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Satellite Application Facility for Numerical Weather Prediction

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1. INTRODUCTION

For many years the NOAA polar orbiting weather satellites have provided a sounding and imaging capability, with instruments operating in the visible, infra-red and microwave regions of the spectrum, and with a direct broadcast system to allow users access to the data in near real time.

In response to requests from the user community, EUMETSAT took the initiative in 1992 to start activities in the area of ATOVS software processing. The goal was to set up a standard package for the processing of locally received ATOVS data from the NOAA spacecraft, and as a result of this initiative the ATOVS and AVHRR Pre-processing Package (AAPP) was developed. The package is now maintained by the EUMETSAT Satellite Application Facility for Numerical Weather Prediction (NWP SAF).

The first satellite in the NOAA-KLM series (NOAA-15) was launched in 1998, replacing the earlier NOAA/TIROS-N series. In 2005 the first satellite in the follow-on NOAA-NN' series was launched (NOAA-18), and the AAPP package (version 5) was extended to accept data from this series.

The next major development was the launch in 2006 of the first European MetOp satellite. MetOp is part of the EUMETSAT Polar System (EPS), which is the European contribution to a joint European-US polar satellite system called the Initial Joint Polar System (IJPS). MetOp capability was added in AAPP v6. The ability to process imager data from the Chinese FY-1D satellite was also added as part of AAPP v6.

The first of the next generation of US operational polar-orbiting weather satellites is the NPP (NPOESS Preparatory Project), to be launched in October 2011. Future satellites in the series will be named JPSS (Joint Polar Satellite System). AAPP v7 is designed to pre-process data from the sounder and imager instruments on NPP, while continuing to support MetOp and the older NOAA satellites.

This document provides a scientific description of the AAPP package.

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2. DOCUMENTS AND TERMINOLOGY

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2.2. TERMINOLOGY

AAPP: ATOVS and AVHRR Pre-processing Package.

ADC: Analog to Digital Converter.

AIP: AMSU Information Processor.

AMSU: Advanced Microwave Sounding Unit.

ANA: Automatic Navigation Adjustment.

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ARGOS: Name of the orbital bulletin emitted by CLS/ARGOS.

Ascending node (HNA) : equator satellite crossing when it comes from south pole.

ATOVs: Advanced TIROS Operational Vertical Sounder.

ATMS: Advanced Technology Microwave Sounder

AVHRR: Advanced Very High Resolution Radiometer.

Attitude: Satellite orientation according the 3 axes (yaw, roll, pitch).

Bb: black body.

Brolyd (Brouver-Lyddane): Orbit extrapolation model algorithm for TBUS bulletin.

CMS: Centre de Météorologie Spatiale (Météo-France)

CNES: Centre National d'études Spatiales.

CrIS : Cross-track Infrared Sounder

DCS: Data Collection System.

Descending node (LNA) : equator satellite crossing when it comes from north pole.

DMSP: Defense Meteorological Satellite Program

DWSS: Defense Weather Satellite System.

Earth's precession: Slow conical motion of the Earth rotation axis around a mean position corresponding to a normal direction to the ecliptic plane.

Ecliptic plane: The Earth orbital plane around the Sun.

ECMWF: European Center for Medium-Range Weather Forecasting.

Ephemeris: The list of the times of various events as: ascending and descending nodes, start and end of acquisition by a station.

EPS: EUMETSAT Polar System

FOV: Field Of View.

GAC: Global Area Coverage.

HIRS: High Resolution Infra Red Sounder.

HRPT: High Resolution Picture Transmission.

IASI: Infrared Atmospheric Sounding Interferometer.

IFOV: Instantaneous Field Of View.

IJPS: Initial Joint Polar System

Image navigation: Conversion of line and pixel numbers into latitude and longitude.

IR: InfraRed.

IWT : internal warm target

LAC: Local Area Coverage.

Mapping : for sounders = computing sounder data to another sounder grid. For imaging radiometer = imaging radiometer data segmentation to sounder ellipse.

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MetOp: Meteorological Operational satellite

MHS: Microwave Humidity Sounder

MIRP: Manipulated Information Rate Processor.

MSU: Microwave Sounding Unit.

μ-waves: microwaves.

Nadir: Satellite vertical direction.

NOAA: National Oceanic and Atmospheric Administration.

NESDIS: National Environmental Satellite Data Information Service.

NORAD: North American Aerospace Defense Command

NWP SAF : Numerical Weather Prediction Satellite Application Facility.

Perigee: Satellite orbit point which is the nearest from the Earth (opposite apogee).

PM: Pulse Modulation.

POES: Polar Orbiting Environmental Satellite(s)

PRT: Platinum Resistance Thermometer.

Rg : Greenwich reference frame

RI : local reference frame

Rs : spacecraft fixed reference frame

Rv : satellite local orbital frame

SEM: Space Environment Monitor.

SDP4: Orbit extrapolation model for deep-space object Two-Line Element sets

SGP4: Orbit extrapolation model for near-Earth object Two-Line Element sets

SSU: Stratospheric Sounding Unit.

SST: Sea Surface Temperature.

TBUS: Name of the orbital bulletin emitted by NOAA/NESDIS.

TIP: TIROS Information Processor.

TIROS: Television Infrared Observation Satellite

TOVS: TIROS Operational Vertical Sounder.

VIIRS: Visible/Infrared Imager/Radiometer Suite

VIS: Visible.

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3. DESCRIPTION OF THE NOAA SATELLITES AND INSTRUMENTATION

3.1. NOAA SATELLITES

The American polar orbiting weather satellites are controlled by NOAA. The first launch occurred in 1978 with the TIROS N satellite, followed by the NOAAxx series (from NOAA6 to NOAA14), and since 1998 by the NOAA-KLM (NOAA15,16,17) and NOAA-NN' (NOAA18,19) series. Each satellite has a lifetime of nominally 4 years, though some have continued operating for very much longer than this. Two satellites must be operational at the same time. The current system records multispectral images (several spectral channels) of the Earth surface, and allows the computation of temperature and humidity profiles of the atmosphere. It is composed of two sun synchronous polar orbiting spacecraft, flying at an altitude close to 835 km. One is planned to fly in the afternoon orbit (PM), and the other in the morning orbit (AM). Due to the Earth rotation, the satellite track is translated westward with each pass. The nodal period is about 102 minutes, which means that each satellite describes 14.2 orbits per day, so the sub satellite track is not daily periodic (the same orbital configuration is achieved every 9 days). The satellites orbital parameters drift slowly, resulting in changes in observation conditions and overpass times.

3.2. ON BOARD INSTRUMENTATION

3.2.1. Introduction

Narrow band radiometers (with channels centered on specific wavelengths) are designed to measure spectral radiances.

If the energy measured by the instrument at a given wavelength is not absorbed by the atmosphere (i.e. atmospheric window), but only by clouds, the instrument is called an imaging radiometer (e.g. AVHRR), whose purpose is to give information (reflectance or temperature) on different types of surfaces (sea, vegetation, ice, snow), or on cloud cover (top).

If the energy measured at a given wavelength is absorbed by the atmosphere, the instrument is called a sounder (e.g. TOVS/ATOVS sounding system with IR (HIRS) and microwave radiometers (MSU/AMSU/MHS)). A sounder is dedicated to measurements of the atmospheric vertical structure.

Table 1 presents the NOAAxx on board instrumentation which is covered by this documentation:

NOAA (6-14)		NOAA (15 16 and 17)		NOAA (18 and 19)	
TOVS	HIRS/2 MSU SSU	ATOVS	HIRS/3 AMSU-A AMSU-B	ATOVS	HIRS/4 AMSU-A MHS
AVHRR/2		AVHRR/3		AVHRR/3	
DCS		DCS		DCS	

Table 1: NOAAxx on board instrumentation

A short description of the previous and current instrumentation is given in the next paragraphs.

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3.2.2. VIS and IR imaging radiometers

These radiometers are designed to study cloud cover and Earth surface properties. Spatial resolution depends on the instrumentation quality and the satellite height from the observation point.

AVHRR/2

is a 5 channel (0.63 to 12 μm) high resolution infrared (IR) imaging radiometer. The first two channels (0.63 and 0,86 μm) measure radiance in the visible (VIS) spectral band. For example, using both channels allows the discrimination of vegetation. The three IR channels (3.74, 10.80, 12.00 μm) are generally dedicated to surface temperature determination. Using VIS and IR channels together allows determination of cloud presence and to distinguish cloud type and depth. Images from this radiometer are used for many varied applications. The internal rotating mirror scans ($\pm 55^\circ$ about nadir) cross track over a swath of ± 1450 km about the sub satellite track. The resolution is 1.1 km at nadir (when the observed point is at the satellite vertical) for an instantaneous field of view of 1.4 mrad. Therefore, in one day, the satellite covers twice the Earth surface, supplying one night-time and one daytime image.

AVHRR/3

has 6 channels (channel 3a: 1.61 μm , the 3.74 μm channel becomes channel 3b) in the VIS and IR spectral bands. The addition of channel 3a improves for example the discrimination between snow and clouds, and provides better aerosol detection. The resolution and the scanning characteristics remain unchanged with respect to the previous AVHRR/2 version. Only 5 channels will be received by the final user: channel 3a (day) or channel 3b (night).

3.2.3. IR and microwave sounders

The sounders have a larger spatial resolution than imaging radiometers, but they have a greater number of spectral channels. These multichannel observations allow the computation of vertical temperature and humidity profiles of the atmosphere. All but very thin cloud is opaque at IR wavelengths, so in cloudy regions microwave sounding channels, which are less sensitive to absorption by cloud, are used to retrieve atmospheric profiles.

TOVS (NOAA6-14)

is a sounding system which provides the data necessary for the retrieval of temperature and water vapour profiles. This system is composed of three different sounding units:

- **HIRS/2** is a 19 channel (from 4.3 to 15 μm) IR sounder for radiance measurements corresponding to carbon dioxide CO₂ (4.3 and 15 μm), water H₂O (6.3 μm) and ozone O₃ (9.6 μm) absorption bands. One VIS channel is dedicated to reflectance measurements (% albedo). The internal rotating mirror scans ($\pm 49.5^\circ$ about nadir) a swath of ± 1120 km on both sides of the sub satellite. One scan line contains 56 FOV. The resolution (pixel size on the ground) is 17.4 km at nadir for an instantaneous field of view (IFOV) of 1.25° , and 58 km at the mirror maximum deviation (largest scan angle).

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- **MSU** is a 4 channel (around 50 GHz) μ -wave sounder corresponding to the oxygen O₂ absorption bands (5 mm). The internal rotating mirror scans ($\pm 47^\circ$ about nadir) a swath of ± 1173 km on both sides of the sub satellite track. One scan line contains 11 FOV. The resolution is 109 km at nadir and 323 km at the mirror maximum deviation (largest scan angle).
- **SSU** is a 3 channel (around 15 μ m) IR spectrometer for stratospheric measurements.

ATOVS (NOAA-15-16-17 series)

is an improved TOVS version:

- **HIRS/3** is basically a modernised version of HIRS/2 with similar channel spectral characteristics. There will be only two calibration lines scan for the thermal channels.
- **AMSU-A** and **AMSU-B** replace MSU and SSU for the retrieval of temperature and water vapor vertical profiles from surface to approximately 3 hPa. **AMSU-A** is a 15 channel (around 23, 30, 50 and 89 GHz) total power μ -wave sounder. The resolution is 50 km at nadir and one scan line contains 30 FOV (rotating mirror by (+/- 48 $^\circ$)). **AMSU-B** is a 5 channel (around 89, 150 and 183 GHz) total power μ -wave sounder. The resolution is 17 km at nadir and one scan line contains 90 FOV.

ATOVS (NOAA-18-N' series)

- **HIRS/4** is basically a modernised version of HIRS/3 with similar channel spectral characteristics. The design changes for the HIRS/4 consist of: 1) radiant cooler operation at 95 K; 2) IFOV size reduced to 10 km; 3) inclusion of a fifth Internal Warm Target (IWT) temperature sensor; and 4) addition of a tertiary telescope temperature sensor.
- **AMSU-A** is a 15 channel (around 23, 30, 50 and 89 GHz) total power μ -waves sounder. The resolution is 50 km at nadir and one scan line contains 30 FOV (rotating mirror by (+/- 48 $^\circ$)).
- **MHS** is functionally similar to AMSU-B, with channels at 89, 157, 183 \pm 1, 183 \pm 3 and 190 GHz.

3.2.4. DCS

The DCS receives and retransmits data from environmental monitoring systems. It receives information as temperature, pressure, currents, wind velocity and direction from various local measurements from ground or immersed stations. Data are processed (signal demodulation, synchronization, etc.) and stored on board until the satellite can contact and transmit the collected information to a NOAA ground station. More precise characteristics are available in references [1] and [4].

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3.3. DATA TRANSMISSION

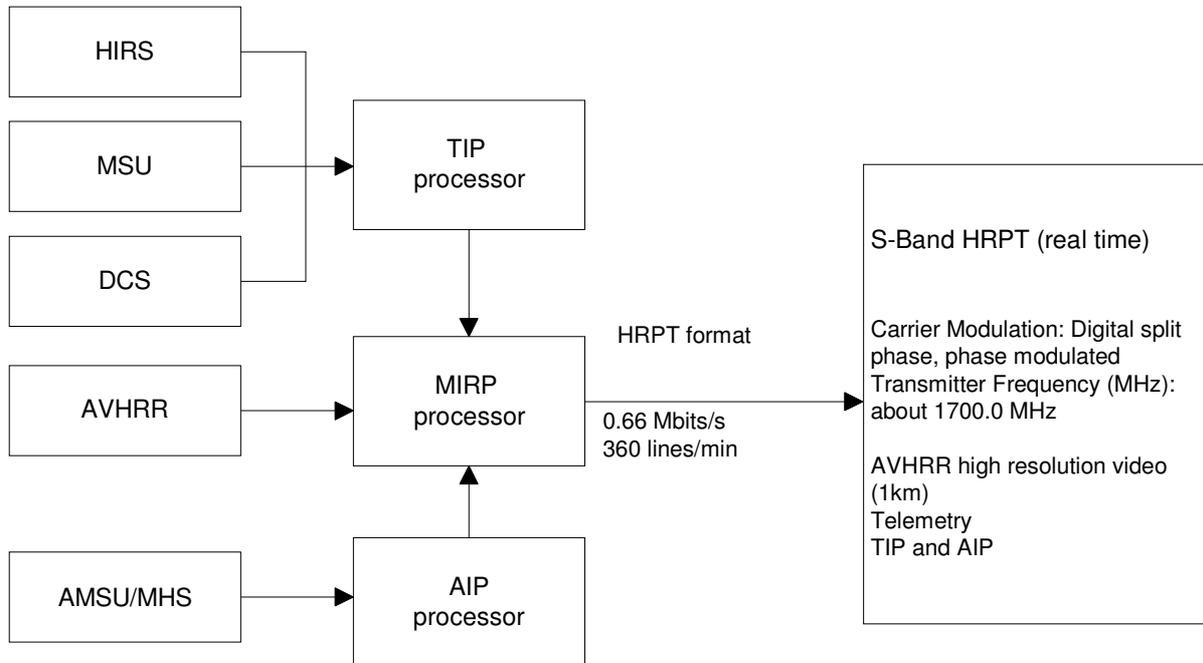


Figure 1: Data transmission in HRPT format.

The radiometric and sounding data are stored on board until the satellite transmits them to a ground station. Two kinds of AVHRR data are transmitted: full resolution data LAC [1] and sampled data (mean of 4/5 pixels 1/3 line) GAC [1]. Global TIP information are also transmitted. The main acquisition stations are located near the north pole, which provide facilities for the acquisition of a great number of recorded orbits. The station transfers these data onto another satellite that can transmit the information to the main NOAA/NESDIS centre, where the data are processed and archived before distribution.

The satellite also transmits multiplexed AVHRR, TIP and AIP data, i.e. HRPT real time data, toward various line of sight acquisition stations located anywhere on the Earth surface. The frames are continuously transmitted, line by line, during approximately 15 minutes (for an orbit segment). The generated data file is about 5000 AVHRR lines (2048 pixels per line for 5 channels) representing 100 Mbytes (10 bit words) of data. The HRPT [1] data transmission is illustrated on the previous figure. Section 8.1.1 also describes the HRPT format.

The MHS instrument was designed for use on the European MetOp spacecraft. To allow it to be used on the NOAA spacecraft its data are re-formatted by the on-board MHS Interface Unit (MIU). The MIU then passes the data to the AIP, such that the MHS data occupies the same HRPT slots as are used for AMSU-B – albeit with a time delay of approximately 1 scan line. Thus from the User’s point of view the processing of MHS appears similar to the processing of AMSU-B

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4. DESCRIPTION OF THE METOP SATELLITES AND INSTRUMENTATION

4.1. METOP SATELLITES

The EUMETSAT Polar System (EPS) is Europe's first polar orbiting operational meteorological satellite system. The EPS consists of a series of three Meteorological Operational (MetOp) satellites, to be flown successively for more than 14 years, together with the relevant ground facilities.

The EPS is the European contribution to a joint European-US polar satellite system called the Initial Joint Polar System (IJPS). Through this international partnership, EUMETSAT will have the operational responsibility for the morning (local time) orbit with the MetOp satellites, while its US counterpart, NOAA, will cover the afternoon orbits. Data will be processed by both EUMETSAT and NOAA. The first MetOp satellite, MetOp-2 (to be called MetOp-A in operation) will be launched in July 2006. Each satellite has a nominal lifetime of 5 years, with a 6 month overlap between the consecutive satellites.

4.2. ON BOARD INSTRUMENTATION

Under the IJPS, EUMETSAT and NOAA have agreed to provide instruments for each other's satellites. Other partners are the European Space Agency (ESA) and the Centre National d'Etudes Spaciales (CNES) of France.

The MetOp satellite carries a payload of 8 instruments for observing the planet. The AVHRR/3, HIRS/4, AMSU-A, MHS and IASI instruments are covered by this documentation.

4.2.1. VIS and IR imaging radiometers

- **AVHRR/3** is the same as on the NOAA satellites.
- The IASI sounder (see below) incorporates an integrated imager which is used to geolocate the sounder data. It is not normally used as a source of imagery for users.

4.2.2. IR and microwave sounders

- **HIRS/4, AMSU-A and MHS** are the same as on the NOAA satellites.
- **IASI:** The Infrared Atmospheric Sounding Interferometer represents a significant advance in the quality of the measurements injected into models for understanding and making atmospheric forecasts. The main goal of IASI is to provide atmospheric emission spectra to derive temperature and humidity profiles with high vertical resolution and accuracy. IASI is a 8461-channel interferometer. The spectral range covers 645 to 2760 wavenumbers (15.50 to 3.62 μm), with 0.25 wavenumber channel spacing. There are 30 cross-track scan positions per 8 second cycle, with 4 fields of view per scan position. The scan cycle is synchronized to that of AMSU-A. The pixel size on the ground is 12 km at nadir for an instantaneous field of view (IFOV) of 0.8225°.

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4.3. DATA TRANSMISSION

There are three methods by which MetOp data are made available to users:

- **Direct readout:** The MetOp direct Readout Service provides to local user stations a real-time transmission of data limited to the instantaneous sub-satellite observation. Readout of instrument data can be achieved in the form of:
 - Advanced High Resolution Picture Transmission (AHRPT), transmission in L-Band. It includes all instruments in full resolution. The data rate is 3.5Mbps, which is higher than that of the NOAA satellites. The formatting uses CCSDS packets.
 - Low resolution Picture Transmission (LRPT), transmission in VHF band. It includes ATOVS in full resolution and compressed data from 3 selected AVHRR channels. The data rate is 72kbps.
- **Global data via EUMETCast:** The Global Data Service provides in near real-time products generated from instrument data. Data are dumped once per orbit to the Central Data Acquisition Station (CDA) (e.g. at Svalbard-Island). They are processed by the EPS Core Ground Segment at EUMETSAT, then the level 1 and level 2 products are distributed to users via EUMETCast. The delivery timeliness will be between 135 and 180 minutes after the time of measurement.
- **Regional data via EARS.** Locally received data from a network of HRPT stations are processed at EUMETSAT and then distributed as part of the EUMETSAT Advanced Retransmission Service (EARS). This comprises ATOVS, AVHRR and ASCAT regional data services.

5. DESCRIPTION OF THE NPP AND JPSS SATELLITES AND INSTRUMENTATION

For detailed information and discussion on the scientific issues related to NPP data processing, please see document [33], which is part of the AAPP v7 distribution.

5.1. NPP AND JPSS SATELLITES

The NPP and follow-on JPSS satellites will provide NOAA's primary operational satellite in the afternoon orbit (14:00 local time northbound equator crossing), complementing MetOp in the mid-morning orbit, and the US military DMSP (and later DWSS) in the early-morning orbit.

5.2. ON BOARD INSTRUMENTATION

NPP carries a payload of 5 instruments for observing the planet. The ATMS, CrIS and VIIRS are covered by this documentation.

5.2.1. VIS and IR imaging radiometers

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The Visible/Infrared Imager/Radiometer Suite (VIIRS) is a 22-channel imaging radiometer, functionally similar to MODIS on the NASA Aqua/Terra satellites. It has three distinct groups of channels:

- Imaging: 5 channels with 370m resolution at nadir, at wavelengths of 0.64, 0.865, 1.61, 3.74 and 11.45 μm .
- Moderate: 16 channels with 740m resolution at nadir, at wavelengths of 0.412, 0.445, 0.488, 0.555, 0.746, 0.865, 1.24, 1.378, 1.61, 2.25, 3.70, 4.05, 8.55, 10.763 and 12.013 μm .
- Day-night band: 1 channel with 740m resolution across the entire swath, operating at 0.7 μm . Uses a charge-coupled device array.

5.2.2. IR sounder

The Cross-track Infrared Sounder (CrIS) is a Michelson interferometer. It has nominally 1305 channels covering the spectral bands 650-1095 cm^{-1} (713 channels, sampling 0.625 cm^{-1}), 1210-1750 cm^{-1} (433 channels, sampling 1.25 cm^{-1}) and 2155-2550 cm^{-1} (159 channels, sampling 2.5 cm^{-1}).

It samples 270 spectra per 8-second scan, with a spatial resolution at nadir of approximately 17km.

5.2.3. Microwave sounder

The Advanced Technology Microwave Sounder (ATMS) has 22 channels ranging in frequency from 23.8 GHz to 183 GHz. Functionally it is similar to the combination of AMSU and MHS, and many of the channels are identical in frequency/bandwidth to channels on AMSU/MHS. There are three new channels (51.76, 183.31 \pm 4.5 and 183.31 \pm 1.8 GHz). Spatial resolutions are as follows:

- 78km at nadir for the 23.8 and 31.4 GHz channels (5.2 $^\circ$ beam width)
- 33 km for the 50-57 GHz sounding channels (2.2 $^\circ$ beam width)
- 17 km for the MHS-like channels at 166 GHz and above (1.1 $^\circ$ beam width).

There are 96 samples per 8/3 second scan line, giving a slightly wider swath than MHS.

5.3. DATA TRANSMISSION

There are three methods by which NPP data are (or will be) made available to users:

- Direct readout: The direct readout service provides to local user stations a real-time transmission of data limited to the instantaneous sub-satellite observation. NPP broadcasts at X-band only (7.8 GHz, 15 Mbps). For JPSS-1 an additional L-band downlink is planned, to contain a subset of channels/instruments.
- Global data: Global data will be made available in near-real-time by NOAA and will be re-distributed by external agencies (e.g. EUMETSAT will distribute data to European users via EUMETCast). Historical data will be available via NOAA-CLASS.
- Regional data via RARS. Locally received data from one or more networks of X-band direct readout stations will be processed at a central hub and distributed to users by mechanisms that include the Global Telecommunications Service (GTS) and EUMETCast. Timeliness will be of the order 30 minutes.

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6. DESCRIPTION OF THE FY-1 AND FY-3 SATELLITES AND INSTRUMENTATION

6.1. FY-1 AND FY-3 SATELLITES

The Feng-Yun FY-1 and FY-3 satellites are the Chinese operational polar-orbiting weather satellites.

The FY-1 series started in 1988, but only FY-1D (launched in 2002) has ever been supported in AAPP.

The first in the FY-3 series, FY-3A, was launched in 2009. There is normally one satellite operating in the morning orbit and one in the afternoon orbit.

6.2. ON BOARD INSTRUMENTATION

The only instrument on FY-1D is the Multispectral Visible and Infra-red Scan Radiometer (MVISR, 10 channels).

On FY-3A and FY-3B, the instruments that are applicable to atmospheric sounding and imaging are as follows:

- VIRR - Multispectral Visible and Infra-red Scan Radiometer (10 channels, as on FY-1D)
- MERSI - Medium Resolution Spectral Imager
- MWTS - Microwave Temperature Sounder
- MWHS - MicroWave Humidity Sounder
- IRAS - InfraRed Atmospheric Sounder

At present, support in AAPP is restricted to the processing of sounder data from MWHS and MWTS.

The FY-3 capability will be developed further in future versions of AAPP.

6.2.1. VIS and IR imaging radiometers

The MVISR on FY-1D (or VIRR on FY-3) is a 10-channel imaging radiometer. Channels 6-10 are similar to AVHRR channels 1-5, while channels 1-5 are additional visible channels used for ocean colour.

MERSI is a 25-channel imager, functionally similar to MODIS (on Aqua/Terra).

6.2.2. IR sounder

The IRAS is a 26-channel visible/IR sounder. The first 20 channels are similar to HIRS, while the last 6 are for the measurement of aerosols, CO₂ and cirrus clouds.

6.2.3. Microwave sounders

The Microwave Temperature Sounder (MWTS) has 4 channels, at 50.3 GHz, 53.6 GHz, 54.94 GHz, 57.29 GHz. It observes 15 earth scenes per 16-second scan. The footprint diameter is 62km at nadir (so the scene is under-sampled).

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The Microwave Humidity Sounder (MWS) has 5 channels in the frequency range 150-183 GHz. It observes 98 samples per scan, with a spatial resolution similar to AMSU-B/MHS. Unlike AMSU-B/MHS, it observes dual polarization at 150 GHz and has no 89 GHz channel.

6.3. DATA TRANSMISSION

FY-3D broadcasts direct readout data at L-band, using a similar format to NOAA HRPT (known as CHRPT). It can be readily received by standard reception equipment. AAPP can decode the HRPT data stream.

The FY-3 satellites have two direct broadcast transmissions, one at L-band (1.7 GHz, 4 MB/s), containing the majority of the instruments, and one at X-band (7.8 GHz, 18 Mb/s), for MERSI. A software package can be obtained from CMA for generating Sensor Data Record (SDR) files from the direct broadcast streams.

7. AAPP PROCESSING PACKAGE DESCRIPTION

For a few years, different European meteorological organizations (Météo France, UK Met Office, ECMWF...) have been developing AAPP (ATOVS and AVHRR Pre-processing Package) software, under EUMETSAT co-ordination. This package is intended for the ingestion and the pre-processing tasks of received HRPT data up to the retrieval of the satellite brightness temperatures. This software can be used with AVHRR, TOVS and ATOVS data.

7.1. PURPOSE AND SCOPE

For the NOAA and FY1 satellites, the decommutation task performs the extraction of data particular to each instrument from the HRPT format. The data from each sounder (HIRS, MSU, AMSU, MHS) and from the imager (AVHRR) are put into separate files. The following tasks perform the computation of the calibration coefficients, the satellite navigation (satellite position calculation on its orbit) and image navigation (longitude and latitude position of the pixels, taking into account the sensor geometry, solar angles, etc.). The pre-processing tasks achieve the conversion of the raw HRPT data (Earth and atmosphere VIS and IR radiances) into physical parameters (brightness temperatures, albedo) and perform data mapping between the measurement grids of the different instruments (AVHRR/HIRS, AMSU-MHS/HIRS mapping...).

In the case of MetOp, it is the responsibility of the ground station to convert received AHRPT data to "PFS level 0 format". In this format the data streams for the various instruments are already separated. Thus there is no MetOp decommutation task. Instead, tools are provided within AAPP to convert PFS level 0 files to AAPP level 1a format – for AMSU-A, MHS, HIRS and AVHRR. The level 1a files can then be processed by the core AAPP calibration and pre-processing modules.

For IASI, processing to level 1c may, if required, be performed by OPS-LRS (Operational Software – Local Reception Station) package. A technical description of this package, together with references to scientific documentation, is given in the OPS-LRS User Manual [29].

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In the case of NPP and JPSS, it is the responsibility of the ground station to convert received X-band direct broadcast data to “Sensor Data Record” format. An external software package is required for this task. At the time of writing, two packages are being advertised to do this task:

1. The *International Polar Orbiter Processing Package* (IPOPP) developed by the NASA Direct Readout Laboratory.
2. The *Community Satellite Processing Package* (CSPP) produced by the University of Wisconsin, with the heritage of the *International MODIS/AIRS Processing Package* (IMAPP).

Both of the above packages are based on the *Algorithm Development Library* (ADL) which is a Linux port by Raytheon of the operational NOAA ground segment software (called IDPS - *Interface Data Processing Segment*).

AAPP may also be used to process global or regional NOAA, MetOp or NPP data received elsewhere, for example:

- AMSU, HIRS and MHS level 1b data from the NOAA archives
- Global MetOp data received from EUMETSAT (e.g. via EUMETCast). AAPP includes the necessary BUFR decoding and encoding routines
- Global NPP data in BUFR format received from NOAA or from EUMETSAT
- Global NPP data in HDF5 Sensor Data Record format from CLASS.

7.2. GENERAL DESCRIPTION

AAPP version 7 presents three distinct components, as was the case for AAPP version 6:

- The core AAPP task, which now includes NPP-specific routines
- Tools to interface the core AAPP with the specific formats of MetOp data.
- A suite for processing IASI data to level 1c, based on the CNES-supplied IASI OPS (Operational Processor Software), named OPS-LRS for Local Reception Station..

The core AAPP can be broken down to six major tasks:

1. Decommuration (only useful for direct acquisition of NOAA data)
2. Calibration/satellite navigation/localisation
3. Preprocessing step 1 (atovin): Apply calibration coefficients, convert radiances to brightness temperatures.
4. Preprocessing step 2 (atovpp): Instrument mapping on another instrument grid
5. AVHRR mapping on HIRS and cloudmask (avh2hirs)
6. Tools to perform a range of tasks, including BUFR encode/decode, reading of HDF5 files, etc.

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The following figures (Figure 2, Figure 3, Figure 4, Figure 5) show the different processing chains according to the origin of the data. The figures don't make mention of pre-NOAA-K satellites, for which the MSU instrument was used instead of AMSU-A and AMSU-B/MHS.

The different levels of AAPP data are defined as follows:

level0: raw HRPT data.

level1a: separated data for each instrument.

level1b: geo-referenced and calibrated data (reversible: calibration coefficients are separated from raw data).

level1c: geo-referenced and calibrated temperatures and albedo (non-reversible: calibration coefficients are applied to numerical data). In the case of IASI, level 1c implies Gaussian apodisation.

level1d: mapped and filtered data (cloud mask).

Note that NOAA use the following product naming convention for NPP/JPSS data:

raw data records (RDR): raw data, separated for each instrument.

temperature data records (TDR): calibrated antenna temperatures (only applicable to microwave sounder).

sensor data records (SDR): calibrated brightness temperatures

environmental data records (EDR): retrieved quantities

climate data records (CDR): A subset of EDRs, with traceability suitable for climate studies.

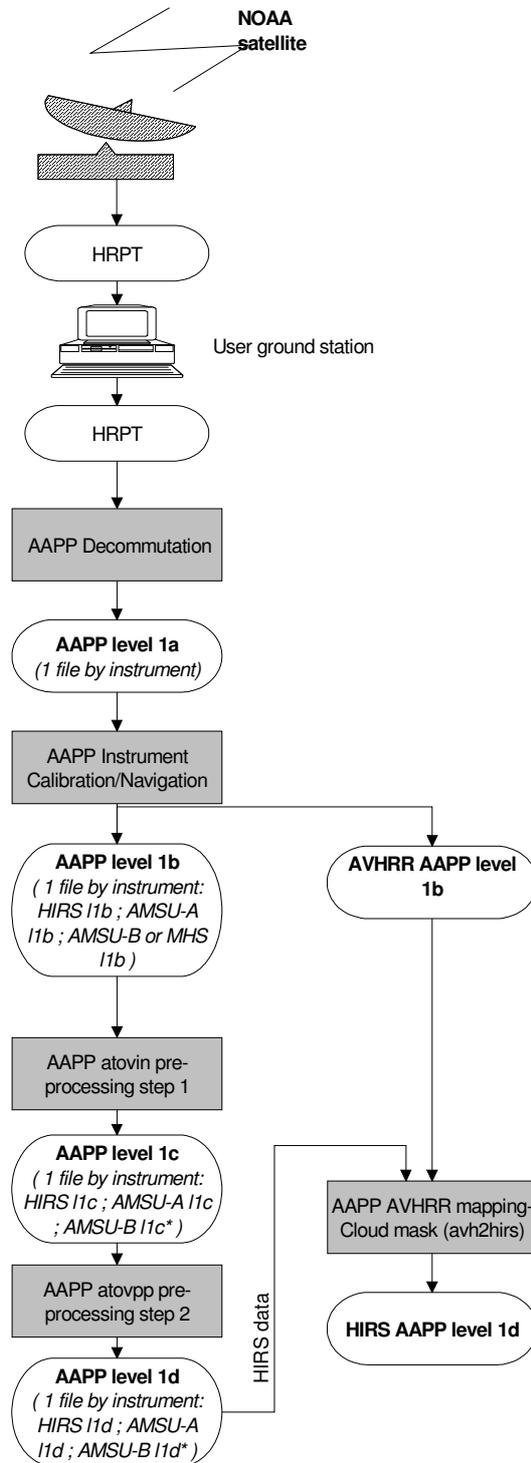


Figure 2: AAPP processing chain for NOAA satellites.

*: AMSU-B 11c and AMSU-B 11d contains MHS data for NOAA-18.

The script, named **AAPP_RUN_NOAA**, allows the user to link up the different independent tasks (see Installation Guide).

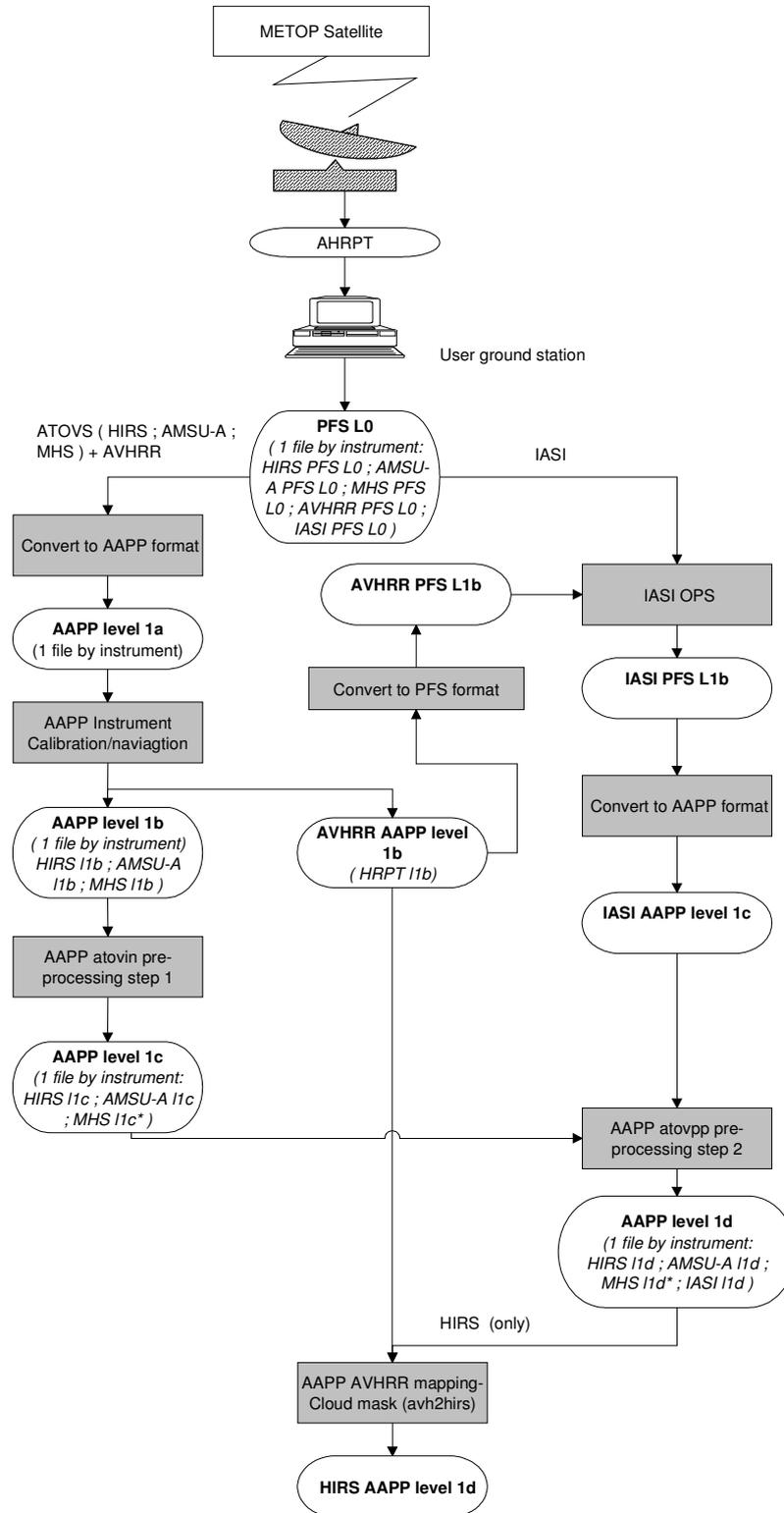


Figure 3: AAPP processing chain for MetOp satellites.

*: MHS 11c and MHS 11c data are ranged into files named AMSU-B 11c and AMSU-B 11d.

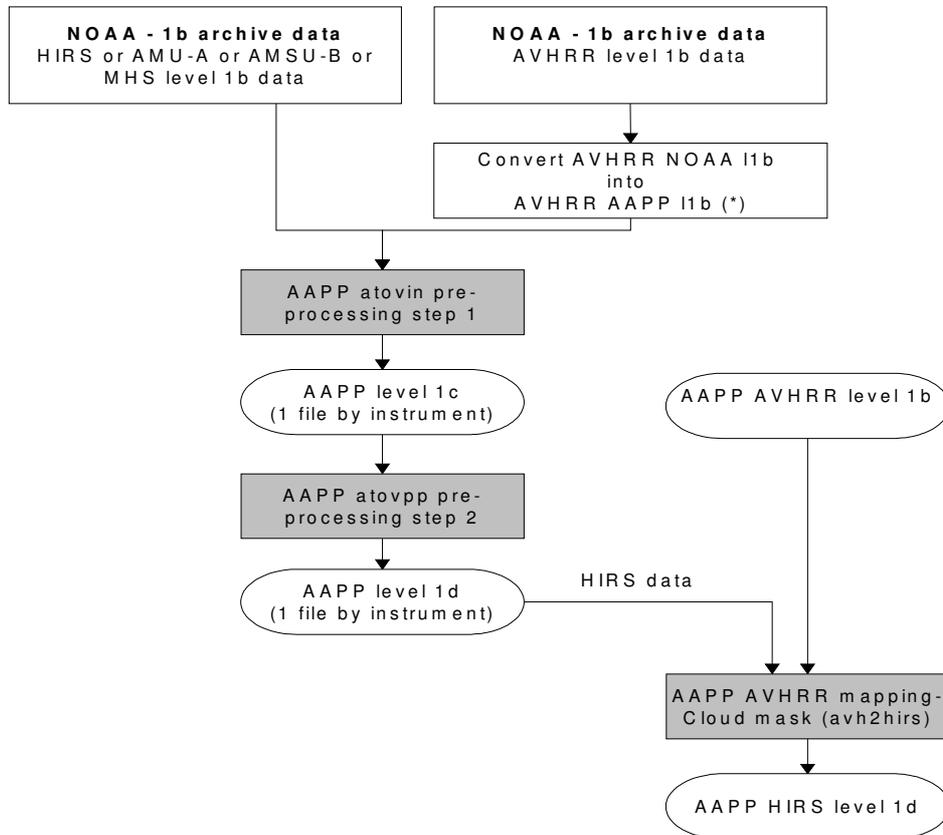


Figure 4: AAPP processing chain for NOAA -1b archive data.

(*): A tool to partially convert AVHRR NOAA 11b into AVHRR AAPP 11b is provided in AAPP (hrpt1b_noaa.exe). See the format documentation for the differences between the two formats.

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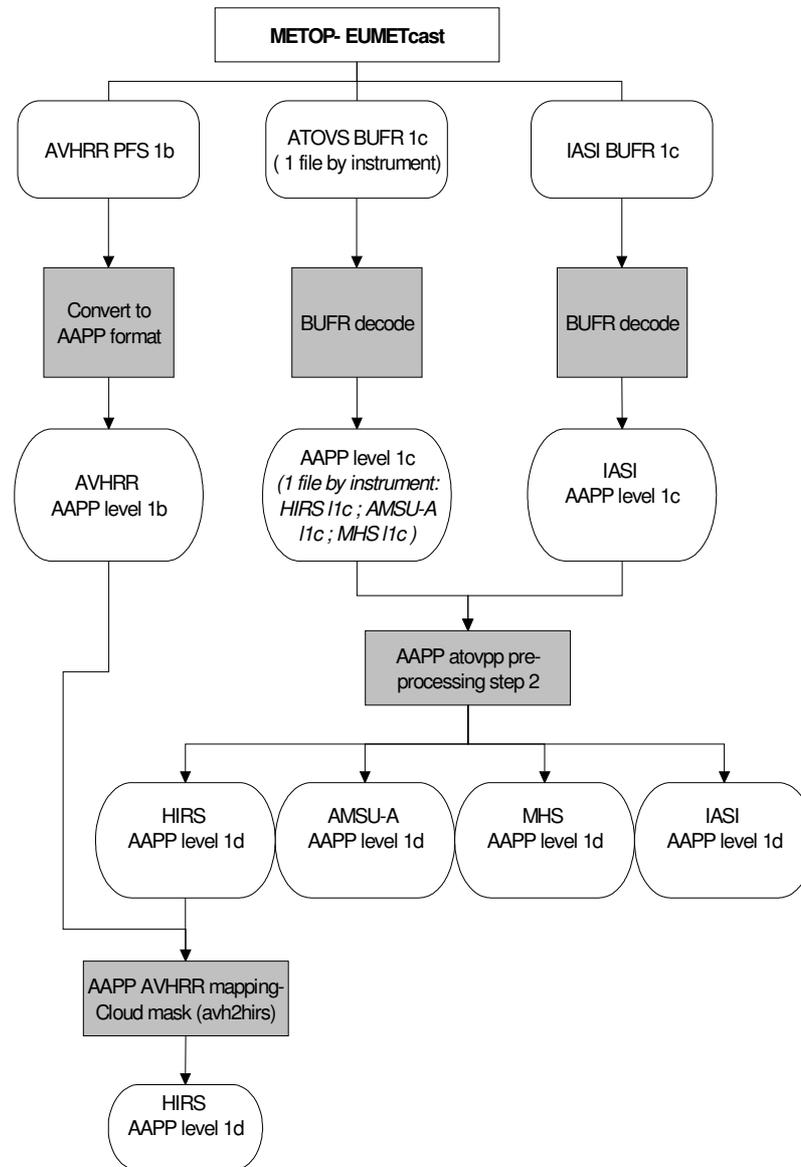


Figure 5: AAPP processing chain for MetOp data received via EUMETCast.

NPP processing

In the case of NPP, the initial release of AAPP v7 will only contain the ability to pre-process the ATMS and CrIS sounder data. A VIIRS cloud mask (and the ability to map VIIRS to CrIS) will be developed at a later date. ATMS and CrIS pre-processing is discussed in detail in [33]. The NPP processing chain within AAPP comprises the following elements:

1. Transform SDR files from BUFR or HDF5 to internal AAPP format
2. Modify the AAPP effective beam width (to reduce noise and/or match footprints for different channels)
3. Run atovpp in order to:
 - map ATMS to CrIS

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- generate derived ATMS cloud quantities
 - perform spectral and/or spatial thinning for CrIS
4. Optionally, BUFR encode the outputs.

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7.3. AAPP MODULES

The tasks are separated for TOVS/ATOVS and AVHRR. The main modules are:

7.3.1. Ingest:

Decommutation (NOAA satellites only):

DECOMMUTATION performs the interface between acquisition and processing system. This function is specific to the AAPP installation site and can be modified by the user if the acquisition system doesn't respect HRPT format. This module calls **HRPTDC** to perform decommutation task.

HRPTDC (ATOVDC and AVHRDC) performs the decommutation task: It reads the raw (level 0) HRPT data streams and puts data from the sounding instruments (HIRS, AMSU-A, AMSU-B, MHS, MSU) and from the AVHRR radiometer into separate files (level 1a).

MetOp tools:

The format conversion tools for MetOp allow the conversion of PFS level 0 format (from the reception station) to AAPP level 1a format – for AMSU-A, MHS, HIRS and AVHRR. Each instrument uses a separate conversion program.

There is also a tool *aapp-eps_avhrr1b* to convert AVHRR AAPP level 1b format to PFS level 1a, for use with OPS-LRS, and a tool *convert_iasi1c* to convert IASI level 1c PFS format (from OPS-LRS) to an AAPP format that can be ingested by ATOVPP.

The tool *convert_avh1b* can be used to convert AVHRR PFS level 1b to a “pseudo”-AAPP level 1b format. In this format, the “counts” are not instrument counts, they are actually scaled radiances, with the “calibration coefficients” (slope and offset to apply to the “counts”) being set to constant values.

Satellite and image navigation - Calibration coefficients:

ATOVCL(=HIRSCL,AMSUACL,AMSUBCL,MHSCL,MSUCL) performs the satellite navigation, the Earth localisation of the pixels, and the calibration coefficients calculation for each TOVS/ATOVS instrument.

AVHRCL performs the same tasks for the AVHRR radiometer.

At the end of this procedure, separated files of Earth located data and calibration coefficients exist. Those (level 1b) files are archived.

7.3.2. Pre-processing:

Calibration:

ATOVIN applies the calibration coefficients calculated by **ATOVCL** to the numeric counts for radiance conversion. Before that, for AMSU-A data, a moon detection/correction is done. For AMSU-B data, corrections are applied. Then **ATOVIN** converts each channel radiance into brightness temperature for each TOVS/ATOVS instrument.

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At the end of this procedure, separate files of Earth located brightness temperature data exist. Those (level 1c) files are archived.

Mapping:

ATOVPP recognises data contaminated by precipitation and maps data between the measurement grids of the different instruments (for examples: HIRS + AMSU-A + AMSU-B/MHS on HIRS grid, HIRS+MSU on HIRS grid, AMSU-A + AMSU-B on AMSU-B grid, AMSU-A + MHS on IASI grid).

The standard ‘**AAPP_RUN_NOAA**’ implements any of these mappings, controlled via the “-i” and “-g” options.

Mapping - Cloud mask:

AVH2HIRS applies the calibration coefficients (calculated by **AVHRCL**) to AVHRR counts and converts radiance into brightness temperatures, maps AVHRR data to the HIRS FOV, and makes the cloud mask (**MAIA**, **MAIA_2.1** for AAPP version 3 and later) in the HIRS ellipse for contaminated pixels discrimination. At the end of this procedure, a level 1d file exists (HIRS level 1d).

The **MAIA3** cloud mask provides a cloud mask on the AVHRR grid.

7.3.3. IASI ingest and pre-processing

The IASI ingest and calibration task is done by the **OPS-LRS** software. It processes IASI instrument data from PFS level 0 (raw instrument data) through to PFS level 1c that includes calibrated, geolocated, Gaussian-apodised radiances.

The software is based on the software used in the EPS Core Ground Segment that was supplied to EUMETSAT by CNES. It has been modified by the NWP SAF for portability and to allow distribution with AAPP.

IASI level 1c data can be ingested by ATOVPP, which can perform various pre-processing operations, depending on the user options that are specified:

- map AMSU/MHS to IASI
- channel selection
- Principal Components (PC) analysis

These are discussed more fully in Chapter 7 and PC processing is also discussed in [34]. The output of this step is an IASI Level 1d file.

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8. AAPP SCIENTIFIC DESCRIPTION

This part will not mention the description of the OPS-LRS software. It is anticipated that relatively few users will wish to run IASI-OPS-LRS because of its complexity and its need for a fairly powerful computer. Documents are available at this address:

<http://www.eumetsat.int/Home/Main/DataProducts/Resources/index.htm?l=en>

(Documents “Spécification Technique de Besoin du logiciel opérationnel IASI” and “Dossier de définition des algorithmes IASI”. They are in French)

8.1. DECOMMUTATION

This section is applicable to the NOAA satellites only.

HRPT (High Resolution Picture Transmission) is a real time transmission of full resolution images coming from the different instruments on board the NOAA satellites. The AVHRR, TIP (HIRS, MSU, DCS, housekeeping data...), and AMSU/MHS data are multiplexed, which means that one HRPT data stream contains mixed information related to all instruments. Data are organized into major and minor frames, in order to easily extract the information belonging to each instrument.

The scope of the decommutation task is to recognize and to extract, from the HRPT format, the measurements and the telemetry data of each instrument. It results in the creation of a separate file of raw data for each instrument.

8.1.1. HRPT format general description

Description

The format of the HRPT, TIP and AIP minor frames is assumed to be as defined in the NOAA referenced document [1]. It is advised to refer to these documents for a precise definition.

The HRPT major frame is made of 3 minor frames. Since the AMSU sounder has appeared on NOAA-K series (and so MSU and SSU have disappeared), the frame structure has changed. Table 2 and Table 3 show one HRPT major frame for both cases.

n°1	synchro + id + date	telemetry + calibration	5 TIP cycles (n)	spare	AVHRR video (n)	aux. synchro
n°2	synchro + id + date	telemetry + calibration	5 TIP cycles (n)	spare	AVHRR video (n+1)	aux. synchro
n°3	synchro + id + date	telemetry + calibration	5 TIP cycles (n)	spare	AVHRR video (n+2)	aux. synchro
words	12	91	5x104	127	10240	100

Table 2: One HRPT major frame and its 3 minor frames for pre-NOAA-K satellites.

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n°1	synchro + id + date	telemetry + calibration	5 TIP cycles (n)	spare	AVHRR video (n)	aux. synchro
n°2	synchro + id + date	telemetry + calibration	backfill	spare	AVHRR video (n+1)	aux. synchro
n°3	synchro + id + date	telemetry + calibration	5 AIP cycles (n)	spare	AVHRR video (n+2)	aux. synchro
words	12	91	5x104	127	10240	100

Table 3: One HRPT major frame and its 3 minor frames for NOAA-K series.

Each minor frame is a record of 11090 words length. The input minor frames are assumed to be 10 bit words unpacked into the least significant bits of 16 bit words. The exact format of the HRPT minor frame depends on the hardware of the reception station, which means that the frames have to be read by centre specific routines. The HRPT minor frames are numbered here from 1 to 3. Each minor frame contains one different AVHRR line (eg. from line n to n+2 for this major frame), whereas the TIP data (of 5 TIP cycles) are repeated 3 times in the same major frame (eg. 3 times line n) for pre-NOAA-K satellites. For NOAA-K and N series, the first minor frame contains 5 TIP cycles data, the second minor frame contains backfill data, and the third minor frame contains 5 AIP cycles data.

HRPT minor frame format:

- Number of minor frames per second: 6.
- Size: 11090 words distributed in:
 - frame synchronization: 6 words.
 - identification: 2 words (synchro. type, cycle number, satellite number, resynchro., AVHRR 3a/3b channel).
 - time code: 4 words.
 - telemetry: 10 words (AVHRR calibration ramp, PRT numeric counts...).
 - AVHRR calibration warm target view data or back scan data: 30 words.
 - AVHRR space numerical counts: 50 words.
 - synchronization: 1 word.
 - 5 TIP/TIP/TIP cycles or TIP/backfill/AIP: 5x104 words (Earth observations).
 - spare words: 127 words.
 - AVHRR video: 10240 words (Earth observations).
 - auxiliary synchronization: 100 words.

80 AIP minor frames are required to give 1 AMSU-A and 3 AMSU-B/MHS scan lines. 64 TIP minor frames are required for 1 HIRS scan line. 256 TIP minor frames are required for 1 MSU scan line, and 320 consecutive TIP minor frames correspond to one TIP major frame (of 32 seconds).

TIP minor frame description (NOAA-K and N series):

One TIP minor frame contains HIRS, DCS, SEM, and SBUV (Solar Backscatter Ultra violet Spectral Radiometer for near ultraviolet solar and terrestrial radiation measurements) data for the NOAA-K series (HIRS, MSU, SSU, DCS, SEM and SBUV for the previous satellites), but also the housekeeping parameters which are required for the data navigation or calibration pre-processing. DCS, SEM and SBUV data can also be extracted from the HRPT format, but are not used by the AAPP operational scheme.

- One TIP minor frame: each 100 ms.

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- Size: 103 words (here 1 word is in fact 1 byte) distributed as follows:
 - frame synchronization: 3 words (0, 1, 2).
 - status: bits 1 to 6 of word 3 (mode: 'orbital', 'memory dump', 'dwell', 'boost', major frame counter incremented each 320 minor frames).
 - 'dwell' mode address: bits 7 to 8 of word 3 and bits 1 to 7 of word 4 (9 bits dwell mode address (between 0 and 511) of analog channel that is being monitored continuously).
 - 9 bits minor frame counter: bit 8 of word 4 and word 5 (from 0 to 319).
 - command verification: 2 words (bits 9 to 24 of each valid received command are placed in the 16 bit slots of telemetry words 6 and 7).
 - time code: 5 words (8 to 12) only given in minor frame 0.
 - Digital 'B'-1 telemetry: 1 word (8). There are 256 digital B-1 inputs. Each input has its own channel number between 0 and 255. A subcommutation system allows selection of each input once every 3.2 s.
 - Analog-1 32 s telemetry: 1 word (9). This format is 320 words length that repeats every 32 s. Each input has its own analog channel number. 191 channels are sampled once every 32 s, and twice for the 64 other channels.
 - Analog-1 16 s telemetry: 1 word (10). This format is 160 length. Each input has its own analog channel number. 128 channels are sampled once every 16 s.
 - Analog-1 1 s telemetry: 1 word (11). 10 channels are sampled once per second.
 - Digital 'B'-2 telemetry: 1 word (12). There are 256 digital B-2 inputs. Each input has its own channel number between 0 and 255. A subcommutation system, allows selection of each input once every 3.2 s.
 - Analog-2 16 s telemetry: 1 word (13). This format is 160 length. Each input has its own analog channel number. 128 channels are sampled once every 16 s.
 - DAU-1: 1 word (14). 8 bit housekeeping telemetry words are formed and read out at the rate of 10 words/s.
 - DAU-2: 1 word (15). 8 bit housekeeping telemetry words are formed and read out at the rate of 10 words/s.
 - HIRS/3 or 4 numeric counts: 36 words between 16 and 93. rate: 360 words/s.
 - SEM numeric counts: 2 words (20 and 21). rate: 20 words/s.
 - DCS numeric counts: 32 words between 18 and 95. rate: 320 words/s.
 - SBUV numeric counts: 4 words (36, 37, 80, 81). rate: 40 words/s.
 - CPU telemetry: 12 words (46 to 51 and 96 to 101). Bus A and B CPU data bus.
 - CPU data status: 2 bits of word 103. Data received or incomplete.
 - parity: bit 3 to 8 of word 103.

There are 7 different telemetry groups. Their respective position in the format depends on the selected TIP mode (the mode described here is 'orbital'). These digital and analog channels provide the required signals (synchronization and clock signals, power...) for all the on board electronics (processors, converters, drivers, memories, instruments, motors...), but also provide data links between the different interfaces (data bus...).

AIP minor frame description (NOAA-K series):

The spacecraft's AMSU Instrument Processor (AIP) collects digital data from the AMSU-A and AMSU-B sensors. These data consist of earth view pixel data, housekeeping data and space and blackbody view data.

- Size: 103 words distributed:
 - frame synchronization: 3 words.

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- spare: 1 word.
- minor frame counter: 1 word (from 0 to 79).
- major frame counter: 1 word (incremented every 80 minor frames, overflow to 0 synchronous with the TIP 32 s major frame pulse).
- spare: 2 words.
- AMSU-A1 numerical counts: 26 words (AIP read out at the rate of 260 words/s).
- AMSU-A2 numerical counts: 14 words (AIP read out at the rate of 140 words/s).
- AMSU-B numerical counts: 50 words (AIP read out at the rate of 500 words/s).
- spare: 4 words.
- AMSU parity: 1 word.

AIP minor frame description (NOAA-N series):

The spacecraft's AMSU Instrument Processor (AIP) collects digital data from the AMSU-A and MHS/MIU (MHS Interface Unit) sensors. These data consist of earth view pixel data, housekeeping data and space and blackbody view data.

- Size: 103 words distributed:
 - frame synchronization: 3 words.
 - spare: 1 word.
 - minor frame counter: 1 word (from 0 to 79).
 - 8 second frame counter: 1 word (last two bits are major (8-sec) frame counter. It is incremented every 80 minor frames, bits 7 and 8 of minor frame 5 will count 8-second intervals, the count overflowing to 0 synchronous with the TIP 32-second major frame pulse).
 - MIU/MHS Status: 2 words (8-bit words formed by the MIU to record status of the MHS and the MIU and read by the AMSU Information Processor at an average rate of 20 words per second).
 - AMSU-A1 numerical counts: 26 words (8-bit words are formed by the AMSU-A1 experiment and are read out by the AMSU Information Processor (AIP) at an average rate of 260 words per second).
 - AMSU-A2 numerical counts: 14 words (8-bit words are formed by the AMSU-A2 experiment and are read out by the AIP at an average rate of 140 words per second).
 - MHS numerical counts: 50 words (8-bit words are formed by the MHS experiment and are read out by the AIP through the MHS Interface Unit at an average rate of 540 words per second).
 - spare: 4 words.
 - bit TIP Parity (AMSU): 1 word.

8.1.2. level1b format general description

Description :

A detailed file format description stemming from the decommutation process is given in the AAPP data format document. The NOAA distributes level1b format data. The idea that is followed here is to keep the same file structure for 1a (after decommutation step) and 1b (after navigation and calibration steps) levels. The difference between 1a and 1b data is that some housekeeping data are converted in 1b and not in 1a, some calibration and navigation indicators are flagged in 1b, the fields relative to navigation (orbital parameters, angles, positions, velocities, attitude...), and calibration (coefficients...) are filled up.

Some general principles were adopted for the format elaboration:

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- The file header can be composed of several records. The header records length is the same as for the data records for a given instrument. Fillers are provided to keep record lengths multiples of 512 bytes.
- All character fields are ASCII and all fields are aligned.
- The dates are corrected from clock errors, and the day is Julian (reference 01/01/1950).
- Data are unpacked into 16 bit words.
- Real type data are converted to integer by a 10 power multiplication.

1b header general structure:

- **General information:** format version, satellite identification, data type, start and end dates, calibration parameter identification.
- **Data set quality indicators:** instrument status, number of lines or records, missing lines, parity errors, clock status, Earth location errors, PACS status bit field, data source.
- **Calibration parameters:** ramp non linearity for each spectral channel, calibration algorithm identification, mean coefficients and standard deviation.
- **Albedo and temperature-radiance conversion parameters:** central wave numbers, correction and non-linearity coefficients...
- **Navigation parameters:** navigation status, 3 attitude angles, orbit date, 6 orbital parameters, position-velocity vectors, Earth/Sun distance ratio.
- **Analog and digital telemetry conversion coefficients:** coefficients for PRT numerical counts to resistance or temperature conversion, numeric counts to current or voltage conversion...
- Filler.

1b record scan line general structure:

- **Scan line information:** date, line number, navigation and calibration quality indicators.
- Quality indicators
- Calibration coefficients.
- **Navigation data:** TIP attitude angles, zenith and azimuth angles in the satellite and sun directions, relative azimuth angles, latitudes/longitudes...
- **Instrumental measurements:** Earth view numeric counts for all spectral channels and all line FOV.
- Digital and analog housekeeping telemetry data:
- Filler.

8.1.3. Ingest format for MetOp data

AAPP/MetOp accepts MetOp data encoded in PFS level 0 format for pre-processing. This format is described in EPS-GGS-SPE-96167 [31].

It is the responsibility of the user to produce correct PFS L0 from the CCSDS instrument packets. Each instrument data shall be encoded in a separate file, with packets sorted by time.

After the decommutation stage traditional AAPP 1B format is used.

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8.2. NAVIGATION

8.2.1. Definitions

This section presents the definitions of the main parameters used in the navigation function. More details can be found in [17], [18] or directly in the Fortran code comments. The sign conventions of most parameters (and the reference frame axis positive directions) are somewhat arbitrary; the ones mentioned here are those used in AAPP.

The navigation is the conversion of the image coordinates, line and pixel numbers, into geographical coordinates, latitude and longitude, and reciprocally. The sun and satellite zenith azimuth angles are also calculated.

The Earth's surface is approximated by an ellipsoid whose center is at the Earth's gravity center.

Greenwich terrestrial reference frame

- The centre is at the Earth's gravity centre.
- The x-axis is the line from the Earth's gravity centre to the intersection between the equator and the Greenwich meridian, which defines the positive direction.
- The y-axis in the equatorial plane, normal to the x- and z-axis.
- The z-axis is the polar axis, positive toward the North Pole.

This Earth-fixed reference is widely used in AAPP. Using the Earth's ellipsoid parameters, the Cartesian coordinates in this frame can be converted in latitude, longitude, altitude, and reciprocally.

Local (geographical) vertical of a point: normal to the Earth's ellipsoid that contains the point, positive upward (the point may be on the Earth's surface or not).

(Geographic) latitude of a point: angle between the equatorial plane and the local vertical of the point, positive toward north.

Beware that the geographic latitude is not equal to the geocentric latitude, which is the angle between the equatorial plane and the line connecting the Earth's center and the point.

(Geographic) longitude : angle between the Greenwich meridian and the meridian of the point, positive toward east.

The navigation function calculates the zenith and azimuth angles of the sun or satellite, seen from an observation point, which is generally the viewed pixel and, for tracking calculations, the ground station. A local reference frame relative to the observation point is introduced for that purpose.

Local reference frame of an observation point

- The center is at the observation point.
- The x-axis is in the horizontal plane and the half plane that contains the meridian of the point, positive toward south.

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- The y-axis is in the horizontal plane, normal to the x- and z-axis.
- The z-axis is the local vertical of the observation point.

The horizontal plane is defined as normal to the local vertical, a vertical plan is any plane that contains the local vertical.

For an object, sun or satellite, seen from an observation point:

- The **zenith angle** is the angle between the local vertical and the point-to-object vector, it varies from 0 to 180 degrees.
- The **azimuth angle** is the angle between a vertical half plane containing the north direction (i.e. opposite to the local reference frame x-axis) and the point-to-object vector ; this angle varies from -180 to 180 degrees, is 0 at true north and positive toward east.

The azimuth angle definition is that of the NOAA level 1b. Beware that the sign conventions of the azimuth angle and local reference frame x-axis are not natural.

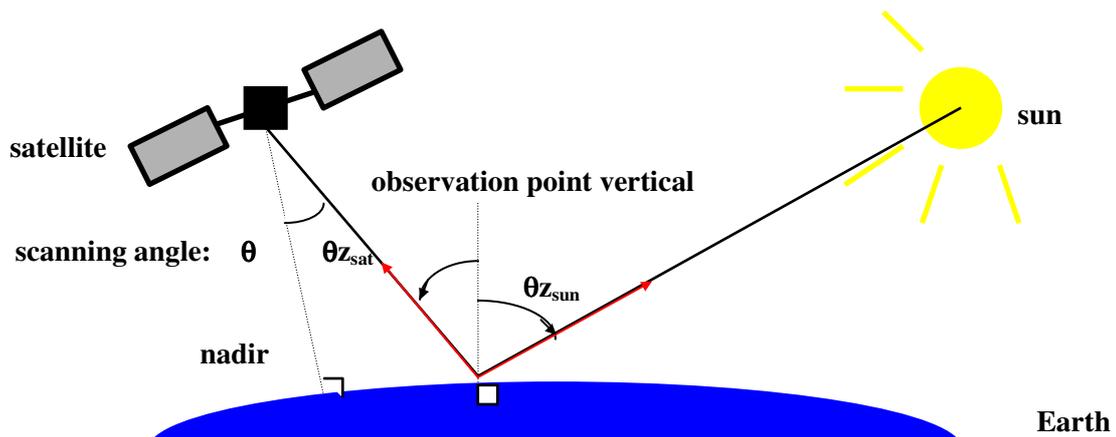


Figure 6:Sun and satellite zenith angles

The sun and satellite zenith angles are generally not in the same plane. The satellite zenith angle and the radiometer scanning angle are in slightly different planes.

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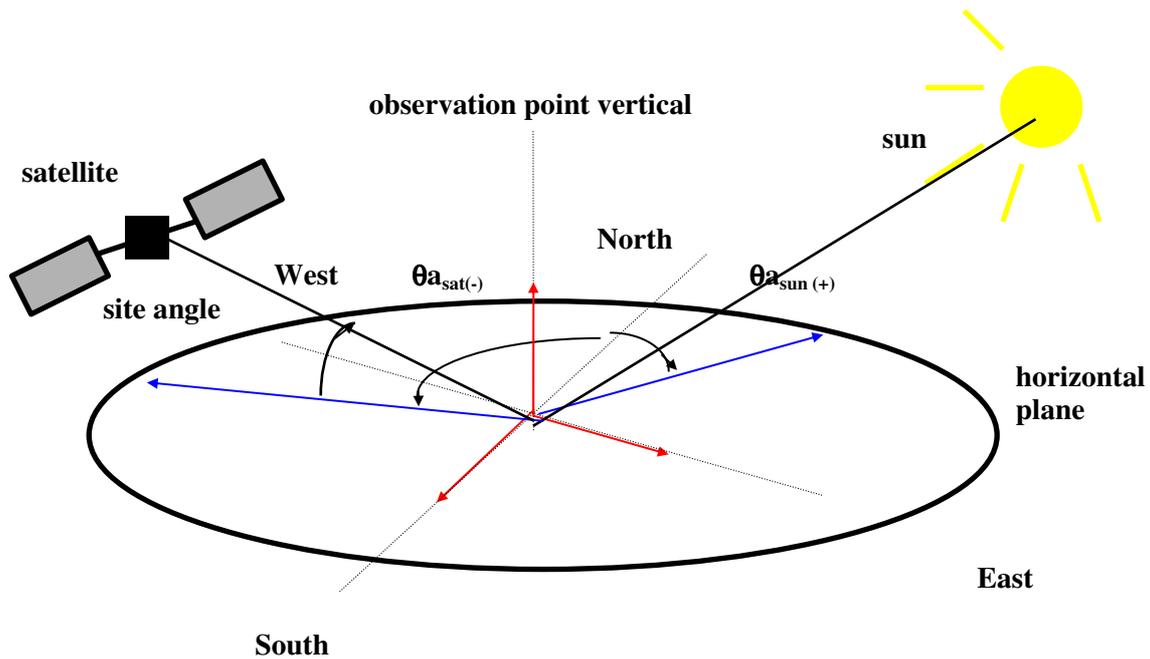


Figure 7: Sun and satellite azimuth angles

Spacecraft nominal orientation reference frame

This frame has a rather complicate definition based on the satellite velocity and local vertical, which depends on the satellite attitude mode.

“Local normal pointing mode”

- The center is at the satellite gravity center.
- The x-axis is opposite to the local terrestrial vertical (positive toward the Earth).
- The y-axis is normal to the x- and z-axis (nearly collinear to velocity, opposite in direction).
- The z-axis is normal to x-axis and to the satellite velocity, positive in the direction of the angular momentum vector of the orbit (nearly orthogonal to the orbit plane).

The local normal pointing mode is the usual mode of NOAA POES:

“Yaw steering mode”

The definition is the same as for the NOAA POES operational mode except that the z-axis is normal to x-axis and to the satellite velocity relative to the Earth.

The yaw steering mode is the usual mode of MetOp.

“Geocentric mode”

- The center is at the satellite gravity center.
- The x-axis is directed from the satellite to the Earth center.
- The y-axis is normal to the x- and z-axis (nearly collinear to velocity, opposite in direction).

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- The z-axis is normal to x-axis and to the satellite velocity, positive in the direction of the angular momentum vector of the orbit, it is orthogonal to the orbit plane.
- The geocentric mode is not a usual mode of NOAA POES neither of MetOp.

Spacecraft-fixed reference frame

- The center is at the satellite gravity center.
- The x-axis is the “vertical” axis of the spacecraft.
- The y-axis is the “longitudinal” axis of the spacecraft.
- The z-axis is the “transversal” axis of the spacecraft.

These axes are defined precisely with respect to some elements of the spacecraft structure, their positive direction being consistent with the spacecraft nominal orientation.

The spacecraft-fixed reference frame should be perfectly aligned with the spacecraft nominal orientation reference frame, but it differs from it by three small rotation angles: yaw about the x-axis, roll about the y-axis and pitch about the z-axis. The sign conventions are the following:

- yaw > 0 : the spacecraft longitudinal axis is orientated toward the right of the trajectory
- roll > 0 : the spacecraft vertical axis is on the right of the sub-track
- pitch > 0 : the spacecraft vertical axis is behind the sub-point

So, the satellite “**attitude error**” or “attitude” represents an orientation error of the spacecraft with respect to its nominal value. It is expressed by three small **attitude angles**, the **yaw, roll and pitch**.

Instrument-fixed reference frame

- The center is at the satellite gravity center.
- The x-axis is nearly aligned with the “vertical” axis of the spacecraft.
- The y-axis is nearly aligned with the “longitudinal” axis of the spacecraft.
- The z-axis is nearly aligned with the “transversal” axis of the spacecraft.

These axes are defined precisely with respect to some elements of the instrument structure. They should be perfectly aligned with the spacecraft-fixed axes, but differ from them by three small rotation angles: in yaw about the x-axis, in roll about the y-axis and in pitch about the z-axis. These **misalignment angles** are constant during the satellite lifetime.

Scanning plane: many instruments considered in AAPP (AVHRR, HIRS, AMSU) are cross-track scanning radiometers, i.e. having a scanning plane normal to the spacecraft longitudinal axis. AAPP may also handle an instrument with a tilted scanning plane, which corresponds to an additional rotation about the spacecraft transversal axis..

Conical scanning: the radiometer viewing direction lies in a cone and rotates about the cone axis at a constant speed, the cone axis being in the instrument longitudinal plane, aligned with the vertical axis or inclined forward or backward.

8.2.2. Principles of the navigation method

The AAPP navigation method is based on precise geometrical calculations using time varying parameters: satellite position and velocity, satellite clock error and satellite attitude (or orientation) and constant parameters defining the scanning of each instrument (AVHRR, HIRS, AMSU or MHS). It

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has been designed initially for NOAA POES data and generalized in order to process MetOp data or, possibly, other satellite data. This section summarizes the essential features of the method, without presenting the equations. The main equations together with a detailed description of the method are presented in [17], some additional equations can be found in [18] and the equations corresponding to AAPP-5 and 6 are given in [22].

The satellite position and velocity are calculated by an analytical orbit extrapolation model that ingests daily orbital elements of the satellite. For NOAA satellites, two options are proposed, based on TBUS bulletins or Two-Line Element sets. For MetOp satellites, two options are also proposed based on Two-Line Element sets or SPOT-5 element sets.

While the orbit prediction and all navigation calculations are made in Universal Time (UT), the NOAA image data are dated with the satellite clock, which drifts and is periodically reset. Until 2002, the satellite clock error values issued by NOAA/NESDIS in the TBUS bulletin were used to correct the satellite clock times into UT values but this step is no longer required.

The scanning direction (from the satellite to the viewed pixel) is defined in a spacecraft instrument-fixed reference frame, which slightly differs from its nominal orientation due to the misalignment angles. These errors are taken into account in the geometrical calculations, assuming constant misalignment angles and a constant value attitude error over a whole HRPT acquisition. The attitude error is expected to vary from one pass to another.

The various steps of the method are clearly separated. The satellite orbit prediction produces an intermediate file of position and velocity vector, which allows replacing the orbit extrapolation program without changing the other navigation modules. Correcting for the satellite clock error can be by-passed. The actual values of the satellite attitude, if any, are read in a separate file.

For NOAA POES, Estimating the actual satellite attitude is not straightforward since NOAA/NESDIS does not distribute this information to the users. The AAPP user has several options to cope with this problem:

- use the default value of each satellite, which is included in AAPP Fortran code; this option only eliminates the systematic errors, which have been well established on historical data,
- calculate some landmark navigation errors and derive from them the attitude error, through some of the AAPP routines,
- interface AAPP with the add-on software ANA-3 (see 8.2.5).

8.2.3. Satellite position and velocity

Orbit prediction

The satellite position and velocity can be calculated by a complex and precise numerical model ingesting numerous trajectory measurements or by a simple analytical model ingesting a set of orbital elements (position-velocity or elliptical parameters), which is valid at a given date. Several services NOAA/NESDIS, NASA NORAD, CNES and Eumetsat routinely produce bulletins containing orbital elements of the NOAA/MetOp satellites, which have been derived from precise orbit calculations. The

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user can enter these orbital elements into a simple analytical orbit prediction model to compute the satellite position and velocity at any time. Better results are expected if the analytical model is consistent with the previous orbit calculations. NOAA/NESDIS, which distributes orbital elements in the TBUS bulletin, recommends and distributes an orbit extrapolation model, called **BROLYD**. NORAD distribute the Two-Line Element sets and the orbit extrapolation models **SGP4** (for near-Earth satellites having a period lower than 225 minutes) and **SDP4** (for deep-space satellites). EUMETSAT distributes the **SPOT-5** element sets and the orbit extrapolation model **SPM** [31]. These orbit extrapolation models have been implemented in the AAPP package without any change.

Orbital element ingest

The orbital elements are not directly used for navigations calculations, but after an “ingest” step, which decodes the TBUS bulletin or the Two-Line Element file or the SPOT-5 file and controls the quality of newly received sets of orbital elements. This control uses the BROLYD, SGP4, SDP4 or SPM model to calculate a forward extrapolation error of the last preceding valid set onto the current set and a backward extrapolation of the current set onto the preceding one. If these are lower than a threshold, the current set is considered as valid. This control eliminates a few orbital element sets having a poor quality when compared to the others. All received bulletins are stored and some essential information (epoch time, orbit, quality...) is stored in an historical index file. The ingest step allows the addition of old sets of orbital elements.

Position and velocity calculation

The satellite position-velocity is required at any step of the navigation and some equations are solved by iteration. Using the orbit extrapolation model whenever position-velocity value is needed is not realistic. Therefore, a two-step method is used:

- The extrapolation model produces position and velocity vectors every two minutes and these values are stored in the so-called SATPOS file; this task is done daily.
- The position and velocity vector at any time are calculated by a cubic interpolation using the SATPOS file values; this interpolation is done whenever needed.

The cubic interpolation, between vectors every two minutes, introduces a 3 m error on the position and 0.01 mrad error on the velocity vector direction, which induce errors of the same order of magnitude on the pixel navigation. Such errors are negligible compared to the AVHRR pixel size (about 1km and 1 mrad) and the two-step method has the same accuracy as, for example, the TBUS+BROLYD orbit extrapolation. There is no need to test the cubic interpolation also with Two-Line+SGP4 or SPOT-5+SPM orbit extrapolation, since interpolation does not rely on the extrapolation model.

A geostationary satellite orbit can be calculated with Two-Line Element sets and SDP4, however this feature is well beyond the scope of AAPP and has not been studied in detail.

8.2.4. NOAA POES Satellite clock error

Before summer 2002

The satellite clock drifts during the life of the satellite. Its error is measured weekly and the clock is periodically reset, when the error becomes too high. Information on the satellite clock is published in the TBUS part IV and consists of four parameters:

- clock error: date and value,
- clock error rate: date and value,

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- clock error after last correction: date and value,
- next clock correction: date only.

As the TBUS is delivered daily, the same information is repeated in several successive bulletins. The next clock correction is generally announced well in advance, but the clock error value after the correction is always unknown. At the time of NOAA-11, the reset scheme was regular and rather predictable. This is not true any more.

As for the orbital elements, the clock error information is used after an “ingest” step. This step decodes the TBUS bulletin, controls the information quality and stores the valid information into an historical clock error file, without any duplication of the redundant information. This file is used to obtain the clock error at any time t, as needed for real time or off-line navigation.

The main rules of the quality control and clock error calculation are the following:

quality control

- The clock error at time t is compared to a predicted value at t, derived from the last preceding clock error and clock error rate values and must be close to this predicted value.
- The clock error after last correction is considered as valid in any case.
- The clock error rate must be close to the last preceding one.

clock error calculation

- The clock error at time t is derived from the last values preceding t of the clock error rate and of the clock error, which may be a usual clock error or a clock error after last correction.
- After a clock correction, a zero value is assumed for the clock error, until a clock error after last correction is issued in the TBUS or is manually inserted by the operator.

parameters entered interactively (ignored by the clock information ingest)

- a “null” flag associated to a date, to force a zero value of the clock error for any time after this date; this flag is expected to be used exceptionally, for instance, when several erroneous values occur in the TBUS, making the quality control inefficient.
- a “bias”correction associated to a date, which is added to the clock error for any time after this date. Different bias values can be used during the satellite lifetime. The bias correction is added in any case, even after a clock correction or with a null flag. The bias correction has been introduced because of the clock problem encountered on NOAA-16 and NOAA-15 since September 16, 1999 (see “NOAA-16 Along Track Error”, “KLM/ATN Timing Discrepancy - Along Track Anomaly” and “NOAA-15 and 16 Elapsed Time Clock Up” in [19]).

Handling the clock error is a rather complicated process, mainly because erroneous values frequently occur in the TBUS. Furthermore, it should be noted that some of them remain undetected by the AAPP automatic control.

Since summer 2002

NOAA has modified its clock error adjustment method, firstly for NOAA-17 and then for all other NOAA POES. The Satellite Operations Control Center (SOCC) is performing daily clock drift corrections at 23:59:00 UTC for each satellite, in order to reduce the clock error to +/-0.075 second. Therefore processing TBUS clock errors is no longer necessary. The corresponding routines and files have not been removed from AAPP-5 or 6, in order to allow re-processing of data earlier than 2002.

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For present data, it is recommended to by-pass any clock error calculation, by introducing a “null” flag and a “bias” correction of 0 in the clock error file of each NOAA satellite.

8.2.5. NOAA POES and MetOp Satellite attitude

The satellite attitude errors induce navigation errors corresponding typically to a few AVHRR pixels. Using a correct attitude value is more important for AVHRR imagery than for HIRS or AMSU imagery.

AAPP has been designed to use an attitude value constant over an HRPT (AHRPT for MetOp) acquisition but varying from one pass to another. The attitude value is supposed to be obtained on an actual AVHRR image by a two-step process:

- locating landmarks in the image to calculate their navigation errors, i.e. the differences between their calculated and true positions in the image
- estimating a satellite attitude error from the landmark navigation errors
- AAPP contains the routines corresponding to the second step, but not to the first one.

The landmark location can be done by the software called ANA-3, i.e. Automatic Navigation Adjustment, version 3 [20]. Such an automatic adjustment has been used operationally at the CMS since 1990 [21]. The software has been re-visited in 2000 to be fully compatible with AAPP and use the precise “World Vector Shoreline” as reference coastline. ANA-3 locates selected coastal landmarks in the AVHRR image, by searching the optimal correlation between small windows in the actual image and the reference landmarks, using channels 1 and 2 for daytime conditions and channels 4 and 5 for nighttime conditions. A cloud mask is calculated to reject the too cloudy landmarks, using MAIA2 routines, which are included in AAPP, version 3 (and later versions).

8.2.6. Image navigation

The image navigation converts the line and pixel numbers into latitude and longitude for any pixel of the image, using the satellite parameters previously described.

A necessary step is the conversion of the line and pixel numbers into time and scanning angle, which is based on constant characteristics of the instrument, AVHRR, HIRS, AMSU, MHS or IASI. The instrument values published in section 3 of [1], which are independent on the satellite number, have been used successfully until NOAA-15. Unusual navigation errors have been observed on NOAA-16 imagery and NOAA/NESDIS has recommended some specific corrections (see “Operational Status of NOAA-16 Level 1B” in [19]). These corrections have been put in AAPP-5 or 6, in the so-called “satid” file where the instrument characteristics are defined for each satellite: lower scanning angle step for AVHRR on NOAA-16 and misalignment angles for HIRS-3 on NOAA-16 and NOAA-17. Two corrections have been introduced in AAPP: a lower AVHRR scanning step angle corresponding to a maximum scanning angle of +/-55.25 degree and a 2-degree offset in pixel of the whole HIRS image (NOAA has recommended a 1.8 degree offset, the 2 degree value has been obtained by matching HIRS channel 8 and AVHRR channel 4 images).

The core of the image navigation, which is common to all instruments, is the conversion of the time and scanning angle into latitude and longitude, or direct problem, and the inverse problem.

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In the direct problem, the satellite-to-pixel vector is known in the spacecraft-instrument-fixed reference frame; the time is also known and so are all the conversion matrices between the spacecraft-instrument-fixed frame and the Earth-fixed frame. The latitude and longitude are calculated by analytical solution of several equations.

In the inverse problem, which is solved only for cross-track scanning radiometers, the time and, consequently, the conversion matrix are unknown. An iterative resolution is required to calculate the time and scanning angle. The iterative scheme uses convergence criteria corresponding to a position error that is significantly lower than the AVHRR pixel size.

The image navigation uses a satellite attitude constant over the whole image. The method could evolve in order to use a time varying attitude, if the attitude can be calculated at any time by analytical formulas or tabulated values.

8.2.7. Expected accuracy

With the standard options (daily TBUS bulletins, clock error corrected and default satellite attitude), the expected navigation accuracy is about 3 km, in terms of r.m.s. error [17].

In a year of high solar activity (with respect to the 11-year solar cycle), the navigation error may reach 6 to 8 km during a limited period (one or two weeks), corresponding to a phase of intense solar activity, which decreases the orbit prediction accuracy.

Unusual errors of 10 to 15 km may occur on a few passes, due to various reasons: an erroneous clock error value (generally associated with a reset), a satellite attitude anomaly or a very strong solar activity event.

With the Two-Line Element sets, the navigation accuracy is expected to be better than with TBUS bulletins, as shown by an experiment on a 6-month period [22]. This period is not long enough to estimate the navigation accuracy of the Two-Line method in case of high solar activity. More recently, in 2005-2006 the navigation accuracy of NOAA-17 and NOAA-18 has been only slightly better with the Two-lines than with TBUS.

In any case, normal situation or exceptional events, the navigation error is generally a “line” error and not a “pixel” error.

If an automatic adjustment on landmark is used together with AAPP, the expected accuracy is 1.7 km for the passes where this adjustment has been successful [17].

8.2.8. Ephemeris and tracking angles

The AAPP software can also produce useful information for the tracking operations of a ground station:

- an ephemeris file, which contains the times of various events (ascending and descending nodes, start and end of acquisition); there are several types, short term and long term, mono- or multi-satellite,
- a tracking angle file, relative to one station and one satellite, which contains site and azimuth values every second (the site is equal to 90 degree minus the satellite zenith angle).

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The **ephe** command produces a short term ephemeris file, i.e. corresponding to duration of the input SATPOS file, which is relative to one satellite and one station. This ephemeris file has the same precision as the image navigation, since the satellite position calculation is based on the SATPOS file with the method presented in section 8.2.3.

The **alleph** command produces the short-term ephemeris and tracking angle files, for one station and several satellites. It also merges the mono-satellite ephemeris files into a multi-satellite ephemeris file where the acquisition conflicts (two satellites passing simultaneously) have been identified and one satellite has been chosen according to priority rule. Here again, the satellite position is calculated with the SATPOS file and all files have the same precision as the image navigation.

AAPP can also produce a long-term ephemeris, i.e. over several months, for one satellite and several stations. In that case, the satellite position is calculated by an approximate method: circular orbit with linear variation of the nodal period and of the node longitude increment. This method is definitely less precise than using SATPOS for a two or three day extrapolation, but its error increases very slowly with time. So, a long-term ephemeris can be used to prepare a planning or an experiment schedule. The long-term ephemeris is produced by two commands:

- **lgepheing**, which ingests a TBUS, extracts the parameters that are ephemeris-related (mainly the nodal period and node longitude increment) and stores them into an historical file.
- **lgephe** , which creates the long-term ephemeris file.

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8.3. CALIBRATION

All the referenced data and all the calibration procedures are detailed in reference [1] for each instrument and [23] for the HIRS calibration algorithm version 4.

8.3.1. Thermal field : Background.

At equilibrium state, the radiative field is only temperature dependent, non-polarised and isotropic. The field is characterised by its monochromatic radiance (or black body radiance) R_σ ($\text{W.m}^{-2}.\text{sr}^{-1}.\text{cm}$) at temperature $T(\text{K})$. Taking into consideration that radiative emission is due to electrical oscillators whose energy is quantified ($h \nu$ integer multiple), Planck's law is expressed as:

$$R_\sigma(T) = B(\sigma, T) = \frac{2hc^2 \sigma^3}{e^{\frac{hc\sigma}{kT}} - 1}$$

with :

- $h = 6.6261 \times 10^{-34}$ J.s, Planck constant.
- $c = 3 \times 10^8$ m.s^{-1} , light velocity.
- $k = 1.38 \times 10^{-23}$ J.K^{-1} , Boltzmann constant.
- σ = wave number in cm^{-1} .
- $B(\sigma, T)$ = Planck's function.

where the temperature is extracted by inverting the previous relation:

$$T = \frac{C_2 \sigma}{\ln\left(1 + \frac{C_1 \sigma^3}{R_\sigma}\right)}$$

- with : $C_1 = 1.191 \times 10^{-5}$ $\text{mW.m}^{-2}.\text{sr}^{-1}.\text{cm}^4$
- $C_2 = 1.439$ K.cm .

8.3.2. Calibration principle

The calibration procedure establishes a relation between the sensor output measured on a n-bits dynamic range (2^n possible values) and the associated physical parameters, i.e. between the observed scene radiance and the corresponding numeric counts. Figure 8 illustrates the IR measurement principle.

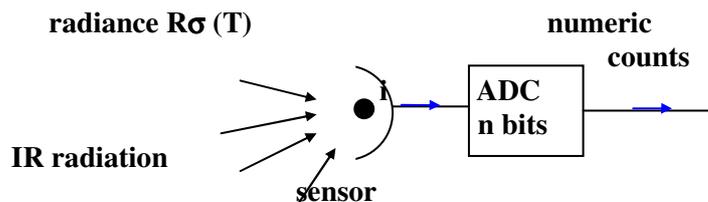


Figure 8: One IR channel for radiance measurements.

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This relation depends on each spectral channel and on the temperature of the whole set up. The thermal channels (IR and μ -wave) are calibrated with the help of a warm black body target (where the radiance versus temperature follows Planck's law), and with a cold target (usually the cold space view). The visible channels are calibrated using halogen lamps. A pre-launch calibration procedure exists for all channels. The measured radiance is converted into brightness temperature by inverse Planck's law application.

8.3.3. HIRS and AVHRR visible channels calibration for albedo determination (AVHRCL and HIRSCL)

The VIS calibration performs the conversion of numeric counts into albedo (in percent). This quantity is calculated applying the linear function:

$$A_i = G_i X + I_i$$

with A_i = albedo percentage
 G_i = channel i gain
 X = numeric counts from measurements on channel I
 I_i = albedo offset for a zero numeric count.

Gains and offsets are measured and referenced before the satellite launch for each VIS channel. An integrating sphere is used as illumination source for the calibration procedure.

The sphere equipped with 20 halogen quartz lamps is calibrated: the spectral radiance emerging from the sphere versus the number of turned on lamps, is determined. The result is a calibration curve where the spectral radiance varies over three orders of magnitude from black (all lamps turned off) to the maximum level of illumination (all lamps turned on). Each instrument channel is illuminated by the light emerging from the sphere, and integrates the sphere output radiance according to the own spectral channel bandwidth. The maximum in-band radiance (20 lamps switched on) is noted $R\sigma_i$. In flight, each channel integrates an $R\sigma_s$ radiance due to the reflected solar radiation at the top of the atmosphere. The albedo percentage is defined as the ratio:

$$A = 100 \frac{R\sigma_s}{R\sigma_i}$$

To convert the albedo percentage into spectral radiance R_λ ($\text{W}\cdot\text{m}^{-2}\cdot\text{sr}^{-1}\cdot\mu\text{m}^{-1}$), the following relation is applied:

$$R_\lambda = \frac{AF}{100\pi W}$$

with : F = integrated and weighted (channel spectral response function) solar flux ($\text{W}\cdot\text{m}^{-2}$).
 W = spectral channel bandwidth (μm).

Some channels (VIS and near IR) are known to degrade in orbit, which means that the pre-launched calibrated values evolve slowly over time. Because of the absence of on board calibration devices for the VIS channels, other in flight calibration techniques based on the observation of radiometrically

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stable terrestrial calibration target sites (ice, desert...) can be used, after some corrections for atmospheric effects.

The calibration coefficients values are listed in reference [1], and read from the *avhcal.txt* (AVHRR) and *calcoef.dat* (HIRS) or *h_calcoef_algoV4.dat* (HIRS calibration algorithm version 4) parameters files for the AAPP calibration procedure. These coefficients are stored in the level1b files: *hrpt11b*, and *hirs11b*. The AAPP operational scheme keeps the coefficient values in agreement with the pre-launch coefficients given by NOAA on the web site of the NOAA user's guide [1].

8.3.4. AVHRR thermal channels calibration (AVHRCL)

The pre-launch calibration procedure establishes a relation between the thermal channels numeric counts and a calibrated black body radiance source. This relation is linear for channel 3 (InSb sensor), but not for channels 4 and 5 (HgCdTe sensor). Non-linearity corrections must be applied for numeric counts to radiance conversion.

After the satellite launch, the results of the calibration performed on the ground can't be applied anymore, because the radiometer characteristics change. The thermal channels are then calibrated in flight, periodically, by radiance measurements on reference sources as space (sp - cold target), and as on board black body (bb - warm target) whose temperature is determined by platinum resistance thermometers (PRT). (The variation of the resistance is a function of temperature, so the current through the PRT varies and is converted into numeric counts to be introduced into the HRPT format). For each spectral channel, a calibration curve is established with the help of the two referenced measurements on the cold and warm targets. Any radiance corresponding to any given numeric count can then be deduced from this curve.

An example of calibration curve is shown on Figure 9.

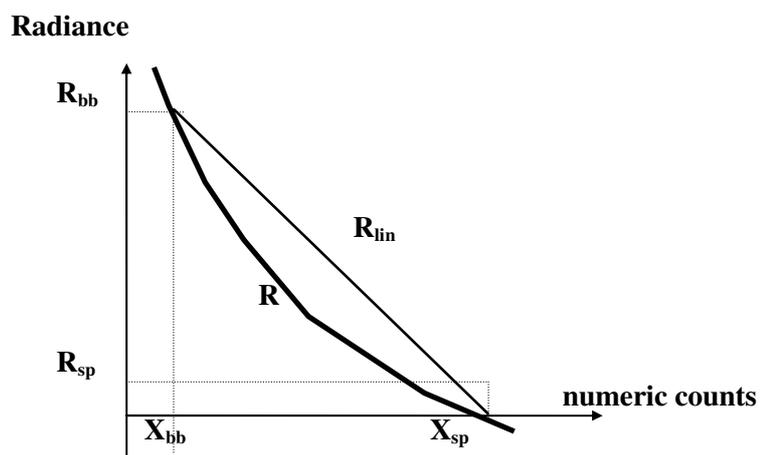


Figure 9: Calibration curve (radiance as a function of the numeric counts).

The radiance is converted into brightness temperature by application of the inverted Planck's formula.

To determine the reference black body radiance, its temperature has to be measured. This task is performed by the PRT numeric counts extraction on the 4 platinum resistances, two of the PRT temperatures being colder than the other two. For one PRT, the temperature (K) is given by the conversion relation (PRT numeric count to temperature):

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$$T_i = \sum_{j=0}^4 a_{ij} (PRT_i)^j$$

with : T_i = PRT number i temperature
 a_{ij} = conversion coefficient
 PRT_i = mean numeric counts associated to PRT number i.

The reference black body temperature T_{bb} (K) is determined by averaging the temperatures derived from the 4 PRTs:

$$T_{bb} = \sum_{i=1}^4 b_i T_i$$

with : b_i = weighted coefficient.

a_{ij} and b_i coefficients are referenced in document [1] for each PRT, and in the *avhcal.txt* parameters file for the AAPP calibration task.

The expression for black body radiance R_{bb} at temperature T_{bb} , is established using the Planck formula $B(\sigma, T)$, and taking into account the AVHRR spectral channels response function $\Phi(\sigma)$:

$$R_{bb} = \frac{\sum_{i=1}^n B(\sigma_i, T_{bb}) \Phi(\sigma_i) \Delta\sigma}{\sum_{i=1}^n \Phi(\sigma_i) \Delta\sigma}$$

with : $\Delta\sigma = \sigma_{i+1} - \sigma_i$ = spectral interval for calculation.

$\Delta\sigma$ and $\Phi(\sigma_i)$ are specified in document [1] for each thermal channel, and in the *avhcal.txt* parameter file for the AAPP calibration task.

Each channel gives a mean (associated to several target observations) numeric count X_{bb} corresponding to R_{bb} .

The cold reference is given by the space radiance R_{sp} . During this measurement, the radiometer scanning mirror is turned toward space, and doesn't look at the Earth. Each channel gives the corresponding X_{sp} numeric counts.

Notes: The PRT numeric counts are included in the HRPT format. The numeric counts for a given PRT are given every 5 minor frames:

HRPT minor frame	parameter
n	REF (for synchro.)
n+1	PRT1
n+2	PRT2
n+3	PRT3

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n+4	PRT4
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Table 4: PRT_i numeric counts occurrence.

One PRT mean temperature is calculated with 11 measurement samples (representing 55 minor frames for the 4 PRTs).

Linear approximation: From (R_{bb} , X_{bb}) and (R_{sp} , X_{sp}), the equation of the calibration curve is easily established for each linear channel:

$$R_{lin} = GX + I$$

with : $G = (R_{bb} - R_{sp}) / (X_{bb} - X_{sp})$

$$I = R_{sp} - G \cdot X_{sp}$$

R_{lin} is the radiance corresponding to X numeric counts associated to Earth observation.

Non linearity corrections: are directly applied on the R_{lin} radiance:

$$R = aR_{lin} + bR_{lin}^2 + c$$

a, b and c are referenced in document [1] for each non linear AVHRR channel, and in the *avhcal.txt* parameters file for AAPP calibration task.

Introducing the R_{lin} , G and I expressions in R formulation, one can deduce a direct relation between R and the corresponding numeric counts X:

$$R = k1X^2 + k2X + k3$$

with : $k1 = b \cdot G^2$

$$k2 = a \cdot G - 2 \cdot k1 \cdot X_{sp} + 2 \cdot b \cdot G \cdot R_{sp}$$

$$k3 = c + a \cdot R_{sp} - a \cdot G \cdot X_{sp} + b \cdot (R_{sp} - G \cdot R_{sp})^2$$

These calibration coefficients are stored in the level1b *hrpt11b* file. The numeric counts X are converted into radiances using the previous relation. The radiances are converted into brightness temperatures using the inverted Planck's law. These results are reported in the level1c file.

Note: The calibration coefficients are calculated for each scan line. This calibration method is valid for AVHRR/2 and AVHRR/3.

Values of parameters useful for computing calibration parameters are written to a file *monavhr.txt*. This historical file allows the study of the target counts, space counts and PRT counts, so that the instrument health can be checked. The AAPP user has to create his own tools to study the values written in the file. The data format is described in the AAPP data format document.

8.3.5. HIRS thermal channels calibration: First algorithm available in AAPP (HIRSCL)

The thermal channels are calibrated in flight, by radiance measurements on reference sources each 40 scan lines. For HIRS/2, 3 or 4 calibration lines are then introduced to produce numeric counts corresponding to space radiance (sp - cold target), and to the radiance of two on-board black bodies

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(bb - one warm and one cold target) whose temperature is determined by platinum resistances (PRT). However, the bb cold target temperature is not used in the computation, because of the large temperature gradients induced by solar contamination. For HIRS/3 and 4, there are only 2 calibration lines, one for space and one for the on-board warm bb target.

For each spectral channel, a linear calibration curve is established with the help of the two referenced measurements on the cold space and on the warm target. Any radiance corresponding to Earth observation numeric counts can then be deduced from this relation.

To determine the reference black body radiance, its temperature has to be measured. This task is performed by the PRT numeric counts extraction on the 4 platinum resistances for HIRS/2 or 3, on the 5 platinum resistances for HIRS/4. For one PRT, the temperature (K) is given by the conversion relation (PRT numeric count to temperature):

$$T_i = \sum_{j=0}^5 a_{ij} (PRT_i)^j$$

with : T_i = PRT number i temperature

a_{ij} = conversion coefficient

PRT_i = mean numeric counts associated to PRT number i.

The reference black body temperature T_{bb} (K) is determined by averaging the temperatures derived from the 4 or 5 PRTs.

a_{ij} coefficients are referenced in document [1] for each PRT, and in the *calcoef.dat* parameters file for the AAPP calibration task.

5 PRT_i measurements performed during the calibration line of the warm target, plus 5X measurements of the PRT_i from X calibration lines around the warm target, are used in the calculation of a PRT mean numeric counts (PRT_i). The X value is written in *testcoef.dat* file. For each calibration cycle (every 40 scan lines), the mean numeric counts PRT_i results from the averaging of $5*(2X+1)$ measurements on the target.

The black body radiance R_{bb} at T_{bb} temperature, is established using the Planck's law:

$$R_{bb} = B(\sigma_c, T_{bb}^*)$$

with : σ_c = central wave number

$T_{bb}^* = b + c.T_{bb}$ effective temperature with band correction.

b and c are referenced in document [1] for each channel, and in the *calcoef.dat* parameter file for the AAPP calibration task.

For each channel, average values of numeric counts X_{bb} (of several target observations) corresponding to R_{bb} and of X_{sp} corresponding to R_{sp} are determined. The computation of the mean numeric counts requires that the 56 calibration line samples are filtered and bad values eliminated (the test parameters are available in *calcoef.dat* and *testcoef.dat* files). This is necessary because the 8 first space views are polluted by the movement of the radiometer (while the 56 samples are correct for the bb target, but the 8 first bb views are also rejected for the homogeneity question). Finally, 48 samples are processed for space and black body target.

Thanks to (R_{bb} , X_{bb}) and (R_{sp} , X_{sp}), the equation of the calibration curve is easily established for each linear channel:

$$R = GX + I$$

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R is the radiance corresponding to X numeric counts associated to Earth observation.

The slope $G = (R_{bb} - R_{sp}) / (X_{bb} - X_{sp})$ and the intercept $I = R_{sp} - G.X_{sp}$ are the calibration coefficients relative to the calibration lines cycle. For every scan line containing Earth view data (between the calibration cycles), new (G,I) coefficients are calculated using a linear interpolation of the coefficients of the two surrounding calibration cycles. These coefficients are stored in the level1b *hirs11b* file. For each channel, the mean (G,I) calibration coefficients are calculated and stored in the header of the *hirs11b* file. The radiances are converted into brightness temperatures using the inverted Planck's law. These results are reported in the level1c file.

Values of parameters useful for computing calibration parameters are written to a file *monhirs.txt*. This historical file allows the study of the target counts, space counts and PRT counts, so that the instrument health can be checked. The AAPP user has to create his own tools to study the values written in the file. The data format is described in the AAPP data format document.

8.3.6. HIRS thermal channels calibration: Second algorithm available in AAPP (HIRSCL_ALGOV4)

Introduction

This algorithm doesn't work for data of pre-NOAA-K satellites. It was developed to manage the HIRS calibration algorithm version 4.0 of the NOAA and described in [23] and [24]. It is also useful to refer to the NOAA KLM User's guide Section 7.2 [1].

This algorithm was developed in AAPP to be very similar to the calibration process of NOAA – the aim being to have consistency between local data and global data. Nevertheless the main difference between the AAPP algorithm and the NOAA algorithm is for the average data (average slopes and B1, coefficients of correlation between the telescope temperature and calibration intercept) NOAA uses 24 hour averages. These are not available from local data, so the average slopes and B1 are computed from past data. The past data are taken from the reference date minus x hours to the reference date. By default, the reference date is the date of the current orbit, x is defined by the AAPP user (see ATOVS_ENV).

The second main difference is that the AAPP algorithm does not control the moon contamination on the space views. This will be done in a future version of AAPP.

The choice of flagging some bits in the level 1b could also be different.

Note that the new algorithm has been validated using a limited amount of NOAA-KLM HIRS data.

Principle

The HIRS thermal channels are calibrated in flight, by radiance measurements on reference sources each 40 scan lines (256 seconds). For HIRS/3 or 4 the reference sources are a space scan line and an on-board blackbody (BB) or internal warm target (IWT) scan line. For each spectral channel, a calibration curve is established with the help of the two referenced measurements on the cold space and on the warm target. Any radiance corresponding to any Earth observation numeric counts can then be deduced.

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It is assumed that radiance can be related to counts through the quadratic equation:

$$R = a_0 + a_1 * CN + a_2 * CN^2 \quad (1)$$

With R = radiance

CN = output in counts from the view

a_0, a_1, a_2 = calibration coefficients

Assuming that a_2 is computed before launch and is an unchanging characteristic of the channel, a_0 and a_1 can be determined if we apply equation 1 to simultaneous views of space and blackbody (warm target) source:

$$\begin{aligned} \text{From } R_{sp} &= a_0 + a_1 * CN_{sp} + a_2 * CN_{sp}^2 \\ R_{bb} &= a_0 + a_1 * CN_{bb} + a_2 * CN_{bb}^2 \end{aligned}$$

With R_{sp} = radiance of the space (the assumption is made that $R_{sp} = 0$)

R_{bb} = radiance of the black body views

CN_{sp} = mean count from the views of space

CN_{bb} = mean count from the views of black body

$$\text{We get } a_1 = [R_{bb} - a_2 (CN_{bb}^2 - CN_{sp}^2)] / (CN_{bb} - CN_{sp}) \quad (2)$$

$$a_0 = -a_2 CN_{sp}^2 - a_1 CN_{sp} \quad (3)$$

a_j is the slope, a_0 the intercept.

The aim of this calibration task is to compute the slope and the intercept.

Step 1: For each internal blackbody view scan line, determine the blackbody temperature and for each IR channel, the radiance (R_{bb}):

To determine the reference blackbody radiance, its temperature has to be measured. This task is performed by the numeric counts extraction on the 4 platinum resistance thermometers (PRT) for NOAA-KLM and the 5 PRTs for NOAA-N. For one PRT, the temperature is given by the conversion relation (PRT numeric count to temperature):

$$T_i = \sum_{j=0}^5 a_{ij} (PRT_i)^j$$

with : T_i = temperature of the PRT number i, a_{ij} = conversion coefficient

PRT_i = mean of the numeric counts associated to PRT number i.

a_{ij} coefficients are referenced in document [1] for each PRT, and in the h_calcoef_algoV4.dat parameters file for the AAPP calibration task.

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5 PRTi measurements are performed during the calibration line of the warm target. 2*5X measurements of the PRTi from X calibration lines around the warm target scan line are also used in the calculation of a PRT mean numeric counts (PRTi).(X in h_testcoef_algoV4.dat file).

The 5*(2X+1) PRTi measurements are checked:

the difference between the maximum PRTi measurement value and the minimum one must be less than a limit prtminmax (in h_testcoef_algoV4.dat file)

the minimum number of valid PRTi measurements to compute a mean is prtminnb (in h_testcoef_algoV4.dat file)

The mean numeric count PRTi results from the averaging of valid measurements.

The reference blackbody temperature Tbb is determined by averaging the temperatures derived from the 4 or 5 PRTs. If only one or zero temperatures are computed, the reference blackbody temperature is declared bad. The calibration cycle is declared unqualified.

The blackbody radiance Rbb at Tbb temperature is established using the Planck's law:

$$R_{bb} = B(\sigma_c, T_{bb}^*)$$

with : σ_c = central wave number

$$T_{bb}^* = b + c.T_{bb}$$

effective temperature with band correction.

b and c are referenced in document [1] for each channel, and in h_calcoe_algoV4.dat parameter file for AAPP calibration task.

Step 2: For each calibration cycle and for each IR channel, compute the averaged output counts for the space views and for the internal blackbody views

At each calibration cycle and for each thermal channel, an average value of numeric counts CN_{bb} corresponding to R_{bb} and of numeric counts CN_{sp} corresponding to R_{sp} is determined.

The HIRS instrument has contamination in the first xx FOVs of the space scan (xx in h_testcoef_algoV4.dat file), polluted by the movement of the mirror. For consistency, the same xx FOVS are eliminated from the scan line of the warm target.

Finally, (56-xx) samples are processed for space and for blackbody target.

The samples are checked:

Samples with counts that are outside the gross limits are removed.

The mean and the standard deviation of the remaining samples are computed if the samples are numerous enough.

The standard deviation is compared to the NEDC specification with

$$NEDC = \text{abs}(NEDN / \text{average_slope}).$$

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NEDN: the noise equivalent delta radiance is referenced in document [1] for each channel, and in *h_calcoe_algoV4.dat* parameter file for AAPP calibration task.

The average slope is computed before the calibration run with calibration data from previous orbits. See the introduction of this paragraph.

If $STD < NEDC$, all samples pass the test. Then the samples that are outside of 3 sigma are removed. The mean and the standard deviation are recomputed. The recomputed mean will be used for further processing.

If $STD > NEDC$, the median value of the samples is computed and will be use for further processing.

If the averaged output counts for the space views or for the internal blackbody views can't be computed, the calibration cycle is declared unqualified.

Step 3: For each calibration cycle and for each IR channel, compute the BB (or raw) slope and intercept.

From equation 2 and 3 (see above) and assuming that a_2 is equal to zero in this algorithm :

$$a_1 = R_{bb} / (CN_{bb} - CN_{sp}) = S \quad (\text{BBslope } S)$$

$$a_0 = - a_1 CN_{sp} = I \quad (\text{BBintercept } I)$$

The quality of the BBslope is controlled:

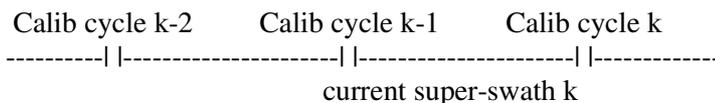
First, each BBslope is checked to ensure that its value is within a threshold from their mean value. If not, the one furthest from the mean value is removed and the mean is recomputed. The process continues till the condition is satisfied.

Then, each BBslope is checked against the average slope (see step 2, NEDC test). If it deviates from the average slope by more than a threshold it is considered an anomaly. If the slope is anomalous, the intercept is also suspect. The calibration cycle is declared unqualified.

Step 4 : For each Earth view scan line and for each channel, compute the slope.

A super-swath is defined as 40 scan-lines of HIRS data that start with a calibration cycle (1 space view line, 1 internal blackbody view line), followed by 38 Earth view scan lines.

For a normal super-swath k (in the middle of an orbit for example), the calibration slope for the 38 Earth view scan lines of the current super-swath k is the running average of 3 values: the BB slope of calibration cycle(k), the BB slope of calibration cycle($k-1$), the BB slope of calibration cycle($k-2$).



$$S'(k-1:k) = [S(k-2) + S(k-1) + S(k)] / M$$

With
 K the current super-swath number

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$S'(k-1:k)$ the running average of the 3 slopes, to be used for the 38 Earth view scan lines in the current super-swath k.

$S(k-2)$ the BB slope for the calibration cycle (k-2)

$S(k-1)$ the BB slope for the calibration cycle (k-1)

$S(k)$ the BB slope for the calibration cycle (k)

M the number of qualified BB slopes (see previous step) used for averaging (M=1 to 3)

Note that the current super-swath number k includes the 2 lines of the calibration cycle k-1 and not the 2 lines of the calibration cycle k.

For a partial super-swath k (when an orbit does not begin or end with a complete calibration cycle or when the data stream is broken in the middle of an orbit for example), the calibration slope for the 38 Earth view scan lines of the current super-swath k is the average value of the qualified slopes from the nearest 2 (or at least 1) calibration cycles. If neither value is qualified, the calibration slope for the 38 Earth view scan lines of the current super-swath k is the average slope computed with the data of the previous orbits (see the introduction of this paragraph). If the average slope is equal to zero or is missing, the calibration slope for the 38 Earth view scan lines of the current super-swath k is also missing.

Step 6 : For each calibration cycle and for each channel, recompute the intercept

The intercept is recomputed using the average slope derived in the previous step. As the space view line of the calibration cycle (k-1) belongs to the super-swath k, the equation is:

$$I'(k-1) = -S'(k-1:k) * CN_{sp}(k-1)$$

With $I'(k-1)$ The recomputed intercept for the calibration cycle (k-1)

$S'(k-1:k)$ The average slope for the current super-swath (k) (lines between the calibration cycles (k-1) and (k)).

$CN_{sp}(k-1)$ The space view count average for the calibration cycle (k-1)

If $CN_{sp}(k-1)$ is bad, the intercept is recomputed using the data of the blackbody view line.

$$I'(k-1) = R_{bb}(k-1) - S'(k-1:k) * CN_{bb}(k-1)$$

With $I'(k-1)$ The recomputed intercept for the calibration cycle (k-1)

$R_{bb}(k-1)$ The radiance of the internal blackbody for the calibration cycle (k-1)

$S'(k-1:k)$ The average slope for the current super-swath (k) (lines between the calibration cycles (k-1) and (k)).

$CN_{bb}(k-1)$ The internal blackbody view count average for the calibration cycle (k-1)

If $CN_{bb}(k-1)$ or $R_{bb}(k-1)$ are bad, the intercept is declared bad.

Step 7 : For each Earth view scan line and for each channel, compute the intercept

If the slope is essentially constant, the intercept varies appreciably throughout an orbit.

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The HIRS instrument measures all radiation falling on the detector. To minimize false fluctuations in the signals, the instrument temperature is carefully controlled, so that most optical components experience temperature changes very slowly with respect to the times between two calibration cycles (256 seconds). However, the baffle (identified as the secondary mirror) is a blackened light material which is subject to short-term temperature changes from emission or blackbody radiation and absorption of incident radiation from the internal warm target source, space and the variable Earth views. So the baffle affects all measurements on a time scale of seconds and this must be accounted for. [1]

So, the intercept is defined at an Earth view scan line by:

$$I'(n) = I(n) + \beta It(n)$$

With n The scan line number in the super-swath (k) numbered 2-39
(n is an Earth scan line between the calibration cycle (k-1) and (k), n=0 for the space line, n=1 for the BB line))

$I(n)$ The linear interpolation of the intercept between two calibration cycles

$It(n)$ The correction to the intercept based on the secondary mirror temperature

β The switch. When β equal to zero, no term based on the secondary mirror temperature is applied (see the option in ATOVS_ENV).

$I(n)$ is computed as :

$$I(n) = I'(k-1) + n \cdot (I'(k) - I'(k-1)) / 40$$

With n The scan line number in a super-swath (k) numbered 2-39
(n is an Earth scan line between the calibration cycle (k-1) and (k))

$I'(k-1)$ The recomputed intercept at calibration cycle (k-1) (see below)

$I'(k)$ The recomputed intercept at calibration cycle (k) (see below)

$I'(k-1)$ and $I'(k)$ are the intercepts computed with the same slope $S'(k-1:k)$.

So $I'(k-1) = I'(k-1)$ computed in the previous step

$$I'(k) = \alpha * I'(k) \quad \text{With } \alpha \text{ the correction}$$

$$\alpha = S'(k-1:k) / S'(k:k+1)$$

For Earth scan lines located before the first qualified calibration cycle:

$$I(n) = I'(1)$$

For Earth scan lines located after the last qualified calibration cycle:

$$I(n) = I'(k)$$

With k , number of the last qualified calibration cycle

$It(n)$ is computed as :

$$It(n) = b_1 \cdot [(T'(n) - T'(k-1)) - n \cdot (T'(k) - T'(k-1)) / 40]$$

With

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- n The scan line number in a super-swath (k) numbered 2-39
(n is an Earth scan line between the calibration cycle (k-1) and (k))
- $T'(n)$ The secondary mirror temperature "prime" at scan line n
- $T'(k-1)$ The secondary mirror temperature "prime" at the space view scan line of the calibration(k-1) (see below)
- $T'(k)$ The secondary mirror temperature "prime" at the space view scan line of the calibration (k) (see below)
- b_1 The correlation coefficient between the secondary mirror temperature and calibration intercept for a given channel.

For Earth scan lines located before the first qualified calibration cycle:

$$It(n) = b_1 \cdot [T'(n) - T'(1)]$$

For Earth scan lines located after the last qualified calibration cycle:

$$It(n) = b_1 \cdot [T'(n) - T'(k)]$$

With k the number of the last qualified calibration cycle

b_1 is computed before the calibration run with calibration data from previous orbits. See the introduction of this paragraph. b_1 is separated by Night and Day (b_{1n} , b_{1d}) and all conditions (b_1) (user option in ATOVS-ENV)

$$T'(n) = T(n-1) + 0.4609 \cdot [T(n) - T(n-1)]$$

With $T'(n)$ the linearly interpolated to the midpoint of the radiometric data (beam position 28.5)

n the line number in the super-swath

$n-1$ the previous line number

T the secondary mirror temperature

For the first line of the orbit:

$$T'(1) = T(1) - 0.5391 \cdot [T(2) - T(1)]$$

For every scan line :
$$T(n) = \sum_{i=0}^5 a_i (CN_s)^i$$

With : n the line number in the super-swath

$T(n)$ the secondary telescope temperature at the line number n

a_i the conversion coefficients

CN_s the numeric count associated to the secondary telescope temperature.

Step 8 : Values of parameters useful for computing calibration parameters are written to a file *hirs_historic.txt*.

This historical file allows the study of the target counts, space counts and PRT counts, so that the instrument health can be checked. The AAPP user has to create his own tools to study the values written in the file. The data format is described in the AAPP data format document.

A script was created to manage this file that can be very big (*hirs_historic_file_manage.ksh*)

The HIRS level1B file is updated:

At each blackbody view line, the BB slopes (S) and BB intercepts (I) are stored as primary and secondary calibration coefficients.

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At each space view line, the recomputed slopes (S') and the recomputed intercepts (I') are stored as primary and secondary calibration coefficients.

At each Earth view line, the recomputed slopes (S') and the final intercepts (I'') are stored as primary calibration coefficients.

At each Earth view line, the recomputed slopes (S') and the linear intercepts (II) are stored as secondary calibration coefficients.

The average slopes and the $b1$ coefficients used are stored in the level 1b header.

8.3.7. MSU μ -waves channels calibration (MSUCL)

The calibration is performed by radiance measurements on reference sources at each scan line. The numeric counts corresponding to space (sp) and 2 on-board black body (bb) radiances, are recorded. A couple of platinum resistance thermometers (PRT) are dedicated to the temperature measurement of each warm target. Each scan line has its own calibration coefficient set. However, the calibration coefficients that have to be applied to convert numeric counts into radiance (concerns all the lines scanned during the same orbit), are computed averaging the slope and intercept of each scan line. This means that there is only one set of calibration coefficients for all the lines covered by the orbit.

The MSU sounder has 2 on-board warm targets. The target number 1 (bb1) is viewed by channels 1 and 2. The target number 2 (bb2) is viewed by channels 3 and 4. Each of the on-board warm targets has 2 PRTs to determine their temperature (PRT1A and PRT1B for bb1, PRT2A and PRT2B for bb2). The conversion of each PRT count output to temperature requires 2 calculation steps: one PRT numeric counts ($X_{A/B}$) \rightarrow to resistance ($R_{A/B}$) \rightarrow to temperature ($T_{A/B}$).

1st step: $X_{A/B} \rightarrow R_{A/B}$ conversion of A or B PRT system is expressed by the following relations:

$$R_A = k_0 + k_1 \frac{X_A - T_{A-CALLO}}{T_{A-CALHI} - T_{A-CALLO}}$$

$$R_B = k_0 + k_1 \frac{X_B - T_{B-CALLO}}{T_{B-CALHI} - T_{B-CALLO}}$$

with : R_A = PRT1A or PRT2A resistance

R_B = PRT1B or PRT2B resistance

X_A = PRT1A or PRT2A numeric counts

X_B = PRT1B or PRT2B numeric counts

$T_{A-CALHI}$, $T_{A-CALLO}$, $T_{B-CALHI}$, $T_{B-CALLO}$ are high and low calibration reference points for electronics systems A and B respectively.

k_0 and k_1 coefficients are referenced in document [1], and in *calcoef.dat* parameters file for the AAPP calibration task.

2nd step: The target bb1 temperature (K) is the average of the 2 temperatures derived from PRT1A and PRT1B. The target bb2 temperature (K) is the average of the 2 temperatures derived from PRT2A and PRT2B. $R_{A/B} \rightarrow T_{bb1/bb2}$ conversion is determined by the following relation:

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$$T_{bb1/bb2} = \frac{1}{2} \left(\sum_{i=0}^2 e_i R_A^i + \sum_{i=0}^2 e_i R_B^i \right)$$

The e_i coefficients are referenced in document [1], and in *calcoef.dat* parameters file for the AAPP calibration task.

The black body radiance R_{bb} at temperature T_{bb} is established using the Planck's law:

$$R_{bb} = B(\sigma_c, T_{bb})$$

with σ_c = central wave number (referenced in document [1] for each channel, and in *calcoef.dat* parameter file for AAPP calibration task).

Non linearity corrections of output counts: The relationship between input radiance and MSU channels output counts $R = f(X)$ is not linear. A correction algorithm must be applied on the numerical counts X :

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

with X' = modified count value to be used in the linear relationship $R = G \cdot X' + I$

d_i is the non-linearity correction coefficients referenced in document [1] (provided by pre-launch measurement), and in *calcoef.dat* parameters file for the AAPP calibration task.

Thanks to (R_{bb}, X'_{bb}) and (R_{sp}, X'_{sp}) , the equation of the calibration curve is easily established for each linear channel:

$$R = GX' + I$$

with : $G = (R_{bb} - R_{sp}) / (X'_{bb} - X'_{sp})$

$$I = R_{sp} - G \cdot X'_{sp}$$

R is the radiance corresponding to X' corrected numeric counts.

The (G, I) calibration coefficients are stored in the level1b *msullb* file. The radiances are converted into brightness temperatures using the inverted Planck's law. These results are reported in the level1c file.

Values of parameters useful for computing calibration parameters are written to a file *monmsu.txt*. This historical file allows the study of the target counts, space counts and PRT counts, so that the instrument health can be checked. The AAPP user has to create his own tools to study the values written in the file. The data format is described in the AAPP data format document.

8.3.8. AMSU-A / AMSU-B / MHS μ -wave channels calibration (AMSunCL/ MHsCL)

AMSUACL, AMSUBCL and MHsCL compute the calibration coefficients for AMSU-A, AMSU-B and MHS. The procedure is similar for the 3 sounders, except for a few minor differences such as the number of PRTs and warm targets. The warm target temperatures are determined with the help of 5 PRTs for AMSU-A (A1-1) channels: 3-15, 7 PRTs for AMSU-A (A1-2) channels: 1-2, and 7 PRTs for all AMSU-B channels: 16-20. MHS has 5 PRTs. There are different black body targets for each subsystem channel. The cold reference is space.

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The pre-launch calibration procedure permits a relation to be established between the μ -wave channels numeric counts and a calibrated black body radiance. This relationship is not linear due to imperfect square law detectors. A band correction is also necessary for channels 19 and 20, since the monochromatic assumption breaks down for warm targets radiance measurement.

To determine the reference black body radiance, its temperature has to be measured. This task is performed by extracting the PRT numeric counts. For one AMSU-A or AMSU-B PRT, the temperature (K) is given by the conversion relation (PRT numeric count to temperature):

$$T_i = \sum_{j=0}^3 f_{ij} (PRT_i)^j$$

with: T_i = PRT number i temperature

f_{ij} = conversion coefficient

PRT_i = mean numeric counts associated to PRT number i.

MHS uses a different measurement technique (based on a constant current source), necessitating a two-stage procedure. Three precision reference resistors are used to calibrate the relationship between counts and resistance, via a least-squares straight line fit – the same relationship being used for all PRTs. Then the resistance, R_i for each PRT is converted to temperature via the calibration constants of the PRT:

$$T_i = \sum_{j=0}^3 f_{ij} R_i^j$$

MHS is further complicated by the fact that it has a redundant Processing Interface Electronics unit (known as PIE-B), with separate PRTs and reference resistors.

For both AMSU and MHS the reference black body temperature T_{bb} (K) is determined by a weighted average of all PRT temperatures:

$$T_{bb} = \frac{\sum_{i=1}^m w_i T_i}{\sum_{i=1}^m w_i} + \Delta T_{bb}$$

with : w_i = weighted coefficient

ΔT_{bb} = warm load correction factor for each channel

m = number of PRTs (5 or 7) depending on the warm target.

Similarly, a cold space temperature correction ΔT_{sp} is provided, because the space view is contaminated by radiation emitted by the spacecraft platform itself: $T_{sp} = 2.73$ (K) + ΔT_{sp} .

A band correction is applied for channel 19 and 20: $T_{bb}^* = b + c.T_{bb}$.

The black body radiance R_{bb} at T_{bb} or T_{bb}^* temperature, is established using the Planck's law:

$$R_{bb} = B(\sigma_c, T_{bb}) \text{ or } B(\sigma_c, T_{bb}^*)$$

with : σ_c = central wave number.

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f_{ij} and w_i , b and c coefficients, and temperature offsets are referenced in document [1] for each PRT, and in *amsua_clparams.dat*, *amsub_clparams.dat* and *mhs_clparams.dat* parameters files for the AAPP calibration task.

The calibration coefficients are calculated for every scan line. For each channel an average value (from 2 samples for AMSU-A and 4 samples for AMSU-B and MHS) for numeric counts X_{bb} corresponding to R_{bb} is computed. Space radiance R_{sp} is used as the cold reference. Each channel gives an average value (from 2 samples for AMSU-A and 4 samples for AMSU-B) for numeric counts X_{sp} corresponding to R_{sp} .

Non linearity corrections: From (R_{bb}, X_{bb}) , (R_{sp}, X_{sp}) and non linearity coefficients (u), the equation of the calibration curve $L = f(X)$ is established by the relationship:

$$R = R_{bb} + \frac{X - X_{bb}}{G} + Q$$

with : $G = (X_{bb} - X_{sp}) / (R_{bb} - R_{sp})$
 $Q = u \cdot (X - X_{bb})(X - X_{sp}) / G^2$

R is the radiance corresponding to X numeric counts associated to Earth observation. Introducing the G and Q expressions in R formulation, one can deduce a direct relation between R and the corresponding numeric counts X :

$$R = a_2 X^2 + a_1 X + a_0$$

The identification of the different terms gives:

$$a_2 = \frac{u}{G^2} \quad a_1 = \frac{1}{G} - u \frac{X_{sp} - X_{bb}}{G^2} \quad a_0 = R_{bb} - \frac{X_{bb}}{G} + u \frac{X_{bb} X_{sp}}{G^2}$$

These calibration coefficients are stored in the level1b *amsual1b*, *amsubl1b* and *mhs11b* files. The nonlinearity coefficients (u) are referenced in the parameters files *amsua_clcoefs.dat*, *amsub_clcoefs.dat* and *mhs_clcoefs.dat*. The radiances are converted into brightness temperatures using the inverted Planck's law. These results are reported in the level1c file.

8.3.9. Detection/correction of moon contamination in AMSU-B and MHS (amsubl/mhsl)

The four space view samples of AMSU-B and MHS are taken at different scanning angles, separated by 1.0° and 1.11° respectively. Consequently when the moon passes close to the space views the four samples are affected differently. (The moon subtends an angle of $\sim 0.5^\circ$). For AAPP version 4 and earlier no account is taken of this, and the calibration is normally rejected by quality control – since the difference between the space view counts exceeds the permitted tolerance. For AAPP version 5 we compute the angle between the moon and each of the four space view samples, rejecting those samples for which the angle is less than a threshold defined in *amsub_clparams.dat* or *mhs_clparams.dat* (nominally 2.0°). If all samples are within this threshold then we use the single sample with the lowest counts value.

The method of computing the moon angles is the same as that described in section 8.3.10.

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8.3.10. Detection/correction of moon contamination in AMSU-A (ATOVIN)

In the reference frame of the fixed stars the AMSU-A space view traces a fixed circle once per orbit, with radius typically 7 degrees. When the moon crosses this circle the space-view antenna temperatures are perturbed by up to 2 K for approximately 10 minutes per orbit. This leads to calibration errors. The errors are not detected by the quality control procedures in AMSUACL, and the level 1b format (prior to NOAA-N) makes no provision for flagging moon contamination. Therefore a correction is applied at level 1c. (The NOAA-N 1b format does make provision for flagging moon contamination, but for AAPP-5 or 6 we use the same method as AAPP-4.)

The right ascension and declination of the moon are first calculated at the start and end of the data period using a standard astronomical formula, and are interpolated for intermediate times. The formula implemented has an accuracy of ± 0.3 degrees.

For each scan the latitude and longitude of the two Earth samples closest to nadir are used to establish the local azimuth of the instrument scan axis. The space view elevation is a fixed instrument parameter. The local sidereal time of the moon is then computed given the observation time, latitude and longitude. Hence the angular separation between the moon and the space view is computed. If the angular separation exceeds a preset threshold then moon contamination is deemed to have occurred and flags are set. Since AMSU-A1 and AMSU-A2 may use different space view angles the calculation needs to be performed for each instrument.

The moon contamination may be corrected as follows:

Using the supplied calibration coefficients, compute the radiometric counts at nominal space and warm target temperatures (i.e. the inverse of the calibration procedure outlined in section 5.3.7) and hence the channel gains. Also compute the nonlinearity parameter.

Interpolate the gains across the period of the contaminated data. A linear interpolation is implemented.

Compute the corrected calibration coefficients assuming that the warm calibration counts and nonlinearity parameter are still valid.

By interpolating the gains rather than the calibration coefficients themselves we ensure that the calibration is not significantly degraded for warm scenes (i.e. close to the internal target temperature), and that the interpolation errors are minimised for cooler scenes.

8.3.11. Scan-dependent correction due to non-unity antenna reflectivity (ATOVIN)

This correction is implemented for MHS in AAPP version 5. It is desirable in view of the fact that MHS uses a different polarization for channels 18 and 19 compared with AMSU-B.

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AMSU and MHS use a 45° antenna that rotates relative to the plane of polarisation of the receiver. Let the antenna reflectivities for electric fields parallel and perpendicular to the plane of incidence be R_{\parallel} and R_{\perp} . From electromagnetic theory we expect R_{\perp} to be larger than R_{\parallel} .

The net reflectivity varies as the antenna rotates, according to

$$R_{\theta} = R_{0^{\circ}} \cos^2 \theta + R_{90^{\circ}} \sin^2 \theta \quad (1)$$

where we define $\theta = 0^{\circ}$ at nadir.

For AMSU-B, all channels have V polarisation, i.e. at nadir the electric field is perpendicular to the plane of incidence ($R_{0^{\circ}} = R_{\perp}$, $R_{90^{\circ}} = R_{\parallel}$). AMSU-A and MHS have some H-polarisation channels.

The antenna temperatures for Earth view, space view and black-body view (t_E , t_{SP} and t_{bb}) are given by

$$\begin{aligned} t_E &= (1 - R_{\theta}) T_{REF} + R_{\theta} T_E \\ t_{SP} &= (1 - R_{SP}) T_{REF} + R_{SP} T_{SP} \\ t_{bb} &= (1 - R_{bb}) T_{REF} + R_{bb} T_{bb} \end{aligned} \quad (2)$$

where T_{REF} is the temperature of the antenna reflector and T_E , T_{SP} and T_{bb} are the true brightness temperatures. (For clarity we are using brightness temperatures rather than radiance).

The calibration process described in section 8.3.8 derives a calibrated Earth-view brightness temperature, B_E , that is a linear function of the antenna temperature. (For a linear detector the antenna temperature is a linear function of instrument counts). So,

$$B_E = \frac{t_E - t_{bb}}{t_{bb} - t_{SP}} \times (T_{bb} - T_{SP}) + T_{bb}$$

For a non-ideal antenna we substitute for antenna temperatures (equ 2) to give

$$B_E = \frac{R_{\theta} (T_E - T_{REF}) - R_{bb} (T_{bb} - T_{REF})}{R_{bb} (T_{bb} - T_{REF}) - R_{SP} (T_{SP} - T_{REF})} \times (T_{bb} - T_{SP}) + T_{bb}$$

Now the reflector temperature is not explicitly measured, but is approximately equal to the temperature of the calibration black body, so

$$B_E \approx \frac{R_{\theta} (T_E - T_{bb})}{R_{SP}} + T_{bb}$$

and the correction to the measured brightness temperature is

$$\Delta T = T_E - B_E = (T_E - T_{bb}) \left(1 - \frac{R_{\theta}}{R_{SP}} \right)$$

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Substituting the angular dependence of reflectivity (equ 1) gives (after some trigonometric manipulation)

$$\Delta T = \alpha (T_{bb} - T_E) (\cos 2\theta_E - \cos 2\theta_{SP}) / 2 \quad (3)$$

where $\alpha = 1 - \frac{R_{90^\circ}}{R_{0^\circ}}$

For V-pol channels $\alpha = 1 - \frac{R_{//}}{R_{\perp}}$ – giving a positive correction if $T_{bb} > T_E$. For H-pol channels the sign of the correction is reversed.

The values of α for the different channels can be derived from pre-launch radiometric calibration tests – from the brightness temperature error when the Earth target (in nadir) is close to the temperature of the space target.

Values of α for MHS are held in file *fdf.dat*. For a typical atmospheric scene, applying the correction changes the channel 19 minus channel 20 brightness temperature difference by up to 0.2K. For AMSU-B the error is similar for all channels, though the correction could be implemented if required simply by adding the antenna coefficients to *fdf.dat*.

8.4. DATA INGEST FOR FILES IN BUFR, HDF5 OR EPS FORMAT

AAPP allows the ingest of certain types of external data that are already calibrated, and are supplied in a standard format such as BUFR, HDF5 or EPS level 1. For example, files transmitted in near-real-time via EUMETCast, or available from the EUMETSAT “UMARF” archive or the NOAA “CLASS” archive. These are listed in Table 5.

Table 5: Ingest of external level 1 datasets

Satellite	Instrument	Level	Format	Processing script	Output
MetOp	AMSU, MHS, HIRS, IASI	Level 1	BUFR	aapp_decodebufr_1c	AAPP 1c
MetOp	AVHRR	Level 1	EPS	convert_avh1b	AAPP AVHRR 1b (pseudo)
NPP	ATMS, CrIS	SDR	BUFR	aapp_decodebufr_1c	AAPP 1c
NPP	ATMS, CrIS	SDR	HDF5	atms_sdr, cris_sdr	AAPP 1c
FY-3	MWTS, MWHS	SDR	HDF5	mwts_sdr, mwhs_sdr	AAPP 1c

Note that the AVHRR 1b file listed above is created in the AAPP format, but it does *not* contain instrument counts, it contains 16-bit (or optionally 10-bit) scaled radiances. These need to be multiplied by the scaling factors that are found in the fields normally used to hold the calibration coefficients (i.e. avh_calvis, avh_calir).

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In the case of MWHS and MWTS, the AAPP ingest includes some additional quality control measures that were found to be necessary when the data were first evaluated, including:

- Time stamp consistency check
- Navigation consistency check
- Examination of the calibration quality flags
- Consistency check of the consistency of the antenna position counts for cold and warm calibration views
- Flagging of lunar contamination of the space view
- Consistency check of the calibration gain (only necessary for MWTS)

Any samples that fail these checks have the radiances set to “missing”. It is likely that over time the data provider will implement additional quality checks, but the AAPP checks may still prove useful. See source code of subroutines mwts_sdr_out.F and mwhs_sdr_out.F for full details.

8.5. PREPROCESSING AND MAPPING

Mapping one sounder to the grid of another is performed by the module **ATOVPP**.

Mapping of the imager AVHRR to HIRS grid is performed by the module AVH2HIRS.

This chapter describes pre-processing (made before and after mapping), LUT map production and then mapping. The end of this chapter describes suggestions for **ATOVPP** customization (e.g. adding new mapping).

After processing, 1D level files will be created.

This document outlines scientific aspects of **ATOVPP**. It describes the pre-processing of the different ATOVS instruments. It details the strategy used when selecting fields-of-view from one instrument to map to another.

The **ATOVPP** 'fixed data files' for each instrument define many of the corrections, coefficients and thresholds used in the pre-processing. Such files are largely described in corresponding software documentation and are provided with software, but can be modified and implemented for users' needs.

8.5.1. Pre-processing

Pre-processing is done for sounders in **ATOVPP**. As they are principally made before mapping, in this documentation if nothing is specified, it means that pre-processing is made before mapping. If pre-processing is made after mapping it is explicitly mentioned. Values given in the text below are for illustration and may differ from those used.

General pre-processing for all sounders

All the instruments share certain elements of pre-processing.

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BIAS CORRECTIONS :

These are added to the brightness temperatures (level 1C) before any other processing takes place. They depend on channel and scan position. If values are not provided in the instrument 'fixed data file' then values of zero are used. Actually this correction is only made for mapping MSU to HIRS.

SURFACE TYPE :

Surface information comes from a land/sea bit mask on a 1/6th degree by 1/6th degree lat/lon regular grid (this mask used topographic data from an ITPP atlas stored in file 'mapbitls.dat'). Surface type is found by examining all grid points within a box centred on the instrument field-of-view (fov) and approximately the same size as the fov. The fov is classed land (or sea) only if every point in this box is land (or sea). Otherwise, the surface type is 'mixed'.

If either latitude or longitude are out range then values of -999999 are returned for surface type.

SURFACE ELEVATION :

Surface elevation information is stored in 'maptopog.dat' file, similar to the one described above (1/6th degree by 1/6th degree lat/lon, heights in 100s of feet). Height provided is that for the nearest point in the grid, and is zero for spots over the sea. If either latitude or longitude are out of range then values of -999999 are returned for surface type.

HIRS pre-processing

No further pre-processing of HIRS is done.

AMSU-A pre-processing

The aim is to define if there is a cloudy/precipitation situation and if the surface type detected from data can influence inversion processing. The two main tests are the scattering index and the surface and cloud cost function. Other tests have also been coded.

Note :Some pre-processing on the AMSU-A grid uses mapped brightness temperatures from AMSU-B. This mapping is done within the AMSU-A pre-processing, and is described below in the section on mapping.

SCATTERING INDEX :

Theory:

Typical atmospheric hydrometeors have sizes around 0.01mm for liquid cloud drops and 0.1mm to 1mm for drizzle and rain drops. Ice crystals are similar in size to rain drops, although exceptionally snowflakes and ice aggregates associated with large cumulus can reach sizes of 10mm. Mie theory, which is generally applicable at these wavelengths, predicts that when the wavelength of observation is long compared to the hydrometeor size, scattering is negligible. For most rain and ice hydrometeors scattering processes become important at wavelengths below around 5mm (frequency > 60 GHz). Absorption remains significant for wavelengths up to 20mm (15 GHz). Therefore rain and ice is characterised by absorption in AMSU channels 1 to 14 (24-57 GHz) and by scattering in AMSU channels 15 to 20 (89 to 190 GHz). In the absence of scattering-sized hydrometeors, absorption by

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smaller hydrometeors will become the dominant radiative process at higher frequency. In the presence of large hydrometeors, scattering may be significant at 50 GHz.

We use this property to compare a prediction of channel 15 brightness temperature based on channels 1, 2 and 3, assuming no scattering hydrometeors, with that observed for channel 15. In the absence of scattering hydrometeors, the agreement will be within 5K. As the population of scattering hydrometeors increases the higher frequency observation will cool and a large difference between observation and prediction will result. This difference is our scattering index, and a simple threshold can be applied to detect scattering hydrometeors. These hydrometeors will contaminate the temperature sounding channels around 50 GHz sufficiently to prevent their use.

In AAPP the scattering index method has only been applied over the sea. Over land surfaces hydrometeor scattering is very obvious but some surfaces (snow, ice, desert) can give scattering signatures. Until we are confident we can separate surface and atmospheric scattering, the method should only be used over the sea. Scattering index is calculated for other surfaces but using coefficients appropriate for the sea and therefore gives erroneous results.

There are known problems with this technique. Firstly it makes no allowance for an emission brightband. Some ice particles, when they melt, create paths of liquid water through the crystal which will absorb radiation strongly because of their length. If sufficient melting snow particles are present the absorption becomes very strong and the brightness temperatures are raised. These types of low density snow flakes do not scatter strongly, and so this warm emission will not be masked. In this case, brightness temperatures will be elevated in all channels, and some contaminated data could give a scattering index of zero. Therefore additional tests are needed, which work by flagging strong emission. It is also possible to get a scattering brightband when ice particles are thinly coated with water. This creates a particle with an effective dielectric property that makes it appear like a much larger particle to the incident electromagnetic wave. If this happens scattering is enhanced, in an identical way to weather radar brightband. This problem is most serious at low frequency.

Method :

Compute scattering index. This consists of estimating AMSU-A channel 15 brightness temperature from channels 1, 2 and 3, and then determine scattering index as : Estimated TB15 - Observed TB15

AMSU-A channel 15 brightness temperature is estimated as :

$$ETB15 = a + b*TB1 + c*TB2 + d*TB3$$

where TB1, 2 and 3 are the observed brightness temperatures in channel 1, 2, 3 and ETB15 is the estimated channel 15 value. Coefficients a, b, c and d are third order polynomials in the secant of the scan angle.

Scattering index is then :

$$SI = ETB15 - TB15$$

We flag fofs where SI > 10K, or < -10K.

Note : this pre-processing is also made, after mapping, on AMSU-A brightness temperature mapped to HIRS grid.

RANGE OF AMSU-B 89 GHZ :

Theory:

We can use the high spatial resolution of the AMSU-B instrument to look for inhomogeneous 89GHz values within the AMSU-A footprint. The variables we will attempt to retrieve have much larger

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spatial scales than those we attempt to preprocess. If there are inhomogeneities, these are most likely due to contamination by one of a number of possible causes, all of which we would like to flag in the preprocessor.

Method:

Calculate the range of the AMSU-B 89 GHz channel over the AMSU-A footprint within the mapping (routine PPB2A). Flag the AMSU-A fov when the range exceeds 12K.

ESTIMATE SURFACE TYPE AND DEEP LIQUID WATER CLOUD DETECTION:

Theory:

To estimate surface type from the brightness temperatures, we use a minimum variance scheme. Mean brightness temperatures and BT covariance matrices have been calculated (with a radiative transfer model) for the 20 AMSU channels for different surface types, with no cloud liquid water. For each surface type (vector TBM, matrix C) we evaluate the cost function:

$$J = (TB - TBM)C^{-1}(TB - TBM)^T$$

where TB are the observed brightness temperatures. The surface type is identified as that minimising J . If the surface type is sea and if J is larger than a threshold value (normalised by number of channels squared) then we set a flag to indicate cloud liquid water may be present.

Method:

This has been installed but the coefficients are not well developed and its results are currently not very meaningful.

We use only selected channels: 1, 2 and 3

Eight surface types are determined:

- 1 = Bare young ice (i.e. new ice, no snow)
- 2 = Dry land (i.e. dry with or without significant vegetation)
- 3 = Dry snow (i.e. snow with water less than 2%, over land)
- 4 = Multi-year ice (i.e. old ice with snow [assumed dry] cover)
- 5 = Sea (i.e. open water, no islands, ice-free, wind < 14 m/s)
- 6 = Wet forest (i.e. established forest with wet canopy)
- 7 = Wet land (i.e. non-forested land with a wet surface)
- 8 = Wet snow (i.e. snow with water content > 2%)

Note : If surface type is 1, 4 or 8 and channel 1 > 275 K surface type is set to

9 = Desert.

Flags are set if:

- the minimum cost exceeds the cloud-test threshold (sea only)
- the estimated surface type incompatible with topography
- the surface type is one where the emissivity is highly variable (2, 3, 6, 7 and 9)

Note : this pre-processing is also made, after mapping, on AMSU-A brightness temperature mapped to HIRS grid.

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CLOUD CATEGORIES :

For the purposes of further processing, we class the fov as contaminated if it is flagged for precipitation/scattering by any of tests described above.

Similarly we consider it contaminated if it is flagged in the preceding test for incompatible surface types, or with a surface type that we cannot use.

If the fov is not contaminated but cloud liquid water has been detected (using the cost function technique) then the fov is considered 'cloudy'.

If the fov is neither 'contaminated' nor 'cloudy' then we call it 'clear'. This means only that we detect no cloud in the microwave. There may be cloud present that would affect the infra-red.

As a rough guide clear means the cloud LWP is less than 100 gm⁻², cloudy means the LWP is less than 500 gm⁻². Higher values of LWP, whether or not combined with precipitation, ice cloud or mixed surface are classed as contaminated. A substantial percentage of the world's extensive stratocumulus sheets will have LWP less than 50 gm⁻², and 500 gm⁻² will rarely be exceeded outside major tropical or middle latitude storm systems, or in deep convection.

EXISTING BUT REDUNDANT CODE :

* CROSBY logistic precipitation test :

Theory:

The theory comes from Crosby, Ferraro & Wu [6]. This test, also uses the relative scattering by hydrometeors at high frequency to flag rain or deep ice cloud. The information is very similar to the scattering index and so this test may be redundant.

Method:

Probability of rain is calculated as :

$$P = 1 / (1 + e^{-f})$$

where $f = 10.5 + 0.184 * TB1 - 0.221 * TB15$

We flag the fov when probability of rain > 0.05

Note : this pre-processing is also performed, after mapping, on AMSU-A brightness temperature mapped to HIRS grid.

* GRODY light rain test :

Theory:

This method is a simple adaptation of a rainfall algorithm for SSM/I to the AMSU-A frequencies [10]. It will be triggered by strong absorption and so should flag deep liquid water cloud or an emission brightband (see earlier discussion). Note NOAA/NESDIS have developed their tests further.

Method:

Estimated channel 1 brightness temperature (ETB1) is computed as :

$$ETB1 = 38 + 0.88 * TB2$$

If observed TB1 < ETB1 then set a flag. Note that presently we do not act on this flag as we expect the scattering index test to flag all such cases.

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Note : this pre-processing is also made, after mapping, on AMSU-A brightness temperature mapped to HIRS grid.

AMSU-B or MHS pre-processing

MEDIAN FILTER :

Theory:

Spikes in the 89GHz field may reveal contaminated data (e.g. due to scattering).

Method:

For each AMSU-B (or MHS) fov, find the median value of 89 GHz brightness temperature in the surrounding box of 3x3 fovs (routine **median**). Flag the central fov if it differs by more than 10 K from central value. Note that we do not act on this flag in mapping AMSU-B (or MHS) to AMSU-A.

SCATTERING INDEX :

This pre-processing is made after mapping. It presumes that we have mapped AMSU-A brightness temperatures. Recalculate AMSU-A scattering index using AMSU-B (or MHS) 89 GHz instead of AMSU-A. A flag is set if AMSU-A and AMSU-B (or MHS) 89 GHz channels differ.

CIRRUS TEST :

This pre-processing is made on full resolution unmapped AMSU-B (or MHS) data. It assumes AMSU-A data have been mapped to AMSU-B (or MHS). It therefore assumes that the AMSU-A fov is homogeneous. Otherwise the concept is identical to the AMSU-A scattering index (see AMSU-A preprocessing scattering index). Recalculate AMSU-B (or MHS) 183±7 GHz (AMSU channel 20) using AMSU-A channels 1 and 2 and AMSU-B (or MHS) 89 and 150 GHz. A flag is set if the recalculated AMSU-B (or MHS) 183±7 GHz value differs from the observed value.

$$ETB20 = a + b*TB1 + c*TB2 + d*TB16 + e*TB17$$

where TB1, 2, 16 and 17 are the observed brightness temperatures in channel 1, 2, 16 and 17 and ETB20 is the estimated channel 20 value. Coefficients a, b, c and d are third order polynomials in the secant of the scan angle.

Scattering index is then:

$$SI = ETB20 - TB20$$

We flag fovs where SI > 10 K, or < -10 K.

NWC-SAF SCATTERING AND PRECIPITATION TEST :

This test was supplied by Ralf Bennartz and was developed for the Nowcasting and Very Short Range Forecasting Satellite Application Facility (NWC-SAF). Full details are provided in reference [25]

A scattering index is computed based on AMSU-B channels 16 and 17, and AMSU-A channel 1. The index is defined as:

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$S_{11} = (T_{89} - T_{150}) - (0.158 + 0.0163\theta)$	AMSU-B land, AMSU-A water or coast
$S_{12} = (T_{23} - T_{150}) - (-1.7428 + 0.0776\theta)$	AMSU-B land, AMSU-A land
$S_{s1} = (T_{89} - T_{150}) - (aveseaback + 0.11\theta)$	AMSU-B sea
$S_c = (1-l) S_{s1} + l S_{11}$	Coast

where θ is the zenith angle in degrees, l is the land fraction in the AMSU-B footprint and *aveseaback* is the average background temperature difference between 89 and 150 GHz over the ocean, computed over the local area.

Based on the scattering index, a likelihood of different intensity classes of precipitation is calculated, using look-up tables. These classes are given below:

Class	Type of precipitation	Min rain rate (mm/h)	Max rain rate (mm/h)
1	No precipitation	0.0	0.1
2	Risk of light precipitation	0.1	0.5
3	Light/moderate	0.5	5.0
4	Intensive	5.0	∞

The precipitation likelihoods are only computed if the scattering index is between -20K and +100K.

MSU pre-processing

LIMB DARKENING

Limb darkening is the effect under which brightness temperatures (especially in channel 1) are cooler at the edge of the scan than at nadir. The effect increases non-linearly with scan angle, and for channel 1 depends strongly on surface emissivity.

This creates two problems in the mapping of MSU to HIRS:

we are mapping a non-linear effect linearly from coarse-resolution data

MSU doesn't extend as far as HIRS at the edge of the scan and so here we are extrapolating the limb-darkening effect

It is possible to specify 'limb-darkening curves' in the MSU fixed data file - one for land and one for sea. These are defined for each channel and for each HIRS scan angle. They represent typical differences in brightness temperature between that scan angle and nadir.

These curves are subtracted from the MSU brightness temperatures at the MSU fovs before mapping, and added back at the HIRS fovs after mapping. This may reduce errors in the mapping.

8.5.2. Look up tables :

This section is applicable to AMSU, MHS, HIRS, IASI and AVHRR. It is not applicable to ATMS/CrIS or to MWHS/MWTS.

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Introduction

Mapping is the process of calculating a representative value for the data of one instrument (the 'mapping' instrument) at the location of a field of view (fov) of a second instrument (the 'target' instrument). The process of mapping can be considered as two separate steps:

- *collocations* : identify mapping fovs 'close to' the target fov
- *estimations* : calculate representative values of the mapping data at the target fov, using results of the collocation (weights)

The fields of view of the two instruments create a pattern that repeats at regular intervals. This pattern is derived and then stored within a look-up-table (LUT) which provides the collocation information.

Creation of LUT, which will identify those mapping fovs which are 'close to' (collocated with) target fovs is made by subroutine **lutmap**. The LUT also provides a weight for each mapping fov for each mapping mode (nearest neighbour, bilinear interpolation, spatial average) to be applied to the BT of each collocating mapping fov to provide the mapped value.

An appropriate LUT must be produced before running mapping routines.

Collocation

The pattern created by the fovs of the mapping and target instruments is modelled on a 'satellite' grid. This is defined by an axis given by the track of the sub-satellite point on the Earth's surface and an axis perpendicular to the first representing an 'instantaneous' scan line at some 'origin' time (say the time of the first target scan line). Displacement along the track axis is given by the time elapsed since the origin time and displacement along the scan axis is given by the scan position and the scanning geometry of the instrument.

Calculations assume:

- 'nominal' geometry (i.e. satellite and instrument characteristics are as given in a NESS107 type document [1])
- the Earth is spherical and non-rotating

Fovs of the mapping instrument are assumed to be point sources which fall either within ('collocated with') or outside of a target fov ellipse determined by the 'beam width' of the instrument. (Note that a multiplier can be applied to the beam width to increase the ellipse size and encompass a greater number of mapping fovs.).

A convenient 'pattern repeat time' (LUT duration) is 32 seconds because in this period there will be exactly 192 AVHRR lines, 5 HIRS lines, 4 AMSU-A lines and 12 AMSU-B lines.

The choice of 'first' lines for line numbering purposes can be quite arbitrary. There is however an advantage in choosing specific first lines, for instance in the mapping of AVHRR to HIRS. If the first HIRS line is taken to be that line started in the first TIP minor frame zero, and the first AVHRR line that line which is within the HRPT frame containing the TIP minor frame, then past monitoring suggests that the time difference between the lines will be very stable. Similar stability would be expected between 'first' lines of other instrument pairs, perhaps also using 'synchronisation' with the first TIP minor frame zero to define the lines.

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Empirical corrections

CONE ANGLE

Ellipse footprints are constructed on the satellite grid for each target fov. Those mapping fovs which fall inside a target fov footprint are taken to be collocated with the fov. The ellipse for target fovs can be artificially increased in size to capture a reasonable number of mapping fovs. This is done by applying a multiplication factor to the nominal cone angle.

TIME/ANGLE ADJUSTMENTS

The assumption stated above of 'nominal' geometry for deriving a LUT will be in error to a greater or lesser extent. Corrections for such errors can be made by empirical adjustment of the scan angle and time of target fovs. Note that because of the design of the AMSU instruments, up to 4 sets of corrections may be necessary for each satellite when mapping to/from an AMSU grid. However it is anticipated that such corrections will only be necessary where the size of the correction is similar to the resolution of the mapping instrument, i.e. when mapping AVHRR data.

Estimation :

The information provided by the collocation step will allow a variety of estimating algorithms to be applied :

- select nearest neighbour
- bi-linear interpolation using the four 'surrounding' mapping fovs
- spatially weighted average (gaussian function or linear)
- Backus-Gilbert convolution (AMSU-B (or MHS) to AMSU-A only)

A weight is assigned to each mapping fov for each mapping mode (nearest neighbour, bilinear interpolation, spatial average). The appropriate weight will be applied to the BT of each collocating mapping fov to provide the mapped value. A rank of the distance from the target fov is also assigned to each mapping fov (1-14, 1=shortest distance).

For the Backus-Gilbert convolution method for mapping AMSU-B (or MHS) to AMSU-A, weights are pre-calculated (routine **ppbginit**) and there is no reliance on **lutmap**.

The Look-Up-Tables

Subroutine **lutmap** returns the LUT for any mapping as a four-dimensional array. Dimensions three and four are the fov and line number of the target fov.

The identification of the mapping fovs close to a target fov is done by locating each mapping and target fov on a 2-dimensional rectangular grid of which one axis represents the track of the sub-satellite point on the Earth's surface and the other axis represents an 'instantaneous' scan line at some origin time (in practice the origin time is taken to be the start time (fov 1 time) of the target line designated 'line 1'). Displacement in the along track direction is a function of time and displacement in the along scan direction is determined by the scanning geometry of the instruments (note displacements are distances along the curved Earth's surface).

Note that the pattern of target/mapping fovs will repeat at regular intervals so the LUT only has to cover this 'pattern repeat' time. The generation of the LUT is based on 'nominal' geometry i.e. satellite and instrument characteristics are assumed to be as given in a NESS 107 type document [1]. Actual characteristics may be systematically different from these. The effect of these differences can be

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investigated and the results incorporated into a correction for the position of each target fov across the scan. The correction is in the form of small increments assigned to the time of the fov and to the scan angle assigned to the fov (note these corrections are believed only to be important when mapping AVHRR to HIRS (or to some other instrument) where the size of the corrections is similar to the resolution of the AVHRR instrument).

An example of a LUT entry for a target fov is shown below for mapping a sounder

818	1523	0	0	0	0	0	0	0	7
8	15	-1115	-962	1	65	94	0	0	0
8	16	3732	-829	2	19	4	0	0	0
9	15	-1115	4291	3	12	1	0	0	0
9	16	3732	4424	4	4	0	0	0	0
8	14	-5982	-1095	5	-1	0	0	0	0
7	15	-1115	-6216	6	-1	0	0	0	0
7	16	3732	-6083	7	-1	0	0	0	0
0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	etc.

Table 6: LUT entry for a target fov for mapping a sounder

There are 10 elements per line and the first ten lines are shown here.

- Line 1 elements 1 and 2 give the position of the target fov within the mapping fovs as a mapping line/spot position (*100) i.e. in the example the fov is at mapping line 8.18 and mapping spot 15.23
- Line 1 element 10 gives the number of mapping fovs collocating with the target fov. In this example there are seven, and lines 2 to 8 provide information on each of these 7 collocating mapping fovs:
- Elements 1,2 give the line/spot of the mapping fov
- Elements 3,4 give the scan/track position (km) of the mapping fov relative to the target fov (*100), i.e. the first mapping fov is displaced 11.15 km to the 'left' of the target fov and 9.62 km 'below' the target fov
- Element 5 gives the ranking of the distance of the mapping fov from the target fov (1 is the nearest).
- Elements 6,7 give the weights (*100) for the fov to use in the mapping (-1 indicates that the fov takes no part):
 - 6 is the weight to be used for bi-linear interpolation
 - 7 is for spatial averaging
- Elements 8,9,10 are spare and can be used for further alternative mapping options.

A target fov LUT entry for mapping AVHRR data have a different structure:

16278	147344	21
153	1470	1477
154	1467	1480
155	1465	1481
156	1464	1483
157	1463	1484
158	1462	1484
159	1462	1485

160	1461	1485
161	1461	1486
162	1461	1486
163	1461	1486
164	1461	1486
165	1461	1485
166	1462	1485
167	1462	1485
168	1463	1484
169	1464	1483
170	1465	1482
171	1466	1481
172	1468	1479
173	1472	1475
0	0	0
0	0	etc.

Table 7: A target fov LUT entry for mapping AVHRR

There are 40 lines and 3 elements :

- Line 1 gives the position of the target fov within the mapping grid, i.e. at map line number 162.78 and map scan position 1473.44. The third element gives the number of mapping 'collocating lines'.
- Subsequent lines provide the AVHRR line number and the range of AVHRR fofs for each collocating line (number of the first and the last spot).

The basic data for mapping will normally be held in a 'level 1C' file for the mapping instrument and there will be a corresponding level 1C (or 1D) file for the target instrument data (into which the mapped data will be finally stored). Such files may contain data for the whole of a local satellite pass or the whole of one orbit of the satellite for global data. In order to process data on machines of limited memory the data in such files will be divided into blocks held in local buffers. Subroutine **lutmap** will normally be run with a 'time difference' appropriate to the line 1 times of the original 1C (or 1D) files and then used on successive blocks of data with offset values providing a link between line numbers implicit in the local buffers and the line numbers of the original 1C (or 1D) files.

Information stored in the LUT buffer :

Each target fov will have information stored against it. The amount and type will depend on whether the mapping instrument is AVHRR or another instrument. This buffer is created by subroutine **lutmap**.

Mapping instrument not AVHRR: buffer dimension is (10, 15, X1, X2) where X1 and X2 depend on the target instrument (X1 = number of fofs, X2 = number of lines). Up to 15 sets of information are allowed of 10 elements each (see description above).

Mapping instrument AVHRR: buffer dimension is (3, 40, X1, X2) where X1 and X2 depend on the target instrument (X1 = number of fofs, X2 = number of lines). Up to 40 sets of information are allowed of 3 elements each (see description above).

8.5.3. Mapping

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In **ATOVPP**, six mappings are available: MSU to HIRS, AMSU-B (or MHS) to AMSU-A, AMSU-A to HIRS, AMSU-A to AMSU-B (or MHS), AMSU-A to IASI and ATMS to CrIS. Mapping AVHRR to HIRS is performed by the module **AVH2HIRS**. Mapping of MWHS to MWTS (the sounders on the Chinese FY-3 satellite) is performed outside of ATOVPP, in a standalone program **mwhs_to_mwts**.

For AMSU, MHS, HIRS and IASI, the mapping routine **ppbtmap** sets up a list of fofs from the mapping instrument that are close to the target instrument fof. The list is passed to the appropriate routine (**ppm2h/ppb2a/ppbgb2a/ppa2h/ppa2b**) to decide which fofs to use. This section describes how these decisions are made.

Mapping MSU to HIRS

Fofs with brightness temperatures derived from secondary calibration coefficients are used only if there are none available derived from primary calibration coefficients.

MSU fofs are used irrespective of surface type. However a flag is set if the surface type of any of those selected differs from that of the HIRS fof. If limb-darkening curves are used, which are significantly different for land and sea, then such fofs should be treated with caution. Another flag is set if less than four MSU fofs were used in the mapping. This is always set for HIRS fofs 1 and 56.

Mapping AMSU-B (or MHS) to AMSU-A

Again, fofs with brightness temperatures derived from secondary calibration coefficients are used only if there are none available derived from primary calibration coefficients.

Only those AMSU-B (or MHS) fofs with the same surface type as the AMSU-A fof are mapped, unless the AMSU-A fof is of 'mixed' surface type, in which case all AMSU-B fofs are mapped. Surface type refers to that returned by routine **surfelev** from the topography datasets.

Mapping AMSU-A to HIRS

This was considerably simplified from the original method, in which care was taken only to map AMSU-A fofs with the same surface type and cloud classification. The original method would often find only one suitable AMSU-A fof for each of several HIRS fofs, and so re-use it several times. The resulting mapped values were then "blotchy".

The new method chooses all nearby AMSU-A fofs with valid brightness temperatures. It takes no account of surface type and cloud in the mapping, but flags are set if the AMSU-A fofs are not of identical surface type, and if any is flagged for cloud.

The pre-processing tests (scattering index, Crosby, Grody light rain and surface estimation) described above are repeated using the AMSU-A brightness temperatures once mapped to the HIRS grid.

Mapping AMSU-A to AMSU-B (or MHS)

AMSU-A brightness temperatures for AMSU-B (or MHS) fofs are taken directly from the nearest AMSU-A fof.

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Mapping AMSU-A to IASI

The method is essentially the same as mapping AMSU-A to HIRS. The same AMSU pre-processing tests are used. Because there are four IASI fields of view per scan position the mapping process is repeated four times, with different along-track and cross track offsets.

The IASI instrument is mounted on anti-vibration mounts on the spacecraft, therefore its relationship to the other instruments is not fixed. However, considering the relatively coarse resolution of AMSU it is sufficiently accurate for ATOVPP to assume nominal IASI scan geometry, and not to take account of vibration.

Mapping AVHRR to HIRS

Mapping AVHRR has not been included in the module **ATOVPP**. However this mapping is performed in HIRS ellipse by the module AVH2HIRS, following the principles described above. This mapping used the routines **lutmap** and **av_map**. In addition AVH2HIRS generates the cloud mask.

Mapping AVHRR to IASI

Mapping AVHRR to IASI is not an ATOVPP option. However AVHRR to IASI mapping is performed as part of the IASI calibration/navigation task OPS-LRS (or within the EPS Core Ground Segment in the case of global or regional data). This mapping process is required in order to accurately geo-locate the IASI sounder data (via the IASI imager). The IASI level 1c format includes a “cluster analysis” of this mapped AVHRR data, giving information on the mean and standard deviation of the AVHRR radiances for each IASI field of view, computed for up to 7 AVHRR “classes”. These classes are not assigned physical meaning (i.e. the OPS-LRS software does not attempt to identify the cloud or surface type), but the results can still be useful to the user – for example the presence of several classes implies that the AVHRR field is non-uniform.

Mapping ATMS to CrIS

For mapping ATMS to CrIS a different approach is used to those described above. This is described in detail in [33]. In brief, the method uses the actual level 1c latitude/longitude values, rather than assuming a nominal scan geometry. The ATMS radiance field for each channel is interpolated to the positions of each CrIS field of view. This function is performed by subroutine **map_atms_to_cris**, within atovpp.

Mapping MWHS to MWTS

The mapping of MWHS to MWTS (i.e. the humidity sounder on FY-3 to the temperature sounder) is *not* performed within ATOVPP, it is done by a standalone program **mwhs_to_mwts**. Using the supplied latitude/longitude values, the viewing angle differences between each MWTS spot and the neighbouring MWHS spots are calculated. Then for any angles less than 2° (threshold specified in **map_mwhs_to_mwts.F**) the *median* MWHS brightness temperature is computed. This method provides a measure of robustness against occasional corrupt BT values, achieves a useful noise reduction, and is independent of prior assumptions on scan geometry.

8.5.4. Suggestions for customisation

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1D format

The format of output on each grid (HIRS, AMSU-A, AMSU-B or MHS, IASI) is intended to be flexible. Some parts of the format are fixed, and other parts will be customized to fit the requirements of individual centres. The AMSU-A and AMSU-B (or MHS) 1D formats may need to be expanded to accommodate extra mappings. A change in format will require changes in the **ppxouth** and **ppxouth** routines (where x = a for AMSU-A, b for AMSU-B (or MHS), h for HIRS and m for MSU). Those routines transfer data from storage arrays to 1D records. Customized parts are labelled [user-defined] within routines and includes.

In the case of IASI and CrIS, the number of channels and Eigenvector scores to be output in the level 1d may be customized by the user.

Pre-processing tests and corrections

The initial implementation of **ATOVPP** does not attempt to correct brightness temperatures for limb effect, surface emissivity, or cloud. However there are dummy routines in place (**ppxcorr** and **pphcloud**) which could be expanded by the individual user to perform these functions.

The routines underneath **ppproc1** and **ppproc2** are intended to be customised by individual centres. **ppproc1** is for pre-processing before any mapping has been done, and **ppproc2** is for after, where the processing depends on the use of brightness temperatures from more than one instrument. The initial implementation breaks these rules slightly. AMSU-B is mapped to AMSU-A within **ppamsua1**, which makes use of the AMSU-B (or MHS) brightness temperatures to pre-process AMSU-A before AMSU-A is mapped to the HIRS grid.

Any additional fixed data needed for the pre-processing can be placed in the 'fixed data file' for that instrument and read by **ppxdf** to be stored in **ppxdfdata.h**.

Mapping

At the heart of the mapping are the routines **ppm2h**, **ppa2h**, **ppb2h**, **ppb2a** (and **ppbgb2a**), **pph2a**, **pph2b**, **ppa2b** and **ppa2i**. Given a target field-of-view and a list of collocated mapping fields-of-view, these routines select which mapping fofs should be used, and then derive mapped brightness temperatures and other parameters. Initially only **ppm2h**, **ppa2h**, **ppb2a**, **ppbgb2a**, **ppa2b** and **ppa2i** have been coded. It is thought that some centres will have rather different requirements and so will need to adapt or code their own versions of these.

Look-up tables creation, which allows the generation of a list of mapping fofs, is made by **lutmap**, called by **pplut** which determines the mapping and initialises the parameters for calling **lutmap** (see software documentation about **ATOVPP**). Subroutine **pplut** must be modified to include a new mapping.

Memory tuning

There are two parameters that may be tuned if memory limits are a problem:

- 'dT' (include file **ppparms.h**) is the size of data block to be read, stored, and processed at a time (in milliseconds). Reducing this will ease memory usage (see software documentation about **ATOVPP**).

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- Subroutine **surfelev** reads the surface elevation dataset as it requires, but for efficiency does store some lines from that dataset. The number of lines 'mx_store' is a parameter defined within **surfelev** and can be reduced if required.

8.5.5. IASI pre-processing

Because the volume of IASI level 1c data is more than 2 orders of magnitude greater than that of the other sounders put together, ATOVPP includes several options to allow the user to reduce this volume, while still retaining as much of the useful information as possible. These options are:

1. Spatial thinning
2. Spectral thinning (channel selection)
3. Principal Components analysis

The options are described below.

Spatial thinning

Spatial thinning is controlled via the *IASI.fdf* file.

IASI has 4 detectors arranged at different viewing angles, thus full-resolution IASI data has 4 fields of view (FOV) per scan position and 120 FOVs per scan line. The user may specify that only one FOV per scan position is to be included in the level 1d output, i.e. a factor 4 reduction in the data volume. Furthermore, the user may specify that only 1 in n scan line is output, where n is any integer.

In order to maximize the usefulness of the data, there are various possible ways of doing the 1 in 4 thinning. Some users will want to use the FOVs most likely to be cloud free; other users might have a preference for uniform cloud; still others may prefer a regular thinning pattern. Thus the following options are provided:

- 0 = full resolution (no thinning)
- 1 = fixed detector
- 2 = the FOV with the warmest mean AVHRR I/R radiance
- 3 = the FOV with the lowest variability in the mapped AVHRR I/R radiances
- 4 = hybrid – option 2 equator-ward of a specified latitude and option 3 pole-ward
- 5 = the FOV with the warmest IASI radiance for a specified channel (typically a window channel)
- 6 = hybrid – option 5 equator-ward of a specified latitude and option 1 pole-ward
- 7 = as for option 1, except the chosen detector is changed each scan line

In many situations – and especially over ocean – the warmest AVHRR field of view is the one most likely to be cloud-free. Similarly, if the standard deviation of mapped AVHRR radiances is low then the cloud is likely to be uniform. However, where there is sea-ice or snow the warmest field of view assumption breaks down – hence the inclusion of hybrid option 4. Options 5 and 6 may be used if for any reason there is no mapped AVHRR data available.

The user is allowed to specify a “primary” thinning mode and a “backup” mode for use if there is insufficient data to use the primary mode, e.g. if AVHRR are missing.

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Spectral thinning (channel selection)

Spectral thinning is controlled via the *IASI.fdf* file. This file includes a list of channels that are to be included in the level 1d output (see [28]).

The level 1d user may customize the 1d format to set the maximum number of channel slots by changing a parameter in *iasi1d.h* – and then re-compiling ATOVPP. However the channels themselves may be changed via *IASI.fdf* at any time, provided the number of channels is less than the maximum.

Principal Components (PC) Analysis

An alternative approach to spectral thinning is to compute the projection of each spectrum along a limited number of orthogonal eigenvectors. If we represent the noise-normalised spectrum as a column vector \mathbf{y} (dimension m channels) and the eigenvectors as a column-orthogonal matrix \mathbf{U} (m channels \times n eigenvectors) then the vector of PC scores, \mathbf{c} , is given by

$$\mathbf{c} = \mathbf{U}^T \mathbf{y}$$

Typically 300 scores would contain most of the useful information in the original spectra. If the spectra are correctly noise-normalised then the score for a given eigenvector is equal to the signal-to-noise ratio (SNR) for detecting the presence of that eigenvector in the spectrum. For data storage purposes the scores are then quantized: in AAPP they are quantized at 0.5 SNR-unit intervals, which gives acceptably small loss.

IASI level 1c spectra are Gaussian apodised (see footnote¹). The process of apodisation results in the noise no longer being “white” in the interferogram domain. Therefore before computing the PC scores it is preferable to “de-apodise” each spectrum back to self-apodised form, based on nominal instrument characteristics supplied to AAPP in a data file (see [27]). If this were not done then information would be lost when the scores are quantized for storage purposes. In practice, most users do not de-apodise (and the eigenvectors distributed by EUMETSAT are for unmodified level 1c spectra), therefore AAPP has been designed to accommodate either option.

AAPP also performs a check on the accuracy of the normalized radiances y' that are reconstructed by inverting the above equation. The “reconstruction score”, RS , is computed for each spectra by summing over channels:

$$RS = \sqrt{\frac{1}{nchan} \sum_{i=startchan}^{endchan} (y'_i - y_i)^2}$$

The reconstruction score is computed for the three nominal IASI bands, which are Band 1 = 645.0-1210.0 cm^{-1} , Band 2 = 1210.0-2000.0 cm^{-1} , Band 3 = 2000.0-2760.0 cm^{-1} . We would expect a reconstruction score of approximately 1.0 – i.e. expect fitting errors to be of the order of instrument noise. If the value is significantly higher it implies that the fitting accuracy is poor for that spectrum. See reference [28] for a more detailed description.

¹ The wavenumber-domain IASI level 1c Instrument Spectral Response Function is the inverse Fourier Transform of an interferogram-domain truncated Gaussian with a cutoff at $\pm 1.96800 \text{ cm}$. The interferogram-domain Gaussian function is the direct Fourier transform of a wavenumber-domain Gaussian with a full width at half height = 0.5 cm^{-1} . See reference [27]

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IASI processing external to AAPP

The user can easily re-construct Gaussian-apodised radiance spectra, \mathbf{R} , directly from the PC scores:

$$\mathbf{R} = \mathbf{U}'\mathbf{c}$$

where \mathbf{U}' is obtained from \mathbf{U} by de-normalising (and optionally apodising). \mathbf{U}' is supplied as an AAPP data file.

AAPP does not include software for the generation of eigenvectors. These will be supplied via a data file. However, for completeness the process of generating the eigenvectors is described below:

1. A set of reference spectra is assembled. These may be either real IASI spectra (post launch) or simulations (pre-launch). Typically the number of spectra used is of the order of 100000.
2. The reference spectra are noise-normalised (and optionally de-apodised). Call the resulting matrix \mathbf{Y} (m channels \times N spectra)
3. Form the covariance matrix $\mathbf{C} = \mathbf{Y}\mathbf{Y}^T / N$
4. Compute the eigenvectors, \mathbf{U} , and eigenvalues, $\mathbf{\Lambda}$, using a standard library function (such as EIGENQL in IDL): $\mathbf{C} = \mathbf{U}\mathbf{\Lambda}\mathbf{U}^T$
5. Save the first n eigenvectors in a data file for AAPP.

8.5.6. CrIS pre-processing

CrIS pre-processing tasks closely parallel those described in the previous section for IASI. The main differences are:

- CrIS has 9 detectors (c.f. 4 for IASI)
- The CrIS 1c file does not come with imager radiances included. In the initial implementation of AAPP v7, VIIRS will not be mapped to CrIS, therefore the thinning options are restricted to those that can be performed with CrIS alone.

Spatial and spectral thinning are controlled using file *CRIS.fdf*. It is possible to specify any combination of detectors to use in the output file. The following possibilities are expected to be most useful:

1. Full resolution
2. Intermediate resolution (detectors 2,4,6,8)
3. Fixed detector (central)
4. Warmest FOV (with option to use a fixed detector pole-ward of a specified latitude)

The thinning options 1-3 are illustrated in Figure 10.

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Figure 10: Illustration of thinning options for CrIS: full resolution (9 detectors), 4 detectors, 1 detector.

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8.6. AVHRR LOCAL CLOUD MASK

8.6.1. Introduction

Two versions of the AVHRR “MAIA” cloud mask are implemented in AAPP v7:

- MAIA2, which produces a cloud mask on the HIRS grid
- MAIA3, which produces a cloud mask on the native AVHRR grid (“AVHRR level 1d” output file)

This documentation describes MAIA2 in detail; for information on MAIA3, please see [35].

The first aim of the AVHRR data processing is the description of the cloud cover within each HIRS field of view in order to help in the temperature and moisture retrieval process.

The cloud algorithm, presented in this chapter aims to determine cloudy AVHRR pixels which were used to describe the clouds within each HIRS spot. Thirteen values will be computed for each HIRS fov :

- 1 percentage clear AVHRR in HIRS FOV (*100)
- 2 surface temperature (K*100)
- 3 climatological sea surface temperature or t2m forecast(K*100)
- 4 mean AVHRR channel 3 over HIRS FOV (degK*100)
- 5 mean AVHRR channel 4 over HIRS FOV (degK*100)
- 6 mean AVHRR channel 5 over HIRS FOV (degK*100)
- 7 black body coverage in HIRS FOV (degK*100)
- 8 top cloud temperature over HIRS FOV for black body clouds (degK*100)
- 9 standard deviation of top cloud temperature over HIRS FOV(degK*100)
- 10 mean clear AVHRR channel 4 over HIRS FOV (degK*100)
- 11 mean clear AVHRR channel 5 over HIRS FOV (degK*100)
- 12 standard deviation of AVHRR channel 4 over HIRS FOV (degK*100)
- 13 standard deviation of clear AVHRR channel 4 over HIRS FOV (degK*100)

The AVHRR image data used as input for the cloud detection are segmented into boxes of 38 lines by 33 pixels centred on each HIRS measurements and including the HIRS field of view. These boxes are called the working boxes.

8.6.2. AVH2HIRS mapping

The **AVH2HIRS** main program first reads the AVHRR level1b and HIRS level1d files. For each HIRS FOV over sea, it computes from the Grody model [10] the total water vapor content by using the AMSU-A channels 23, 31 and 50 GHz already mapped in HIRS level1d. It reads the 3 climatological files of reflectance, SST and specific humidity. It creates a look-up table (see 8.6.3) and maps AVHRR data into HIRS FOV. It applies the cloud mask (MAIA) to the HIRS ellipse for contaminated pixels discrimination. The section for the cloud description of the HIRS level1d format which is not documented in the input file is then filled with the 13 output cloud parameters of the MAIA software.

8.6.3. Look up table

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A look-up table (LUT) identifies those mapping fields of view (fovs) which are 'close to' (collocated with) target fovs.

The identification of the mapping fovs close to a target fov is done by locating each mapping and target fov on a 2-dimensional rectangular grid of which one axis represents the track of the sub-satellite point on the Earth's surface and the other axis represents an 'instantaneous' scan line at some origin time (in practice the origin time is taken to be the start time (time of the fov1) of the target line designated 'line 1'). Displacement in the along track direction is a function of time and displacement in the along scan direction is determined by the scanning geometry of the instruments (note displacements are distances along the curved Earth's surface).

Ellipse footprints are also constructed on the grid for each target fov. Those mapping fovs which fall inside a target fov footprint are taken to be collocated with the fov (the ellipse for target fovs can be artificially increased if required to capture a reasonable number of mapping fovs).

The pattern of target/mapping fovs will repeat at regular intervals so the LUT only has to cover this 'pattern repeat' time.

The generation of the LUT is based on 'nominal' geometry, i.e. satellite and instrument characteristics given by the documentation. Real (after launch) characteristics may be systematically different from these. The effect of these differences can be investigated and the results incorporated into a correction for the position of each target fov across the scan. The correction is in the form of small increments assigned to the time of the fov and to the scan angle assigned to the fov.

8.6.4. AVHRR cloud mask

A - Generalities

The AVHRR cloud mask is a subroutine called by the **av_map_maia_2** subroutine. Its aim is to describe the cloud cover within each HIRS pixel. Its name is MAIA for 'Mask Avhrr for Inversion Atovs'.

The main input arguments of the MAIA subroutine is a box of npb pixels * nlb lines of AVHRR observations (the 5 channels) and the shape of the sounder ellipse. npb and nlb depend on the size of the sounder ellipse.

TEST SERIES

The cloud detection algorithm is a succession of thresholds tests applied to every AVHRR pixel, inside the input sounding ellipse shape, to various combinations of the AVHRR channels. An AVHRR pixel is said to be cloudy if one test is not satisfied (so a pixel is said to be 'clear' if all tests are satisfied).

The series of tests applied depend on:

- the surface type (land, sea or coast) of the box
- the solar zenith angle which determines the period of the day (day, twilight or night) and whether or not there is specular reflection during the daytime (sunglint)

The surface type, altitude and solar zenith angle are input arguments of the subroutine and are defined in the calling program from the sounder pixel processing.

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Daytime period is defined by solar zenithal angle less than 83 degrees, night-time period by solar zenith angle is higher than 90 degrees and twilight if the angle is between 83 and 90 degrees.

Depending on the surface type, daytime period and specular reflection, different subroutines are invoked (e.g.: **testsd.F** for sea and daytime conditions) with different series of tests and threshold values. Successions of tests for each case are described below in tables.

The tests are done on single channels (11µm brightness temperature, visible reflectance), on combination of channels, in brightness temperature, for 11-12 µm (t4-t5), 11-3.7 µm (t4-t3), 3.7-12µm (t3-t5), on spatial local variances of 11 µm brightness temperatures computed on a 3*3 box centered on each AVHRR pixel.

THRESHOLD DEFINITION

Applied thresholds in the tests could be constant values (cst_...) initialized within the 'include' file **maia.h** or computed values (IR threshold, VIS threshold, threshold 34 etc.).

The constant values were determined by a long experience over the Europe acquisition area and were used in the first version of the software. Some of them are still applied in this version. However, variable thresholds are now computed to allow the use of the cloud mask in other climates (e.g.: wet tropical).

The computed thresholds depend on:

- the environmental conditions obtained from external information at the sounder pixel position from provided global and monthly climatologies or from a forecast. They are :
 - over sea: the surface temperature from a climatology
 - over land: the air surface temperature from the forecast
or the warmest pixel in the fov if the forecast is not available
 - the visible reflectance from a climatology over land and daytime
 - the total water vapor content (twvc) from
 - over sea: a regression with AMSU-A channels
the forecast when AMSU-A is not available
the climatology if nothing else is available
 - over land: the forecast
the climatology if nothing else is available

The surface temperature, reflectance and twvc are used to adapt the values of the thresholds to the specific conditions of each processed box.

- the satellite through tables computed off-line : these tables which describe the variation of some thresholds (ex: t4-t5) with the twvc and the secant of the zenithal angle, depend on the characteristics of the channels and have to be recomputed for each new satellite.

Three sets of monthly climatologies are provided with the software for the sea surface temperature over sea (**atlas_sst_mm.dat**), the visible reflectance over land (**atlas_alb_mm.dat**) and the specific humidity (**atlas_cwv_mm.dat**), where mm is the month to take into account.

FORECAST AVAIBILITY

Several thresholds are computed from the forecast values of 2 meter air temperature (K*10) over land and the total water vapor content (g/cm²*100), extracted at the sounder position (mainly for land situations).

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The total water vapor content is computed inside the software from the forecast temperature and humidity profile, when the twvc is not directly available in the forecast file.

Two formats for reading forecasts are available: GRIB (WMO standard format) and ASCII (described in the AAPP software documentation [appendix C]).

Over sea, the forecast is only used to determine the twvc when AMSU-A data are not available. So the non-availability of the forecast over sea should have no impact for cloud cover in HIRS pixel.

Over land, the forecast is used to determine the air surface temperature and the twvc. If the forecast is not available, the software takes the warmest AVHRR pixel in the ellipse instead of the air surface temperature to compute the IR threshold and the twvc from climatology to compute the thresholds for the channel combination.

To summarise, MAIA does not fail if the forecast is not available, it is still accurate over oceans but the accuracy is highly degraded over land for some surface conditions (cold surface temperature during winter) or cloud type (warm clouds).

B - Cloud mask input/output arguments

The MAIA scheme is an independent library of the main program and can also be invoked by other programs (other applications) provided the input arguments are correctly filled.

INPUT

The input data are the following:

- the geometry definition (latitude, longitude, local zenith and azimuth angles, solar zenith and azimuth angle)
- surface altitude
- surface type (sea, mixed, land)
- the pixel and line size of the input working box
- the brightness temperatures of the 5 AVHRR channels on the box. The box is centered on each HIRS pixel and includes it.
- the corresponding radiance on box for the 3 IR channels
- the shape of the HIRS ellipse, with 0 outside the pixel and 1 inside.
- the HIRS pixel and line numbers (only for information)
- a logical parameter for the written option mode (put to local in **avh2hirs**).

OUTPUT

Two output formats are available:

- A chart of 13 parameters (**maia_par**). Each parameter is a mean value on the HIRS fov. They are:
 1. percentage clear AVHRR in HIRS pixel (*100)
 2. surface temperature from AVHRR split-window (K*100)
 3. climatological sea surface temperature or 2 m temperature forecast (K*100)
 4. mean AVHRR channel 3 over HIRS pixel (degK*100)
 5. mean AVHRR channel 4 over HIRS pixel (degK*100)
 6. mean AVHRR channel 5 over HIRS pixel (degK*100)
 7. black body coverage in HIRS pixel (%*100)
 8. top cloud temperature over HIRS pixel (degK*100) for black body clouds

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9. standard deviation of top cloud temperature over HIRS pixel (degK*100)
 10. mean clear AVHRR channel 4 over HIRS pixel (degK*100)
 11. mean clear AVHRR channel 5 over HIRS pixel (degK*100)
 12. standard deviation of AVHRR channel 4 over HIRS pixel (degK*100)
 13. standard deviation of clear AVHRR channel 4 over HIRS pixel (degK*100)
- An area of nlb lines *npb pixels (same size as the input AVHRR area) with the clear/cloudy flag for each AVHRR pixel. This table can be used for further developments (e.g.: AVHRR images with full resolution).

C - External geographical information

SURFACE TEMPERATURE ATLAS

Global and monthly climatological data-sets of SST at a resolution of 0.15 * 0.15 degrees are provided with the scheme. Each of the 12 binary files contains the minimum of the monthly SST on the grid. Unit of SST is degrees Celsius*100. Information over land exists in the files but is not used. There size is of 5.8 MB each. They are of the form **atlas_sst_mm.dat**, mm=month.

All the information from the file for the month in question is read in by the **maia_clim_sst.F** subroutine called by the main program. The **sst_clim** value at each HIRS spot is the nearest value in latitude, longitude of the spot position (**maia_init.F** routine).

SURFACE VISIBLE REFLECTIVITY ATLAS

Global and monthly climatological data-sets of visible reflectivity (AVHRR channel 1) at a resolution of 0.15 * 0.15 degrees are provided with the scheme. Each of the 12 binary files contains the mean of the monthly visible reflectivity on the grid over land only. Unit of visible reflectivity is %*100. More information on the data sets is given in [11]. The size of the files is of 5.8 MB each. They are of the form **atlas_albedo_mm.dat**, mm=month.

All the information from the file for the month in question is read in by the **maia_clim_alb.F** subroutine called by the main program. The **alb_clim** value at each HIRS spot is the nearest value in latitude, longitude of the spot position (**maia_init.F** routine).

SPECIFIC HUMIDITY ATLAS

Global and monthly climatological data-sets of specific humidity atlas and the corresponding surface pressure at a resolution of 2.5*5.0 degrees (lat, lon) are provided with the scheme. Each of the 12 binary files contains the mean of the monthly specific humidity on 11 atmospheric levels and surface pressure on the grid over land and sea. The specific humidity is in g/kg*100 and the surface pressure in mb. More information on the data sets is given in [13]. The size of the files is of 1.3 MB each. They are of the form **atlas_cwv_mm.dat**, mm=month.

The data for each month is read in by the **lec_clim_cwv.F** subroutine called by the main program. The **cwv_clim** value at each HIRS spot is the interpolation of the specific humidity profiles at the 4 nearest grid nodes to the spot position (**maia_init.F** routine). The interpolated profile is then converted to total water vapor content (**maia_twvc.F**).

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FORECAST INFORMATION

When available, the forecast file is read by the scheme, in ASCII (with `lec_previ_ascii.F`) or GRIB (with `lec_previ_grib.F`) format. The script takes the most recent forecast with a maximum delay of 48h. The two files are:

The extracted forecast fields of the file:

- the geometric altitude at the nodes of the forecast field, necessary for interpolating the forecast air surface temperature to the HIRS position.
- the air surface temperature (2 m altitude).
- the forecast profile (T, H, P) on atmospheric levels. The level pressures are fixed in the `lec_previ.F` routine. The field of total water vapor content is computed from the forecast profile (`lec_previ.F`).

Then, for each processed AVHRR box, T2m and TWVC values are interpolated at the HIRS spot position from the values of the 4 nearest grid nodes (`maia_init.F` routine). The routine `maia_init.F` makes use of the mean surface altitude of the sounder FOV to determine the air surface temperature at the HIRS position.

The name of the forecast file in GRIB format is of the form `yyyymmddhh00.0ec` where `yyyy` is the year, `mm` the month, `dd` the day, `hh` the hour of the file creation and `ec` is the delay. They are under the `${DIR_FORECAST}/yyyymm` directory.

The name of the forecast file in ASCII format is of the form `previ_yyyyymmdd_hh00.txt` where `yyyy` is the year, `mm` the month, `dd` the day, `hh` the hour of the date of satellite observation.

INPUT GEOGRAPHICAL INFORMATION DETERMINATION

The input climatologies and forecast data are used to compute in-line adapted thresholds to the geographical position of the HIRS spot. Some priorities are given to the geographical information depending on the surface type and the data available. One purpose of this is that the software can be run even without forecast data. This section summarizes the priorities and the details are given with each test series.

Surface temperature

Over sea: the climatological SST (from the monthly SST climatologies provided with the software) is always used.

Over land: when the forecast is available, the forecast surface temperature is used. Otherwise, the maximum T11 μ m in the ellipse is used.

Remark: the surface temperatures over land archived inside the SST climatologies are never used.

Visible reflectivity

Over sea: the visible reflectance is computed with a theoretical model (in `phulpin.F`) and no input external data are used.

Over land, the visible reflectance comes from the monthly visible reflectance climatologies provided with the software.

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Total water vapor

Over sea:

When AMSU-A observations are available in the main program, the total water vapor content (TWVC) is computed from the N. Grody model [10] and is summarized:

t23=AMSU-A channel 1

t31= AMSU-A channel 2

t50= AMSU-A channel 3

DF1=2.85 + 0.020*t23 - 0.028*t50

If Abs(Latitude)<50 and DF1 < 0.2 then

A=247.92 - (69.235 - 44.177 cos θ) cos θ

B=-116.270

C = 73.409

TWVC=[A+B*Log(285-T23)+C*Log(285-T31)]*cos θ

End if

The accuracy of the computed TWVC is about 0.6 cm. This algorithm is only usable over sea and can be used in place of forecast data. That is to say that, if no forecast file is present, the cloud cover will be accurate over sea.

Over land or over sea when no AMSU-A observations available:

- the forecast TWC is used.
- If forecast data are not available, the TWVC is extracted from the specific humidity atlas. This makes it possible to run the software in all cases, even without forecast data. However, the total water vapor content is very variable and a monthly mean value in place of the forecast data, has to be used with caution in wet tropical areas. See for example the variation of the T3-T5 threshold with TWVC (Figure 11).

D - Thresholds determination

CONSTANT THRESHOLD OR OFFSET VALUES

There are often 2 different values for each threshold, one for the sea (s for sea) and one for the land and coast. Unit is K*100 or degrees*100 when used as the difference of 2 temperatures.

IR thresholds :

cst_ir = 1000

offset used to calculate IR threshold over land during night

cst_irlj = 700

offset used to calculate IR threshold over land during day

cst_irs = 600

offset used to calculate IR threshold over the sea

cst_sstirs = 400

offset used to calculate IR threshold over the sea

cst_irs_nd = 300

IR threshold over the sea when there is no climatologic SST

Uniformity :

cst_sd33 = 120

threshold for standard deviation of channel 4 BT in the AVHRR 3x3 box within HIRS ellipse.

cst_sd33s = 20

same over the sea

Climato thresholds. :

cst_lstmin = 26315

threshold of minimum land surface temperature

cst_sstmin = 27015

threshold of minimum sea surface temperature

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sature3 = 32000
cst_sst = 27515

Channel 3 saturation threshold
sst threshold

Sunglint thresholds :

cst_irg = 1000
cst_glint2 = 1500
cst_glint34 = 500
cst_glint13 = 1000
cst_glint2coef = 1.7

IR threshold
VIS threshold
threshold for BTs difference between channels 3 and 4
threshold for BTs difference between channels 1 and 3
coefficient for VIS threshold

Snow and ice thresholds :

sn4thrmax = 27915
sn4thrmin = 24315
sn4thrfou = 500
sn34thrplain = 1500
sn34thrmoun = 2000
mountain = 700
sn2thromb = 2000
sn1thrmax = 7000
sn45thrmax = 200
sn45thrmin = -20
snszenmax = 80.0
separ1637 = 18000

threshold 4 maximum accepted to determine snow
threshold 4 minimum accepted to determine snow
constant used to calculate IR threshold
constant used to calculate 34 threshold in plain
constant used to calculate 34 threshold in mountain
constant used to determine if we are in mountain or plain (m)
constant used to determine cloud shadows with visible canal
threshold 1 maximum accepted to determine snow
threshold45 maximum accepted to determine snow
threshold45 minimum accepted to determine snow
maximum solar zenithal angle accepted to determine snow
constant used to determine if 1.6 µm or 3.7 µm is available.

Land & desert index :

cst_desert45max = 0
cst_desertalbmin = 2500
cst_rlivthr = -0.1
cst_rsivthr = -0.04
cst_desertrele43 = 200

threshold45 maximum over desert
threshold minimum of albedo over desert
constant used over desert
constant used over land
constant used to calculate t4-t3 over desert

Black body thresholds :

bb45thr = 100
pourcentmincor noir = 5
seuilsigmaunecouche = 1000
pourcenminclair = 95

constant used to determine black body threshold
threshold of minimum percentage of black body
std threshold for black body homogeneity
threshold of minimum clear percentage

THRESHOLD FILES

Seven thresholds files given with the scheme are used to determine the thresholds, depending on the total water vapor content and the secant of the zenith angle. These have been computed off-line for each specific satellite using the TIGR2 data-set and RTTOV6. They are of the form:

T45_mercot_-3:+3_noaaxx.dta

T45_veget_-3:+3_noaaxx.dta...

In the present version, files for NOAA14, NOAA15, NOAA16, NOAA17 and NOAA18 are provided. New files must be created for future satellites.

These files are read by the routines **iniseuil.F** and **iniseuil45.F** to fill 6 tables :

s45mer (sea), s45terre_jn (land, day/night),
s35mer (sea), s35terrenuit (land, night),

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s43mer (sea), s43terrenuit (land, night) and the adapted values for conditions at each HIRS fov are extracted by the **valseuil.F** routine. The method of threshold file creation is described in the last chapter. An example of a threshold table is given in Figure 11.

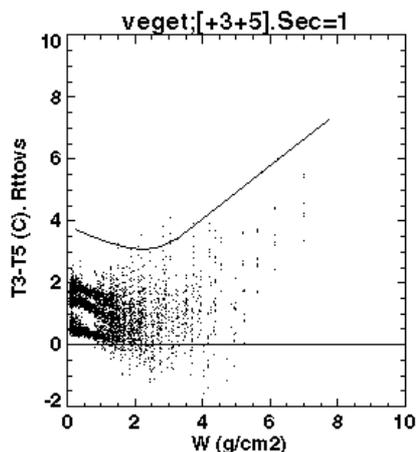


Figure 11: Threshold 6-5 over land, satsec = 1

We can see that the threshold is dependent on the TWVC. This varies depending on climate regime (e.g. tropical, polar, temperate). For example, if TWVC is 7 g/cm², then the T3-T5 threshold value is 6.5 °C and for TWVC equal to 3 g/cm², the threshold is 3.5 °C.

E - Cloud detection tests

See for more details the reference document [8].

Channels 3, 4 and 5 (BTs) are in K*100 and channels 1 and 2 (albedo) are in %*100.

T4 TEST

channel 11µm.

Its aim is to detect low temperature pixels corresponding to medium or high clouds. The main problem encountered is the threshold definition, which must be as high as possible to make the test efficient. It is very important during night-time or at dawn for detecting medium clouds.

Over ocean, a minimum SST climatology has been established based on NOAA-07, NOAA-09 and NOAA-11 AVHRR imagery. The resulting atlas corresponds to 12 monthly global at a 0.15 degree horizontal resolution in latitude and longitude (i.e., 15 km at the latitude of France). The threshold is then computed for each AVHRR working box from the minimum SST value of the 3x3 grid nodes centered on the HIRS position. Six degrees Kelvin (cst_irs) are then subtracted to account for water vapour absorption and imperfection of climatology. If climatological SST < 1.8 °C, the sea ice temperature can be as cold as land, so the land threshold will be used.

Over land, radiative AVHRR temperatures are estimated using air temperature forecast near the surface from the most recent forecasts (between 06 and 48 hours delay). Forecast information used are 2 meters air temperature (m).

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Each T2M of the 4 nearest nodes are first reduced from the grid altitude to the sea surface (alt = 0) T2M by using the geometric altitude of the forecast nodes. 3 steps are performed:

- reduction of the T2m of the nodes at alt=0
- interpolation of T2m at the HIRS fov
- computation of T2m at the correct altitude (use of the mean altitude of the HIRS fov)

The threshold s_{ir} is then computed from this value by subtracting an offset of 7 K (cst_{irj}) for some daytime periods and of 10 K (cst_{ir}) for the other periods to account for difference between the 2-m air and radiative temperature over land. The daytime period is for solar zenith angle less than 60 degree and solar azimuth greater than 180 (afternoon). The 7 K and 10 K values have been empirically derived. The quality of this threshold not only depends on the forecast quality and the real vertical structure of the atmosphere (a dry adiabatic law is used to account for the height effect), but also on the land type (emissivity effect, presence of snow), the solar conditions (radiative cooling during night-time or maximum warming at around 14 h solar local time depending on the land type), and the delay between the time of AVHRR observations and the time of the forecast field.

If no forecast temperatures are available, the T4 infrared threshold over the continent is computed by subtracting a 10 K offset to the maximum T4 brightness temperature in the ellipse that is supposed to represent cloud-free surface temperature. The threshold computed with this method is valid only if the underlying surface inside the working box is relatively homogenous, which is not the case in mountains or in coastal regions. The infrared test using such a threshold fails to detect cloud layers covering the entire box, as no cloud-free or clear cold surface can be found (continental surface during winter).

T4-T5 TEST

$T_{11\mu m} - T_{12\mu m}$.

This test is applied to detect cirrus clouds, which are characterized by higher $T_{11\mu m} - T_{12\mu m}$ brightness temperature differences than cloud-free surfaces. Channel 4 and 5 radiation absorptions are affected by the water vapor continuum and lines (of course different for the two channels), by CO₂ lines, surface temperature and emissivities. As a result, T4-T5 depends on the TWVC in the atmosphere and on the type of surface.

Over coast and sea, the thresholds used are calculated from a table which depends on satellite zenith angle and total water vapor content (TWVC). Interpolation is done in the table to the secant of the correct zenith angle and TWVC (**valseuil.F**).

Over land, 2 tables exist to calculate the thresholds: one for day time and another one during night ($t45_veget_{-10:-10_noaaxx.dta}$ and $t45_veget_{+3:+5_noaaxx.dta}$) and the threshold is an interpolation between the 2 tables with the zenith angle.

The tables used to determine the thresholds have been calculated off-line with the forward radiative transfer model (RTTOV6) for TIGR2 profiles representing the global atmosphere. Different tables exist for the different satellites.

T4-T3 TEST DURING NIGHT-TIME

$T_{11\mu m} - T_{3.7\mu m}$

This test is used to detect low water clouds. It is only applied during night-time, since it assumes that the 3.7 μm infrared channel is not affected by the solar irradiance. Its efficiency is based on the spectral variation of the water clouds emissivity, which is lower at 3.7 μm than at 11 μm . The 'T4-T3'

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brightness difference temperature is large for small water-particle clouds, whereas continental or oceanic surfaces (except the sandy deserts in Africa) have similar brightness temperatures in the two channels.

Different thresholds are used over land or sea. As for T4-T5, the thresholds are determined from tables which are dependent of satellite zenith angle and total water vapor content (t43_mercot_+3:+3_noaaxx.dta and t43_veget_+3:+5_noaaxx.dta).

T4-T3 TEST DURING DAYTIME

The T3.7 μ m -T11 μ m is used to detect shadows over low clouds. In this version, the thresholds are the same as for night-time.

T3-T5 TEST DURING NIGHT-TIME

T3.7 μ m - T12 μ m

This test is only applied at night-time to detect semi-transparent ice clouds or subpixel cold clouds. It is based on the fact that the contribution to the brightness temperature of relatively warm ground is higher at 3.7 μ m than at 12 μ m, due to the lower transmittance of ice cloud and to the high non linearity of the Planck function at 3.7 μ m. The brightness temperature difference T3-T5 is a function of the cloud height, thickness (for cirrus) and cloudiness (for subpixel clouds).

The thresholds are also calculated from tables; one for land (t35_veget_+3:+5_noaaxx.dta) and one for sea (t35_mercot_-3:+3_noaaxx.dta).

INFRARED SPATIAL LOCAL VARIANCE TEST

T11 μ m standard deviation.

This test is used to detect cloud edges, thin cirrus and small cumulus. For each AVHRR pixel in the ellipse, a local standard deviation is computed in the small box of 3x3 pixels (channel 4) centered on the pixel (**ppellip.F**). If this value is higher than a threshold corresponding to the ground heterogeneity, the central pixel is said to be cloudy.

This test is applied during daytime and night-time over the oceans with a constant value (cst_sd33s). The threshold has been empirically determined.

A1 OR A2 TEST

Visible channel 0.6 μ m (A1) and near-infrared channel 0.9 μ m (A2)

This test, applied to the visible or near-infrared channel, is very useful in detecting low clouds. The reflectance measured over the oceans corresponds mainly to Rayleigh and aerosol scattering (if no sunglint is assumed), which is weaker in the near-infrared (0.9 μ m) than in the visible (0.6 μ m).

Over sea, the near-infrared channel 2 reflectances are used, as they are less sensitive to aerosol and molecular scattering effects (Rayleigh) than the visible. High reflectances are mainly due to clouds. Sea surfaces have a low reflectance. All pixels with reflectances above a reflectance threshold are assumed to be cloud-contaminated. The subroutine **albmer.F** which calls **phulpin.F** and **simulatmos_ocean_35.F** is used to calculate the threshold.

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Over land, channel 1 reflectances are used since the reflectance of land surfaces in channel 1 is much less than in channel 2 due to the vegetation spectral radiance behaviour at these two wavelengths. This increases the contrast between land and cloud. The threshold computation is a problem, since the cloud-free land reflectance depends on the atmosphere (scattering and absorption) and on the land cover, but also on the viewing geometry. This calculation, described in chapter 'threshold vis over land', is made by the routine **albter.F** which calls **roujean.F** and **simulatmos_terre_35.F** subroutines. It is based on values from monthly reflectance climatologies (albedo), on which directional and atmospheric corrections are applied.

A2 AND T3-T4 TESTS ON SUNGLINT CONDITIONS

A2 and T3-T4

The near-infrared test over the oceans is usually very efficient, except inside sunglint areas. Thus, it is not possible to simply use the near infrared channel, since the ocean reflectance can reach very high values. Low cloud detection is then a problem.

The portion of the AVHRR passes that may be affected by this phenomenon can be determined by simple geometrical considerations on the sun and satellite respective positions.

It has been shown that simultaneous use of the near-infrared (A2/0.9 μ m) and medium infrared (T3/3.7 μ m) channels allows the detection of low clouds even in case of specular reflection. In fact, the solar reflection at 3.7 μ m, approximated by T3-T4 brightness temperature difference, is much higher over ocean in the case of specular reflection than over clouds for a given 0.9 μ m reflectance.

Thresholds used are computed from the constant values (cst_glint34, cst_glint2, cst_glint13, cst_glint2coeff) normalized by the solar zenith angle.

F - Tests series

General comment: the test T3<separ1637 is used to discriminate between the 1.6 μ m and 3.7 μ m channels.

The values of all the thresholds are given in K*100 and %*100.

SNOW DETECTION UNDER CLOUD-FREE CONDITIONS DURING THE DAY

Scientific description

This test is applied over land only if the solar elevation is greater than 10 degrees, since it relies on the analysis of the solar reflection in the visible (0.6 μ m) and the medium-infrared (3.7 μ m) wavelengths. It is mainly based on the fact that cloud-free snow reflects sunlight relatively weakly at 3.7 μ m and has high reflectance at 0.6 μ m, whereas water clouds have relatively high reflectance in both channels. The 3.7 μ m channel measurements include solar reflection and thermal emission. The solar reflection part can be roughly approximated by the T3-T4 brightness temperature difference. It can be also computed when assuming that the surface does not show transmittance at 3.7 μ m and has emissivity at 11 μ m equal to 1. In fact, distinction between clouds and snow is better performed using the brightness temperature difference. Snow detection is, however more complex than the first study indicated.

Rayleigh scattering is more important at 0.6 μ m than at 0.9 μ m and is negligible at 3.7 μ m. Consequently, shadows of high clouds over low clouds are characterized by no solar reflection at 3.7 μ m, but relatively high visible reflectances and can therefore be confused with snow. However,

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they can be distinguished from snow by their low near-infrared reflectance and their near-infrared to visible reflectance ratio smaller than 0.75.

Some clouds (cirrus and stratus or stratocumulus) may also have a relatively small T3-T4 brightness temperature difference, even less than 10 K. Cirrus clouds can be easily detected by their high T4-T5 difference, but remaining stratus or stratocumulus are very difficult to identify. The only remaining possibility is using the near infrared channel in the scheme. However, even the use of near-infrared channel, together with the channels at 0.6 μm , 3.7 μm and 11 μm , does not allow a perfect separation of clouds from snow.

test series

Snow detection is determined by a succession of tests with the **deneig.F** routine. If snow is detected, the pixel is said to be 'clear'. This test is only applied over land.

Snow detection	
If $T3 < \text{sature3}(=32000)$ and $\theta_s \leq 80$ deg. then:	
If: $T4 \leq 27915$ and $T4 \geq \text{Threshold IR4 Min}$ and $A1 \geq \text{Threshold VIS2 Min}$ and $A1 \leq \text{Threshold VIS1 Max}$ and $A2 \geq \text{Threshold VIS2 Shadows}$ and $[(T3-T4 < \text{Threshold 34 mountain and } T3 \geq \text{separ1637}(=18000))$ or $(T3 < \text{Threshold 3 Max and } T3 \leq \text{separ1637})]$ then:	
If: $\text{alt} \leq \text{mountain}(=700)$ and $T4-T5 \leq 200$ and $T4-T5 \geq -20$ and $[(T3-T4 < \text{Threshold 34 plain})$ and $(T3 \geq \text{separ1637})$ or $(T3 < \text{Threshold 3 Max})$ and $(T3 \leq \text{separ1637})$ \Rightarrow Snow	
Else: $\text{alt} \geq \text{mountain}(=700)$ \Rightarrow Snow	

Table 8: Succession of tests to detect snow, only applied over land.

Threshold determination

Threshold IR4 Min =	Max (24315, (IR Threshold - 500))
Threshold VIS2 Min. =	Threshold VIS
Threshold VIS2 shadows =	$\text{nint}(2000 * (\cos(\theta_s * \pi / 180)))$
Threshold 34 mountain =	$\text{nint}(2000 * (\cos(\theta_s * \pi / 180)))$
Threshold 34 plain =	$\text{nint}(1500 * (\cos(\theta_s * \pi / 180)))$
Threshold VIS1 Max. =	$\text{nint}(7000 * (\cos(\theta_s * \pi / 180)))$
Threshold 3 Max =	$\text{seuil16neige}(\text{szen}, \text{sazi}, \text{vzen}, \text{vazi}) * (\cos(\theta_s * \pi / 180))$

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$\theta_s =$ zenithal angle

IR Threshold and Threshold VIS are defined in the routine which calls the **deneig.F**.

The seuil16neige integer function computes the theoretical reflectance in channel 3 (for 1.6 μm only) over snow for the input geometric angles. It is done in a very similar way than for visible channel over land. First, the surface theoretical reflectance *albsans* over the snow surface is computed with the subroutine **leroux.F** and depends on the geometry angles (it applies an angle correction to a theoretical reflectance). Then, the **simulatmos_terre_35.F** subroutine returns a0, a1 and a2 values for the atmospheric diffusion over land.

The channel 1.6 μm reflectance is then computed as follow:

$\text{seuil16neige} = 100 * (\text{brdf6s} + \text{offset})$

where $\text{brdf6s} = 100 * (a_0 + a_1 * \text{surface} / (1 - \text{surface} * a_2))$

$\text{surface} = (\text{albsans} / 100.) / 100.$

$\text{offset} = 5.$

ICE DETECTION UNDER CLOUD-FREE CONDITIONS DURING THE DAY

A similar test than for snow detection exists to detect ice over sea during day with the **deglac.F** routine.

Tests series

Ice detection
$T_3 < \text{sature3}(=32000)$ and $\theta_s \leq 80$ deg. (snszenmax) then:
If: $T_4 \leq 27915$ (sn4thrmax) and $T_4 \geq \text{Threshold IR4 Min}$ (sn4thrminloc) and $A_2 \geq \text{Threshold VIS2 Min}$ (sn2thrminloc) and $A_2 \leq \text{Threshold VIS1 Max}$ (sn1thrmaxloc) and $A_2 \geq \text{Threshold VIS2 Shadows}$ (sn2thrombloc) and $[(T_3 - T_4 < \text{Threshold 34 mountain and } T_3 \geq \text{separ1637}(=18000))$ or $(T_3 < \text{Threshold 3 Max and } T_3 \leq \text{separ1637})]$ then:
If: $T_4 - T_5 \leq 200$ sn45thrmax and $T_4 - T_5 \geq -20$ sn45thrmin and $[(T_3 - T_4 < \text{Threshold 34 plain})$ and $(T_3 \geq \text{separ1637})$ or $(T_3 < \text{Threshold 3 Max})$ and $(T_3 \leq \text{separ1637})$ <div style="text-align: center;">\Rightarrow Ice</div>

Table 9: Succession of tests to detect sea ice.

Threshold determination

Threshold IR4 Min = Max (24315, (sst_clim_cst_irs - 500))

Threshold VIS2 Min. = Threshold VIS

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Threshold VIS2 shadows = $\text{nint}(2000 * (\cos(\theta_s * \pi / 180)))$
Threshold 34 mountain = $\text{nint}(2000 * (\cos(\theta_s * \pi / 180)))$
Threshold 34 plain = $\text{nint}(1500 * (\cos(\theta_s * \pi / 180)))$
Threshold VIS1 Max. = $\text{nint}(7000 * (\cos(\theta_s * \pi / 180)))$
Threshold canal3 Max = $\text{seuil16neige}(\text{szen}, \text{sazi}, \text{vzen}, \text{vazi}) * (\cos(\theta_s * \pi / 180))$
IR Threshold and Threshold VIS are defined in the routine which calls the **deglac.F**.

TESTS APPLIED DURING DAYTIME WITHOUT SUNGLINT

These tests are done in **testsd.F** (sea & day), **testld.F** (land & day) and **testcd.F** (coast & day) routines.

Tests series

Land	Sea
Snow detection If Snow \Rightarrow clear	Ice detection If Ice \Rightarrow clear
Else $T4 \geq$ Threshold IR over land	Else $T4 \geq$ Threshold IR over sea
And $A1 \leq$ Threshold VIS	And $A2 \leq$ Threshold VIS
And $T4 - T5 \leq$ Threshold45	And $T4 - T5 \leq$ Threshold45
And $T4 - T3 <$ Threshold4-3 or $T3 >$ sature3 or $T3 <$ separ1637 or $\text{albedo_clim} >$ cst_desertalbmin \Rightarrow clear	And $T4 - T3 <$ Threshold4-3 or $T3 >$ sature3 or $T3 <$ separ1637
-	And Uniformity: $\text{SD } T4 \leq \text{cst_sd33s}$ \Rightarrow clear

Table 10: Daytime tests over land and sea without sunglint

Coast	
Snow detection If Snow \Rightarrow clear	
Index \geq Rivthr \Rightarrow Land	Index $<$ Rivthr \Rightarrow Sea
$T4 \geq$ Threshold IR over land	$T4 \geq$ Threshold IR over sea
$A1 \leq$ Threshold VIS	$A2 \leq$ Threshold VIS
$T4 - T5 \leq$ Threshold 45 over land	$T4 - T5 \leq$ Threshold 45 over sea
$T4 - T3 <$ Threshold4-3 or $T3 >$ sature3 or $T3 <$ separ1637 or $\text{albedo_clim} >$ cst_desertalbmin	$T4 - T3 <$ Threshold4-3 or $T3 >$ sature3 or $T3 <$ separ1637

$$\text{Index} = (A2 - A1) / (A2 + A1)$$

Table 11: Daytime tests over coast without sunglint.

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Threshold determination

Threshold RIVTH:

It is used to determine if we are over sea or land with the vegetable index. If the climatological albedo is greater than a `cst_desertalbmin` value, then `rivthr = cst_rlivthr (-0.1)`, else `rivthr =cst_rsivthr (-0.04)`.

Threshold IR over sea:

If climatologic SST is present (`sst_clim`)

Threshold IR = `sst_clim - cst_sstirs`

In that case, the test is not done by using the observed T4 but an estimated split-window sst computed with T4 and T4-T5 by `sstval.F` routine.

if (`sst_clim < 1.8°C`) then (Threshold IR = `t2m_prev - s_ir`)

else

Threshold IR = `max(cst_sstmin, t4max_el-cst_irs_nd)`

where `t4max_el` is maximum T4 value in the ellipse.

Threshold IR over land:

If 2-m air temperature forecast is present (`t2m_prev`)

Threshold IR = `t2m_prev -s_ir`

else

Threshold IR = `max(cst_1stmin, t4max_el- cst_ir)`

Threshold IR over coast:

This Threshold will be different whether the AVHRR pixel is considered over land or over sea.

Over sea with climatologic SST present (`sst_clim`) :

Threshold IR = `sst_clim - cst_sstirs`

if (`sst_clim < 1.8°C`) then (Threshold IR = `t2m_prev - s_ir`)

Over sea without climatology:

Threshold IR = `max(cst_sstmin, t4max_el - cst_ir*1.5)`

Threshold IR over land is determined as in the previous paragraph 'THRESHOLD IR OVER LAND'.

Threshold VIS over sea :

The subroutine **albmer.F** simulates the visible reflectance over sea as function of the geometry angles. First, the maximum reflectance (`albsans`) over the sea surface is computed with the subroutine **phulpin.F**, following the Cox and Munck theory. Then, the `simulatmos_ocean_35.F` subroutine returns `a0`, `a1` and `a2` values for correcting the surface albedo of the atmospheric diffusion over sea.

The visible reflectance is then computed as follow:

Threshold VIS = `albmer = 100 * (brdf6s + 5.)`

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where : $brdf6s = 100. * (a0 + a1 * surface / (1 - surface * a2))$

surface = (albsans/100.) / 100.

If the albmer value is negative, the threshold is computing by using a simple function depending of the solar zenithal angle in the subroutine **svmer.F**

Threshold VIS= svmer

Thresholds IR and VIS over sea for ice detection:

Threshold IR = Max(24315, sst_clim - cst_irs-500)

Threshold VIS is computed as above over sea.

Threshold VIS over land:

The **albter.F** subroutine simulates the visible reflectance over land in a very similar way to **albmer.F** over sea. First, the surface reflectance over the land surface is computed with the subroutine **roujean.F** and depends on the climatological albedo (alb_clim) and the geometry angles (it applies an angle correction to the climatological albedo). Then, the **simulatmos_terre_35.F** subroutine returns a0, a1 and a2 values for the atmospheric diffusion over land.

The visible reflectance is then computed as follow:

albter = 100*brdf6s where: $brdf6s = 100. * (a0 + a1 * surface / (1 - surface * a2))$

surface = (alb_clim/100. * brdf6s + offset)/100.

offset = 8.

threshold VIS = albter* cos (zenithal angle)

If the albter value is negative, the threshold is computed by using a simple function depending on the zenithal angle in the subroutine svterre.F

Threshold VIS = svterre *cos(zenithal angle)

Thresholds IR and VIS over land for snow detection:

Threshold IR = max(sn4thrmin, Threshold IR - sn4thrfou) with Threshold IR computed as above over land.

Threshold VIS computed as above.

Threshold VIS over coast :

The VIS threshold will be different whether the AVHRR pixel is considered over land or over sea. The VIS thresholds over land or sea are applied as above.

Threshold 45 over sea :

This threshold is extracted from a pre-calculated table of (T4-T5) brightness temperature differences for sea situations. The extraction depends on the satellite zenith angle secant and the input total water vapor content.

Threshold 45 over land :

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Same method as above but from a pre-calculated table of (T4-T5) brightness temperature differences for land situations.

Threshold 45 over coast :

Two thresholds are extracted, one for sea and a second for land.

Threshold 43 over sea, land and coast :

Same method as for the thresholds 45 with the corresponding (sea or land) pre-calculated 4-3 tables.

TESTS APPLIED DURING DAYTIME WITH SUNGLINT

Theses tests are only applied over sea and coast, in the **testsg.F** (sea, glint) and **testcg.F** (coast, glint). The determination of the sunglint condition is done in the **glint.F** routine, called by **masque.F** before calling any test*.F routines.

Specular reflection test

It determines if specular reflection is present by computing the specular reflection (Phulpin model) in the routine **glint.F**:

$$\mu_n = \frac{\mu_{so} + \mu_{sa}}{\sqrt{2(1 + \sin \theta_{so} \sin \theta_{sa} \cos(\varphi_{sa} - \varphi_{so}) + \mu_{so} \mu_{sa})}}$$

where :

$$\mu_{so} = \cos(\theta_{so})$$

$$\theta_{so} = \theta_s * \pi / 180 \text{ where } \theta_s \text{ is the solar zenith angle}$$

$$\mu_{sa} = \cos(\theta_{sa})$$

$$\theta_{sa} = \theta_l * \pi / 180 \text{ where } \theta_l \text{ is the satellite zenith angle}$$

$$\varphi_{so} = \varphi_s * \pi / 180 \text{ where } \varphi_s \text{ is the solar azimuth angle}$$

$$\varphi_{sa} = \varphi_l * \pi / 180 \text{ where } \varphi_l \text{ is the satellite azimuth angle}$$

If $\mu_n \geq 0.999 \Rightarrow$ **specular reflection**

Else if $\mu_n > 0.90$ then :

$$val = \frac{n \text{ int}(200.*\exp(-1))}{4.*\mu_{sa} * \mu_{so} * \text{abs}(\mu_n^2 - \mu_n^4)}$$

If val > 1000 \Rightarrow specular reflection.

Tests series

Sea
Ice detection
If Ice \Rightarrow clear
Else T4 \geq Threshold IR
And T4-T5 \leq Threshold 45 over sea

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And Uniformity : $SD\ T4 \leq cst_sd33s$
And $A2 \leq Threshold\ VIS$
And $T3 \geq Sature3$ or $A2 \leq Threshold\ VIS\ Glint$ or $T3-T4 \leq Threshold34\ Glint$ or $T3-T4 \geq A2*1.7$ or $T3 < separ1637$
And $T4-T3 \leq Threshold4-3$ or $T3 \geq sature3$ or $T3 < separ1637$ ⇒ clear

Table 12: Daytime tests over sea with sunglint

Coast	
Snow detection If Snow ⇒ clear	
Index $\geq Rivthr$ ⇒ Land	Index $< Rivthr$ ⇒ Sea
$T4 \geq Threshold\ IR\ over\ land$	$T4 \geq Threshold\ IR\ over\ sea$
-	$T3 \geq Sature3$ or $A2 \leq Threshold\ VIS\ Glint$ or $T3-T4 \leq Threshold34\ Glint$ or $T3-T4 \geq A2*1.7$ or $T3 < separ1637$
$A1 \leq Threshold\ VIS\ over\ land$	$A2 \leq Threshold\ VIS\ over\ sea$
$T4-T5 \leq Threshold\ 45\ over\ land$	$T4-T5 \leq Threshold\ 45\ over\ sea$
$T4-T3 < Threshold4-3$ or $T3 > sature3$ or $T3 < separ1637$ or $albedo_clim > cst_desertalbmin$ ⇒ clear	$T4-T3 < Threshold4-3$ or $T3 > sature3$ or $T3 < separ1637$ ⇒ clear

$$index = (A2-A1)/(A2+A1)$$

Table 13: Daytime tests over coast with sunglint

Note: over land, tests and thresholds are the same as Table 10: Daytime tests over land and sea without sunglint.

Threshold determination

Thresholds IR:

Those thresholds are computed as above during daytime without sunglint.

Thresholds VIS:

Those thresholds are computed as above during daytime without sunglint.

Thresholds 45

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Those thresholds are computed as above during daytime without sunglint.

Threshold VIS with sunglint:

Over sea and coast : Threshold VIS Glint = $1500 * \cos(\theta_s * \pi / 180)$

where θ_s : solar zenith angle

Threshold34 glint :

Over sea or coast : Threshold34 Glint = $500 * \cos(\theta_s * \pi / 180)$

where θ_s : solar zenith angle

Threshold 43 over sea, land:

Those thresholds are computed as above during daytime without sunglint.

TESTS APPLIED DURING NIGHT-TIME

They are done in the subroutines **testsn.F**, **testln.F** and **testcn.F**.

tests series

Sea	
T3 ≤ separ1637	T3 ≥ separ1637
T4 ≥ Threshold IR over sea	T4 ≥ Threshold IR over sea
-	T3-T5 ≤ Threshold 35
-	T4-T3 ≤ Threshold43
Uniformity: SD T4 ≤ cst_sd33s	Uniformity: SD T4 ≤ cst_sd33s
T4-T5 ≤ Threshold45	T4-T5 ≤ Threshold45

Table 14: Night-time tests over sea.

Land and Coast	
T3 ≤ separ1637	T3 ≥ separ1637
T4 ≥ Threshold IR over land	T4 ≥ Threshold IR over land
-	T3-T5 ≤ Threshold 35
-	T4-T3 < Threshold43 or albedo_clim > desert threshold
-	T4-T3 ≤ Desert threshold43 or albedo_clim < desert threshold or T4-T5 < Desert threshold4-5
T4-T5 ≤ Threshold45	T4-T5 ≤ Threshold45

Table 15: Night-time tests over land and coast.

Threshold determination

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Threshold IR over sea and land:

Over sea and land Threshold IR is computed as above.

Threshold IR over coast :

Depends on climatological SST (sst_clim) presence and/or 2-m air forecast temperature (t2m_prev) presence.

- If sst_clim and t2m_prev present : Threshold IR = min(t2m_prev - cst_ir, sst_clim - cst_ir)
- If no t2m_prev present: Threshold IR = max(cst_lstmin, t4max_el - cst_ir)
- If only t2m_prev is present : Threshold IR = t2m_prev - cst_ir
- If no sst and no t2m_prev : Threshold IR = max(cst_lstmin, t4max_el - cst_ir)

Threshold45 over sea, coast and land:

Over sea, the threshold45 is the same as the one used for the daytime test.

Over land, a nighttime table is used.

Over coast, the maximum threshold between sea and land is used.

Threshold35 :

The same method as above is applied: a different table is used for each surface type (sea and land), over coast the maximum between both is used.

Threshold43 :

The same method as above is applied: a different table is used for each surface type (sea and land), over coast the minimum value is used.

Desert Thresholds over land and coast

The climatologic visible reflectance (%*100) is compared to *cst_desertlbmin*. This is a constant defined in **maia.h** equal to 2500. If the climatologic value is lower than *cst_desertlbmin*, we consider that the surface is a desert.

The desert threshold43 over land and coast is:

$$\text{Desert threshold43} = \text{Threshold43(defined above)} + 200$$

The desert threshold45 over land and coast is the *cst_desert45max* which is equal to 0.

TESTS APPLIED DURING TWILIGHT

They are done in the subroutines **testst.F**, **testlt.F** and **testct.F**.

Tests series

Sea
T4 ≥ Threshold IR over sea
T4-T5 ≤ Threshold45
Uniformity: SD T4 ≤ cst_sd33s
T4-T3 < Threshold43

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$A2 \leq \text{Threshold VIS}$

Table 16: Tests applied during twilight over sea.

Land	Coast
$T4 \geq \text{Threshold IR over land}$	$T4 \geq \text{Threshold IR over land}$
$T4-T5 \leq \text{Threshold45}$	$T4-T5 \leq \text{Threshold45}$
$T4-T3 < \text{Threshold4-3}$ or $T3 > \text{sature3}$ or $T3 < \text{separ1637}$ or $\text{albedo_clim} > \text{desert threshold}$	$T4-T3 < \text{Threshold4-3}$ or $T3 > \text{sature3}$ or $T3 < \text{separ1637}$ or $\text{albedo_clim} > \text{desert threshold}$
$T4-T3 \leq \text{Desert threshold43}$ or $\text{albedo_clim} < \text{desert threshold}$ or $T4-T5 > \text{Desert threshold4-5}$	$T4-T3 \leq \text{Desert threshold43}$ or $\text{albedo_clim} < \text{desert threshold}$ or $T4-T5 < \text{Desert threshold4-5}$
$A1 \leq \text{Threshold VIS1}$	$A2 \leq \text{Threshold VIS2}$ or $A1 \leq \text{Threshold VIS1}$

Table 17: Tests applied during twilight over sea and coast.

Threshold determination

Threshold IR over sea and land:

Over sea and land Threshold IR are computed as during night-time.

Threshold IR over coast :

Depends on climatologic SST (sst_clim) and/or 2-m air forecast temperature (t2m_prev) presences.

- If sst_clim and t2m_prev present : $\text{Threshold IR} = \min(\text{t2m_prev} - \text{cst_ir}, \text{sst_clim} - \text{cst_ir})$
- If only t2m_prev is present : $\text{Threshold IR} = \min(\text{t2m_prev} - \text{cst_ir}, \text{t4max_el} - \text{cst_ir})$
- If only sst_clim is present : $\text{Threshold IR} = \min(\text{sst_clim} - \text{cst_ir}, \text{t4max_el} - \text{cst_ir})$
- If no sst_clim and no t2m_prev: $\text{Threshold IR} = \max(\text{cst_lstmin}, \text{t4max_el} - \text{cst_ir})$

Threshold45 over sea, land and coast:

The threshold45 are computed as during night-time

Threshold43 :

The same method as during night-time is applied.

Desert thresholdS over land and coast:

The same thresholds as during night-time are used.

ThresholdS VIS over land and coast:

They are the same as above.

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G - AVHRR surface and cloud top determination

SEA SURFACE TEMPERATURE

For each AVHRR pixel declared clear by the test series in the ellipse and over sea, a surface temperature at the AVHRR resolution is computed with the following functions, in the **tempsurfm.F** routine:

If zenith angle less than 110° the NLC algorithm is used:

$$\text{tempsurfm} = a_0 * t_4 + (a_1 * \text{sst_clim} + a_2 * (\text{sec}-1)) * (t_4 - t_5) + a_3 + b_0$$

otherwise the TRI algorithm is used:

$$\text{tempsurfm} = (a'_0 + a'_1 * (\text{sec}-1)) * t_3 + (a'_2 + a'_3 * (\text{sec}-1)) * (t_4 - t_5) + a'_4 * (\text{sec}-1) + a'_5 + b'_0$$

sec is the secant of the zenith angle.

sst_clim is the climatological value of SST

the a_i and a'_i are coefficients of simulation with MODTRAN

the b_0 and b'_0 are bias to simulation on observed data

Then an average value of the individual sea surface temperature is computed in the **maia.F** routine and archived as the surface temperature (output parameter number 2).

LAND SURFACE TEMPERATURE

For clear pixels over land the same process is applied as for sea conditions but with an other function similar for NOAA14 and NOAA15, in the **tempsurft.F** routine :

$$\text{tempsurft} = t_4 + (1.31 + 0.27 * (t_4 - t_5)) * (t_4 - t_5) + 1.16$$

CLOUD TOP TEMPERATURE

At the end of each **testxx.F** routine, for each AVHRR pixel rejected with one of the tests (flagged as cloudy), a first step is applied to detect if the cloud is black-body or not (**cornoir.F** routine), by comparing T4-T5 to a threshold :

$$T_4 - T_5 < \text{bb45thr.} \quad \text{with } \text{bb45thr} = 1\text{K}$$

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Then if more than 5% of the pixels in the HIRS ellipse are declared as covered by black-body clouds, an average value together with its standard deviation is computed in the routine **tempsommet.F** and stored in the parameters number 8 and 9 (among the 13 output parameters).

8.6.5. Off-line threshold files creation

The threshold files were created off-line to give the variation of the different threshold files (t4-t5, t4-t3, t3-t4, surface temperature-t4) with the secant of the zenith angle and the total water vapor content in the atmosphere.

First, we used the TIGR2 dataset (1761 profiles) which represents the global atmosphere. The RTTOV6 fast forward model was used to compute synthetic brightness temperatures for AVHRR channels 3, 4 and 5, for 5 different secant angles (from 1 to 2 with a step of 0.25), 7 surface-air skin temperatures (-10,-5,-3,0,+3,+5,+10) and 60 emissivities from 0.8 to 1. (with 2 different steps of 0.005 and 0.0025).

The brightness temperatures depend on the channel characteristics and consequently on the satellite number.

The output file `noaaxx_rttovs.tigr` is very large, about 500MB.

Each profile is documented with a profile code (sea, coast, land), its position and date, its total water vapor content.

Secondly, sub-files of smaller size were extracted differently for 3 conditions: sea/coast, vegetation and desert. Only profiles with the correct code are kept, and a selection in the range of emissivity is done. For vegetation, 3 sets of emissivities are considered and 2 over desert. Over sea, the emissivity depends on the secant. We get 3 independent files of much smaller size (between 3 and 10MB).

```
noaaxx_mercot_tigr.dta
noaaxx_veget_tigr.dta
noaaxx_desert_tigr.dta
```

The extraction takes about 15 minutes for one satellite.

The 3 preceding files are read by the **crea_table_rttovs** routine, which creates the tables of the channel differences. Then means and standard deviations for the secant angles, and 7 twvc (from 0.25 to 7.75) are computed and curves of maximum values of the channels differences are estimated by:

$$\text{Channel difference} = \text{mean} + 2 * \text{std} + \text{noise}$$

The noise comes from statistics between RTTOV synthetic brightness temperatures and observations.

The resulting curves are then interpolated and extrapolated on 7 secant angles (from 1. to 2.5) and 16 twvc (from 0.25 to 7.75).

The results correspond to 24 files for t45, t43, t35, ts4 and (sea, vegetation, desert) and 2 air-skin surface temperature departures. The resulting files are of the form:

```
Ex: T45_veget_-3 :+5_noaaxx.dta
```

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In practice, only seven of them are useful and are in input of avh2hirs software:

T45_mercot_-3:+3_noaaxx.dta, T35_mercot_-3:+3_noaaxx.dta , T43_mercot_-3:+3_noaaxx.dta
T45_veget_-10:+10_noaaxx.dta , T45_ veget_-3:+5_noaaxx.dta , T45_ veget_-3:+5_noaaxx.dta
T45_ veget_-3:+5_noaaxx.dta