-2 Azimuth angles and solar zenith angles at day 269

In order to understand the impact of the reflectivity anomalies on the ozone measurement, we have investigated the following scenarios as the possible causes: (i) incorrect instrument calibration; (ii) processing software error; (iii) spacecraft attitude uncertainty; (iv) inaccurate ephemeris; (v) non-Lambertian effects of the ocean, clouds, ice, and earth surfaces; (vi) inadequate atmospheric model; and (vii) Aerosol effect from the Mt. Pinatubo eruption.

Among all these possibilities, we have found many of them are unlikely to be the cause and plan to focus our study on the following aspects:

(1) Impact of attitude uncertainties and inaccurate ephemeris

Sensitivity studies of the reflectivity indicate that the measurements at high solar zenith angle are more sensitive to errors in angle determination. This is illustrated in Figures 6.2.1.2-3 and 6.2.1.2-4. Because large portions of the Meteor-3/TOMS measures are performed at high solar zenith angles, any attitude or ephemeris uncertainties will result in larger impact than that for Nimbus-7/TOMS.

Figure 6.2.1.2-5 indicates that at a view angle of 67°, one degree of solar zenith angle error will result in insignificant errors in reflectivity for solar zenith angle less than 70°. At large solar zenith angle, however, the reflectivity error from one degree solar zenith angle error could be as large as 100% . This suggests that the derived negative reflectivity distributed along the terminator is likely due to attitude uncertainties.

(2) Non-Lambertian effects of the surface

Current ozone retrieval algorithms assume that the surface of the lower boundary of the atmosphere is Lambertian, i.e., the diffusely reflected light is isotropic in the outward hemisphere and is natural, independent of the state of polarization and the angle of incidence of the incident light. Our reflectivity is derived from measured albedo using these assumptions.

Several previous studies show that the reflectance of the earth's surface including the ocean, and ice can be quite non-Lambertian. These non-Lambertian effects are sufficient to produce the high reflectivities we have observed in Meteor-3 data. The solar zenith angle and azimuth angle dependence of the observed reflectivity anomalies also strongly suggest that the non-Lambertian effects of the surface could be the dominant feature. We plan to conduct further studies along this direction, including comparisons of Meteor-3/TOMS reflectivity with the results of the Earth Radiation Budget Experiment on board Nimbus-7.

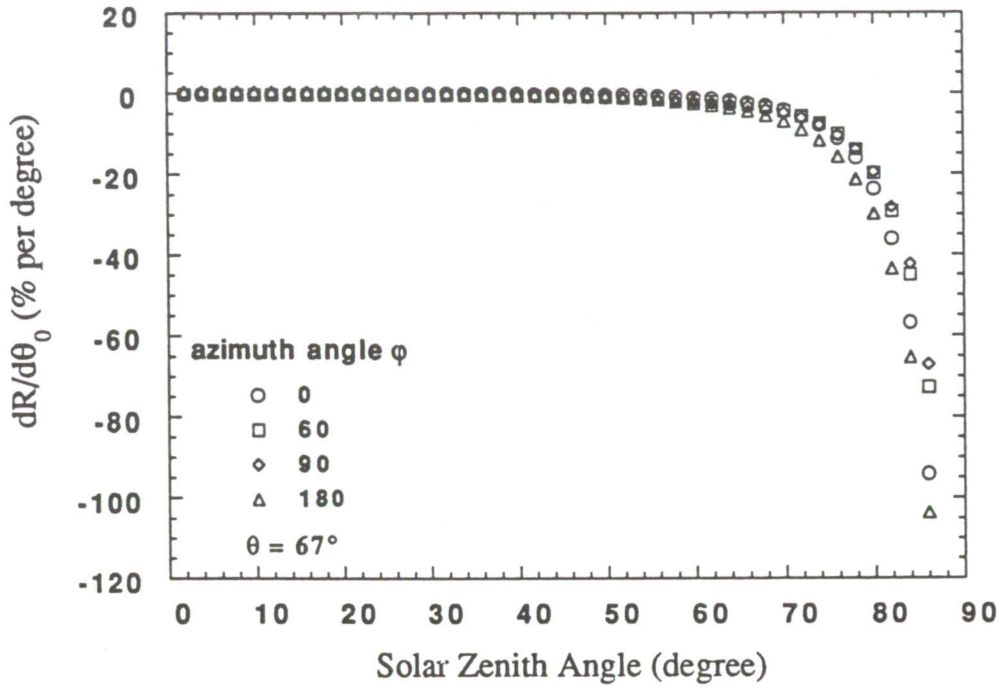


Figure 6.2.1.2-3 Sensitivity to errors in angle determination

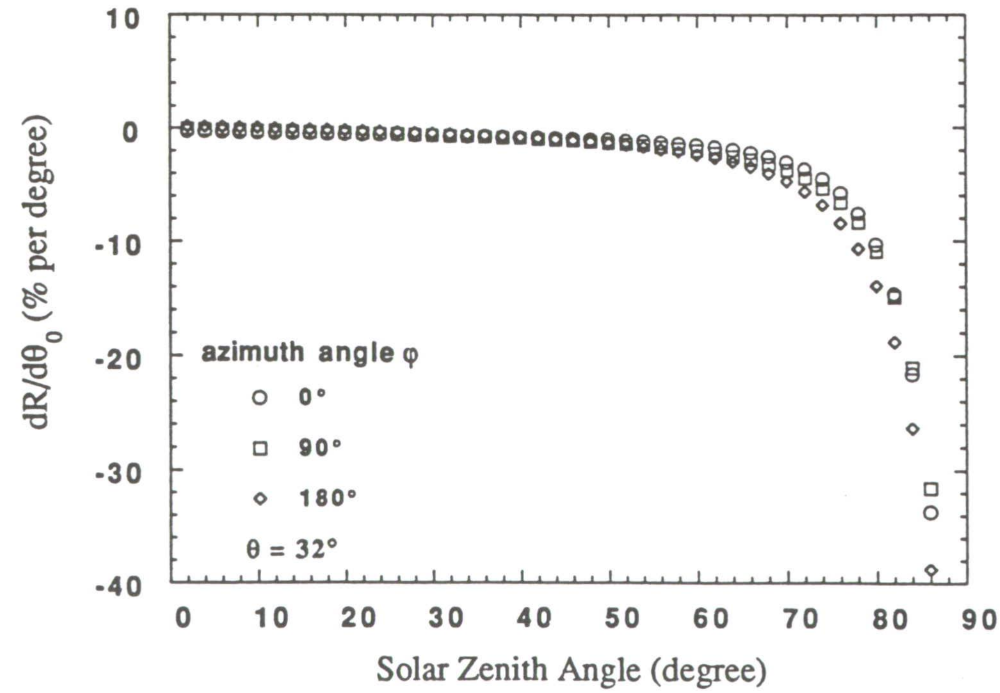


Figure 6.2.1.2-4 Sensitivity to errors in angle determination

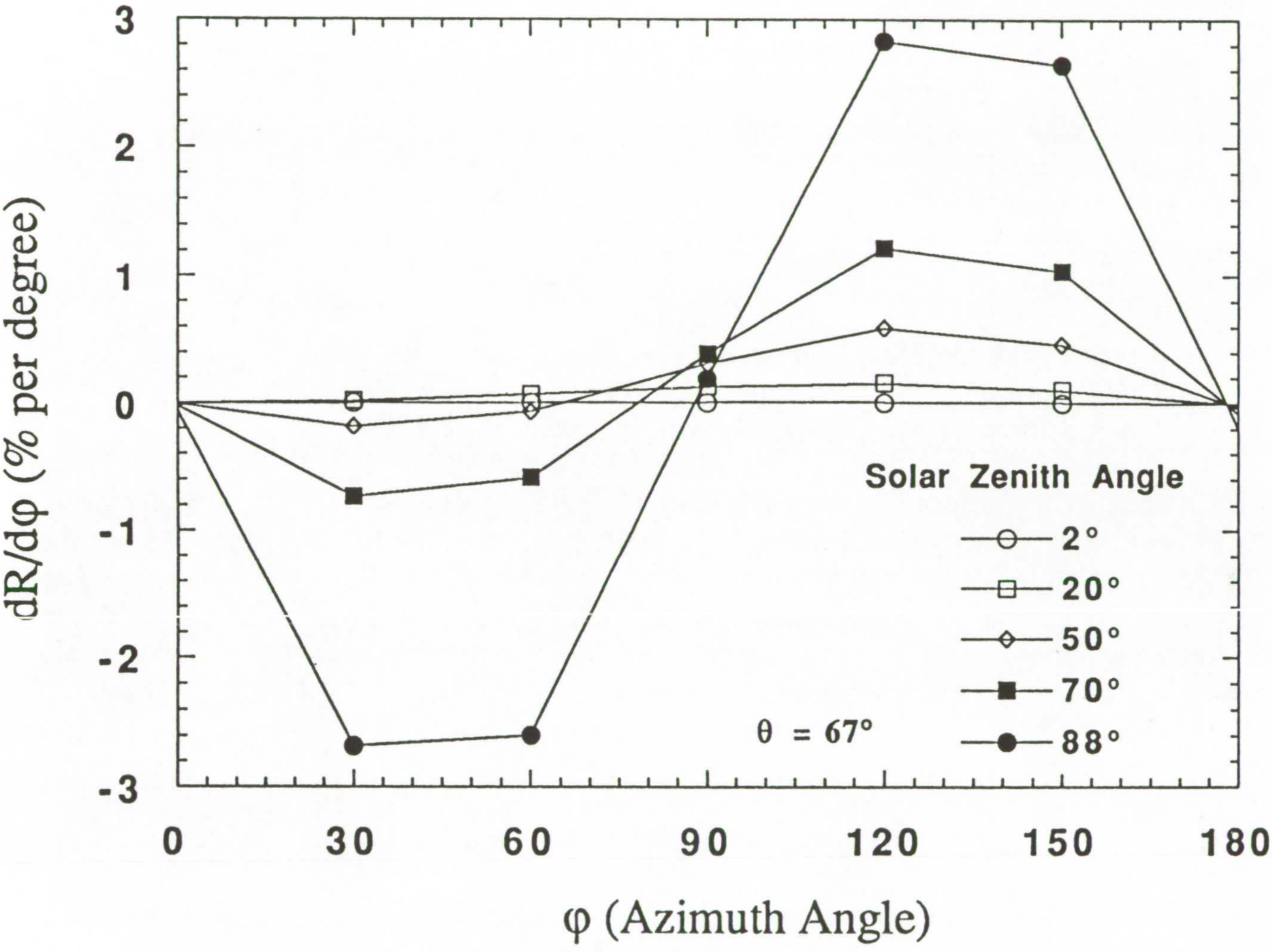


Figure 6.2.1.2-5 Sensitivity to errors in angle determination

6.2.2 Level 3 Products

METEOR-3/TOMS has been acquiring global ozone data since August 1991. In an effort to take advantage of previous work, the basic data products for the METEOR-3/TOMS have been designed to conform to a modified NIMBUS-7/TOMS format. There are four types of data products which are made available to the users. The first is derived from Level 2 orbital data sets, and contains the original data along with all data flags. The second and third are obtained from the Level 3 or the gridded data set for both IBM and VAX formats. The fourth data set, the Reduced Ozone or RO data sets, have a 2° x 5° (latitude x longitude) resolution and are primarily used by scientists at GSFC and other research institutions.

Current production status of the data files are:

Level 2 orbital	- daily data files through April 30, 1992
Level 3 gridded(IBM)	- daily data files through April 30, 1992
Level 3 gridded(VAX)	- monthly data files through April 30, 1992
Level 3 Reduced(RO)	- monthly data files through April 30, 1992.

In addition to the formal data products listed above, Global Monthly Mean, Daily Zonal Means, and Monthly Zonal Means files are created from the RO data sets. These data sets enable the user to look at individual latitude zones with out accessing the entire data set. For each of the production runs, data products for all levels were produced and examined fully. Quality control (of ozone and reflectivity) consists of the following tests:

1. Do they fall within expected range?
2. Are all days present in the monthly data sets?
3. Perform a detailed examination of the daily data on a global scale through the use of color images and various map projections (see Figure 6.2.2-1).

Since October, a temporary (initial Perkin Elmer data) calibration has been used for data reduction. All data files on the VAX are validated by checking ozone and reflectivity values, and insuring the correct number of days and dates are contained in the monthly files. The data used for the monthly maps are examined on a daily basis for quality before the entire month is summarized into one plot. This reduces labor and production costs. If an anomaly is seen in a particular day, a larger image is created along with additional plots as they are requested.

Since a month before launch, software that was previously used for the NIMBUS-7/TOMS has been modified to accommodate both data sets. System logicals

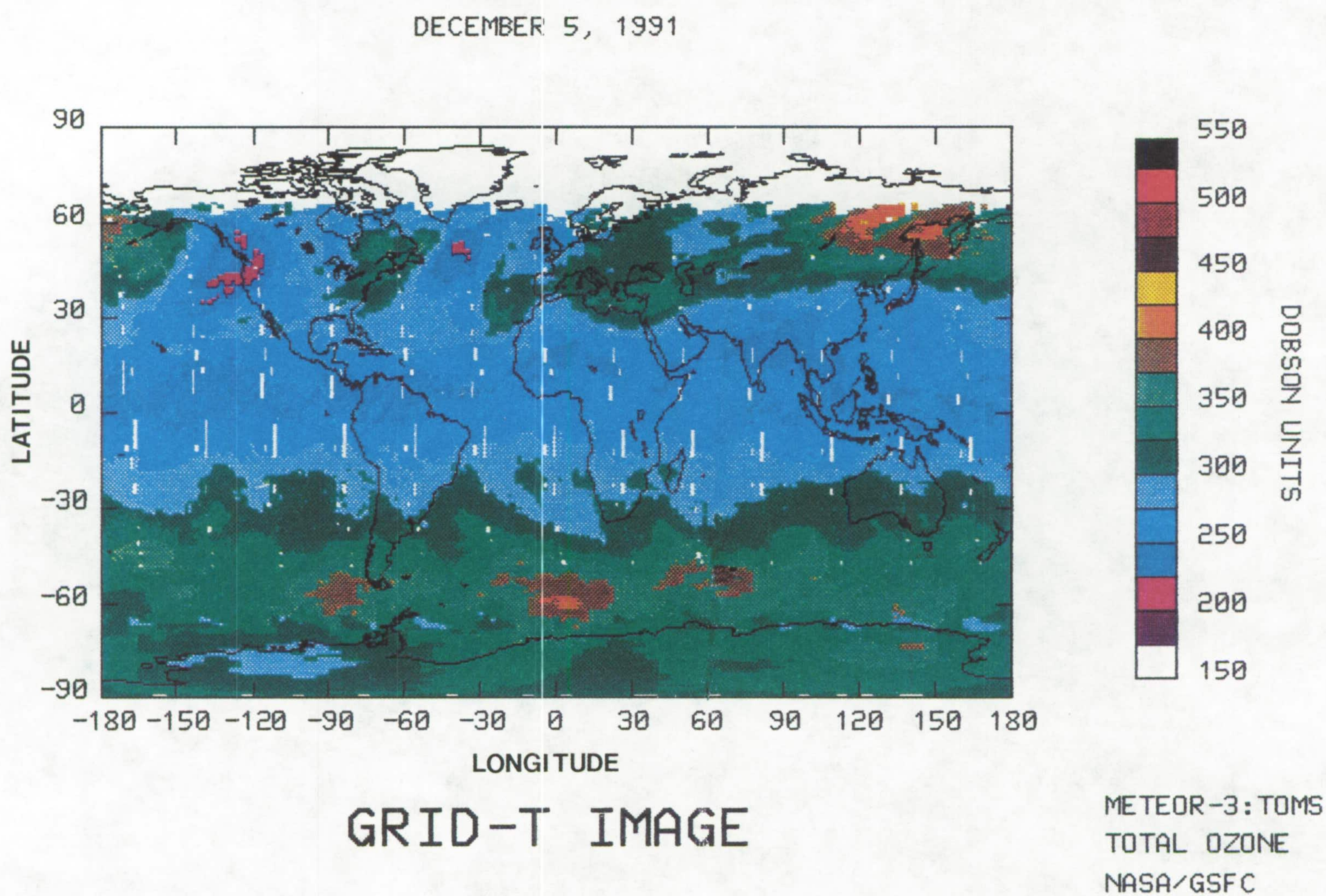


Figure 6.2.2-1 Sample data validation plot for Meteor-3/TOMS

have been created so that all users can access the data files easily. Work continues to add headers to the VAX formatted gridded and RO data sets so that users will not mistake one data set for another.

6.3 Meteor-3 TOMS Calibration

6.3.1 Solar Calibration

The TOMS instrument measures atmospheric spectral albedos by comparing the radiance of an onboard diffuser plate with the radiance of the earth when both are illuminated by sunlight. Instrument sensitivity and solar irradiance changes cancel in the earth/diffuser reflectivity ratio; the earth reflectivity is then proportional to the diffuser reflectivity. The accuracy of ozone retrievals depends on knowledge of the diffuser reflectivity. From past experience the reflectivity of diffuser plates changes with exposure to space conditions. The Meteor-3/TOMS is unique in the first use of three separate diffusers deployed with differing duty cycles as a means for evaluating exposure related diffuser degradation. This arrangement allows separation of diffuser reflectance changes from radiometric response changes.

The diffusers are installed on a carousel in which two of the three surfaces, designated the Working and Reference Plates, are within a protective cover except during the solar measurements. The third plate, designated the Cover Plate, is exposed continuously. The working plate is exposed once per week during the period when the sun is within the field of view of the diffuser plate. The reference plate is exposed twice per 212 day orbit plane rotation period. Deployment of the working and reference Plates was delayed for 12 and 18 weeks after launch, respectively, to allow for outgassing of the instrument and spacecraft. This report covers the first six months of operation of Meteor-3/TOMS.

6.3.2 Instrument Response During Solar Calibrations

6.3.2.1 Cover Diffuser

Figure 6.3.2.1-1 shows the instrument response during solar calibrations (proportional to the product of diffuser reflectance times instrument radiometric response), corrected for the prelaunch BRDF of the diffuser plates, for each of the six wavelengths and each of the three diffuser plates during the first six months since launch. The cover diffuser measurements are made on each orbit beginning at TOMS activation on August 22, 1991. The series is interrupted from August 30 until November 2 when the sun was out of the field of view of the diffuser due to precession of the local time of the orbit plane. The

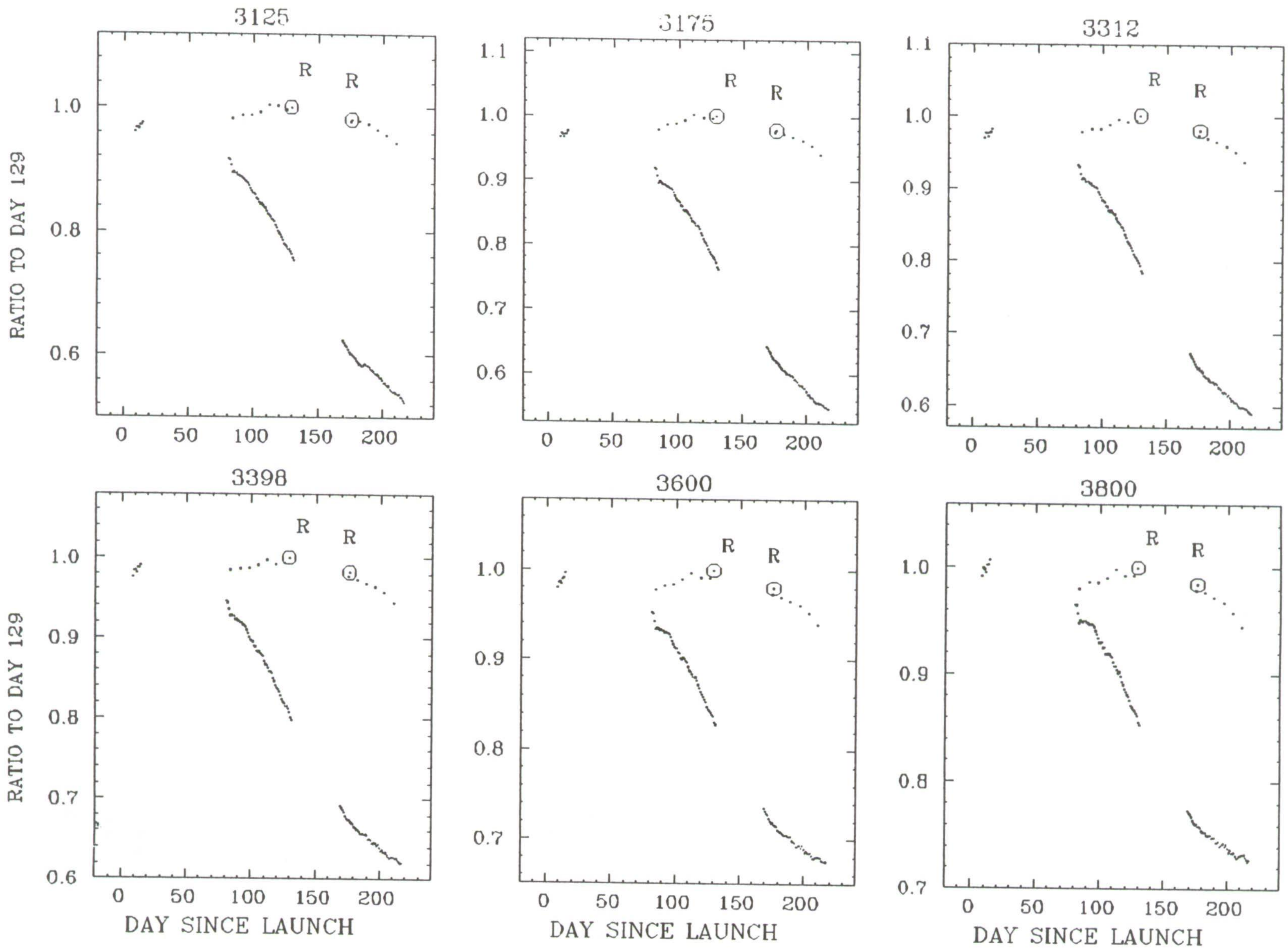


Figure 6.3.2.1-1 Diffuser plus instrument response during solar calibrations.

second calibration sequence starts on November 3 and continues until December 28. A second dark period lasts until January 30, 1992. The reflectivity of the cover diffuser has decreased significantly since launch, similar to the degradation in diffuser reflectivity observed on the Nimbus-4 BUV, which also carried an unprotected diffuser plate. An unexpected aspect of the cover diffuser degradation is the behavior during dark periods. The record shows continuous decreases in reflectivity although the mechanism for degradation previously assumed that contaminants were polymerized by UV sunlight. The Meteor record requires an additional mechanism for diffuser degradation.

6.3.2.2 Working and Reference Diffusers

The working diffuser measurements are shown in Figure 6.3.2.1-1 as the series of weekly points from November 6 to December 18, 1991 and from February 5 to March 18, 1992. These are observed to be similar in magnitude to the cover diffuser plate immediately after launch. This is consistent with the prior observations that protected diffuser plates degrade more slowly than exposed plates. The relative reflectivity of the cover diffuser as a function of time can be inferred from the ratio of cover to working diffuser measurements during solar calibrations. If it is assumed that no degradation occurs in the working diffuser plate then the Earth reflectivity is known by comparison of Earth measurements with the cover diffuser measurements. This assumption is tested using data from the reference diffuser plate which is exposed two times during each 212 day rotational period of the orbit plane. Reference diffuser measurements were made on December 21, 1991 and on February 6, 1992. These are shown in Figure 6.3.2.1-1 as the points marked "R". The ratio of working diffuser signals to reference signals changed by less than $0.2 \pm 0.05\%$ in the two comparisons. This is consistent with negligible degradation of protected diffuser plates.

6.3.2.3 Postlaunch Cover Diffuser Reflectance Changes

The TOMS ozone calibration is primarily dependent on the ratio of reflectivity of the diffuser plate in wavelength pairs. The reflectivity of the cover diffuser plate, normalized to unity at launch for the A, B, and C pairs as a function of time in days after launch is shown in Figure 6.3.2.3-1. From August 1991 until February 1992 the A and B pair calibrations decreased by 9% and 5%, while the C-pair decrease is 3%. The series are fit to better than 0.5 % with second order polynomials, shown by the lines in Figure 6.3.2.3-1.

The TOMS surface reflectivity calibration is dependent on the diffuser reflectivity at the two longest wavelengths. Figure 6.3.2.3-2 shows the cover reflectivity at 360 and 380 nm as a function of time normalized to unity at launch. During the first six months of operation, the reflectance decreased by 23 and 27% at these wavelengths.

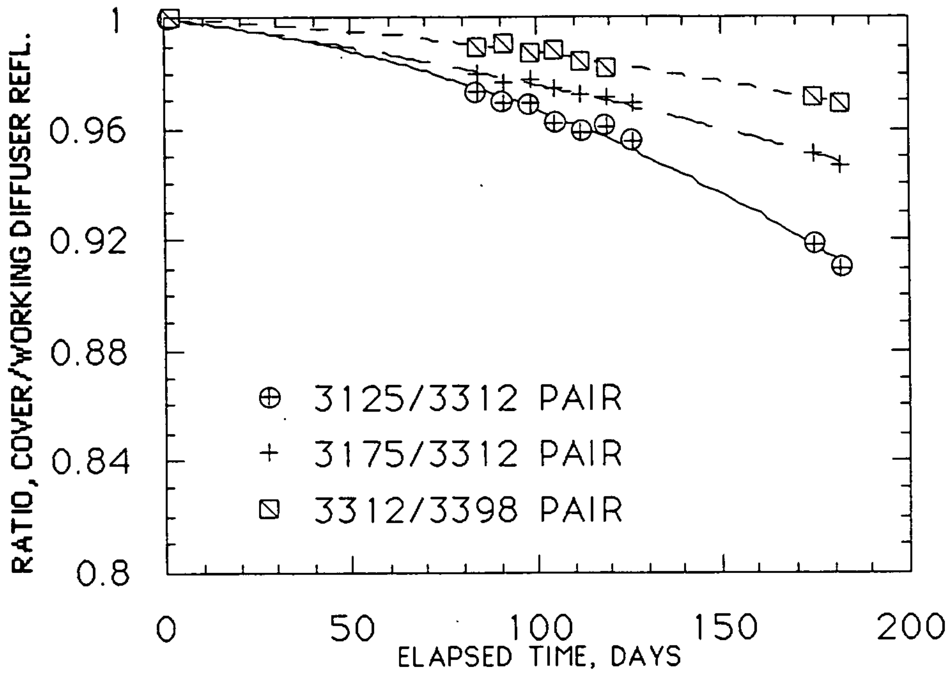


Figure 6.3.2.3-1 Cover diffuser plate reflectivity, normalized to unity at launch.

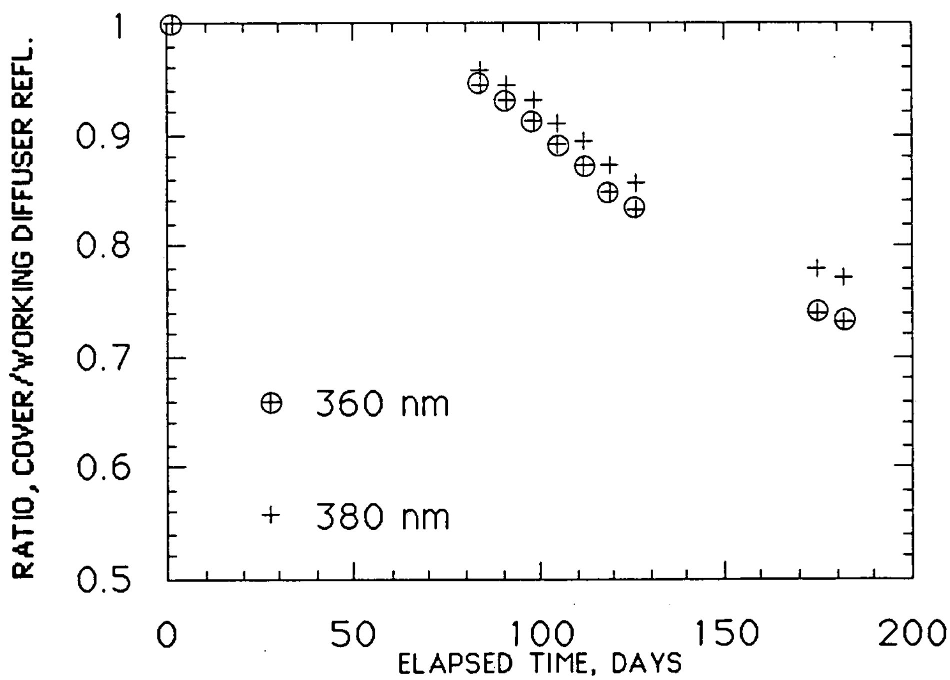


Figure 6.3.2.3-2 Cover reflectivity at 360 and 380 nm.

6.3.3 Postlaunch Radiometric Calibration Changes

The radiometric response of the instrument is determined by the transmission of the monochromator and the gain of the PMT. If the diffuser reflectance is known as a function of time then the time dependence of radiometric response can be calculated from the instrument response to solar calibrations (Figure 6.3.3-1). The radiometric response is not needed for data analysis when solar calibrations are possible; however, if it can be predicted from housekeeping data (eg. temperature) then the ozone data accuracy can be maintained even when solar calibrations are not possible during twilight orbits. Figure 6.3.3-1 shows the derived instrument response vs time for the A pair of wavelengths. The data are normalized to the response on the first reference diffuser calibration on Day 129. Data gaps occur during the twilight orbit periods . The A-pair response has remained constant within 0.5 % after an initial increase of about 1 % from the turn on value in August. The short term variations in instrument response are due in part to temperature effects and to BRDF calibration errors. The B-pair radiometric response is shown in Figure 6.3.3-2. Compared with the A-pair response there are smaller amplitude fluctuations and a small negative trend during this time period.

Figure 6.3.3-3 shows the radiometric response at the 380 nm reflectivity wavelength during the first six months. The data are normalized to unity on the day of the first reference diffuser calibration. In this case the changes are much larger than for pairs because temperature and PMT gain variations do not cancel. The trend is for decreasing sensitivity with time. The change was within 2 % during the first 180 days.

6.3.4 Prelaunch Calibration

Production has used a set of preliminary radiance and irradiance calibration constants which were provided by the instrument contractor soon after launch of the satellite. These constants were measured during final testing of the instrument prior to shipment. However, reanalysis of the constants has disclosed several errors in their calculation. Recent effort has been devoted to reconciliation of the sources of error in the calibration.

The Meteor-3 /TOMS instrument was calibrated in two ways: 1) by measuring the absolute BRDF of the flight diffuser plate and of a $BaSO_4$ laboratory reference diffuser plate and 2) by measuring the irradiance and radiance response of the completed instrument to standard QTH lamps. The latter calibration used three calibrated QTH lamps to illuminate the flight and laboratory reference diffuser plates. The flight data have been compared with coincident Nimbus-7/TOMS data. The results indicate that the BRDF calibration give closer agreement than the irradiance/radiance calibration.

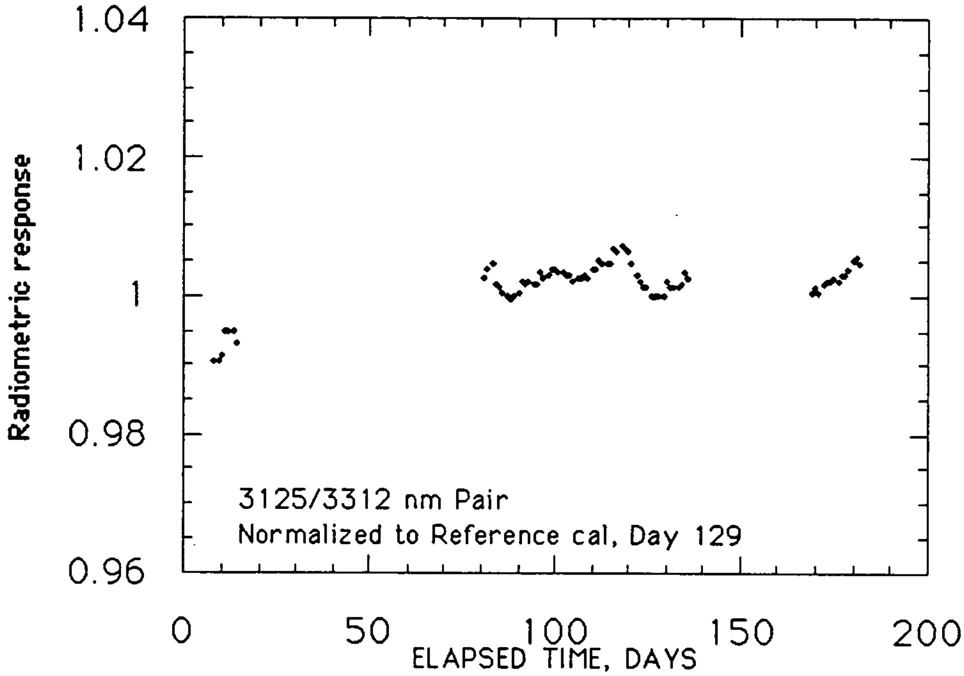


Figure 6.6.3-1 A-pair radiometric response vs. time.

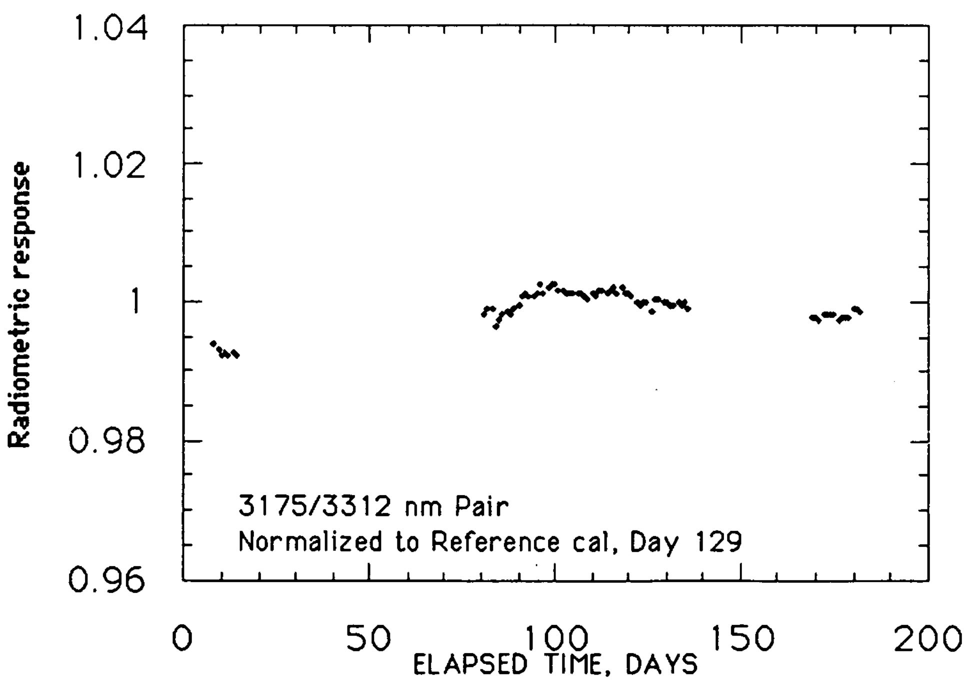


Figure 6.6.3-2 B-pair radiometric response vs. time.

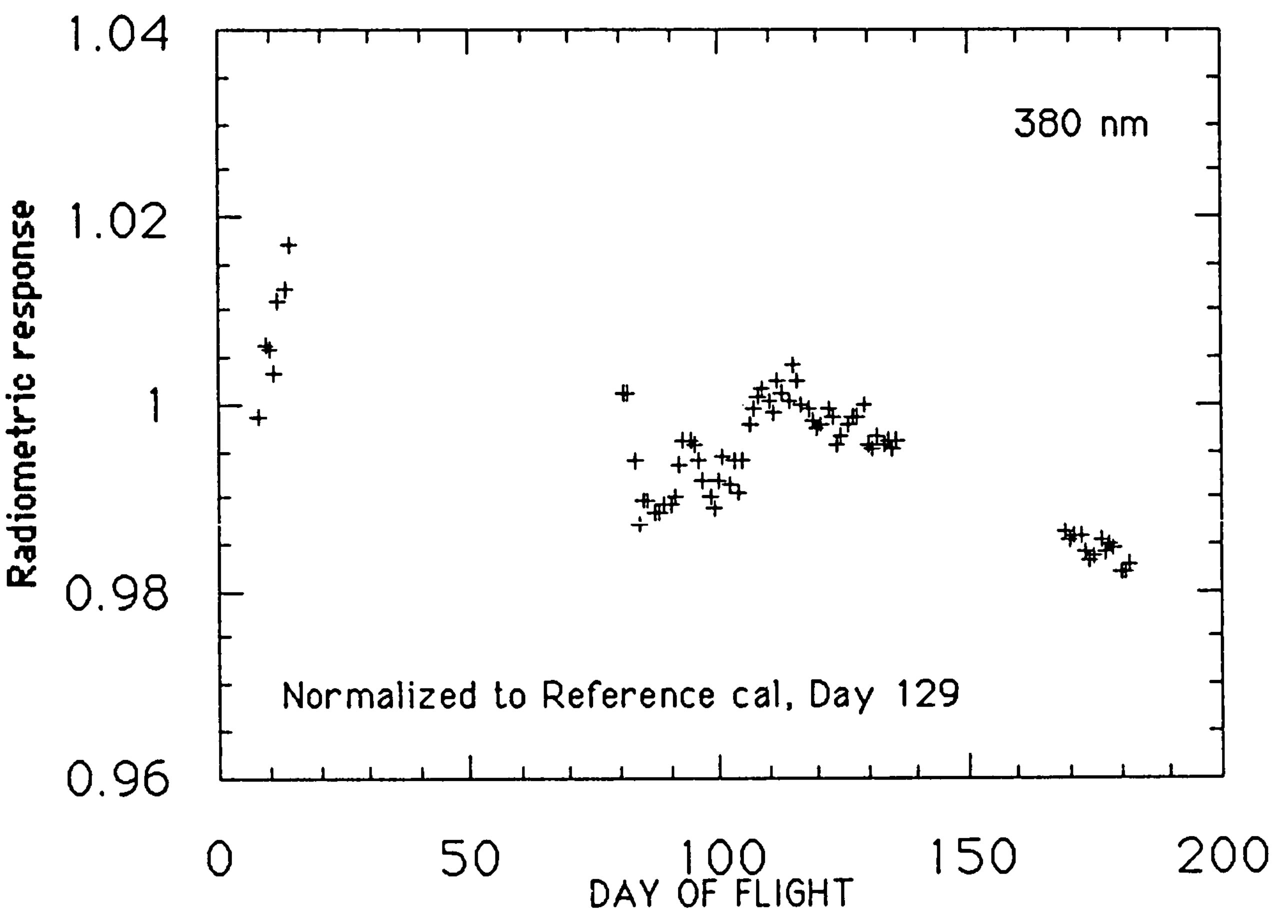


Figure 6.6.3-3 380 nm radiometric response vs. time.

6.3.5 Wavelength Calibration (WCAL)

The onboard wavelength monitor operates during Earth night once every 24 hours, providing regular updates of shifts in the instrument's wavelength selection by viewing an emission line from a Mercury lamp. This function has performed well since launch. Figure 6.3.5-1 shows plots of the wavelength calibration shift in Angstroms and of the instrument housing temperature since launch. The magnitude of the wavelength shifts will result in less than a 1% error in ozone determination if left uncorrected. Comparisons of the wavelength shifts with instrument housing temperature show clear correlations; wavelengths decrease as temperature rises. This correlation was expected based on pre-launch tests. The correlations are more clearly illustrated when wavelength shift is plotted versus temperature, as in Figure 6.3.5-2. This plot shows that while wavelength varies linearly in some temperature regions, the trend is asymptotic at high and low temperatures. Another curious feature is the apparent upward shift in wavelength with time. The mechanism for this feature is not yet understood. However, a true wavelength shift will show up as changes in solar calibrations due to Fraunhofer structure in the solar spectrum. Since this is not observed, it is believed that the apparent wavelength changes are artifacts resulting from mechanical changes in the chopper wheel in the instrument.

6.3.6 Electronic Calibration (ECAL)

The electronic calibration system tests signal amplification and subsequent onboard processing by injecting a regulated current into the instrument electrometer. The resulting instrument output is then monitored on the ground. Constant amplification in the 4 different gain ranges is critical to accurate ozone measurement. The ECAL system had an apparent failure in mid-October resulting in a complete loss of ECAL data. The failure, of an as yet undetermined cause, does not appear to affect other operating modes of the instrument. Nor should the loss of ECAL information adversely affect ozone determination. Noise levels in the ECAL data prior to the failure were inexplicably high, but it is not known what relation, if any, the two might have. Similar noise levels were observed during tests at Perkin Elmer when a cable connection failed.

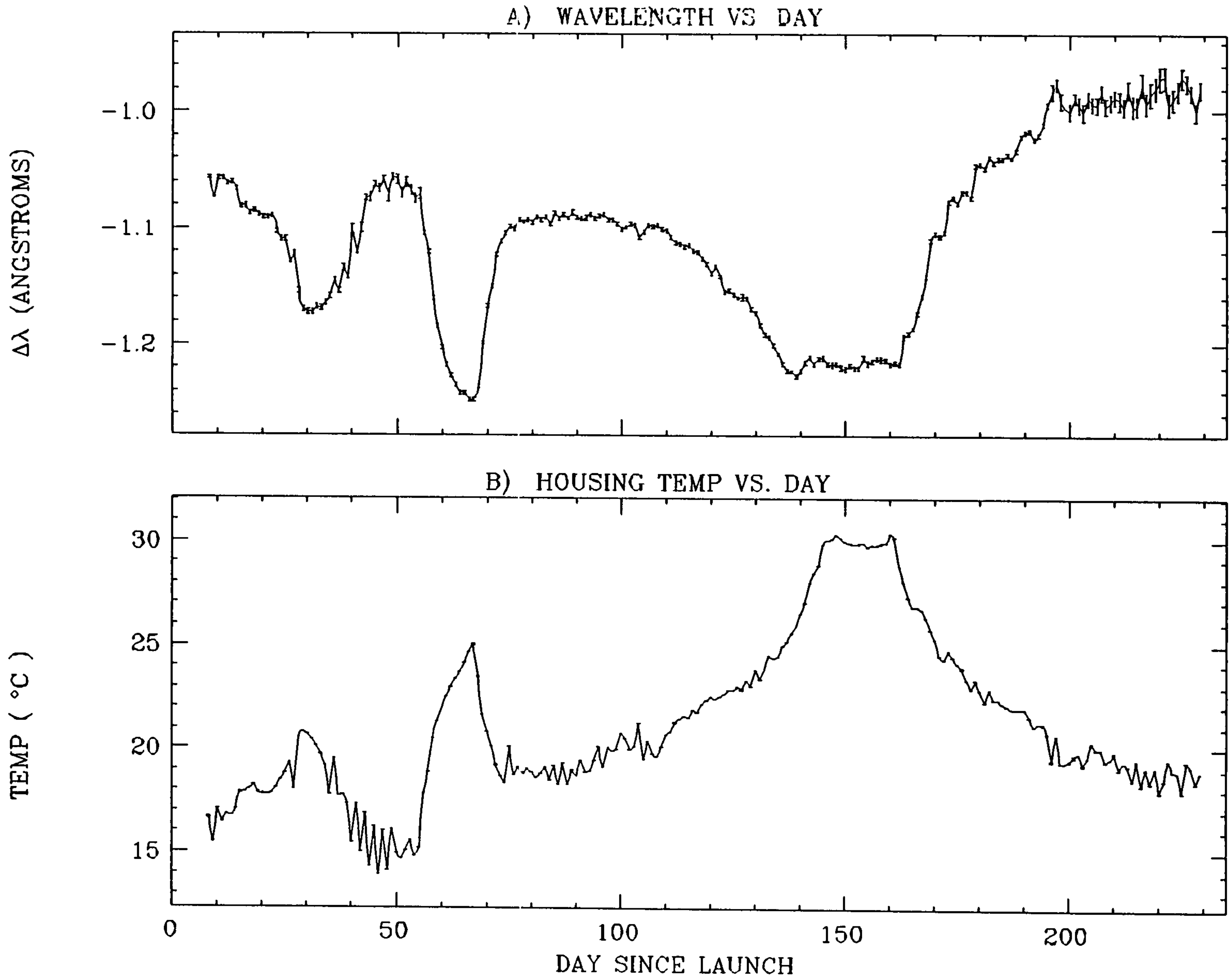


Figure 6.3.5-1 Wavelength calibration shift and instrument housing temperature.

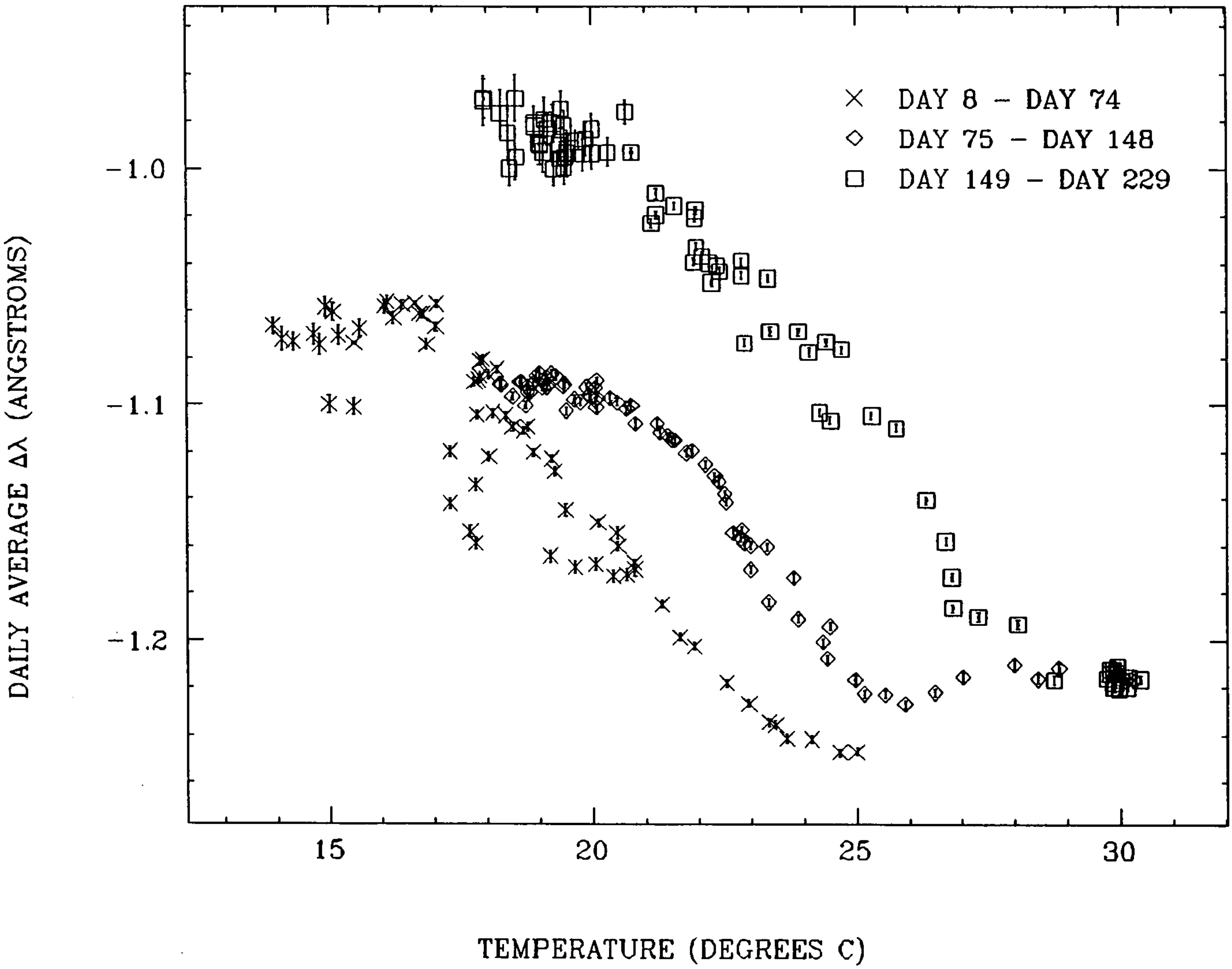


Figure 6.3.5-2 Wavelength shift versus temperature.

7.0 METEOR-3/TOMS SCIENCE DATA PROCESSING STATUS
(15 AUGUST 1991 - 15 MAY 1992)

Section Contributor:

William Byerly

The Meteor-3/TOMS Level 1, 2, and 3 science data processing is performed following receipt of Level 0 data from TIOCC, spacecraft clock checks from CAO, and spacecraft ephemeris data from FDF. This report details the processing experience during the first nine months of operation of Meteor-3/TOMS.

7.1 Level 0 Data Acquisition

Two hundred seventy-nine (279) Level 0 datasets were acquired from TIOCC. Each Level 0 dataset contains one playback (i.e. downlink). Two hundred seventy-six (276) Level 0 Data Tapes were received, inventoried and copied to disk. Two hundred forty-eight (248) of these 9-track computer tapes were original data covering the 15 August 1991 through 6 April 1992 and the 14 through 21 April 1992 periods. The remaining twenty-eight (28) were redo tapes. Attachment A contains a tabulation of the dates and reasons for this redo data. Thirty-one (31) Level 0 datasets were transferred electronically to the NCCS IBM 9021. These covered the 7 through 14 April 1992 and the 22 April through 15 May 1992 periods. Requests for retransmission from TIOCC were necessary for four (4) of these electronically transferred datasets as the original transmissions were incomplete or garbled. These retransmissions are included in the Attachment A tabulation.

Since High Voltage Turn-on (22 August 1991) there were 278 minor frames found to be flagged as bad quality (approximately 0.001% of the data). A log of bad quality minor frames, as found in the Level 0 data, is included in Attachment B. A time series plot of number of bad quality frames per day is also in Attachment B. The worst case, 14 September 1991, had a little over 1% of the data for the day flagged as bad quality. There have been no bad quality minor frames since 31 January 1992.

Data gaps are listed in Attachment C. This list does not include data gaps which may exist during periods of bad quality data. The most significant gap occurred between playbacks on 9 September 1991. Here approximately six (6) minutes of data is missing. There have been no data gaps since 30 November 1991.

Time code errors were present throughout the period due to the asynchronous sampling of the spacecraft clock by the TOMS IAM. Attachment D includes a table of each occurrence. A plot of the asychronous clock sampling error occurrence period versus date is included in Attachment D. Variations in this period may be associated with changes in temperature as the spacecraft's orbit precesses. Other than during periods of asynchronous clock samplings and bad quality episodes, only two other time code anomalies have been noted. On 16 December 1991 a sub-second time code error of 7/16 second was observed in one minor frame. During the clock reset of 5 March 1992 one minor frame had a sub-second time code error of 4/16 second. All time code anomalies present in good quality minor frames are being smoothed as part of Level 1 processing. Corrupted time code associated with bad quality data have not been smoothed as gaps which occur during periods of bad quality data prevent a unique determination of time.

7.2 Spacecraft Clock Checks

On a bi-weekly basis (weekly during first month of operation) CAO provides via EMail a value for the offset between a true ground clock and the spacecraft clock. Attachment E contains a table which lists the clock data provided by CAO (i.e. orbit number, time, and time offset) as well as the clock drift rate computed between data points. The times of the resets and clock checks prior to 30 September 1991 are estimates as only an orbit number was provided. Also included in Attachment E is a plot of the reported time offsets versus time.

In converting Meteor-3/TOMS timecode from spacecraft time to Greenwich Mean Time (GMT) the following assumptions are made:

1) the time period for one complete scan, including retrace, is nominally 8 seconds and
2) all reported clock check and reset times are accurate.

During the period from the 20 August 1991 clock reset to the clock check of 3 March 1992 there was reasonable consistency observed among spacecraft clock checks with clock drift rates varying from -133 ms/day to -181 ms/day. However after 3 March the clock information that has been received has been inadequate for the confident determination of time. Apparent inconsistencies exist in the information that has been provided to us. Furthermore there has been no precise information provided for the time offsets immediately prior to and following the clock reset of 5 March 1992 and clock swap(s) of 24 March 1992.

Estimates of time offset were determined by fitting the observed discontinuities in the timecodes of the Meteor-3/TOMS telemetry to the reported clock checks and reset times. There are 3 discontinuities in the time offsets since 20 August.

The first is the clock reset of 5 March 1992. In order to fit the observed discontinuity in the minor frame timecodes to the reported reset time, an estimated 0.1 second time offset was introduced immediately prior to the reset. However, the resultant clock drift rate between the 3 March clock check and the 5 March reset is an unrepresentative -533 ms/day.

On 24 March there were two time code discontinuities observed in the Meteor-3/TOMS telemetry. The first occurred at approximately 04:09:11 GMT and was presumably due to the preannounced swap to the reserve clock. Approximately 16 hours later, at spacecraft day change, a smaller discontinuity was observed, possibly due to another clock swap or a clock reset. Having no time offset information corresponding to either of these events, these periods have been smoothed based on the observed time discontinuities and the clock checks provided for 18 March and 25 March. The resultant clock drift rates are in the opposite direction to that which is expected (i.e. 253 ms/day, 142 ms/day and 611 ms/day).

7.3 Spacecraft Ephemeris

Twenty-six (26) spacecraft ephemeris data tapes were received from the Flight Dynamics Facility (FDF) and processed. Twenty-two (22) of these were "definitive" data; the remaining four (4) were predictive. "Definitive" ephemeris refers to those data which are bracketed by the orbital state vectors provided by CAO on a bi-weekly basis (weekly during first month of operation). "Definitive" ephemeris is used during routine Level 1 processing. Predictive ephemeris extends beyond the latest state vector by about six (6) weeks. Predictive ephemeris has been used to service special quick-look processing requests.

Each ephemeris data set contains some overlap with the previous dataset. It has been noted that the equator crossing times in this overlap period may disagree by 1 to 3 seconds (i.e. 7 to 21 km) when comparing "definitive" data and as much as 5 seconds (35 km) when comparing predictive to "definitive". CAO has provided revised orbital state vectors for the entire first five months. FDF has concluded that these replacements would not significantly change the ephemeris data product.

7.4 Level 1 (RUT) Processing

Level 1 (RUT) processing has been performed routinely as soon as all inputs were received. In addition various special quick-look processing requests were accommodated during the first month after High Voltage Turn-on, to process solar calibration data near-realtime, to examine the terminator orbiting case, and to provide comparative data during joint US/Russian Meteor-3/TOMS Data Working Group Meetings. This processing has assumed nominal spacecraft attitude. As changes to the processing system were implemented, the entire dataset was reprocessed to assure a consistent Level 1 product.

Changes have been made to the Level 1 processing which redefined orbit number at the ascending node versus the descending node convention used by Nimbus-7, to disable Earth location of bad quality frames (due to possible time code corruption), and to perform time smoothing and time corrections as a Level 1 preprocessing activity. Level 0 data containing time adjustments applied during Level 0 processing (i.e. 25 September to 30 October 1991) was reversed to contain unadjusted times prior to time smoothing and time correction by the Level 1 Preprocessor.

Subsets of the RUT dataset have been produced for calibration mode data (solar, wavelength, and electronic calibrations) and for recorder status studies.

Attachment F presents processing logs for each month from August 1991 through May 1992 as reported by the Level 1 processing subsystem during routine processing activity. These have been updated to reflect the most current processing statistics. Each RUT data product has been quality checked for data accountability, data format, and data content.

7.5 Level 2 (OZONE) Processing

Ozone products have been produced routinely following each RUT generation. The entire dataset has been produced using a consistent version 0 calibration version (modified initial calibration) and albedo correction factors (ACF) set to unity. It is expected that the entire ozone dataset will be reprocessed once a final calibration has been established. Other Level 2 processings have been performed to support science analysis activities.

7.6 Level 3 (GRIDTOMS) Processing

GRIDTOMS production has proceeded immediately following ozone product generation. As the daylit portion of the precessing Meteor-3/TOMS orbit may be either on the ascending node or descending node, the GRIDTOMS software was modified to accept either. A monthly montage of GRIDTOMS images is generated on a routine basis.

Other Level 3 processing activity has occurred in support of science analysis activities.

7.7 DATA QUALITY SUMMARY

7.7.1 Meteor-3/TOMS Level 0 Redo/Retransmission Log

(15 August 1991 to 15 May 1992)

Acquisition Date (yy.ddd)	Reason for Redo
91.234 to 91.243	Time Adjustment
91.252	Missing Data (Sub-second Time Code Corrupted on Redo)
91.281	Unreadable
91.286	Unreadable
91.296	Unreadable
91.302	Corrupted Minor Frame
91.304 to 91.309	Sub-second Time Code Corrupted by Level 0 Processing
91.309	Corrupted Minor Frame
91.310	Data Gap
91.316	Corrupted Minor Frame
91.334	Corrupted Minor Frame
92.001	Corrupted Minor Frame
92.008	Corrupted Minor Frame
92.102	1st Transmission Corrupted
92.104, 120, 133	1st Transmission Incomplete

7.7.2 Meteor-3/TOMS Bad Data Quality Summary

Year	Day	Time	Record	
1991	234	19:39:32 7/16	2423	|
		28:20:53 15/16	2424	|<-- No Data Gap (invalid times)
		30:04:55 1/16	2424	|
1991	237	03:37:23 14/16	200	
1991	239	22:54:34 1/16	4671	
1991	242	04:29:18 6/16	706	
		05:47:58 6/16	1001	
		31:63:63 15/16	1824	<-- No Data Gap (fill time)
		17:47:02 1/16	3698	
		22:24:29 15/16	4737	
		23:49:33 14/16	5056	
1991	247	01:47:25 9/16	37	
1991	250	00:54:59 11/16	39	
1991	251	00:30:59 2/16	15	
		00:34:51 2/16	29	
		00:39:47 2/16	48	
		00:40:43 2/16	51	
		00:45:31 2/16	69	
1991	252	00:18:50 9/16	14	|<--- Many (59) Bad Quality
		to		| Frames
		04:55:14 6/16	1043	|
1991	256	13:11:52 4/16	5	|<--- Many (30) Bad Quality
		to		| Frames
		22:45:12 2/16	2155	|

Year	Day	Time	Record	
1991	257	01:33:36 1/16	2787	|<--- Many (103) Bad Quality
		to		| Frames
		12:46:15 13/16	5306	|
1991	258	02:15:35 10/16	3010	
		17:00:07 5/16	993	
1991	263	11:15:25 3/16	31	
		11:47:57 2/16	153	
		12:25:41 2/16	294	
		13:09:57 2/16	460	
		14:13:33 2/16	699	
1991	265	05:39:40 5/16	4238	
		31:63:63 15/16	4238	<-- No Data Gap (fill time)
1991	266	01:41:07 15/16	2998	
1991	272	17:56:09 12/16	1715	
1991	277	02:43:02 13/16	3544	|<--- Many (36) Bad Quality
		to		| Frames
		07:13:34 12/16	4557	|
1991	294	11:44:39 5/16	954	
1991	310	9:18:49 9/16	644	
(Redo)		9:19:37 9/16	647	
		9:19:45 9/16	647	
		9:20:09 9/16	649	
		9:29:29 9/16	684	
1991	318	00:54:05 14/16	1650	

Year	Day	Time	Record	
1991	326	17:20:26 6/16	132	
		20:43:30 5/16	894	
1991	329	12:14:01 8/16	4516	
		22:09:37 5/16	1416	
1991	330	8:44:09 3/16	3795	
1991	331	12:48:48 14/16	4779	
1991	334	16:10:31 13/16	399	
1991	343	31:63:63 15/16	5015	<-- Fill Time @ 12:09:58
1991	344	18:23:57 14/16	1150	
		18:25:33 14/16	1156	
1991	349	31:63:63 15/16	273	<-- Fill Time @ 14:51:49
1992	2	12:05:27 5/16	18	
		12:05:35 5/16	19	
1992	5	7:24:16 3/16	4496	
1992	16	9:20:29 11/16	5247	
		9:25:49 11/16	5267	
1992	19	2:54:23 0/16	3996	
1992	21	23:15:28 7/16	2963	
1992	31	20:07:07 4/16	2509	

7.7.3 Meteor-3/TOMS Data Gap Summary

Year	Day	Time		Record	
1991	242	18:17:10	0/16	3811	
		18:17:34	0/16	3811	<-- 2 Scan Gap Within Major Frame Data Record
1991	252	00:09:38	0/16		
		00:15:30	0/16		<-- 44 Scan Gap Between Playbacks
1991	252	02:23:58	14/16	527	
		02:31:02	14/16	538	<-- 16 Scan Gap Between Playbacks
1991	265	09:35:24	4/16	5122	
		09:35:48	4/16	5122	<-- 2 Scan Gap Within Major Frame Data Record
1991	306	12:13:47	8/16	1036	
		12:14:11	8/16	1036	<-- 2 Scan Gap Within Major Frame Data Record

7.7.4 Meteor-3/TOMS Asynchronous Clock Sampling Errors

Date	Time	# Scans	Min. Error (sec)	Max. Error (sec)	Period (days)
23-Aug-91	10:39:00	2	1	1	
24-Aug-91	23:55:08	3	2	4	1.553
26-Aug-91	12:52:18	3	1	1	1.540
28-Aug-91	01:30:58	2	2	2	1.527
29-Aug-91	13:14:31	3	1	1	1.489
31-Aug-91	04:11:11	4	7	10778	1.623
01-Sep-91	18:19:59	3	1	1	1.589
03-Sep-91	08:51:43	3	2	2	1.605
04-Sep-91	23:37:17	3	1	1	1.615
06-Sep-91	13:48:30	4	2	4	1.591
08-Sep-91	06:07:23	3	1	1	1.680
10-Sep-91	01:12:50	4	1	2	1.795
11-Sep-91	22:07:13	4	1	1	1.871
14-Sep-91	05:44:00	6	6	86	2.317
16-Sep-91	13:26:39	4	1	1	2.321
18-Sep-91	17:25:27	3	2	2	2.166
20-Sep-91	20:52:13	3	1	1	2.144
22-Sep-91	23:07:58	5	2	4	2.094
24-Sep-91	21:32:59	4	1	1	1.934
26-Sep-91	19:33:01	4	2	2	1.917
28-Sep-91	18:37:31	5	1	1	1.961
30-Sep-91	15:59:39	5	2	4	1.890
02-Oct-91	13:01:12	4	1	1	1.876
04-Oct-91	13:38:27	4	2	2	2.026
06-Oct-91	12:28:22	4	1	1	1.951
08-Oct-91	08:14:22	4	2	4	1.824
10-Oct-91	13:33:15	5	1	1	2.221
14-Oct-91	20:19:13	16	1	2	4.282
22-Oct-91	15:21:11	5	1	1	7.793
25-Oct-91	00:33:19	5	2	4	2.383
26-Oct-91	22:17:57	4	1	1	1.906

Date	Time	# Scans	Min. Error (sec)	Max. Error (sec)	Period (days)
28-Oct-91	19:48:12	4	1	2	1.896
30-Oct-91	17:19:06	4	1	1	1.896
01-Nov-91	15:25:10	6	2	10832	1.921
03-Nov-91	14:08:19	4	1	1	1.947
05-Nov-91	13:22:18	4	1	2	1.968
07-Nov-91	13:07:29	4	1	1	1.990
09-Nov-91	13:39:22	5	2	4	2.022
11-Nov-91	15:44:47	4	1	1	2.087
13-Nov-91	19:59:58	5	1	2	2.177
16-Nov-91	01:03:25	5	1	1	2.211
18-Nov-91	09:49:58	5	2	10832	2.366
21-Nov-91	00:56:59	6	1	1	2.630
23-Nov-91	23:26:03	6	2	2	2.937
27-Nov-91	05:22:57	5	1	1	3.248
30-Nov-91	04:18:58	7	2	3	2.956
03-Dec-91	17:46:23	7	1	1	3.561
09-Dec-91	17:42:22	17	1	2	5.997
27-Dec-91	02:18:55	10	1	2	17.359
01-Jan-92	16:57:19	8	1	1	5.610
04-Jan-92	17:22:16	6	2	10832	3.017
06-Jan-92	22:52:01	4	1	1	2.229
08-Jan-92	23:24:11	3	2	2	2.022
10-Jan-92	22:25:23	3	1	1	1.959
12-Jan-92	22:10:35	6	4	60	1.990
14-Jan-92	21:46:05	3	1	1	1.983
16-Jan-92	23:26:37	4	2	2	2.070
19-Jan-92	01:01:34	4	1	1	2.066
21-Jan-92	02:14:47	6	4	10816	2.051
23-Jan-92	04:05:05	4	1	1	2.077
25-Jan-92	23:33:53	6	1	2	2.812
30-Jan-92	01:22:35	9	1	1	4.075
21-Feb-92	07:52:03	14	1	1	22.270
26-Feb-92	19:04:01	6	2	2	5.467
01-Mar-92	01:37:53	5	1	1	3.274
04-Mar-92	02:43:06	8	2	7	3.045

Date	Time	# Scans	Min. Error (sec)	Max. Error (sec)	Period (days)
07-Mar-92	23:52:04	8	2	75630	3.881
10-Mar-92	19:26:53	3	1	1	2.816
13-Mar-92	07:33:10	3	1	2	2.504
15-Mar-92	16:28:37	2	1	1	2.372
17-Mar-92	22:57:24	5	6	75504	2.270
20-Mar-92	02:55:31	2	1	1	2.165
22-Mar-92	05:14:18	3	1	2	2.096
24-Mar-92	04:14:00	6	7	10832	1.958
26-Mar-92	07:14:55	2	1	1	2.126
28-Mar-92	03:10:14	3	1	2	1.830
29-Mar-92	23:21:57	2	1	1	1.841
31-Mar-92	16:05:16	4	7	10832	1.697
02-Apr-92	08:57:39	2	1	1	1.703
04-Apr-92	01:23:22	3	1	2	1.685
05-Apr-92	19:16:09	2	1	1	1.745
07-Apr-92	14:51:04	5	2	4	1.816
09-Apr-92	13:03:11	3	1	1	1.925
11-Apr-92	14:36:54	4	1	2	2.065
13-Apr-92	12:53:25	2	1	1	1.928
15-Apr-92	09:13:48	4	4	10814	1.847
17-Apr-92	02:45:15	2	1	1	1.730
19-Apr-92	06:53:30	3	1	2	2.172
21-Apr-92	03:05:37	3	1	1	1.842
23-Apr-92	05:32:24	4	2	10831	2.102
25-Apr-92	03:01:27	4	1	1	1.895
27-Apr-92	01:52:54	3	1	2	1.952
29-Apr-92	04:38:21	2	1	1	2.115
01-May-92	06:52:04	4	2	4	2.093
03-May-92	02:27:07	3	1	1	1.816
05-May-92	06:01:54	3	1	2	2.149
07-May-92	06:41:05	2	1	1	2.027
09-May-92	15:45:44	6	2	119	2.378
12-May-92	00:49:35	3	1	1	2.378
14-May-92	01:38:14	4	1	2	2.034

7.7.5 Meteor-3 Spacecraft Clock Checks

Date	Orbit #	Time (GMT) (hh:mm:ss)	True - S/C (sec)	Drift (s/day)
20-Aug-91	66	07:30:28	31.5	
29-Aug-91	182	03:07:30	29.9	-0.181
03-Sep-91	250	07:10:36	29.2	-0.135
10-Sep-91	346	14:18:30	28.2	-0.137
17-Sep-91	436	10:29:40	27.3	-0.132
01-Oct-91	617	04:41:25	25.0	-0.167
16-Oct-91	815	05:52:23	23.0	-0.133
30-Oct-91	1001	09:12:20	20.6	-0.170
12-Nov-91	1173	10:53:18	18.6	-0.153
26-Nov-91	1361	17:11:32	16.6	-0.140
10-Dec-91	1524	08:09:00	14.6	-0.147
24-Dec-91	1726	16:24:00	12.2	-0.167
08-Jan-92	1926	15:41:47	10.2	-0.134
20-Jan-92	2081	10:20:10	8.2	-0.170
05-Feb-92	2293	12:54:05	5.6	-0.161
19-Feb-92	2475	08:50:03	3.4	-0.159
03-Mar-92	2647	10:30:01	1.4	-0.153
05-Mar-92	2679	21:00:23	0.1	-0.533 est.
		21:00:30	30.8	reported reset
18-Mar-92	2842	06:04:28	28.6	-0.178
24-Mar-92		04:09:03	30.1	0.253 est.
		04:09:11	31.3	clock swap ?
		21:00:31	31.4	0.142 est.
		21:00:39	31.6	clock reset ?
25-Mar-92	2935	07:39:28	32.0	0.611
01-Apr-92	3028	07:21:53	31.0	-0.141 rev.
15-Apr-92	3212	08:49:28	30.4	-0.043
27-Apr-92	3373	14:45:00	29.0	-0.114
12-May-92	3568	10:18:26	26.6	-0.162

8.0 SUMMARY

Section Contributor:

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Since launch on August 15, 1991, the Meteor-3/TOMS spacecraft and instrument have performed with a minimum of problems. The ozone data set obtained from the telemetered radiances and irradiances is proving to be a useful extension of the Nimbus-7/TOMS ozone data. Difficulties with the data, caused by the drifting orbit for Meteor-3/TOMS, has forced the project scientists to extend our understanding of the radiative transfer properties of the Earth's atmosphere.

The Meteor-3/TOMS mission has taken on an additional importance with the approaching end of useful data from Nimbus-7/TOMS. At the beginning of February 1992, Nimbus-7/TOMS lost its ability to obtain solar calibration because its orbit has drifted from noon to 10:45 am (after 13-years of operation). This means that the 13-year TOMS ozone trend data record can only be maintained by using other instruments to transfer calibration to Nimbus-7/TOMS for the remainder of its expected lifetime (1996).

Meteor-3/TOMS data is also being used to study the aerosol contamination of the atmosphere caused by the eruption of Mt. Pinatubo. This study improves upon the data obtained from Nimbus-7/TOMS because of the greater range of zenith and azimuth angles available to map out the aerosol phase function.

From an operational point of view, the Meteor-3/TOMS project has demonstrated the possibilities for launching highly complex scientific payloads using the talents and resources of two countries. The success of this mission occurred only because of the motivation and high degree of cooperation between the scientists and officials of both Russia and the United States.

9.0 GLOSSARY

ACF	Albedo Correction Factors
BCU	Bench Checkout Unit
BIT	Built In Test
BRDF	Bidirectional Reflectivity Distribution Function
C	Celsius
C.I.S.	Commonwealth of Independent States
CAERO	Sovam Teleport Code for Telemail Messages
Cal	Calibration
CAO	Central Aerological Observatory
cm	centimeters
CMOS RAMs	Complimentary Metal Oxide Silicon Random Access Memory
CYCLONE	Launch Vehicle for the Meteor-3/TOMS
DC	Direct Current
ECAL	Electronic Calibration
EDAC	Error Detection and Correction
ELM	Electronic Logic Module
ergs	Energy Unit
ETHERNET	Networking System used World-wide
FDF	Flight Dynamics Facility
FEL	1000 Watts QTH External calibration lamp
FIFO	First In, First Out
FM-1	Flight Module 1 (Nimbus-7/TOMS)
FM-2	Flight Module 2 (Meteor-3/TOMS)
FOV	Field of View
FVNIIEM	Subsidiary of All-Union Research Institute for Electromechanics
Gbytes	Gigabytes
GMT	Greenwich Mean Time
GOSHYDROMET	International Department of USSR
GRIDTOMS	The results of Level 3 Data
GSE	Ground Support Equipment
GSFC	Goddard Space Flight Center
HDTOMS	High Density TOMS (the basic data set used for scientific ozone studies)
Hg	Mercury
Hydromet	The USSR State Committee for Hydrometerology
IAM	Interface Adapter Module
IFOV	Instantaneous half power Field of View
Kbits	kilobits

kHz	kilohertz
km	kilometer
LECT	Local Equator Crossing Time
LEVEL 0	TOMS data converted to counts in major frame format
LEVEL 1	Reads the data output from Level 0
LEVEL 2	Reads the RUF data from Level 1
LEVEL 3	Analyzed ozone data: maps, grids, plots, etc.
M3	Meteor-3 (USSR Spacecraft)
mA	Milliamp
Mbyte	Megabyte
MHz	Megahertz
ms	millisecond
N7	Nimbus-7
NASA	National Aeronautics and Space Administration
NASCOM	NASA Communications
Nimbus-4 BUV	Nimbus-4 Backscatter Ultraviolet
nm	nanometer
NSSDC	National Space Science Data Center
OPM	Optics Module
OPT	Ozone Processing Team
PCS	Program Control System
PDSK	Phase Difference Shift Keying
PE	Perkin Elmer
PMT	Photomultiplier Tube
QTH	Quartz Tungsten Halogen
RAM	Random-Access Memory
RF	Radio Frequency
RO	Reduced Ozone
ROM	Read Only Memory
RUF	Raw Unit File
RUT	Raw Unit Tape
S/C	Spacecraft
SBCs	Single Bit Corrections
SBUV	Solar Backscatter Ultraviolet Spectrometer
SDRF	Scientific Data Reduction Facility
sec	second
SEU	Single Event Upset
Solar CAL	Solar Calibration
sr	steradian
SSR	Solid State Recorder
STAGE 1	Heater Power On

STAGE 2	Initialization
STAGE 3	Electronics Calibrations
STAGE 4	High Voltage Verification
STAGE 5	High Voltage Full-Time/Solar Calibrations
STAGE 6	Lambda Calibration (Full Orbit)
TIOCC	TOMS Instrument Operations Control Center
TOMS	Total Ozone Mapping Spectrometer
UHF	Ultra High Frequency
U.S.S.R.	Union of Soviet Socialists Republics
USSR	Union of Soviet Socialists Republics
UV	Ultra-Violet
VDC	Volts Direct Current
VFC	Voltage-to-frequency counter
VIP	Versatile Information Processor (telemetry system)
VNIIEM	USSR All-Union Research Institute for Electromechanics
WCAL	Wavelength Calibration
WFF	Wallops Flight Facility
W/L	Wavelength Calibration
WOTS	Wallops Island Orbital Tracking Support

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13. ABSTRACT *(Maximum 200 words)*
The development of Meteor-3/TOMS (Total Ozone Mapping Spectrometer) was a joint project of the United States and Russia to fly a U.S. ozone measuring instrument (TOMS) onboard a Russian spacecraft (Meteor-3) and rocket (Cyclone), launched from Plesetsk, Russia. The Meteor-3/TOMS (M3TOMS) was launched into a 1202-km-high, near-polar orbit on August 15, 1991, where it can obtain complete global coverage for most of each year. Both the U.S. and Russian sides have successfully received and processed data into ozone amounts from August 25, 1991 to June 1, 1992, and expect to continue for the life of the instrument and spacecraft. The successful development of the instrument hardware, spacecraft interface, data memory, telemetry systems, and software are described. Descriptions are given of the U.S. and Russian ground stations for receiving M3TOMS data. In addition, the data reduction software was independently developed by the U.S. and by the Russians, and is shown to agree to better than the precision of the measurements.

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