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IASI : An Advance Sounder for Operational Meteorology

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ABSTRACT

IASI is an infrared atmospheric sounder. It will provide meteorologist and scientific community with atmospheric spectra. The IASI system includes 3 instruments that will be mounted on the Metop satellite series, a data processing software integrated in the EPS (EUMETSAT Polar System) ground segment and a technical expertise centre implemented in CNES Toulouse.

The instrument is composed of a Fourier transform spectrometer and an associated infrared imager. The optical configuration is based on a Michelson interferometer and the interferograms are processed by an on-board digital processing subsystem, which performs the inverse Fourier transforms and the radiometric calibration. The infrared imager co-registers the IASI soundings with AVHRR imager (AVHRR is another instrument on the Metop satellite).

CNES is leading the IASI program in association with EUMETSAT and is supported by Météo-France for scientific aspects.

This paper presents the IASI mission, an overview of the IASI system and a description of the instrument.

IASI PROGRAMME

IASI (Infrared Atmospheric Sounding Interferometer) is a key element of the payload on the Metop series of European meteorological polar-orbiting satellites. The first flight model in this series is scheduled for launch in 2005. IASI is a significant technological and scientific step forward that will provide meteorologists with atmospheric emission spectra to derive temperature and humidity profiles with a vertical resolution of one kilometre and accuracies of one kelvin and 10% respectively.

The instrument is designed to measure atmospheric spectra in the infrared. It comprises a Fourier transform spectrometer and an associated imager.

CNES led the IASI project as prime contractor up to the end of the preliminary definition phase. The innovative technical solutions and technologies used to build IASI will pave the way for a new generation of spaceborne optical instruments.

The instrument development phase started in November 1998. This phase and production of recurring models are being led by Alcatel Space Industries as industrial prime contractor. The corresponding contract covers the supply of three flight models, with delivery of the first model in 2003.

For the IASI programme a cooperation agreement has been approved by CNES and EUMETSAT. Under this agreement, CNES has technical oversight responsibility for the instruments up to the end of in-orbit commissioning, and will develop the data processing software and operate a technical expertise centre. EUMETSAT is responsible for operating IASI, archiving and distribution of the data to users. The cooperation agreement has been extended to the Swedish Space Agency (SNSB), which is helping to fund the programme.

IASI OBJECTIVES AND METEOROLOGICAL CONSTRAINTS

Scientific objectives

At the beginning of the IASI project, it was necessary to specify the instrument's scientific objectives, including radiometric and geophysical characteristics.

IASI is designed to provide data to operational meteorology and atmospheric research organisations, which will be used to retrieve temperature and humidity vertical profiles of a much higher quality than those currently obtained from the TOVS sounder. The levels of

accuracy required for numerical weather forecast or data assimilation systems are :
- 1 K absolute accuracy and 1 km vertical resolution for temperature measurement;
- 10% relative accuracy and 1 km vertical resolution for humidity measurement.

These figures represent the performance expected from IASI in places where radiometric measurements will be operable, i.e. in areas of clear sky or partly cloudy sky. Global coverage of the sounding system will be ensured by the simultaneous use of the microwave sounders AMSU-A and MHS.

For the surveillance of trace gas evolution, IASI must also be able to measure the contents of O_3, CH_4, CO and N_2O gas constituents. The accuracy expected is over 5% for ozone measurement (and whenever possible, a description of the profile at 2 or 3 levels) and over 10% for other gases.
IASI must be able to determine ocean and continent surface temperatures. In this case, the instrument must also help to improve the knowledge of surface spectral properties.

Finally, IASI must contribute to the study of interactions between the clouds and atmospheric radiation; on the one hand, it must be able to characterise the clouds in terms of part coverage, cloud top temperature, type and transparency; these measurements are performed by means of the IASI integrated imager and in conjunction with the AVHRR imager; on the other hand, it must be capable of measuring cloud optical property variations with the wavelength.
The definition of measurement objectives is supplemented by the description of the temporal and horizontal resolutions expected, i.e 12 hours (lapse of time between two successive satellite crossings) and 25 km at sub-satellite point.

Spectral characteristics

The operable spectral range extends from the end of the atmospheric transmission window at 3.62µm (2 760cm^{-1}) to beyond the Q branch peak of the CO_2 absorption band, circa 15.5µm (645 cm^{-1}). Inside this range, the spectral regions presented in table 1 contain the major part of the relevant information.

Table 1 – Main spectral regions used by the IASI instrument

Name	Spectral region	Absorption band	Iasi application
R1	650 to 770 cm^{-1}	CO_2	Temperature profile
R2	790 to 980 cm^{-1}	Atmospheric window	Surface and cloud properties
R3	1 000 to 1 070 cm^{-1}	O_3	O_3 sounding
R4	1 080 to 1 150 cm^{-1}	Atmospheric window	Surface and cloud properties
R5	1 210 to 1 650 cm^{-1}	H_2O	Humidity profile CH_4 and N_2O column amount
R6	2 100 to 2 150 cm^{-1}	CO	CO column amount
R7	2 150 to 2 250 cm^{-1}	N_2O and CO_2	Temperature profile N_2O column amount
R8	2 350 to 2 420 cm^{-1}	CO_2	Temperature profile
R9	2 420 to 2 700 cm^{-1}	Atmospheric window	Surface and cloud properties
R10	2 700 to 2 760 cm^{-1}	CH_4	CH_4 column amount

The spectral resolution specification results from the line spacing within the CO_2 absorption band at 15µm, i.e 1.5 cm^{-1}. The spectral resolution required from IASI after apodisation(1) is equal to 0.5 cm^{-1}, i.e 0.25 cm^{-1} before apodisation.
Knowledge of the IASI spectral response function must be of a quality such that the error induced on the determination of an atmospheric target temperature will be less than 0.1 K.

Finally, in terms of instrument wave number calibration, the central wave number of each channel must be measured with a relative accuracy higher than 2.10^{-6}.

Radiance measurement characteristics

The instrument radiometric sensitivity is defined as the temperature variation which gives a black body radiance variation equivalent to the measurement's noise. Its evaluation in terms of radiance implies its multiplication by the temperature derivative of the Planck function; it depends therefore on the wave number and the temperature. For reasons of convenience, this temperature is specified independently from the channel and the reference temperature adopted is 280 K. For primary spectral regions such as defined in table 1, the radiometric sensitivity specified is indicated in table 2.

Table 2 – Radiometric sensitivity (K) specified for the different IASI spectral regions.

R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
0,20	0,24	0,20	0,24	0,20	0,36	0,36	0,36	0,36	1,53

Outside the regions, performance degradation in relation to adjacent regions is acceptable within a 20% tolerance. The noise taken into account by this specification includes all noise sources (detectors, amplifiers, digitising, processing) and errors considered as noise (e.g. errors linked to wave number calibration or instrument function knowledge).

(1) Apodisation : cancellation of secondary rings from the spectral response function

The radiometric calibration specification includes several aspects : the first (a) corresponds to the absolute accuracy of equivalent temperatures measured by IASI and, therefore, to the total calibration error. The second aspect (b) corresponds to calibration reproducibility and represents, therefore, errors other than biases. The third aspect (c) corresponds to error terms which have a different behaviour between spectral bands, between pixels of detector matrices or angular positions different from the scanning mirror.

(a) The calibration system must be suitable to determine, in flight, equivalent temperatures with an accuracy of over 1 K in the range of 200 to 300 K (objective of 0.5 K)

(b) Calibration reproducibility must be such that the variations do not induce errors on the equivalent temperature higher, than 0.3 K in the 200 to 300 K range.

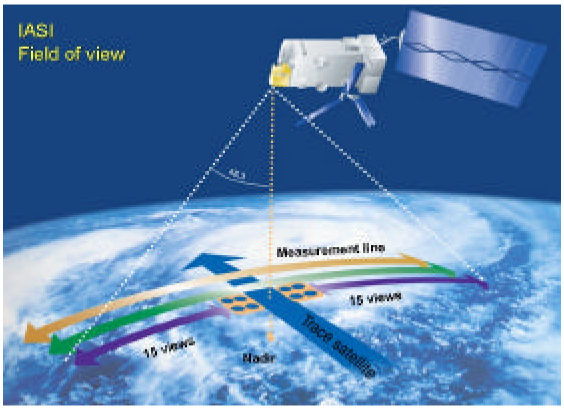
(c) Calibration differences between the bands, between simultaneous pixels and between different positions of the scanning mirror, must not introduce, for a target having the same equivalent temperature, differences higher than 0.2 K. This part of the specification restricts the amplitude of non modelled variable effects or of residual errors after modelling (mirror reflectivity or polarisation variations)

Finally, as far as the temperature range is concerned, IASI must be able to measure equivalent temperatures from 4 K to 315 K.

Geometrical characteristics

The IASI scanning is compatible with that of the AMSU-A sounder, which means that both IASI and AMSU-A optical axes are oriented toward the same ground positions during scanning. More precisely, the IASI optical axis scans the space in a plane which is perpendicular to the satellite orbit track (Figure 1). The scanning process is step by step, with rapid move between the different look positions, and a stop during the look (acquisition of interferogram). There are 30 look positions on the measurement track, spaced by approximately 3.3 degrees, and symmetrical with the nadir. Therefore, the optical axis moves from -47.85 degrees to +47.85 degrees in relation to the nadir. In addition to the 30 views in the ground direction, the scanning includes views to the calibration targets and return to the starting position; overall, it lasts 8 seconds. Bearing in mind that METOP will be in orbit at an altitude close to 840 km, the IASI swath (length of ground measurement track) will be approximately 2400 km.

Figure 1 – IASI scanning



The instrument field of view shall remain fixed during interferogram acquisition, so as to avoid contamination of the spectrum resulting from scene radiometric variation. A field motion compensation device is integrated in the scan mechanism to ensure view stability

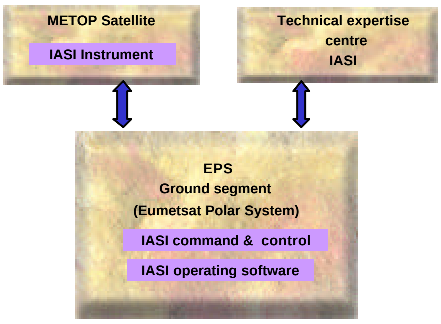
The IASI total angular field is conical with a vertex angle of 3.3 degrees. It is analysed by a matrix of 2 x 2 circular cells corresponding to a 1.25 degree angle and whose centres are positioned on lines and columns located at ±0.825 degrees from the instrument optical axis. On the ground, each cell of the analysis matrix corresponds therefore to a circular pixel of 12 km diameter at sub-satellite point.

IASI SYSTEM DESCRIPTION

The IASI system is strongly linked to EPS (European Polar System) which is developed by EUMETSAT.
The IASI system is composed of the following elements :
The on-board segment which is mainly constituted of the instrument, and its associated on-board software, mounted on the Metop satellite. This segment includes also the software developed for the instrument on-ground acceptance tests. Three instruments will be delivered for integration on the Metop series in the frame of the IASI programme.
The operational software in charge of the instrument scientific data level one processing. This software will be integrated in the EPS core ground segment. The outputs of the scientific

data processing are presented in the IASI product paragraph. The algorithms of the operational software have been validated using the IASI numerical end to end model and the instrument breadboard developed by CNES.
The TEC (Technical Expertise Center) in charge of the instrument performance monitoring, the performance anomaly investigation, the development and validation of new algorithms and the maintenance of the on-board and ground software. An overview of the IASI system and the links with EPS is presented in the figure 2

Figure 2 : IASI system overview

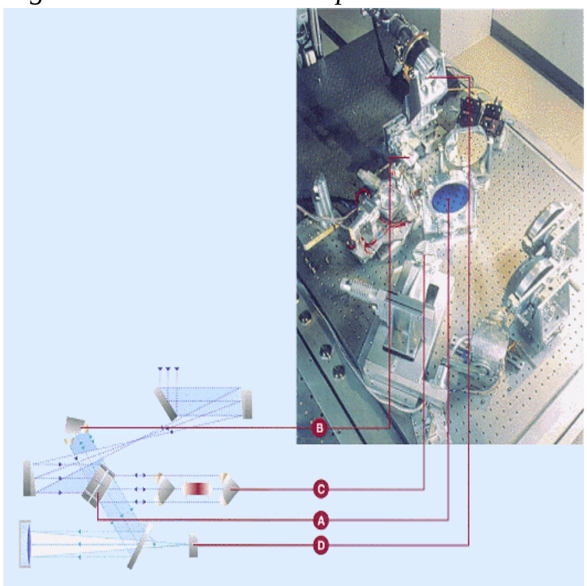


INSTRUMENT TECHNICAL DESCRPTION

All technology selections are the result of a continuous trade-off procedure. This procedure consists in classifying trade-offs, in priority order and allocating priorities to the selection criteria. The first selection criterion is compliance with the specification, but all items in the specification do not have the same importance and must be prioritised; preference has been given to spectral resolution and radiometric quality, as well as reliability and availability, which are fundamental qualities for an instrument to be operational.

The selection performance order has been such as to limit the range of technological choices as early as possible. The first selection has confirmed the interferometer technique as being preferable to grating spectrometry. In addition, the required quality of radiometric calibration imposes the use of a bilateral interferometer.
The instrument concept is thus based on the Michelson interferometer (figure 3). Incident radiation is divided into two beams by a beamsplitter (A) : the first beam follows a path of constant length (B); the other is reflected by a moving mirror and follows a path of variable length (C). The difference between both paths is called the optical path difference. The energy of the beams, when they recombine on the detector (D), varies with the path difference. It is maximum when the path difference is a multiple of the wavelength (beams in phase). It is zero when the path difference is an odd multiple of half the wavelength (beams in phase opposition). Energy on the detector thus varies with the movement of the cube corner mirror. This variation produces what is called an interferogram, which represents the Fourier transform of the spectral distribution of analysed radiation.
The electrical signal from the detector is then digitized before performing a mathematical inverse Fourier transform to restitute the incident radiation spectrum.

Figure 3 : Instrument concept



The components of IASI, along the light path through the instrument are:
- **Scan mirror**. It provides a swath of ±48.3 degrees perpendicular to the satellite track, with field motion compensation to avoid scene variations during acquisition. It also views a calibration blackbody and the deep space, considered as a cold blackbody. Fluid lubricated bearings are used for the step by step scene scanning and the field motion device is based on flexural blade pivot. Life tests were successfully performed on two scan mechanism breadboards.

- **Off-axis afocal telescope** that transfers the aperture stop onto the scan mirror.
- **Michelson interferometer**, including a beamsplitter, a compensating plate and two silicon carbide cube corner mirrors: one cube

corner moves linearly by ±1 centimetre within 151 milliseconds, which corresponds to an optical path difference of 2 centimetres, taking into account the return light path. This path difference is necessary to obtain the specified spectral resolution. The cube corner reflector is preferable to plane mirror; due to the high sensitivity of plane mirrors to alignment performance which imposes dynamic alignment. The very significant number of cycles in the instrument life time (5 years x 365 days x 24 hours x 3600 seconds x 2 cycles/second = 300 millions cycles) and the high reliability required are incompatible with ball-bearing runners for moving the mobile cube corner. Therefore, the interferometer mechanism is based on flexible metal guiding blades device.

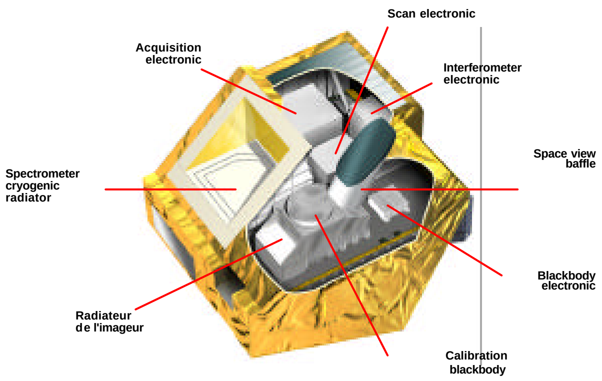
A 1.54 µm frequency-stabilized laser is injected into the interferometer. Stabilization is achieved by locking the frequency to an acetylene absorption line. The interferometer output of the laser beam is a sinus signal. This signal is used as a reference to sample the interferogram directly as a function of the optical path difference. This sampling leads to an important relaxation of the speed stability requirement of the moving reflector.

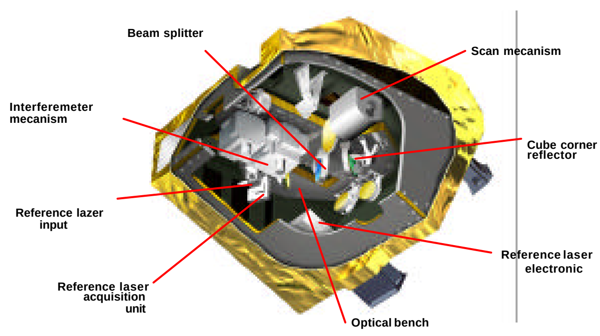
- **A folding mirror** directs the recombined beam onto the **off-axis focusing mirror**, which images the Earth at the entrance of the cold box.
- **The cold box** contains field and aperture stops, the field lens that forms the image of the pupil on the cube corners, the dichroic plates that divide the whole spectrum range into three band, aspheric lenses that image the field stop on the detector unit and the three focal planes, equipped with microlenses, detectors and preamplifiers. Radiometric performance requires cooling the cold box to below 100 Kelvin using a three-stage passive radiator to reduce the instrument background and thermoelectronic detector noise. The choice of a passive detector cooling system rather than a cryogenic machine was dictated by the lack of experience concerning life time and by the generated vibration level inside the instrument which might have a negative impact on spectral quality.

Interferograms are digitized with a 16 bits resolution by the **acquisition electronics** and processed by the **digital signal processing subsystem**. The transmission data rate allocated by Metop to IASI is limited to 1.5 Mbits/s and IASI provides data (interferograms) at a rate of 45 Mbits/s. A study of compression capabilities demonstrated, at early project stages, that the only means to achieve a compression rate of 30 without quality loss was to convert the interferogram into a complex spectrum (rate of 15), then to perform the radiometric calibration (rate of 2 by disappearance of the imaginary part). Therefore the inverse Fourier transform and the radiometric calibration are performed on-board. This last is achieved by viewing the internal hot blackbody and cold deep space, every eight seconds.

A wide spectral band **infrared imager** is integrated in IASI to facilitate the processing of partly cloudy regions by a fine analysis of the properties of the clouds present in the IASI field, in conjunction with the AVHRR imager. The IASI imager relies on a microbolometer matrix. It includes a unique spectral channel which extends from 10.5 to 12.5 µm (atmospheric window). Its radiometric sensitivity must be higher than 0.5 K at 300 K and it must be calibrated for an accuracy higher than 1K. Its 64 x 64 detector matrix analyses a square field with sides of 3.3 degrees, focused on the sounder optical axis. Each detector of the integrated imager, therefore, sees a square pixel of 0.8 Km sides at sub-satellite point.

Figure 3 : Instruments views





IASI PRODUCT DESCRIPTION

The IASI processing system (figure 4) generates calibrated atmospheric spectra from raw interferograms. These spectra are ready for assimilation by users and are processed on-board the instrument and by the associated ground segment.

On board processing reduces the data rate from 45 Megabits per second to 1.5 Megabits per second. The algorithms used to process the raw interferograms basically correct non-linearities in the detection process, calculate the inverse optical Fourier transform and perform radiometric calibration of the spectra obtained.

These spectra are downlinked from the satellite to the ground segment and form level 0 data. Data are processed on the ground at three levels:

- level 1A comprises decoding, spectral calibration, radiometric post-calibration,
- IASI/AVHRR co-registration, location and dating;
- level 1 B consists in resampling the spectra;
- level 1 C comprises an apodization function and analysis of AVHRR radiance levels in IASI pixels.

All level 1 data are available for users.

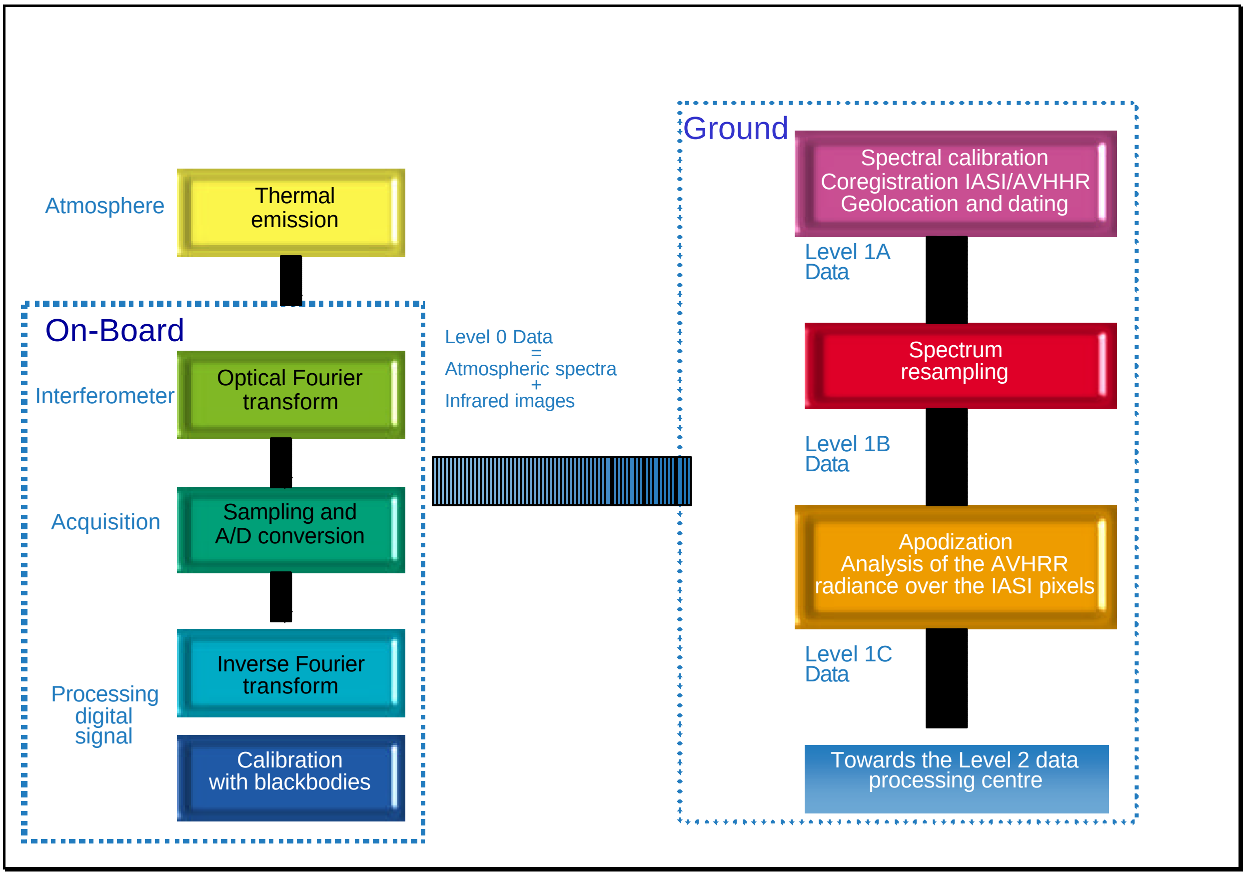


Figure 4 : Data processing

PERFORMANCES EXPECTED FROM IASI

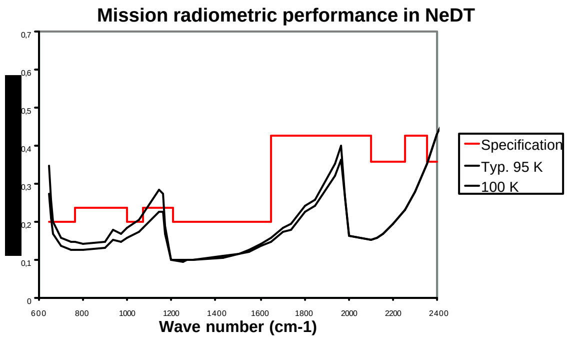
The performance expected from the IASI sounder, first from a radiometric point of view, then from a geophysical point of view, is examined below.

Instrument performance

The instrument performance will be entirely characterised at final acceptance test only, just before delivery by the manufacturer. This will be supplemented by the flight acceptance procedure, in the first six months of IASI in orbit. However, it is necessary, during the instrument development phase, to obtain an estimate of its performance at any time. This estimate is the result of an instrument numerical model which links the IASI performance to that of its different components. This model was first used, during the instrument definition phases, to write a set of specifications consistent for all components. Now development has started, it is used to appraise the impact of component properties as the manufacturer's unit measurements become available.

To date, we have obtained the results below concerning IASI radiometric sensitivity and the spectral response function, which influence its performance in terms of accuracy and vertical sounding resolution. The IASI radiometric sensitivity, including the noise of all processes applied, is presented in Figure 5, which also gives the corresponding specifications. It can be observed that the performance expected is significantly better than the specifications in most of the spectral range, particularly in the water vapour R5 band (1210-1650 cm^{-1}). However, there are some spectral regions where the sensitivity is outside the specifications. Among them, the regions corresponding to inter-band spaces are not a cause for disruption since band limits have been selected so as to avoid operable spectrum parts. However, the 650-680 cm^{-1} region is a cause for much more concern, as most of the information is focused on the temperature profile in the stratosphere; the project leaders and the manufacturer are doing their best to improve performance in this region. Similarly, at the other end of the range, beyond 2400 cm^{-1}, the sensitivity reaches only marginally the level specified. Here, the difficulty is inherent in the Planck function behaviour, but the impact on the profiles is low, since the major part of this region is an atmospheric window where spectral resolution is not indispensable, and where it is therefore possible to group channels in order to reduce noise.

Figure 5 - IASI radiometric performance budget with initial specifications



The IASI spectral performance is presented in Figure 6, which shows the width variation half way up the spectral response function, superimposed on the specifications. Figure 7 shows the spectral response functions for several wave numbers; the effect of the apodisation can be seen, expanding the response function while decreasing the size of its secondary rings.

Figure 6 : Spectral performance

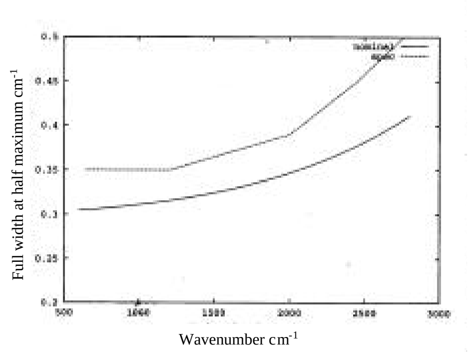
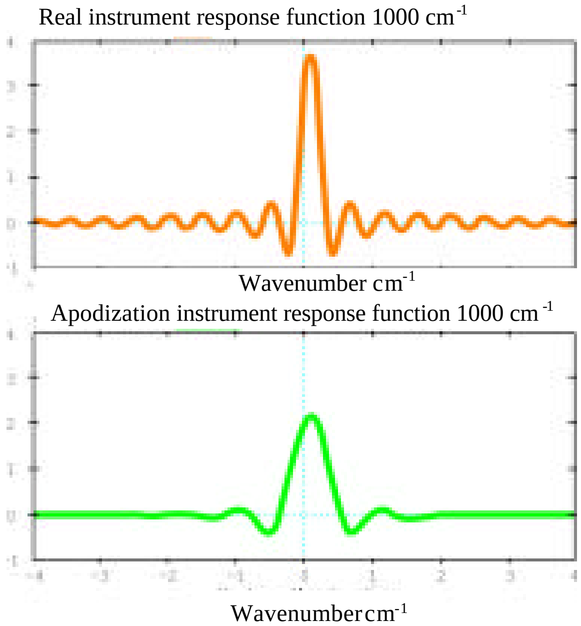


Figure 7 : Spectral response function

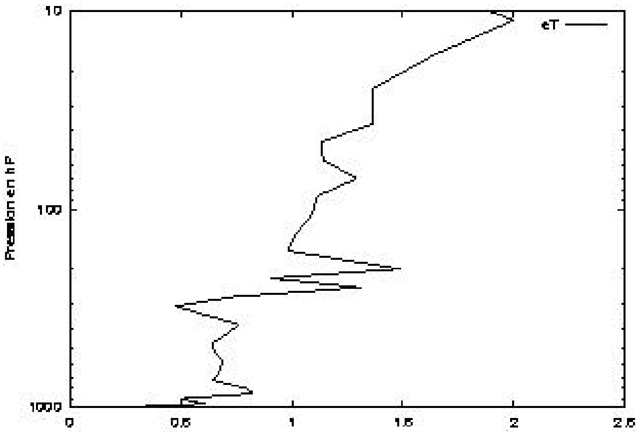


These results have been obtained from mock-ups. However, Figure 8 shows the measured spectral response function superimposed, with the instrument mock-up, on a laser transmitting at 2948 cm^{-1} and the calculated function, which demonstrates the very satisfactory predictability of the interferometer spectral characteristics.

Sounding performance

Similarly to the instrument quality, the quality of the atmospheric profiles deduced from the IASI measurements will only be known after launch. However, it is possible to obtain an *a priori* evaluation of this quality by simulation or analysis of the operator's properties subjecting atmospheric profiles to the radiance measured by IASI. This evaluation has been the subject of many studies carried out by the IASI scientific task force; the results obtained, although they present a certain degree of variability, lead to the conclusion that the temperature profiles determined by IASI will ensure, in the troposphere, a quality significantly better than the 1 K specification for a 1 km vertical resolution (in the case of measurements made in the absence of clouds). Figure 8 shows the error profile on the temperature calculated by Cassé and Prunet (2000). Similarly, Cassé and Prunet estimated the accuracy of humidity profile restitution and confirmed the quality will be in conformity, below 500 hPa, to the 10% specification for a 1 km vertical resolution (Figure 9).

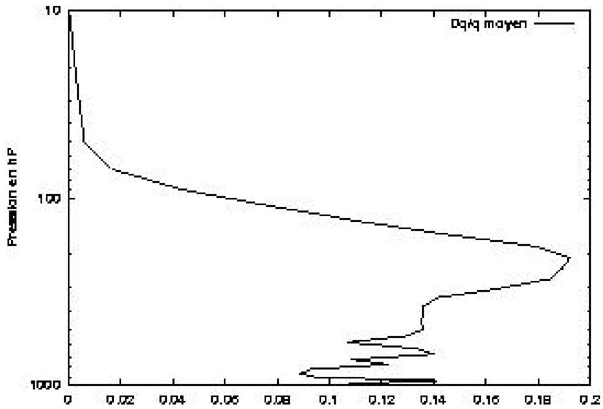
Figure 8 – Absolute error of atmospheric temperature profile restitution by IASI, for a 1 km vertical resolution (According to Cassé and Prunet, 2000).



It must be noted that the evaluation tools give a rather optimistic picture of the situation since they rely essentially on linear estimation tools and do not take into account instrumental biases or those of the radiative transfer models used. These biases may, in theory, be estimated, but this would require lengthy data series and significant efforts from the part of the users.

Another highly critical point concerns the influence of cloud presence and the benefit of simultaneous use of microwave sounders. The work carried out by the AIRS scientific task force, which may be applied to IASI, tends to show that, if significant efforts are made to model the clouds, both in infrared and in microwave regions, the quality of the profiles obtained in a partly cloudy situation could also meet the specifications.

Figure 9 – Relative error of IASI restitution of the water vapour mixture ratio profile, for a 1 km vertical resolution (According to Cassé and Prunet, 2000).



This being said, it remains difficult to quantify the effect of this observation system improvement on the quality of meteorological forecasts. The methods adapted to the investigation of this issue, i.e. observation system simulation experiments, involve the simulation of measurements for a relatively long period of time and, above all, require a representative model of profile restitution software on the basis of data. An experiment of this type is in progress within the IASI scientific task force, but the results will only be known in two years.

In the shorter term, Prunet and Al. (1998) tried to understand how IASI would avoid major weather forecast errors; they show how, in the case of the Floyd storm (12-13 December 1993), IASI would have helped to remedy, with good accuracy, the lack of knowledge of the initial state which lead to this erroneous forecast.

To conclude on geophysical performance and in an attempt to moderate the impression of a purely mathematical exercise, remember that the simulation tools used for IASI have been applied to the existing sounders, first to HIRS, but also to HIS *(High spectral resolution Interferometer sounder)*, much closer to IASI, which enables us to have more confidence in the performance forecasts.

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