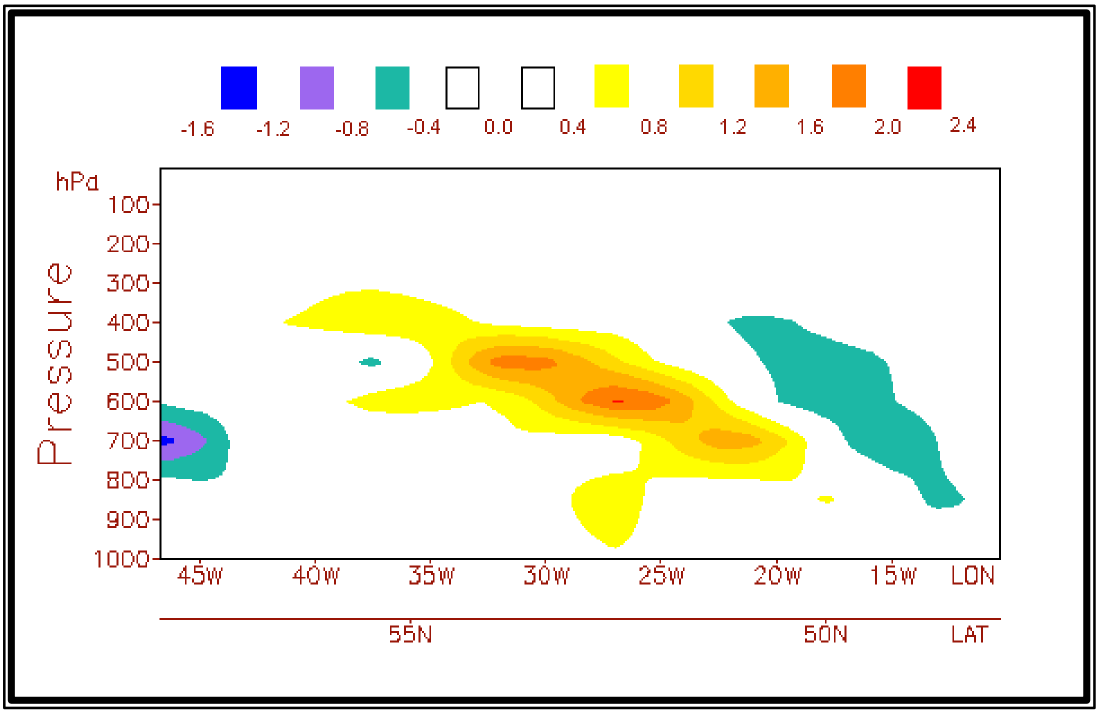
SCIENCE PLAN



A Report From The IASI Sounding Science Working Group

Edited by C. Camy-Peyret and J. Eyre

Title:	IASI Science Plan
Version:	Issue 1
Date:	September, 1998
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Printed for the ISSWG by EUMETSAT, Am Kavalleriesand 31, 64295 Darmstadt, Germany.

Front cover figure: Temperature perturbation profile of the "Floyd case", showing the remainder of hurricane Floyd on 10 September 1993, 12:00 UTC, that later developed into an intensive extra-tropical cyclone of strong gales and heavy rain that affected Brittany and south-west England. The instrumentation of the time was unable to detect this atmospheric anomaly. The IASI specifications have been tailored to provide an improved sounding capability for this type of application. Contour colours temperature deviations in degrees Kelvin. (Prunet *et al., 1998)*

SCIENCE PLAN

Executive Summary

Aim of the report

IASI is a remote sensing instrument that will use the information contained in the thermal infrared spectrum emitted by the atmosphere-surface-cloud system. A detailed knowledge of all relevant radiative processes, and a consolidated capability to model them precisely and accurately in the framework of operational meteorology, will be required to fully exploit the radiance spectra collected by the infrared sounding interferometer, and from which information on the atmospheric state will be retrieved (temperature and humidity as a function of altitude, column amounts for minor constituents, radiative properties of clouds and surfaces, etc.).

The IASI Science Plan has been prepared by members of the IASI Sounding Science Working Group, (ISSWG), a group established by CNES and EUMETSAT in 1995 with the objective of providing the scientific preparation for the IASI mission, under the coordination of its chairmen. The Science Plan provides a framework for the scientific research and development that will be required to ensure that the IASI mission objectives are met, establishes the main areas where scientific research and development activities are needed in order to achieve these mission objectives, and reviews the currently available scientific expertise in these areas, in order to identify where current studies may best be directed.

Many of these studies will provide the input required for the definition of the EPS Ground Segment and the IASI Technical Expertise Centre, and for this reason, research and development activities will need to be closely coordinated the development of these systems. Parallel studies approaching the same problem from different directions have been encouraged, so that methods can be compared when choosing algorithms to be used in the final processing chain.

It is envisaged that this Science Plan will be updated in regular steps in order to keep current with the results of the most recent investigations from both within and outside the ISSWG.

Synopsis of the Science Plan

The Science Plan is divided into five main sections. Section 1 is an introduction to the EPS mission in general and the IASI programme in particular. Section 2 provides a summary of the main scientific objectives of the IASI mission and the subsequent requirements placed on the IASI system in order to meet these mission objectives. The specifications of the IASI instrument arising from the mission requirements are described in Section 3. Following this, Section 4 summarises the current scientific knowledge, concepts and methods for IASI operational and research activities, and details the further investigations that are required. Finally, in Section 5, the research activities identified in Section 4 are broken down and prioritised.

Acknowledgements

We would like to acknowledge the contributions to the Science Plan made by ISSWG and ISUP members, EUMETSAT and CNES, and to thank Tim Patterson, a consultant at EUMETSAT, for his efforts in compiling, proofing and typesetting this document.

Claude Camy-Peyret and John Eyre
ISSWG Chairs
September, 1998

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1 INTRODUCTION

1.1 The EPS/Metop programme

Data from polar orbiting satellites have been made freely available to the worldwide meteorological community by the USA for more than thirty years and on a fully operational basis for nearly two decades. Currently the National Oceanic and Atmospheric Administration (NOAA), which is responsible for the related satellite programmes, supports two meteorological missions, one in a morning, the other in an afternoon orbit. NOAA has indicated that it would not be able to maintain the two satellite system - which is considered as the minimum for meteorological applications - beyond the year 2000.

Following discussions between the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) and NOAA about future cooperation regarding operational meteorological satellites, it has been agreed that EUMETSAT will take over the provision and operation of the Metop series of satellites in a morning orbit while NOAA would continue to provide and operate satellites in an afternoon orbit. The Metop satellite for the EUMETSAT Polar System (EPS) will be developed in cooperation between EUMETSAT and the European Space Agency (ESA). The launch of the first of the three currently planned satellites is foreseen for 2003. EUMETSAT will be solely responsible for the development and operation of the related EPS Ground Segment to control and monitor the satellite and to process data up to level 1. The operational processing of level 1 data to higher levels, i.e. the generation of geophysical products, will be done by external entities in the EUMETSAT member states (the "Satellite Application Facilities") or within the EPS Ground Segment.

The Metop satellites will carry a payload which is primarily dedicated to operational meteorology with a second focus on climate monitoring. In addition to these operational applications, the EPS/Metop system will contribute to a wide range of research activities, including global change, atmospheric chemistry and physics, hydrology, oceanic research and the study of the cryosphere.

NOAA will contribute to the suite of instruments through the provision of the Advanced Very High Resolution Radiometer (AVHRR) imager, and of the infrared (IR) and microwave (MW) temperature sounders, the High Resolution Infrared Radiation Sounder (HIRS) and the Advanced Microwave Sounding Unit (AMSU-A). The Microwave Humidity Sounder (MHS) to be also embarked on future NOAA satellites will be procured through EUMETSAT. Further instruments will be developed in cooperation with the Centre National d’Etudes Spatiale (CNES), i.e. the Infrared Atmospheric Sounding Interferometer (IASI), an advanced IR sounder for temperature monitoring, and Argos, a data collection and location system, and with ESA, i.e. the Advanced Wind Scatterometer (ASCAT), a scatterometer for surface wind measurements, the Global Ozone Monitoring Experiment (GOME-2), an ozone monitoring instrument, and the GNSS Receiver Atmospheric Sounder (GRAS), a radio occultation sensor of temperature and humidity. The payload is further described in Annex 2.

1.2 The IASI programme

In order to improve the vertical resolution and accuracy of the existing satellite IR temperature sounders (namely the High Resolution Infrared Radiation Sounder (HIRS) on the NOAA satellites), in 1990 the French and Italian space agencies, CNES and the Agenzia Spaziale Italiana (ASI), initiated a joint study for an instrument based on a Michelson-type interferometer, IASI. After demonstrating the feasibility of achieving the identified IASI mission objectives with this concept, a further definition study was started in 1992, initially still with participation by both CNES and ASI.

Since the discontinuation of ASI funded activities, CNES has carried on the definition study with additional support by EUMETSAT. Detailed design studies started in 1997, funded jointly by CNES and EUMETSAT with contributions from other European countries. Following the completion of the feasibility and design activities, the development and manufacturing phase for IASI began in 1998. The agreed embarkment of IASI on three Metop satellites will guarantee the continued provision of operational IASI data for a period of nominally 14 years.

The processing algorithms from raw data up to calibrated radiance spectra will be developed under the responsibility of CNES. The operational chain of these algorithms will be implemented in the EPS Ground Segment which will be operated centrally at EUMETSAT to process, archive and distribute data from IASI and the other instruments. In parallel, CNES will maintain an off-line chain, the IASI Technical Expertise Centre (TEC), with the processing software and additional software needed to monitor and analyse the instrument performance, and to define and validate algorithmic evolutions.

1.3 The role of ISSWG and ISUP

For the scientific preparation of the IASI mission, CNES and EUMETSAT have established the IASI Sounding Science Working Group (ISSWG), following the release of a first Announcement of Opportunity (AO) for the scientific preparation of the IASI mission in 1995. Principal Investigators (PIs) of selected proposals are members of the ISSWG (see Annex 3). Some of the objectives of this working group are: To advise CNES/EUMETSAT on the scientific requirements of IASI mission, system, instrument and ground processing, and especially on requirements related to the EPS Ground Segment; to review the progress of projects initiated under the IASI Announcement of Opportunity; to give recommendations to CNES/EUMETSAT on the direction of future work; to participate in the coordination of the ISSWG activities with external groups.

In particular the ISSWG has been asked to provide this Science Plan which provides a detailed discussion of the need for databases, retrieval methods, data assimilation, impact studies, etc.. EUMETSAT and CNES are to be advised on the selection of the most suitable methods for implementation in the EPS Ground Segment and the IASI TEC.

A second group established in parallel by EUMETSAT and CNES is the IASI Science and User Panel (ISUP) which consists of users and scientists interested in the ongoing activities but who are not directly involved in the IASI scientific studies. Its role is primarily to follow the activities of the ISSWG and to assist the ISSWG, CNES and EUMETSAT with decisions to be taken in the course of the IASI project. (See Annex 4 for the Terms of Reference of ISSWG and ISUP.)

1.4 Purpose of the Science Plan

The Science Plan details the scientific work needed to meet the IASI mission objectives and provides a framework for required scientific research and development activities. Firstly, it defines the main areas of activity to be covered and outline the links between these areas. Secondly, it identifies the on-going activities and currently available methods, software and data that comply with the identified needs. This first issue of the IASI Science Plan focuses on these aspects and provides guidance to EUMETSAT and CNES regarding the emphasis for the next phase of IASI studies that follows the conclusion of the initial two year period.

The Science Plan will be updated at regular intervals to take into account new results from studies conducted both within and outside the ISSWG. Later issues will also have to contain further advice on implementation related aspects, such as the selection of the most suitable methods and tools for an operational environment, and so will need to describe requirements and methods for the validation and intercomparison of the results obtained from the various studies.

1.5 Ground Segment development plan

In addition to this Science Plan, it will be necessary for EUMETSAT and CNES, with advice from the ISSWG and ISUP, to develop appropriate Ground Segment development plans. These will be described in separate documents.

2 IASI MISSION RATIONALE AND OBJECTIVES

2.1 Operational rationale

2.1.1 Numerical Weather Prediction (NWP)

Space-borne temperature soundings of improving vertical resolution (and hence accuracy), in particular resolving the vertical structure of baroclinic instabilities, are acknowledged to be a prerequisite to progress in mid-latitude weather prediction. Furthermore, a more accurate retrieval of moisture soundings from space is needed to improve the capability of models to simulate moist convection and realistic water budgets, and also to establish and ultimately control the relationship between dynamics and humidity fields. The IASI system is designed to reach the accuracy of 1K for temperature profiles and 10 % for humidity with a vertical resolution between 1 and 2 km in the troposphere, as deemed necessary by the international NWP community and formalised in the observational requirements of the World Meteorological Organization (WMO) (CEOS, 1995).

2.2 Climate monitoring

The Global Change Observing System (GCOS) programme was established to ensure that consistent observations of high quality are systematically provided for climate studies and applications (WMO, 1995). IASI will contribute to the products requirements of GCOS through its potential to yield information on temperature, humidity and cloud, to monitor ozone and other minor constituents, including possibly aerosols, and to provide information on surface temperature, surface emissivity and radiation budget.

2.3 Research rationale

As the role of clouds in the climate system represents the primary source of uncertainty in predictions of the equilibrium global warming, a first-order problem is to establish with sufficient accuracy the relationship between, on the one hand, the radiative properties of cloud systems and radiation fluxes at the top of the atmosphere (TOA) and, on the other hand, large-scale weather patterns and the vertical structure of the atmosphere which generate clouds. Accurate retrievals of vertical profiles of atmospheric temperature and moisture provided by IASI (or, more directly, high-resolution IR radiances), together with enhanced measurements of TOA radiation fluxes and cloud top properties, will make a major contribution to the refinement of climate models. IASI measurements will be of particular interest to several components of the World Climate Research Programme dealing with issues such as cloud climatology, land surfaces characterisation, water cycle description and ocean monitoring.

Concerning atmospheric chemistry, one of the key issue is to assess the concentration of the very reactive OH radical which strongly affects the cleaning efficiency of the atmosphere. There are still large unknowns regarding trace gases that steer the distribution of OH such as O_3, CO and NO_2, and it is important to obtain this information on a global scale by space-borne sensors such as IASI. Simultaneous land- and ocean-surface observations are needed to identify and quantify the origin of the above trace gases from natural sources, industry and agricultural activities, such as tropical biomass burning. For example, the relationship between terrestrial activities and global concentrations of tropospheric CO, CH_4 and O_3 as to be derived from IASI is one objective of the International Global Atmosphere Chemistry (IGAC) project (IGAC, 1998).

2.4 Mission objectives

This section summarises the IASI mission objectives which are fully described in the document “IASI mission rationale and requirements” (CNES/EUMETSAT, 1996).

IASI measures the spectrum of IR radiation emitted by the Earth from a low altitude sun-synchronous orbit, over a swath with a minimum width of 2000 km. The primary objective is to provide information on:

- Atmospheric temperature profiles in the troposphere and lower stratosphere
- Profiles of water vapour (WV) in the troposphere
- Total amount of ozone and some information about its vertical distribution
- Fractional cloud cover and cloud top temperature/pressure

The secondary mission objectives of IASI are the derivation of:

- Total column amounts of CO, CH4, N2O
- Sea surface temperatures

In addition, the IR spectra measured by IASI should also allow estimates to be derived for:

- Spectral dependencies of cloud emissivity
- Land surface spectral emissivities and the land surface temperatures under cloud-free conditions

The objectives for the accuracy, vertical resolution and horizontal sampling required for the atmospheric variables corresponding to primary and secondary objectives are given in Table 1. The large impact of cloud contamination on retrieval quality calls for an optimisation of the number of cloud free measurements. A footprint size of 12 km at nadir has been shown to provide adequate coverage but is considered as the maximum size acceptable.

GEOPHYSICAL VARIABLES	ACCURACY*	VERTICAL RESOLUTION	HORIZONTAL SAMPLING
Temperature profile	1K (cloud-free)	1 km	25 km (cloud-free)
Humidity profile	10 % (cloud-free)	1 - 2 km (troposphere) (cloud-free)	25 km (cloud-free)
Ozone total amount	5% (cloud-free)	N/A	25 km (cloud-free)
Ozone vertical distribution	10% (cloud-free)	2 or 3 pieces of independent information	25 km
Fractional cloud cover	TBD	TBD	25 km
Cloud top temperature	TBD	TBD	25 km
CO, CH_4, N_2O total content	10 %	N/A	100 km
SO_2, CFCs	TBD	TBD	TBD
Sea surface temperature	<0.5 K (cloud-free)	N/A	25 km
Cloud emissivity	TBD	TBD	25 km
Land surface temperature	1K (cloud-free)	N/A	25 km
Land surface emissivity	TBD	TBD	25 km

Table 1 Required characteristics for IASI products
(* accuracy of the IASI-derived geophysical variables are root mean square errors)

The IASI system will also have a built-in imaging capability to image each sounding pixel at a kilometric resolution in order to:

- Allow co-registration with images from the Advanced Very High Resolution Radiometer (AVHRR) within a fraction of the sounding pixel (typically 1 km) after ground-based processing

- Help detect clouds in day and night conditions and estimate autonomously the amount of coverage and basic characteristics of the clouds present in each sounding pixel. The imager would also provide a back-up capability for cloud detection/characterisation in case of AVHRR failure.

2.5 Measurement capabilities

This section summarises the IASI measurement requirements which are described in more detail in the document “IASI mission rationale and requirements” (CNES/EUMETSAT, 1996).

The useful spectral range extends from the edge of the thermal IR at 3.62 µm (corresponding to 2760 cm^{-1}), up to 15.5 µm (645 cm^{-1}). This range includes absorption bands by CO_2, H_2O and all relevant trace gases in addition to window regions to derive surface and cloud properties.

A factor restricting the vertical resolution of retrieved soundings is the width of the weighting functions, usually $\partial\tau/\partial \ln p$, where τ is the channel average transmittance and p the pressure (e.g. Kaplan *et al*., 1977). Narrow weighting functions are obtained if measurements are performed with high spectral resolution instruments in the line wings of absorbing atmospheric gases. As compared to sounders of the existing generation (e.g. TOVS), the much larger number of much narrower channels of IASI, will definitely improve the sounding capabilities in terms of vertical resolution for temperature and humidity and in terms of sensitivity and precision for trace species columns (see examples for IASI of selected weighting functions for temperature in Figure 1).

The spectral resolution requirements for IASI are determined by the line spacing in the 15 and 4.3 µm CO_2 absorption bands. As this spacing is equal to 1.5 cm^{-1} in most of the bands and to 0.75 cm^{-1} in some parts, the necessity to resolve CO_2 lines (at least in the 15 µm band) leads to an absolute minimum value of 0.75 cm^{-1} for sampling (Nyquist frequency) and consistent resolution. As a minimum of oversampling above the Nyquist frequency is desirable, a commensurate spectral resolution (defined in terms of full width at half maximum (FWHM) of the instrument spectral response function (ISRF)) is 0.5 cm^{-1} after apodisation, i.e. 0.35 cm^{-1} unapodised. The adequate nominal spectral sampling is constant over the full spectral range and equal to 0.25 cm^{-1}.

Due to the very sharp spectral patterns present in atmospheric spectra it is important to maintain a very accurate spectral calibration of the order of 1% of the apodised spectral resolution, as can be achieved with IASI, which will measure equivalent temperature in the range 180 K to 315 K.

The radiometric accuracy is related to the noise affecting the measurement and the calibration accuracy. The Noise Equivalent Temperature (NEΔT) for unapodised spectra at nominal sampling will be better than 0.28 K (at 280 K) from 645 to 1650 cm^{-1} and better than 0.49 K (at 280 K) from 1650 to 2400 cm^{-1}. Above 2400 cm^{-1} the noise is specified in terms of Noise Equivalent Radiance (NEΔR) and is equal to 17.5 $\mu W/(m^2 \cdot sr \cdot cm^{-1})$. The noise covered by these specifications includes all noise contributions (detectors, amplifiers, A/D converters, processing, etc.) and all error sources which do not result in a bias.

There are three calibration requirements:

- Absolute calibration with an accuracy better than 0.5 K at 280 K
- Calibration stability/repeatability that will not induce errors larger than 0.3 K on the determination of the equivalent temperature at 280 K
- Inter-calibration differences will not cause an error larger than 0.2 K at 280 K

The IASI built-in imager will have at least one channel in a thermal IR atmospheric window region probed by both the IASI sounder and the AVHRR, in order to allow:

- Detection of most cloud types within each sounding pixel in day and night conditions
- Straightforward comparison with coincident observations by the sounder and the AVHRR

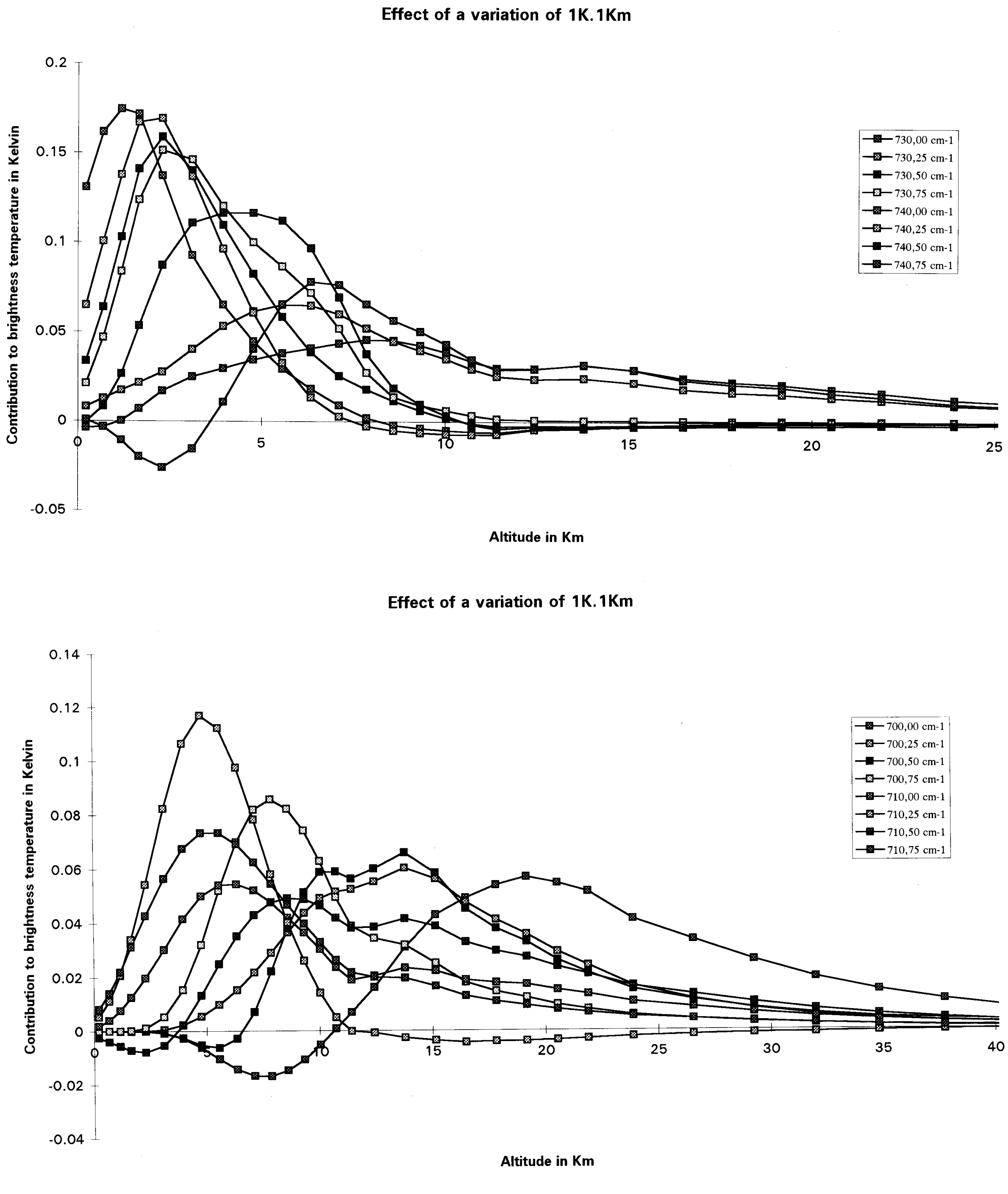

Figure 1 Modified weighting functions in narrow regions of the IASI spectrum around 730 to 740 cm-1 (top) and 700 to 710 cm-1 (bottom)

The figures illustrate (for 4 consecutive spectral samples at 0.25 cm^{-1} step size in each case) the strong spectral dependence of the shape and width of the weighting function which, for the selected wave numbers, have narrow peaks in the lower troposphere (top),but broader peaks in the mid- to upper troposphere and lower stratosphere (bottom). The curves give the brightness temperature variation (in K) for a 1 K temperature increase in a 1 km layer as a function of the altitude of the layer (in km). (CNES, 1998a)

The wavelength(s) will be selected in such a way as to allow autonomous cloud detection in the widest range of conditions possible, in particular in day and night.

The built-in imager will have a spatial resolution of the order of 1 km at nadir to be compatible with the requirements for:

- The co-registration of AVHRR-type imagery and IASI soundings within 1 km in the nominal mode, based on processing on-ground

- The co-registration of IASI imagery and soundings within 1 km in the IASI stand-alone mode, based on processing on-ground

- The partitioning of each sounding pixel into the number of imaging pixels sufficient to determine the proportion of up to five scene classes within each sounding pixel with an accuracy better than 5 %

The IR channel of the IASI built-in imager should have a NEΔT of 0.5 K at 280 K and be on-board calibrated with an accuracy better than 1.0 K at 280 K.

3 THE IASI INSTRUMENT

3.1 Basic principles

IASI is a Michelson interferometer and its general characteristics are described in Annex 1. The beam of radiation (see Figure 9 of Annex 1) at wave number σ is divided by a beamsplitter in two parts of equal amplitude α along two different optical paths, δ_1 and δ_2. Recombination of the two coherent beams with a phase difference:

$$\Phi = 2\pi(\delta_1 - \delta_2)\sigma$$

gives interferences at the detector and the amplitude of the recombined wave is:

$$A = 2\alpha\cos(\pi(\delta_1 - \delta_2)\sigma)$$

The optical path difference ($\delta = \delta_1 - \delta_2$) between the two beams varies with the displacement of one of two mirrors (in case of IASI two corner cube reflectors are used). IASI explores an Optical Path Difference (OPD) range symmetrical around the Zero Optical Path Difference (ZPD). The intensity of radiation at the detector is a function of δ:

$$I(\delta) = A^2 = 4\alpha^2\cos^2(\pi\delta\sigma) = 1/2\ I(0)\ (1+\cos(2\pi\delta\sigma))$$

where $I(0) = 4\alpha^2$ is the intensity of the input radiation.
Considering the spectral distribution of the source of radiation, $S(\sigma)$, the input intensity is $\int_0^\infty S(\sigma)d\sigma$. The measured radiance is then:

$$I(\delta) = 1/2 \int_0^\infty S(\sigma)\,(1+\cos(2\pi\delta\sigma))d\sigma$$

The varying term of I, named the interferogram $I'(\delta)$, is the real part of Fourier transform of the spectrum of the incoming flux $S(\sigma)$.

During the displacement of the reflector the modulated flux $I'(\delta)$ is detected, amplified and finally digitised at sample positions equally spaced in terms of the OPD. The spectrum of the incoming radiation is finally obtained through inverse discrete Fourier Transform of the sampled interferogram. The resulting spectrum, obtained after the Fourier Transform, is sampled uniformly in wave number with a step equal to $1/(2\delta_{max})$. In reality, the spectrum is not the result of the Fourier Transform of an infinite interferogram, but the result of the Fourier Transform of the product of the infinite interferogram by a window function of width equal to twice δ_{max}. As a consequence the measured spectrum is equal to the convolution of a spectrum with infinite resolution and the Fourier Transform of a rectangular window, i.e. a sin(x)/x function (sinc) of the variable $x = 2\pi\sigma\delta_{max}$.

The inherent advantages of Michelson interferometers as high spectral resolution instruments compared to other techniques are:

- The multiplex advantage in the thermal IR which leads to the simultaneous measurement of a broad spectral region using a single detector
- An instrument spectral response function that is a theoretically well known function of measurable instrument parameters
- A highly accurate spectral calibration
- A well established for the radiometric calibration that has been demonstrated with ground based and airborne instruments and is well understood

3.2 Performances

The mission and measurement objectives given in Section 2 have been translated into instrument specifications. These are given in “IASI instrument specification” (CNES, 1998). The following paragraphs summarise the instrument performance specifications. As performance at mission level will depend also on Ground Segment processing, the performances specified at instrument level might be less stringent that the ones given in “IASI mission rationale and requirements” (CNES/EUMETSAT, 1996). Conversely, the mission level noise includes various pseudo-noise contributions and is therefore higher than the purely radiometric instrument noise. The instrument noise is constrained through the specification of instrument characteristics measurable in a laboratory environment. Specifications apply to the duration of the in-orbit instrument life time.

The performances for the IASI sounder are separated in spectral, radiometric and geometric performances (Sections 3.2.1, 3.2.2 and 3.2.3). Performances of the integrated imager are discussed in Section 3.2.4.

3.2.1 Spectral specifications

IASI covers the full spectral range from 645 cm^{-1} to 2760 cm^{-1}, sampled at a 0.25 cm^{-1} interval.

Depending on the spectral wave number σ, the non-apodised resolution $\delta\sigma$ as defined by the FWHM of the ISRF, will be better than:

$645\ cm^{-1} \leq \sigma < 1210\ cm^{-1}$	$\delta\sigma \leq 0.35\ cm^{-1}$
$1210\ cm^{-1} \leq \sigma < 2000\ cm^{-1}$	$\delta\sigma \leq 0.39\ cm^{-1}$
$2000\ cm^{-1} \leq \sigma < 2450\ cm^{-1}$	$\delta\sigma \leq 0.45\ cm^{-1}$
$2450\ cm^{-1} \leq \sigma < 2760\ cm^{-1}$	$\delta\sigma \leq 0.50\ cm^{-1}$

Spectral calibration will be known to an accuracy better than $2.10^{-6}\sigma$.

The shape error index, e, characterises the error on the knowledge of the ISRF. Due to the high sensitivity of the radiometric noise induced by the shape error due to microvibrations, the contributions of microvibrations to the shape error index, ε_2, are specified separately from the other contributions, e_1. The shape error index, $\varepsilon = \varepsilon_1 + \varepsilon_2$, shall be less than:

	ε_1	ε_2
$645\ cm^{-1} \leq \sigma < 1210\ cm^{-1}$	≤ 0.02	≤ 0.026
$1210\ cm^{-1} \leq \sigma < 2000\ cm^{-1}$	≤ 0.03	≤ 0.026
$2000\ cm^{-1} \leq \sigma < 2450\ cm^{-1}$	≤ 0.04	≤ 0.030
$2450\ cm^{-1} \leq \sigma < 2760\ cm^{-1}$	≤ 0.05	≤ 0.042

The specified shape error index is a linear mean value calculated on the 4 pixels.

3.2.2 Radiometric specifications

IASI will measure, without saturation, radiance from blackbody at temperatures in the range 4 K to 315 K. In this temperature range the radiometric noise requirements are constant in terms of NEΔR for a given wave number. The NEΔR for samples at 0.25 cm^{-1} is specified through the following NEΔT values at 280 K:

R1	650 – 770 cm^{-1}	0.28 K
R3	1000 – 1070 cm^{-1}	0.28 K
R5	1210 – 1650 cm^{-1}	0.28 K
R6	2100 – 2150 cm^{-1}	0.47 K
R7	2150 – 2250 cm^{-1}	0.47 K
R8	2350 – 2400 cm^{-1}	0.47 K

In the intervals between these specified regions a degradation of 20% with respect to the interpolated values could be tolerated.

IASI calibration relies on measurements of cold and hot reference targets once every scan line. The calibration requirements will be met in the 200 to 300 K range. The absolute calibration will have an accuracy better than 0.5 K at 280 K. The calibration homogeneity with respect to the following parameters, is specified with errors less than:

spectral position	0.10 K
orbital repeatability	0.15 K
lifetime repeatability	0.15 K
geometry	0.10 K

3.2.3 Geometric performances

IASI axes are indicated in Figure 2. The nominal viewing direction will scan 96°40’ symmetrically with respect to the –OiZi axis (nominally nadir) i.e. from –48°20’ to +48°20’, staring at 30 measurement positions in each line. The nominal spacing between two measurement positions is 3°20’. The nominal scan pattern will also include measurements viewing the blackbody and the cold space in order to perform the radiometric calibration. During the time necessary for the interferogram acquisition the position on Earth of the Instantaneous Field Of View (IFOV) will not move. The whole sequence associated to a line will be performed in eight seconds and remain synchronised with the platform eight second synchronisation clock.

The IASI instantaneous field of view consists of a matrix of 2 × 2 circular pixels. Each pixel will have a field of view without vignetting smaller than 14.65 mrad and larger than 11.00 mrad (that is between 12 to 9 km on ground at nadir). The nominal pixel pattern is shown in Figure 3. The pixel centres will not deviate by more than 2.5 mrad (TBC) from the nominal positions.

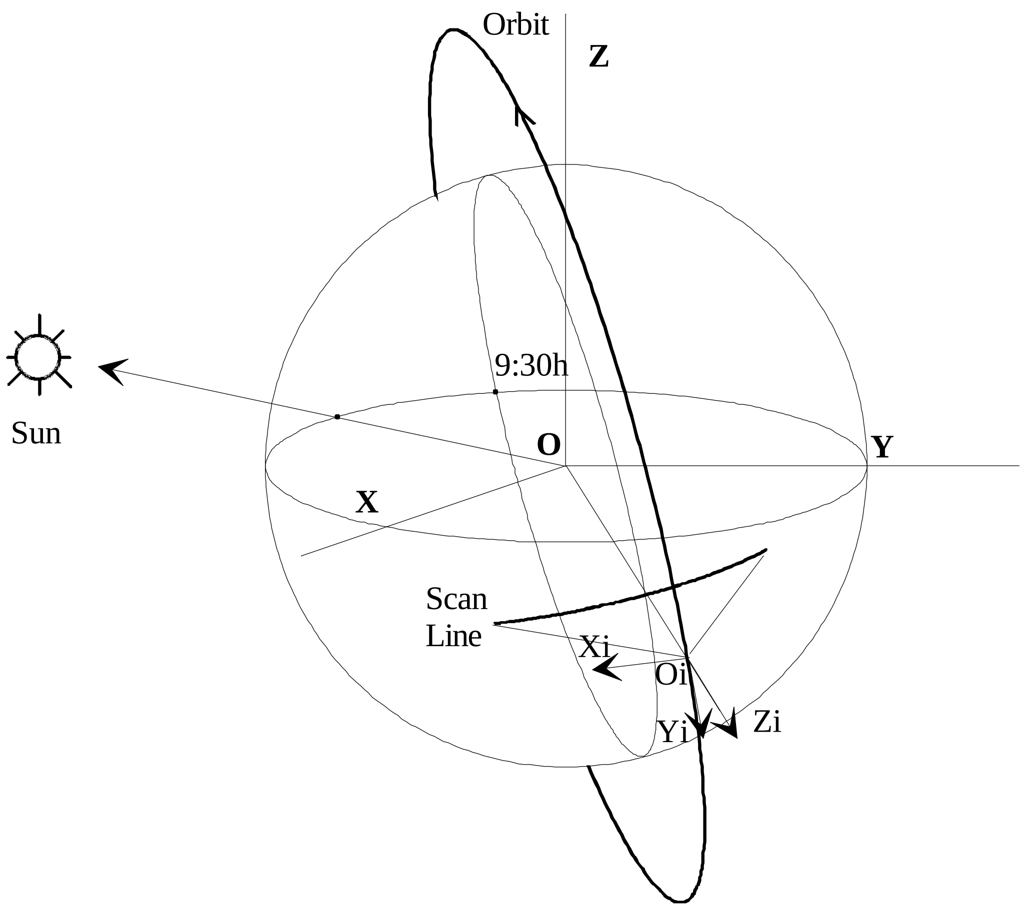

Figure 2 IASI scan pattern axis definition

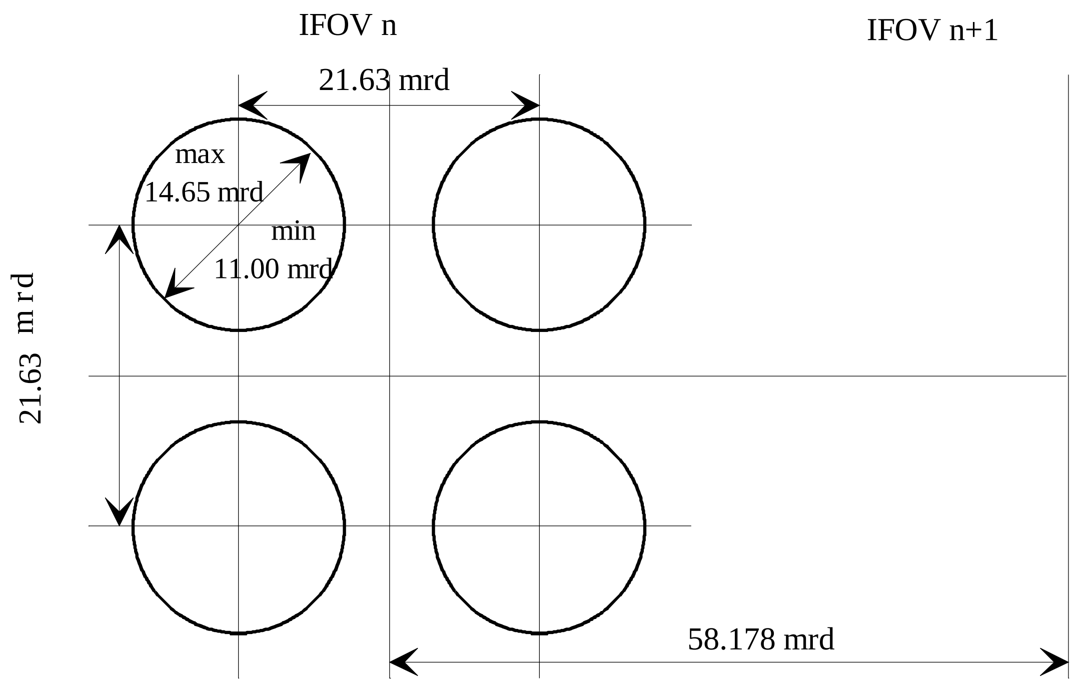

Figure 3 IASI nominal pattern of sounder pixels

3.2.4 Imager specifications

In order to process partly cloudy pixels of the sounder, it is helpful to perform a detailed analysis of cloud properties inside the pixel. This analysis requires the synergistic use of an integrated imaging system and the AVHRR. As an intrinsic part of IASI, the imaging system is a broadband radiometer in the thermal IR having a high spatial resolution.

The imaging system will have a single spectral channel in a spectral window which is also covered by AVHRR and will be able to measure a blackbody radiance in the 4 to 315 K temperature range. Contributions of reflected solar radiation (maximum albedo 40 %) over the thermal emission term will be taken into account in the definition of the dynamic range. NE∆T will be less than 0.5 K at 280 K (the radiometric noise is constant in terms of NE∆R). The calibration accuracy will be better than 1 K at 280 K.

The imaging system design is based on a detector matrix, analysing a square field of view, centred on the IASI nominal viewing direction. Its lines are parallel to the lines of the matrix of the pixels of the IASI sounder. The IFOV will be at least 59.63 mrad × 59.63 mrad (equivalent to 3°25’ × 3°25’) and will be covered by 64 × 64 elementary pixels.

The imager will be aligned with the sounder with an accuracy better than 5 mrad.

4 IASI SCIENCE

4.1 Overview

IASI data will have potential for use in a range of operational and research applications. To exploit this potential, substantial research and development is required to prepare for successful interpretation and application of IASI data and products. Many areas of scientific activity are involved, and these can be divided into the following main areas:

- Earth/atmosphere radiative transfer

  IASI measures the spectrum of IR radiation emitted from the top of the atmosphere, and this measured spectrum is then used to retrieve information on the state of the atmosphere. Before we can solve this “retrieval” problem, we must understand, and be able to model accurately, the associated “forward” or “radiative transfer” (RT) problem. In other words, we must be able to simulate, given a description of the state of the atmosphere, the radiance spectrum emitted from the top of the atmosphere at a spectral resolution comparable with that of the IASI instrument, for a wide range of atmospheric conditions. For many aspects of the IASI data processing problem, such calculations must be performed not only accurately but also very efficiently.

- IASI instrument processes and data ingest

  IASI does not measure the emitted radiation spectrum in a simple way. IASI is an interferometer; it transforms the incident spectrum and measures the associated interferogram. This must then be converted back to a radiance spectrum, it must be calibrated, and artefacts of the measurement process that affect the interpretation of the data must either be removed or accurately characterised. In order to do all of this, we must be able to simulate, to adequate accuracy, the many stages through which the radiance spectra incident on the IASI instrument are processed – first by the instrument itself, then by the on-board processing system and then by the on-ground “ingest” processes – to give calibrated radiance spectra (level 1b/1c data).

- Data pre-processing

  Before information on atmospheric temperature and composition can be extracted from the radiance spectra, they must be “pre-processed” in certain ways. This includes combining the IASI data with information from other Metop instruments that may assist the interpretation. It also includes detecting, and possibly adjusting for, atmospheric effects that would otherwise complicate subsequent stages in the processing. We must develop “pre-processing” methods for converting the calibrated radiance spectra from IASI, together with equivalent data from companion instruments, into the radiance forms required for input to subsequent retrieval and assimilation stages.

- Retrieval of geophysical parameters

  The procedures for extracting from the measured spectra the information on geophysical parameters to which they are sensitive – temperature, humidity, minor constituents and other variables – are not straightforward. They require the capability not only to model the "forward problem" (as explained above) but also to solve the associated inverse problem. In other words, given the measured radiance spectra, how do we estimate the most probable geophysical parameters to which they correspond. We must develop methods for retrieving geophysical products (level 2) – temperature, humidity, minor constituents and other variables – from the pre-processed data.

- Monitoring, quality control and tuning of IASI data and products

  When the IASI data become available, they must be monitored, at various stages of the processing, to ensure that their characteristics conform to those expected by the data processing and to quantify aspects of their quality and quantity. It is expected that a small proportion of the data will not meet normal standards of quality. These data must be detected, through quality control procedures, otherwise they will seriously degrade subsequent products. Some characteristics of the data will be uncertain prior to launch and may change with time after launch. These characteristics must be monitored carefully, and relevant aspects of the data processing must include ongoing tuning to take account of these changes. We must develop appropriate methods and tools for:

  - Monitoring the performance of the IASI instrument and each stage of the data processing
  - Performing necessary quality control steps
  - Tuning relevant stages of the data processing

- Validation of IASI data and products

  Pre-launch studies are needed to validate aspects of the proposed data processing systems and to assess the accuracy to be expected of data and products at various stages of processing. After launch, the data/products must be compared with other measurements or information, to quantify the accuracy of the data/products and to compare it against expected accuracies. We must develop appropriate methods and tools for:

  - Validating aspects of proposed data processing systems, including the radiative transfer models (RTMs) used
  - Assessing, pre-launch, the data/product accuracies to be expected
  - Validating, post-launch, the accuracies achieved for the level 1b/1c data, level 2 products and some other levels of product

- Applications of IASI data/products

  IASI data/products will have many applications: in operational meteorology, in climate and global change studies, and in atmospheric chemistry monitoring and research. For each application, we must assess in more detail the contributions that IASI will bring to it, and we must prepare for effective exploitation of IASI data/products, through the development of appropriate interfaces between the IASI data/products and the application, and through other preparatory studies.

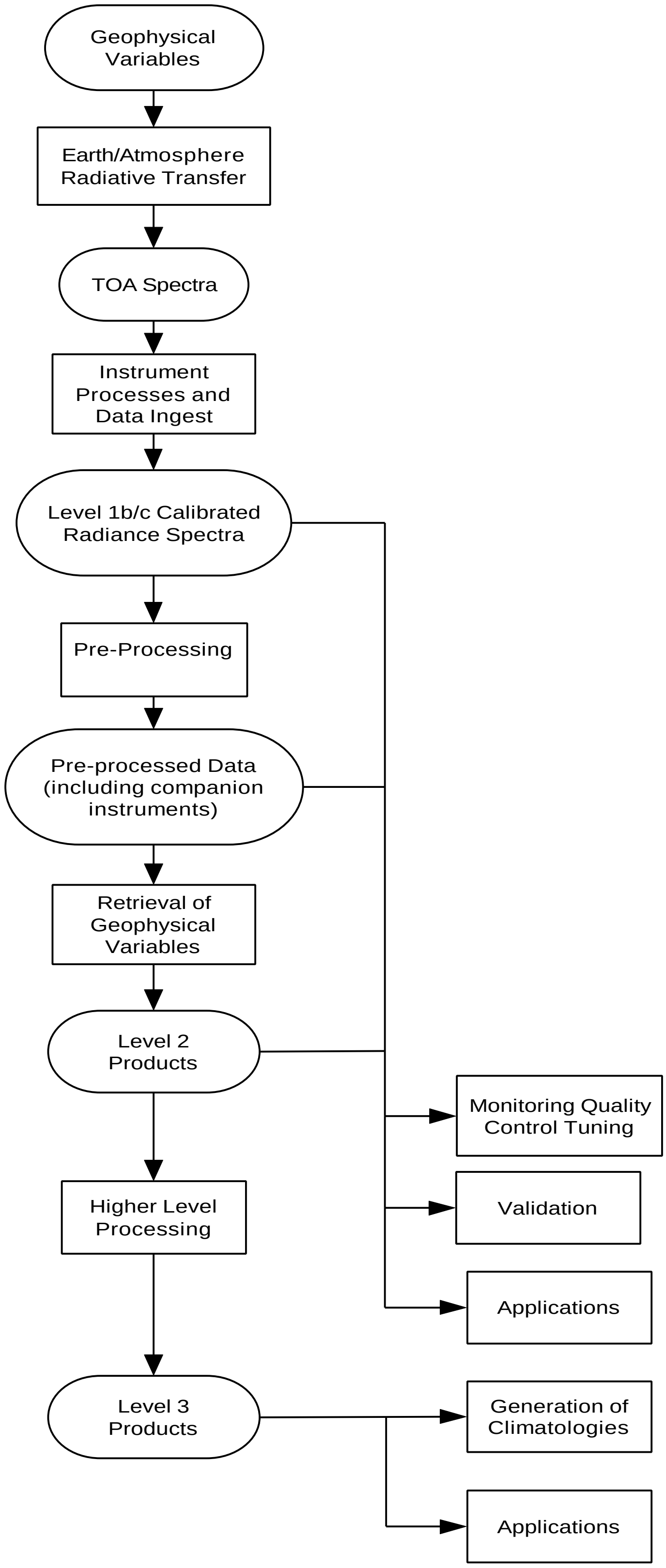

Figure 4 Main areas of scientific research and development required for IASI. (Square boxes are research and development processes. Rounded boxes are products and data).

These elements are related to each other as shown in Figure 4. Research and development is required for each of the "process boxes". In addition, supporting studies are required, and each study should support one (or more) activities in the process boxes. All science activities in preparation for IASI should "map" on to one of the activities shown in Figure 4. One of the purposes of this Science Plan is to assist with the planning of these activities - to ensure there are no gaps and to avoid unnecessary work. The following sub-sections describe in more detail the contents of each "process box" and the associated research and development required.

4.2 Earth/atmosphere radiative transfer

4.2.1 Atmospheric and surface variables

4.2.1.1 Atmosphere

Atmospheric RT studies in preparation for IASI require datasets of realistic profiles of atmospheric temperature, gaseous constituents, cloud water/ice and aerosols. These variables should be given on a defined set of pressure levels from about 0.1 hPa to 1050 hPa with levels spaced at least every 30 hPa in the troposphere. Constituent profiles may also be required with pressure and temperature specified on constant absorber amount levels, in order to ensure there is enough information on the absorber in the layers in which most of the absorption is occurring. These levels will vary from gas to gas, e.g. with more levels for ozone in the stratosphere and more levels for WV in the lower troposphere.

Atmospheric gases range from those that are constant or predictable in time to those that are variable and unpredictable. At one end of the range are well-mixed gases, with known height profiles and constant or slowly varying concentrations. For these gases one profile is sufficient. Carbon dioxide and oxygen are examples of this class. In the case of carbon dioxide, the concentration is gradually increasing with time and so a profile valid for the period that IASI is expected to be in orbit is required. At the other end of the range is WV, which varies enormously in time and space. Ozone and other minor constituents are intermediate to varying degrees. For some purposes (e.g. temperature retrieval) they may be treated as quasi-fixed, i.e. for these gases, profiles for different latitude bands and seasons may be sufficient to capture the variability. For other purposes, namely constituent retrieval, they must of course be treated as variable gases.

Radiosondes are the primary source of data for temperature and WV profiles. Temperature profiles are normally reliable up to 10 hPa although above 200 hPa corrections may have to be applied to remove consistent biases in the measurements due to radiative heating. Rocketsondes are used to provide upper stratospheric and mesospheric temperatures, and recently the GPS/MET satellite has provided radio occultation measurements, giving an additional source of global temperature profiles from 3 to 50 km altitude. Ground based Raman lidar are another source of temperature profile information although there are only a few of these instruments in operation and they still require an absolute calibration.

For WV, radiosonde measurements are at best accurate to 5% and in many cases the accuracy is much worse. In the vicinity of rapid transitions (e.g. top of boundary layer, transitions in and out of cloud, etc.), they will give large errors and they do not give accurate values at temperatures below -40 °C (i.e. above about 350 hPa at mid-latitudes). As for temperature ground-based Raman lidar can provide good relative WV measurements in the low and middle troposphere. The lack of reliable WV profiles frustrates attempts to accurately validate RTMs. Another problem is that lidars and radiosondes measure different atmospheric paths from those measured by a nadir viewing interferometer. Stratospheric WV is best measured by limb sounders such as the Microwave Limb Sounder (MLS) for MW emission, the Improved Stratospheric and Mesospheric Sounder (ISAMS) for IR emission, and the Stratospheric Aerosol and Gas Experiment (SAGE) and the Halogen Occultation Experiment (HALOE) for solar occultation. (For an overview of these and other meteorological satellites and instruments described in this document, see (CEOS, 1992; CEOS, 1997)). A good stratospheric WV profile dataset will be required to exploit the regions of the IR spectra with strong WV absorption lines.

Ozonesondes provide important data for ozone profiles in the upper troposphere and lower stratosphere although a ground-based network of total column ozone measurements gives more information on the total column variability in space and time. There are several satellite sensors which can provide total column ozone amounts globally (e.g. the Total Ozone Mapping Spectrometer (TOMS) , HIRS, GOME) or stratospheric profiles (SAGE, the Solar Backscatter Ultraviolet radiometer (SBUV)). The remaining atmospheric constituents of interest are in general measured in special campaigns and/or by research satellites (e.g. the NASA Meteorological Satellites (NIMBUS), the Atmospheric Trace Molecules Observed by Spectroscopy mission (ATMOS), the Upper Atmosphere Research Satellite (UARS), etc.). In Europe, the Environmental Satellite (ENVISAT) will provide a focus for new measurements of many stratospheric and some tropospheric constituent profiles.

For IASI simulations, a minimum requirement is for a dataset with profiles of temperature and H_2O, O_3, CO_2, N_2O, CO and CH_4 concentrations. Profiles of the chlorofluorocarbons (CFCs) are also required as these exotic gases can have significant effects in some spectral bands. As with some other gases their concentration is variable and so the value should be estimated for the period after the launch of Metop. In this case the concentration has to date been increasing but it is anticipated that some of the CFCs will start to decrease during the next decade.

4.2.1.2 Clouds

At IR wavelengths clouds are an important modulator of the top of atmosphere radiance. Most water clouds have an emissivity close to unity, and so the key parameter is the cloud top pressure which defines the temperature of the cloud top. Ice clouds are more transparent and so the profiles of ice water content, crystal size and shape are also important. Several research aircraft can provide various cloud properties profiles including cloud particle size (drop or crystal) and shape in addition to concentration.

4.2.1.3 Aerosols

Aerosols generally produce a small contribution for nadir sounders in the IR but when present in noticeable amounts, they can be significant particularly at the shorter wavelengths of the IASI spectral range. Their absorption and scattering properties vary with aerosol type. Datasets exist of extinction coefficients defined for various types of aerosol which include maritime, urban and desert types. These can be used together with an aerosol concentration profile for each type to estimate the total aerosol extinction.

4.2.1.4 Surface

For the regions of the IR spectrum where the atmosphere is relatively transparent the surface properties also need to be defined. At IR wavelengths the surface skin temperature and the emissivity of the surface, which is a function of surface type, viewing angle and wavelength, are the primary variables affecting the up-welling radiance. For the sea surface the skin temperature is normally within a few tenths of a degree of the bulk sea surface temperature (SST) and the emissivity is close to unity which allows the SST to be a good approximation for the radiative skin temperature. Datasets exist that give the small departure of the sea surface emissivity from unity as a function of viewing angle and wind speed over a range of wavelengths.

Over land, however, the definition of both the land skin temperature and the land surface emissivity is difficult to specify and is a subject of active research. Land surfaces can be sub-divided into specific surface types with defined emissivities (e.g. desert, agricultural, forest, snow, etc). A parameterisation relating type of surface to an emissivity spectrum for different times of year could then be used. Land surface skin temperatures are computed by NWP models although they can have large differences (~5 K) when compared with measured radiative skin temperatures. Over sea-ice the emissivity is close to unity but the ice radiative temperature can be difficult to estimate as over land. The surface elevation is also an important parameter as the intervening atmospheric absorption will be reduced as the path length is reduced.

4.2.1.5 Profile datasets required for simulations

Model atmospheres are often used as a source of profiles to create a few transmittance/ radiance spectra representative of a typical air mass. Commonly used model profiles are the US AFGL profiles for mean tropical, mid-latitude and polar atmospheres and the US standard atmosphere as a global mean profile (Rothman *et al*., 1983). These profiles are of pressure, height, temperature, WV and all other atmospheric constituents relevant for IASI. The model profiles are from the surface to 100 km and so encompass the full range of heights of interest for IASI transmittance modelling. There are two major limitations of model atmospheres. Firstly they do not encompass the full range of extremes encountered in the real atmosphere in terms of temperature and constituent concentration. Secondly the profiles are much smoother than in the real atmosphere with no sharp structures present.

For these reasons it is often desirable to use a selection of real atmospheric profiles measured by *in situ* or remote sensing techniques subjected to careful quality control. These datasets exist for temperature, WV and ozone profiles and many minor constituents. One such dataset is the NESDIS 1200 diverse set of radiosonde profiles and 383 diverse set of ozone profiles. These profiles are on 40 levels from 0.1 to 1000 hPa. Another is the TIGR dataset (Chedin et al., 1985) generated by LMD which has 1761 profiles on levels from 0.05 hPa to 1013 hPa. Other datasets have been generated for the North Atlantic/European area (e.g. CMS Lannion, UKMO) primarily for European direct read-out users of satellite data. A profile dataset which has collocated radiosonde (and/or other profile measurements), satellite radiances and NWP model profiles is a useful tool for assessing the accuracy of a forward model (see below) for an instrument once it has been launched. Several operational centres maintain such databases for TOVS.

Finally, for a full 3-D simulation of the radiances, analyses from an NWP model can be used to define the 3-D state of the atmosphere from which a set of atmospheric profiles with realistic horizontal variability can be provided to a fast radiative transfer model (RTM) to simulate a complete swath of IASI radiances. Currently NWP models only have pressure, temperature and specific humidity as variables but there are plans to include ozone in the near future in some models.

4.2.2 Radiative transfer modelling for IASI

There are two main classes of RTMs for IASI. The first are line-by-line (LBL) models which attempt to simulate the atmospheric transmittance and radiance spectra based on a fully physical representation of the underlying spectroscopy. They can be used for simulations at a spectral resolution higher than the instrument resolution. The second class are fast RTMs, based on empirical approximations to the spectroscopy, which can compute sets of radiances rapidly to allow simulations of many thousands of profiles. These are necessary for near real-time radiance monitoring, retrieval or assimilation. They are also needed for some off-line studies in which full LBL calculations are not feasible.

4.2.2.1 Line-by-line models

To simulate IASI radiances as accurately as possible, spectra are required at the same or better resolution than IASI and at a sufficient number of levels to allow the transmittance profile to be adequately described. There are several LBL models available (e.g. FASCODE (Smith *et al.*, 1978), GENLN2 (Edwards, 1982), HARTCODE (Miskolczi *et al.*, 1988), 4A, LBLRTM (Clough *et al.*,1991). They all require as input, in addition to an atmospheric profile, a spectroscopic dataset which contains all the parameters (e.g. central frequency, line strength, line half width etc) for each known absorption/emission line for each atmospheric gas. The two principle spectroscopic databases for the IR are HITRAN from the US AFGL (Rothman *et al*., 1992, Rothman *et al*., 1997) and GEISA from LMD (Husson *et al.*, 1992, Jacquinet-Husson *et al*., 1998). Both are frequently updated with new laboratory measurements. The line parameters from these databases together with the absorber amount and atmospheric pressure and temperature allow the absorption/emission due to discrete molecular transitions to be computed at any frequency assuming a line shape function. In the troposphere, where pressure broadening dominates, a Lorentz line shape is normally used but in the stratosphere, where Doppler broadening is more important, a convolution of Lorentz and Doppler line shapes (Voigt shape) is more appropriate. In addition there is the so-called "continuum absorption" for which, even after several decades of research, the physical mechanisms are still not fully understood. Several empirical parameterisations have been developed based on laboratory and aircraft measurements. WV is the main source of continuum absorption in the IR, but carbon dioxide, oxygen and nitrogen also have continuum contributions which need to be taken into account. Each model has a parameterisation for this continuum absorption and care has to be taken to ensure the absorption from the LBL component is combined with the continuum component in a consistent manner.

These LBL models are used to compute a relatively small number of radiance spectra at high spectral resolution so that they can be convolved with the instrument response function to simulate the measured radiance spectra. The LBL model transmittances are used as the baseline or dependent dataset from which fast model coefficients can be computed. In addition it is necessary to have LBL calculations for a separate independent set of profiles of transmittance as a means of checking the fast models.

Data compression techniques are being explored in which a matrix of absorption coefficients for a defined frequency interval and for a set of atmospheric levels can be reduced in size by singular value decomposition of the matrix. It is then possible to interpolate absorption coefficients in the compressed matrix and then recover the full transmittance profile. This technique allows calculations two orders of magnitude faster than LBL models but to a similar resolution.

4.2.2.2 Fast semi-empirical radiative transfer models

There are several methods proposed for fast RTMs described briefly below. One class of fast models are designed specifically for radiometers with fixed channels (e.g. TOVS). These models express transmittance (or optical depth) as the sum of a series involving atmospheric "predictors" (selected functions of atmospheric variables). The coefficients for the predictors are derived from atmospheric LBL transmittances calculated for a set of diverse atmospheric profiles. Transmittances can be computed for each channel on fixed pressure levels (e.g. the RTTOV (Eyre, 1991) or PLOD (Hannon *et al.*, 1996) models) or on layers of constant absorber amount (e.g. the OPTRAN model (McMillin *et al.*, 1995)). Having computed the transmittances from the polynomial expressions the RT integration can be carried out to obtain top of atmosphere radiances.

Another class of fast model which can be used for radiometers are library look-up models (e.g. 3R). These make use of an extensive library of profiles and associated radiances created from a collocation dataset. They match the input profile with one or a group of profiles in the library and then compute a radiance from those linked to the selected profiles.

A third approach is to use neural network techniques which are now being applied to the problem of fast RTMs for satellite data. These techniques are empirical/statistical as the radiances or transmittances are predicted from key elements of the atmospheric temperature and constituent profiles. The training dataset needed to compute the coefficients to relate the inputs (temperature and constituent profiles) to the outputs (radiances or transmittances) has to be large (>500 profiles) to cover the full range of atmospheric variability.

Fast models are being used operationally at a number of NWP centres for the assimilation of TOVS radiances. There are obvious advantages if one model can be used for all the atmospheric sounders (i.e. IASI, ATOVS, AVHRR, GOES) to allow a unified forward model to be developed. For NWP applications, with the current variational techniques, in addition to computing the radiance for a given profile it is also necessary to provide the gradient (i.e. tangent linear) of the model with respect to all the input variables (e.g. temperature, constituent profiles and surface parameters) and its adjoint.

4.2.2.3 Fast surface, cloud and aerosol models

In addition to the clear air RTMs, it is necessary to have radiative sub-models for surfaces and clouds.

For water surfaces or thick water cloud the emittance is close to unity, and it can often be assumed to be unity without major errors. However the non-unit emissivity should be taken into account for applications such as retrieving SST from IASI data. The sea surface emissivity decreases as the surface is viewed more obliquely and it is also a function of surface roughness and hence wind speed. It also decreases with decreasing wavelength and at 3.7 µm it is significantly less than unity (~0.97). Both of these effects can be easily parameterised. Over land the emissivity is more variable and a parameterisation has to be found to relate surface type, surface wetness, surface heterogeneity and viewing angle to emissivity averaged over a IASI field of view. This is still an area of research and should be investigated further with AVHRR radiances.

Cloud models have been developed in the LOWTRAN (Kneizys *et al.*, 1988) and MODTRAN (Berk *et al.*, 1989) models for various cloud types and work is actively being pursued to relate the cloud microphysical properties to emitted radiance using aircraft and satellite data. For water clouds the assumption of unit emissivity is a reasonable approximation but more research is needed in relating cloud tops of ice clouds to IR emissivity.

Parameterisations which relate profiles of cloud drop/crystal size and concentration to optical properties are under development and could be useful for IASI cloudy radiance simulations at least for the optically thin clouds (Francis *et al.*, 1994). The IASI radiances are likely to be sensitive to ice crystal size and concentration.

For simulating the effect of aerosols on IASI radiances a simple table of absorption coefficients which are a function of aerosol type and wavelength can be used. Scattering is much less important at IR wavelengths as compared to visible wavelengths. As the absorption coefficients do not vary rapidly with wavelength this is a relatively simple calculation which can be included after the molecular absorption has been computed. The exception to this may be for extreme aerosol concentrations (e.g. after a volcanic eruption) where a more sophisticated model may be required.

4.2.2.4 Radiative transfer model validation

In order to estimate the accuracy of the RTMs they have to be validated. Two approaches are possible: comparison with other models and comparisons with real measurements.

There are two types of model comparisons. Firstly comparing similar models (e.g. all LBL models) to check the basic spectroscopic data and coding of the model results in realistic transmittances. Such comparisons have been carried out in the past and have been useful to identify problems with the models or their implementation on various computers. The differences should only be due to differences in input data and model formulation. The second class of comparison is to compare fast model results with those from a LBL model to assess the accuracy of the fast model. This comparison should be carried out on a set of profiles independent of those used in the training dataset.

Comparisons of model predictions with reliable radiance measurements can be used to assess the accuracy of the models. However care must be taken to ensure not only that the radiance measurements are accurate but also that the characteristics of the atmospheric path through which the radiance is emitted are fully known, otherwise differences may be due to an inaccurate description of the atmospheric path. There are several possible configurations for atmospheric measurements by an interferometer similar to IASI. An up looking ground-based system can view the down welling atmospheric emission from the zenith or slant paths. If the measurements are made coincident with good quality profile measurements these data can be valuable for validation of the models. Cold space provides a known background radiance. Downward and upward looking measurements from an aircraft-borne or balloon-borne interferometer can validate the models for a wider range of different path conditions. In particular a nadir-looking interferometer under a stratospheric aircraft or balloon could encompass a range of optical thickness (variable during ascent up to float) which could provide stringent tests of the LBL forward models. Finally, satellite radiance measurements with similar characteristics to IASI (e.g. IMG, AIRS) may also be available shortly to validate the models. The latter have the advantage of making measurements over a wide range of different atmospheric conditions. Comparisons can be made globally by collocation with profiles from NWP analyses. However these are likely to be most accurate in the vicinity of reliable radiosonde stations.

One way to assess fast RTM error characteristics in advance of IASI is to look at the biases of the models with other satellite IR radiometers already flying (e.g. HIRS, GOES-IR sounder, Meteosat IR/WV channels). Collocation datasets which compare modelled and measured radiances over the globe can be useful to characterise the biases and determine how they vary with mean layer temperature, scan angle, total column, WV, etc.. These biases have to be removed before assimilation into NWP models. Difficulties arise when trying to assign the biases to the instrument calibration or pre-processing or to the RTM and the studies described in the previous paragraphs need to be carried out to give an absolute error estimate for the RTMs.

4.3 IASI instrument and ingest processes

4.3.1 The IASI sounder

It is helpful when describing instrument and ingest processes to follow the information flow first in form of photons through the optical system down to conversion to electrical signals, then to follow these signals through the analogue electronic chain down to conversion to digital sample values, and finally to follow these values through the digital processes both onboard and inside the ingest section of the EPS Ground Segment down to the deliverable level 1 data.

The first process of IASI is the collection of light emitted from the Earth-atmosphere along directions specified by the scanning pattern of the scan mirror and its transport through the interferometer toward the detectors. This is similar to any IR radiometer and relies on one cold physical aperture stop and four cold physical field stops (diameter such that the imaged ground diameter is 12 km, optionally 9 km), one for each of the sounder pixels, which delimit the fluxes belonging to each pixel; these fluxes are collected through optical components imaging the aperture stop on the corresponding detectors; up-front optical components conjugate the aperture stop with the scan mirror and image at an infinite distance the field stops; finally the scan mirror allows positioning of the direction of the image of the field stops according to the specified scanning pattern which imposes one line every eight seconds, synchronised with the others instruments onboard Metop. Each line includes 30 earth positions and two calibration targets (i.e. a space view and an internal blackbody at a temperature between 270 and 300 K).

Specific constraints are associated with the use of an interferometer and they impose a conjugation of the aperture stop with the interferometer reflectors and a limitation on the angular spread of the beam inside the interferometer.

Finally the scan mirror motion allows stabilisation of the IFOV during the interferogram acquisition; this dwell time lasts 151 ms.

This whole process is characterised by the instrument point spread function (IPSF) which includes, in addition to the purely optical effects described above second order contributions from detectors sensitivity mapping due to optical aberrations in the imaging of the aperture stop on the detectors.

The second optical process is the optical Fourier Transform. It takes place in the heart of the instrument, a Michelson type interferometer, in which the incoming radiation is separated by the splitting device (beam splitter and compensating plate) in two beams each one reflected by a corner cube reflector and recombined on the splitting device. The recombined radiation is divided between two output ports, one being collected to the detector, the other one is unused and is in fact the entrance aperture of the interferometer. It is convenient to separate the process in two sub-processes, one dealing with an elementary interferometer of solid angle $d\Omega$, a second one dealing with the integration of the elementary contribution over the solid angle covering each pixel. For a monochromatic input of wave number σ inside an elementary solid angle $d\Omega$, the fraction redirected toward each output port is a function of the cosine of the phase difference Φ between the recombined beams. The form of the function is $(a+b \cos\Phi)$ for the detector port (i.e. transmitted through the interferometer) and $(c-d \cos\Phi)$ for the unused port (i.e. reflected back through the entrance aperture). For an ideal interferometer one should have $a=c=b=d=½ I_{tot}$.

The phase difference is:

$$\Phi = 2\pi\sigma\delta$$

where δ is the optical path difference (OPD) which is, in case of corner cube reflectors, equal to twice the dot product of the unit vector of the propagation direction with the vector joining the apex of the corner cube 1 with the image of the apex of the corner cube 2, through the splitting device. A mechanical drive displaces corner cube 2 in order to explore the OPD between -2 to +2 cm.

When considering the integration of the elementary solid angles over the instrument pixels, using the IPSF as weighting function, it is necessary to define a unique X coordinate representing the OPD on the average direction; on this coordinate the interferogram will be equal to the elementary interferogram in the reference direction multiplied by a function of X which will both decrease its modulation amplitude and slightly distort its phase for increasing absolute values of X. As the overall effect, in the spectral domain, is to broaden the ISRF, while also damping the ringing of the usual sinc function, this effect is called self-apodisation.

The last optical process performs the separation of the radiation at the output of the interferometer into different spectral bands. Indeed for technological reasons associated to availability of IR detectors operating at a temperature around 100 K it is not possible to use a single detector for the full wave number range. Also due to the rapid decrease of the Planck function at high wave number for atmospheric temperatures, the useful signal in this domain would be buried under the photon noise if the full range was measured by a single detector. As a consequence the wave number range has to be broken in three bands:

Band 1:	645 to 1210 cm^{-1}
Band 2:	1210 to 2000 cm^{-1}
Band 3:	2000 to 2760 cm^{-1}

which are optically separated by a set of two dichroic plates.

The next group of processes includes all analogue electronic processes starting with the detection and following with classical amplification and anti-aliasing filter down to the analogue to digital conversion. The detection is performed for each pixel by a set of three detectors. Band 1 uses a mercury cadmium telluride (MCT) photoconductive detector associated to a circuit minimising the non linearity. Band 2 uses a MCT photovoltaic detector and band 3 an indium antimonide (InSb) photovoltaic detector.

After a band specific pre-amplifier stage the three circuits are identical and include amplifiers, saturation detection (spikes) and an anti aliasing filter (5^{th} order Butterworth low pass filter with a 3dB cut off frequency corresponding to 4400 cm^{-1} at a nominal corner cube velocity where there are 13000 samples per cm of OPD).

The process of analogue to digital conversion is constrained by the fact that sampling must be performed at very stable and precisely known increments of the OPD. The difficulty to achieve, just by mechanical means, a highly constant velocity prevents constant time increment sampling. Instead an interferometric measurement of the OPD using an auxiliary stable and monochromatic laser beam (propagating inside the IR interferometer using a path parallel to the corner cube velocity vector and limited to small fractions of the pupil) triggers the sampling of the interferograms. A high reliability laser diode developed for optics fibre telecommunications has been chosen for IASI and frequency stabilisation is achieved by locking the laser emission to a molecular absorption line (C_2H_2 in a gas cell) through proper servo-control. The auxiliary interferogram is detected with an indium gallium arsenide (InGaAs) photo-diode and the corresponding signal (almost a pure sine) is band-pass filtered around the nominal frequency (determined by the nominal corner cube velocity) to improve noise characteristics.

IR signal sampling is triggered at each zero crossing of the sinusoidal signal of the filtered auxiliary interferogram. The electronic filter introduces a specified delay in order to compensate in the auxiliary interferometer analogue chain the main interferometer ones (mostly generated in the anti-aliasing filter). Triggering with pulses generated by the fringes is only effective once the position of the corner cube is within a given geometrical range and once its motion has reached a sufficiently stable velocity (changes in the moving direction of the corner cube lead to velocity transients at the limits of the range of OPD).

The paragraph above has explained how the sampling is triggered; in order to complete the description of the process we will now concentrate on the operations following the triggering pulse. For the first points the full signal is digitised and these values allow the generation of a baseline level. For the rest of the interferogram this baseline level will be analogically subtracted from the interferogram. Using this method, only a difference has to be converted to count allowing a better dynamic range for the ADC. This techniques is better than pure analogue high-pass or DC filtering as it allows retention of the information on the baseline level. The conversion is performed with a 12-bit ADC chip working on the last non-saturating output of a set of three amplifiers of gain 1, 4, and 16. The resulting 16 bit sample includes the 12 bit value provided by the ADC together with a 2-bit number identifying the amplifier used and two additional bits, one used as spike detection flag and the other as ADC saturation flag. In this manner proper digitisation is achieved as if it was provided with a 16 bit ADC for more than 99 % of the samples.

At this stage the information will enter the set of numerical processes which will transform the raw interferograms into level 1 products. The detailed description can be found in the document “Data processing algorithms in IASI on-board and Ground Segment”, (CNES, 1996) and only general features will be presented here. Although there is no logical boundary in the sequence of numerical processes, practical design constraints demand their separation into two groups, one being performed on-board and the other one assigned to the Ground Segment.

All digitised interferograms are processed on-board for detection and if possible correction of spurious effects, and correction of known systematic effects affecting the detection chain. At present the following processes will be applied:

- Spike detection and, if possible, correction (algorithm to be defined)
- Non-linearity correction according to non-linearity laws determined on ground
- ZPD determination i.e. identification of the rank of the sample associated to the zero path difference

The corrected interferograms are then Fourier transformed producing complex spectra or raw spectra.

The raw spectra for the two reference targets (cold space and internal blackbody) are further processed to generate complex calibration coefficients assuming linearity in the complex plane. As individual calibration spectra are affected by radiometric noise, accumulation of successive determinations allows the attainment of a more robust set of calibration coefficients. They are applied onboard to convert the raw spectra for the Earth views to calibrated spectra on a pixel by pixel basis. (It should also to be noted that different sets of calibration coefficients are applied according to the sign of the corner cube velocity.) In the band overlap region, two determinations of the spectrum values are available, from which a merged value is obtained by combining the measured values in a weighted average with weights inversely proportional to the square of the expected noise. The spectrum is then coded in order to bring the data rate inside the Metop allocation.

After recording in the spacecraft mass storage system the data are down-linked to the EPS receiving stations. After separation of the data flows from the different instruments, the IASI data enter the IASI level 1 processing system which converts the incoming raw instrument telemetry (level 0 data) to level 1 products. Detailed definition of sub levels 1a, 1b and 1c is part of the document “IASI level 1 data” (CNES, 1996a), and is summarised below.

Level 1a data are spectra values fully calibrated both spectrally and radiometrically, localised geographically and with respect to the AVHRR raster, but retaining the instrument distortions of the nominal spectral sampling law.

The following processes are performed to reach this level:

- Spectral calibration based on correlation of measured spectra to synthetic spectra. This process runs on a subset of the spectra and assumes calibration stability over 80 seconds. At the same time scale of 80 seconds, the ISRF are computed based on spectral calibration information.

- Radiometric post-calibration correction of instrument calibration distortions not accounted for during on-board calibration (i.e. incidence of spectral calibration deviation from nominal values, incidence of the deviation from unity of the emissivity of the reference blackbody taking into account temperature distribution in the instrument enclosure, variation of scan mirror reflectivity with scan angle)

- Location both in terms of geographical coordinates and with respect to the AVHRR raster through correlation of the integrated imager data with AVHRR pictures

Level 1b data are level 1a data which are re-sampled on a nominal wave number grid. The equalisation of the ISRF between pixels is being studied but is not considered as part of the specification at the present time.

Level 1c data are level 1b data provided at a common (to be determined (TBD)) apodised ISRF. They are associated with a summary of collocated AVHRR information the generation of which is not an ingest process and is described in Section 4.4.

4.3.2 The IASI Integrated Imager System

Following the same logical steps as for the interferometer sounder, the description of the IASI imager will be simpler. The optical process amounts to collection of scene radiance inside the specified spectral domain.

The IASI imager optics share the scan mirror with the sounder and image the IFOV on a detector matrix. The individual detectors of the matrix are the physical field stops for the imager pixels; the physical aperture stop is conjugated with the scanning mirror.

The imaging system detector is a 128×128 matrix of MCT photo-voltaic detectors with a charge coupled device (CCD) for read out. The CCD electrical output is converted to 12-bit values.

Onboard digital processes will include co-addition (if necessary for radiometric noise reduction) of up to four frames measured within the 151 ms dwell time of the sounder, a process which assumes instrument linearity, and relies on the same reference targets as those used for the calibration of the interferometer.

The 128×128 pixels are compressed to 64×64 through averaging over super pixels of 2×2 original ones. The averaging process takes into account blind pixels.

Processing of the imager data on the ground include radiometric calibration, and details have been presented in the description of the process leading to co-registration of the interferometer pixels within the AVHRR raster using the IASI imager as an intermediate step (Section 4.3.1).

4.4 Data pre-processing

At this stage all instrument data are available at level 1b, i.e. decommutated, Earth located and calibrated. The time annotations and the synchronisation of the data buffers of the different instruments has been performed. A time-synchronised sub-set of a defined time range (e.g. 256 sec) will be used, containing all available data required for pre-processing.

The IASI pre-processing consists of three main tasks:

- To assure that the IASI data are prepared for the retrieval step
- To assure the appropriate use of the IASI companion instruments if they available and similarly prepared, so that they can be used to assist in the retrieval of information from IASI data where desirable. These companion instruments are:
    - The IASI imager
    - ATOVS (AMSU-A, MHS, and HIRS, the latter more for validation)
    - AVHRR
    - GOME-2
- To identify and flag all those data which are deemed unsuitable for the further processing for atmospheric sounding and ozone retrieval. In particular, these data comprise those which are contaminated by precipitation, some cloud conditions, etc..

4.4.1 Remapping

4.4.1.1 Remapping of sounder data

One main task is the mapping of the IASI instrument data. The four sub-pixels have to be collocated with the companion instruments. For the companion ATOVS instruments mapping routines will be available via ATOVS software development. With this we shall have a solid basis for mapping these data to IASI pixel locations, in particular to any combination which is possible with ATOVS data and (with minor modification) to any other instrument with a similar scan geometry. Software to map IASI information to the fields of view of another instrument may also be of interest.

4.4.1.2 AVHRR co-registration

A separate task though closely related to the above mentioned is the mapping of the AVHRR to the IASI pixel position, using the IASI imager to improve AVHRR co-registration. A method will be required to apply the IASI imager data in this way. We shall also need an algorithm to determine the maximum correlation between the IASI imager scene and the AVHRR scene of given time-synchronised data.

4.4.1.3 AVHRR radiance analysis

With the co-registration established we need to apply multi-spectral analysis of the AVHRR scenes for a time-synchronised IASI scene. Mapping of the detected centres of gravity (contrast) of the AVHRR radiances to the appropriate IASI FOV will be achieved by weighting with the IASI IPSF.

4.4.2 Cloud detection

4.4.2.1 IASI only

Methods are required to detect the presence of cloud in single IASI pixels, or groups of adjacent pixels, solely using IASI data. Cloud detection algorithms could include radiance threshold techniques, inter-channel difference tests, etc., similar to procedures developed for HIRS.

4.4.2.2 IASI and ATOVS

Inconsistencies between radiances in IR and MW channels are also effective for detecting some types of cloud. Appropriate cloud tests between IASI and AMSU/MHS channels may be useful, and such methods will be developed for ATOVS (Goodrum *et al.*, 1998).

4.4.2.3 IASI and IASI Imager

The IASI imager should be particularly useful for detecting small amounts of broken cloud within an IASI pixel. Simple threshold and variance tests will need to be developed.

4.4.2.4 IASI and AVHRR

AVHRR imagery can be used for the same purpose as the IASI imager, but making use of the increased number of spectral channels. Again, the details of appropriate tests will need to be developed. Experience of using AVHRR with TOVS/ATOVS data is expected to provide the basis of these methods.

4.4.2.5 Further contamination information and consistency check

There is a need to pre-process the companion instruments, in particular AMSU-A and MHS, to detect contamination effects, which will create problems in the retrieval process. Among the contamination effects to be detected are precipitation, large cloud ice particles and surface emissivity effects. Among the various instruments the consistency of contamination information needs to be checked.

4.4.3 Optional cloud clearing

“Cloud clearing” is the term used to describe the process of estimating, from cloud-affected radiances, the clear radiance that would have been measured if the cloud had not been present. This step might be part of the retrieval step, but could also be performed here. Several approaches are possible, including the adaptation of currently used methods.

4.4.4 Optional adjustments to the radiances

Any other effects that cause difficulties for subsequent retrieval processes should be detected, and possible adjustments for such effects considered. Appropriate pre-processing modules should be developed for this purpose. “Nadir-adjustment” (i.e. the estimation, from off-nadir measurements, of the radiances that would have been measured at nadir from the same atmospheric profile) is one possibility, but it is not yet clear whether any retrieval procedure will require this step.

4.4.5 Pre-processor output

The pre-processor should be flexible and allow the use of the data in different modes, depending on the subsequent application. There should be several solutions possible, depending on the available instruments:

- IASI + AMSU-A + MHS (+ HIRS, if embarked) data on the IASI grid (nominal case)
- IASI + AMSU-A data on the IASI grid
- IASI + MHS data on the IASI grid

In addition, the cases foreseen in the ATOVS pre-processor could be implemented, with the necessity of mapping the IASI data onto the appropriate ATOVS (i.e. HIRS or AMSU-A) grid.

4.4.6 Pre-launch validation

We need to achieve the testing and the validation of the pre-processor before launch. For this purpose cloud-contaminated simulated IASI data need to be established and transformed to the foreseen level 1b/c format. To study some aspects of the problem, simulated global data is needed, for instance from NWP model fields. Other aspects of the problem will be most effectively studied using real data (e.g. from ATOVS and AVHRR).

4.5 Retrieval of geophysical parameters

4.5.1 Introduction

From IASI spectra, it will be possible to retrieve information on many of the geophysical variables to which the spectra are sensitive. The extent to which some of the variables can be retrieved with useful accuracy and/or resolution requires research. However, the following variables should be considered:

- Temperature and WV profiles
- Other minor constituents (O3, CH4, N2O, CO, CFCs)
- Cloud parameters (such as fractional coverage, pressure and phase) in at least one layer, and possibly more
- Surface temperature (of climate research quality) and surface emissivity
- Aerosols

For each of these we will consider briefly the retrieval methods available. The literature is very rich in possible methods for such retrieval problems and it is not possible to consider them all in detail, but some of the general characteristics are indicated, together with comments on research required to adapt existing methods to IASI data.

4.5.2 Channel selection/rejection

A general problem for the retrieval of all variables is the selection of appropriate IASI channels. For some variables, particularly minor constituents, the primary questions are: Firstly, which channels are sufficiently sensitive to the variable that they are candidates for the retrieval? Secondly, of these channels, which sub-set is the most effective? For other variables, particularly temperature, the question may be put the other way round: of all the channels, which should be excluded from the retrieval (because, for example, their forward model is not sufficiently accurate)? There are also problems concerning how to perform retrievals in the most economical way, perhaps using sets of "pseudo-channels" (see Section 4.7.1.4). Theoretical studies of information content will be useful as an aid to answering all these questions (see Section 4.7.1.3).

4.5.3 Retrieval of temperature and water vapour profiles

These variables will be considered together, as many applications make use of both products together and many retrieval schemes retrieve them either simultaneously or in close association. Also, for most purposes, surface skin temperature may be included as an element of the temperature profile, rather than as a separate variable (although the retrieval of high-quality surface temperature for climate studies is considered separately in Section 4.5.6).

Many methods of temperature/humidity retrieval have been developed for passive sounders of low spectral resolution, such as TOVS, and so it is natural to consider the adaptation of these methods to sounders of high spectral resolution, such as IASI. In many respects the retrieval problem is the same, and so methods/tools developed for TOVS are highly relevant. However, there are two aspects of the extension to IASI that need special consideration:

- The massive increase in the number of channels. This does not, in itself, change the mathematics of the retrieval problem but it changes the technical considerations on economical ways to solve it. It raises questions of channel selection and channel combination that do not arise for TOVS. It also requires a reconsideration of the convergence performance and convergence criteria for non-linear, iterative retrieval methods.

- The improved vertical resolution. This greatly changes the role of the background constraints in the retrieval process, compared with TOVS, to such an extent that we can now consider some approaches to the retrieval problem that are not feasible for TOVS. Because of the improved vertical resolution of IASI, the dependence on background information is substantially reduced.

Possible retrieval methods may be categorised in many ways; a convenient division is as follows:

(a) Purely statistical methods (e.g. regression)

(b) Purely physical methods (often with *ad hoc* mathematical constraints)

(c) Physical-statistical methods

Methods of type (a) and (b) have been widely used in the past but are not currently favoured. Type (a) methods are fast, but cannot cope easily with the specific non-linearities of the RT problem. Type (b) methods cannot easily accommodate the inherently statistical aspects of the retrieval problem (e.g. instrument noise) and usually make no attempt at optimality.

Most methods used at present (and proposed in the context of the IASI Announcement of Opportunity (CNES/EUMETSAT, 1995)) are of type (c). These can be sub-divided further into two types:

(i) Those requiring RT calculations "on-line" for each retrieval

(ii) Those in which the RT calculations are all performed "off-line"

Neural network methods, as applied to the retrieval problem, may be considered as a special case of (ii).

From the possible methods in category (c), it is not possible to nominate a "best" method. This is because the "best" method depends on the application and on the operating constraints (what computing resources are available, whether it is desirable to maintain independence from a NWP model, etc.). Also, the extension from TOVS to IASI requires us to revisit some of our previous assumptions as to which methods are to be preferred. Therefore it is desirable that, within the IASI programme, a range of research and development is encouraged to explore various options for retrieval methods.

Methods of type (c) do have some requirements in common:

- A clear statement of the mathematical problem to be solved (e.g. the equation to be solved or the function to be minimised, which in turn involve clear statements concerning the nature of any constraint information to be used)

- An accurate RTM, and usually a means of computing its gradient with respect to atmospheric variables

- An adequate understanding of the error characteristics of measurements and of the forward model

4.5.4 Retrieval of other minor constituents

The theoretical aspects of the retrieval problem are basically the same for other minor constituents as they are for WV, and many of the comments in Section 4.5.3 equally apply. However there are substantial differences to note:

- The nature of the prior information on minor constituents is qualitatively different from that of temperature or WV.

- The vertical resolution possible with IASI is much lower; for ozone, about 3 pieces of vertical information may be retrievable, and probably only one for other species, compared with many more for both temperature and WV.

- Compared with temperature and humidity, there is very limited experience in applying retrieval problems to similar data (i.e. passive nadir sounding of tropospheric minor constituents).

4.5.5 Retrieval of cloud parameters

IR sounders are very sensitive to the presence of cloud, and information on cloud can be retrieved from their data. Experience with low resolution sounders such as HIRS has shown that accurate estimates of cloud amount and cloud top pressure may be obtained for single-layer cloud, but that difficulties arise with more complex cloud fields. With IASI data, it will be possible to detect cloud more effectively, to retrieve its amount and pressure more accurately, and probably to extend useful retrievals to more than one layer of cloud. Also the highly-resolved spectra will yield information on other features of the cloud such as phase and particle size. The derivation of this information has already been demonstrated from aircraft interferometer data, but more research is required to develop robust retrieval methods for IASI data.

4.5.6 Retrieval of surface temperature and surface emissivity

Retrieval of sea surface temperature of the quality needed for climate research requires careful attention to a number of problems: the detection of even small amounts of cloud, the treatment of absorption/emission by atmospheric gases and aerosols, the treatment of surface emissivity. IASI data, in conjunction with high resolution image data, will provide opportunities for improvements in these areas. This application is also very demanding on the absolute accuracy and stability of the radiometric calibration, and so work to quantify the performance of IASI in this respect, and if necessary to improve it through vicarious calibration, will be needed.

For land surface temperature, IASI data offer opportunities for improved retrievals through the highly resolved spectra, which should allow more effective separation of surface temperature and emissivity effects, and also the retrieval of the IR emissivity characteristics of different land surfaces.

4.5.7 Retrieval of aerosols

IASI measurements are sensitive to atmospheric aerosols and so it may be possible to retrieve some information on aerosols. The presence of many rather clear windows in the IASI spectrum may allow this, but studies are required to assess the information content on aerosols and to explore how this might be retrieved, perhaps in combination with data from other Metop instruments or *in situ* measurements.

4.6 Monitoring and validation of IASI data and products

Monitoring and validation will be important activities for IASI. They will require significant pre-launch preparatory activities and substantial routine effort after launch. Separate and more detailed plans will be required for:

- Monitoring, quality control and tuning

- Validation

This section describes some of the issues that must be addressed by these plans.

4.6.1 Monitoring, quality control and tuning

4.6.1.1 Instrument performance

Systems are required to monitor various aspects of instrument performance, including any sudden changes in instrument output and variations in output on various timescales (e.g. orbital, annual). Key aspects of the instrument requiring careful monitoring are: responsivity, noise performance, spectral stability and calibration stability. However, many other instrument sub-system characteristics must also be monitored.

Routine instrument monitoring will provide certain information required by users for optimal interpretation of the data, such as the noise spectrum.

Quality control is necessary to detect the small proportion of data that is expected to contain excessively large errors. It includes on-board "noise spike" elimination but should also include, through on-ground processing, removal of any other phenomena with comparable effects. Criteria must be established for defining the affected data, and procedures must be developed for detecting and flagging them, in order that they are not allowed to contaminate higher level data/products.

4.6.1.2 Data and products

The quantity and quality of data and products must be monitored to detect any sudden changes (which must then be investigated) and to assure that products meet basic criteria. These criteria need to be carefully defined, and studies are required in this area. However, it is clear that an important aspect of quality is accuracy, and hence there is an important link between routine monitoring activities and product validation activities.

Certain aspects of system performance can be measured by monitoring characteristics of data/products over time and detecting changes that exceed given criteria. However other aspects can only be monitored by comparing data/products with independent "ground truth" data.

The full range of monitoring required is extensive and requires special study. However, some aspects of the monitoring can be anticipated where similar systems are already in place for current operational satellite sounding instruments.

Monitoring of retrieved temperature and humidity fields, and of the clear-column radiance spectra from which they are derived, can be performed in two ways: by comparing with NWP fields (analyses or short-range forecasts) or by comparing with other types of observation.

As an example, the GRAS instrument will deliver atmospheric sounding information on an irregular grid. Temperature profiles at high vertical resolution may be used for IASI validation purposes as reference profiles in appropriate situations (e.g. not too much horizontal variability).

- Comparison with NWP fields

  Similar systems are already in place for TOVS data at NWP centres. Each retrieved temperature and humidity profile can be compared with a coincident profile from the NWP model field. The difference is calculated and ensemble are statistics derived. This approach has the following strengths: using a global model, a comparison can be obtained for every retrieved profile; also, these fields are usually quite accurate - in areas where other observations (of all types) have recently been assimilated, the NWP fields should be more accurate than the observations they are derived from. (This type of monitoring is effectively a comparison with other observations using the NWP model as a transfer medium.) In data sparse areas, accuracy is lower but, with modern NWP systems, it is found in practice to be surprisingly good and quite effective for this monitoring function (Derber and Wu, 1998). In addition to level 2 products, some intermediate products can be monitored in the same way. For example, clear-column radiances can be monitored by comparison with radiances calculated from NWP fields using a RTM.

- Comparison with other observations

  Comparison with NWP fields is not effective for monitoring all potential problems. This is particularly true if the NWP system is subsequently assimilating the data it has monitored, and hence acquiring some of the characteristics of these data (e.g. any biases). To avoid these problems, monitoring directly against other observations is also advisable. Radiosonde profiles provide the main source of observations for routine monitoring of retrieved temperature and humidity profiles (and of clear-column radiances). They have various strengths and weaknesses, which are discussed in Section 4.6.2.2. Other observations should also be considered for use in routine monitoring: aircraft observations and radio occultation data (see Section 4.6.2.2).

Monitoring systems should also be implemented for other products. However, the range of effective monitoring tools is more restricted here, and studies are required to define effective methods.

In association with monitoring systems, quality control systems are required to detect and flag data/products that depart considerably from normal standards of quality. These will include detection of gross errors, i.e. products that differ greatly from geophysically reasonable values. NWP fields are also useful for quality control, but close dialogue is required with the NWP community to define how this should be done.

Quality control is required for the radiance spectra (level 1b/1c) to detect anomalous or inconsistent spectra. One possibility is to use eigenvector analysis: spectra can be reduced to a truncated set (e.g. 100) of eigenvector coefficients, then recomputed from the truncated set. Large differences between the regenerated and the original data are used to flag the data as questionable. Other checks may be needed, and studies are required here.

Some characteristics of the data will be uncertain prior to launch or may change after launch. These characteristics must be monitored carefully, and relevant aspects of the data processing must include ongoing tuning to take account of these effects. An example of this is the tuning of biases between measured and calculated radiance spectra (see Section 4.7.1.5). Other areas where tuning might be needed should be identified and appropriate tuning systems developed.

4.6.2 Validation

4.6.2.1 The constraints for reliable validation studies

The validation of the detailed LBL forward models will not be complete if based only on laboratory studies. Firstly, the extremely wide range of atmospheric conditions and, secondly, the number of possible absorbing species and/or processes (including aerosols and particles) make "real world" validations essential, since they can help to identify problem areas with the forward models.

An exact replica of the IASI instrument is not needed, however, for performing these field studies, as a suite of instruments is available (or will be available in the near future) to contribute to validation studies of the forward models. It is appropriate at this point to examine separately the elements involved in the modelling of field experiments.

Firstly, because the atmospheric state has to be documented in the most precise manner, great care has to be taken to corroborate the spectral radiance measurements by any field spectrometer (of comparable or better resolution than IASI), on any platform (ground, ship, aircraft, balloon) with a precise knowledge, through independent but well-calibrated sensors, of the profiles of temperature, WV, aerosol, etc.. Problems of homogeneity along the optical path have also to be carefully examined.

Secondly, because the instruments used for the validation will have their own transfer function (resolution, field of view, calibration, etc.), a detailed knowledge of their specific properties should be known to deconvolve the observed spectra (or convolve the calculated spectra) to match the forward model to be validated to the proper validation instrument characteristics.

Thirdly, the test of the forward model itself can be performed in a geometry which can be different from IASI (looking up from the ground; looking up, down or at an angle from aircraft; looking at the limb from balloon) as far as the absorber amount and pressure/temperature conditions are representative of the IASI nadir viewing geometry. Ancillary data (surface temperature, emissivity, albedo, etc.) should be also well documented.

Once these conditions are reasonably fulfilled, direct validation of the forward model can be achieved. A test of the capabilities of the IASI pre-operational retrieval algorithms could also be performed with a nadir looking instrument on a platform flying at sufficiently high altitude (stratospheric aircraft or balloon) not to mention real satellite data of resolution comparable to IASI which will be available sooner (e.g. IMG, AIRS).

Clear sky atmospheric conditions have been considered up to that point. Cloud studies performed in the framework of these field measurements are also of special interest for optimising the IASI operational retrieval in case of partly cloudy or cloudy conditions as well as for a number of RT studies related to the climate mission of IASI. An intensive validation effort is needed in this respect (see Section 4.7.2.6 for the importance of cirrus) and can be coordinated with campaigns for the clear sky validation studies.

4.6.2.2 Pre-launch validation studies

Pre-launch studies are required to validate various aspects of the processing systems and of the science underlying these systems. Some of these studies have already been undertaken and will be covered here, other coordinated measurements involving the IASI breadboard available at CNES (Toulouse) will be organised as part of the instrument hardware and software qualification process.

For validation of pre-processing and retrieval systems, data bases are required of realistic profiles/fields of geophysical variables and the IASI radiance spectra corresponding to them. Simulated cloud-free radiance spectra are needed for the validation of many aspects of retrieval schemes. Simulated fields of cloud-affected radiance spectra are required for validating aspects of pre-processing systems, such as cloud detection and cloud clearing. These data sets are more useful if they also contain simulated data for IASI's companion instruments.

With regard to validation from field measurements, spectra obtained from interferometers (with a similar spectral resolution to IASI), mounted on aircraft or accommodated under balloon, together with co-located in-situ profile observations, provide the basis for checking in detail and validating the RT algorithms used for simulating the IASI spectra. A set of such spectra, for a limited sample of atmospheric conditions, is available from the HIS instrument (University of Wisconsin) aboard the US high flying aircraft ER-2 (Knuteson, 1997). Other spectra are being measured by the ARIES instrument mounted on the UK Meteorological Office's C130 aircraft. These spectra differ from the HIS spectra mainly in being made at a range of angles from 0 to 50 degrees downwards (plus a zenith view) and at a range of altitudes from 10 m up to 15 km. Comparison between the aircraft spectra and the higher resolution spectra acquired by IMG from space is also a very important exercise. Analyses and modelling of these data will contribute to the establishment of the ability to theoretically calculate IASI spectra in the key spectral regions to an accuracy of 0.3 K and also to identify problems with the current spectral line parameters and cross-section databases as well as with the modelling of the relevant continuum absorptions.

Although not in the nadir geometry, but at higher spectral resolution, limb emission spectra of the MIPAS balloon instrument (University of Karlsruhe) (Fischer and Oelhaf, 1996), as well as limb absorption spectra of the LPMA balloon instrument (CNRS, Paris) (Camy-Peyret *et al.*, 1995) are already available, and new spectra will be acquired by these experiments during future atmospheric campaigns. The corresponding data has been (and will be used) to validate in an independent manner the presently available LBL, line shape and continuum algorithms and to understand and correct their present deficiencies.

In all cases these field measurements (from ground, aircraft or balloon) will benefit the forward model comparison exercises, already discussed and planned (but which will expand as more field data is available) within the ISSWG activities for the preparation of the IASI mission algorithms.

4.6.2.3 Post-launch validation based on routine monitoring

The routine monitoring activities described in Section 4.6.1.2 provide considerable information for use in post-launch validation. Validation against NWP fields is useful, for the reasons given in Section 4.6.1.2, particularly in areas rich in observations from other systems. These results must, however, be used with caution, particularly with respect to biases.

Collocated radiosondes also provide an effective validation tool. They provide globally distributed measurements of temperature in the troposphere and lower stratosphere and of humidity in the lower/mid troposphere. However their limitations should be noted. Different radiosonde types have different characteristics; validation should be restricted to those types that are well understood and characterised. Radiosonde temperatures are subject to biases, particularly in the stratosphere, as a result of radiation effects and the local measurement environment. Radiosonde humidities must be used with care, particularly at low humidities and low temperatures. Also, the spatial variability of the WV field can give rise to large errors as a result of collocation mismatches in space and time. This is also true for near surface temperature, as a result of diurnal effects. Systematic differences in observation time between radiosonde and satellite measurement may also introduce artefacts into validation statistics. Fortunately, a wealth of information exists on all these problems.

Commercial aircraft are increasingly providing observations of atmospheric profiles (in the vicinity of airports). Radio occultation measurements (from GRAS on Metop, and perhaps from other systems) could be used for validation of temperature in the stratosphere and upper troposphere, and of humidity in the lower troposphere.

Routine ozonesonde measurements will provide validation information for ozone in the troposphere and lower stratosphere. Routinely available observations of other profiles of other variables are less abundant, although ground-based *in situ* measurements are made at a number of sites. Studies are required to determine to what extent validation can be provided through such observations and to what extent it must be supplemented by special campaigns or studies.

4.6.2.4 Post-launch validation based on special studies and campaigns

Special studies and campaigns will be needed to supplement the validation that will be possible using operationally available information provided by the IASI sounder. They will be needed for some aspects of validation for temperature and humidity products and will be essential for most aspects of the validation of other products. Special studies and campaigns should be carefully targeted to address those aspects of the validation that cannot be performed adequately through routinely available observations. Special studies will be required where validation information is potentially available (i.e. the observations are made) but cannot be acquired routinely. Special studies will be required where additional observations must be made to meet the validation requirements. The link with quality control of the IASI products and tuning of the operational algorithms, for the lifetime of the sounder, has also to be carefully established.

Such validation studies may include measurements from time-controlled radiosondes, rocketsondes, manned and unmanned aircraft, balloons with appropriate *in situ* or remote sensing instruments, lidars and other satellite instruments. They may also make use of existing dedicated and well instrumented surface sites, such as those of the Atmospheric Radiation Measurement programme (ARM) (DOE, 1996).

As an example of a possible approach to these validation studies, the idea of a Baseline Upper Air Network has been proposed, but has yet to be implemented. The Upper Air Working Group for the Commission for Instruments and Methods of Observation (CIMO) is tasked inter alia with reviewing and making recommendations for improving the compatibility between upper air networks and space-borne remote sensing. Currently 100 radiosonde sites have been selected as part of the Global Climate Observing System, several of which are operated by National Meteorological Services (NMS) in Europe, which are also directly involved in running NWP centres assimilating satellite data and which will be using IASI data when the instrument is in orbit. The requirements for special studies and campaigns are not yet fully specified. They require a detailed definition of the validation requirements, followed by careful studies of the requirements that can and cannot be met using routinely available observations, and of the opportunities offered by campaigns or facilities planned for other purposes. A study is required to address these aspects and to propose a strategy for additional campaigns to meet the validation requirements in an economical manner.

But given the range of pre-launch activities aimed at identifying and resolving problems with forward modelling algorithms, post-launch surprises with the details of the actual atmospheric clear sky spectra observed by IASI are expected to be few and more likely attributable to quirks in the IASI instrument and/or software, rather than to a lack of basic spectroscopic knowledge. This may not be completely true for IR optical cloud properties as well as continuum and aerosol emission/absorption parameters, not to mention detailed surface spectral characteristics. A number of under-flight campaigns with a suitable interferometers mounted on aircraft or under balloon during the commissioning phase of the flight model is then essential. Due to the multi-lateral coordination needed to prepare these campaigns and to operational constraints to implement them, planning should be initiated about 2 to 3 years before launch.

4.7 Applications of IASI data and products

4.7.1 Operational meteorology

4.7.1.1 Objectives

As discussed in Section 2, the primary objective of the IASI mission is to provide improved information on the 3-D field of atmospheric temperature for use in NWP. Errors in the initial analysis of the atmospheric state are one of the main causes of error in subsequent short- and medium-range forecasts. IASI data will be used to reduce the analysis errors of temperature (and hence also of wind), particularly over the oceans and other data-sparse areas. IASI data will also contribute to improving the analysis of other fields to which forecasts are sensitive, particularly the 3-D field of tropospheric WV, but also fields of surface temperature and cloud. IASI data/products will be assimilated into NWP models using techniques similar to those already developed for other passive sounder data such as TOVS (see Sections 4.7.1.2 to 4.7.1.5). In addition, because IASI measurements will be sensitive to quasi-passive tracers - WV and ozone - it may also be possible, within advanced data assimilation systems, to infer information on atmospheric dynamics (see Section 4.7.1.6).

The primary benefits of IASI to operational meteorology are expected through NWP, at both global and regional scales. However, IASI products will also have applications in other aspects of operational meteorology (see Section 4.7.1.7).

4.7.1.2 IASI data and products in Numerical Weather Prediction

The definition of appropriate interfaces between IASI data/products and NWP systems is an important task. Data assimilation for NWP is an area of rapid development, and so the interface to each NWP system is likely to evolve during the operational lifetime of IASI. Also, different NWP centres operate with different resources and constraints, and so a variety of interfaces will be required to meet their needs. However, it is possible to describe the range of interfaces that might be needed:

(a) Retrieval of level 2 products (temperature/humidity profiles), independent of NWP systems, followed by assimilation of these products. This approach has the logistic advantage of decoupling the retrieval from the NWP system. However, the extent to which it is likely to be acceptable to NWP centres depends on the degree of "guess dependence" of such retrievals (see Section 4.7.1.3).

(b) Assimilation of cloud-cleared radiance spectra into the assimilation system, either directly (e.g. through 3-D or 4-D variational assimilation schemes(3-D or 4-D VAR)) or indirectly (e.g. through a 1D variational or "interactive retrieval" scheme). With such schemes, there is an intimate coupling between the retrieval of information from the IASI data and the NWP system itself. In principle, such schemes could be applied to full resolution IASI spectra. However, in practice, it should be more efficient and adequately accurate to use a limited number of "pseudo-channels" (see Section 4.1.7.4). In either case, information at the radiance level must be passed to NWP centres, but the cloud-clearing process could be handled independently.

(c) Using one of the approaches described in (b), but applied to cloud-affected radiance spectra. In such schemes, the NWP system would either play a role in detection/clearing of cloud, or else the cloudy radiances would be inverted directly, probably using the NWP model's cloud field as a constraint and possibly using IASI information on cloud directly to improve the model's analysis of cloud.

It is clear that considerable work is required to explore these options and to implement some of them, to meet the requirements of evolving NWP systems. Whichever approach is adopted for the assimilation, the interface between IASI data and NWP systems will require:

- Fast RTM(s), either within the NWP system for direct radiance assimilation or within a retrieval scheme prior to the assimilation

- Information on the error covariances of the data presented to the assimilation system, principally in the vertical (i.e. the inter-channel covariance of radiance error or the vertical covariance of retrieval error)

4.7.1.3 Information content studies

Theoretical studies of the information content of IASI data are useful for a number of purposes. Firstly, through studies of sensitivity to instrumental and forward modelling errors, they can provide valuable input to instrument and Ground Segment trade-off studies and to understanding forward modelling requirements.

Secondly, studies of information content relative to an NWP system (i.e. measures of the new information that IASI data can bring to the NWP system) can inform decisions on the NWP interface, as discussed in Section 4.7.1.2. They can be used to quantify the "guess dependence" of the retrieval problem, i.e. the extent to which the retrieval draws information from the background information rather than from the measurements. Since the guess dependence is particularly sensitive to vertical resolution, it will vary considerably from model to model, and is likely to increase as NWP models move to higher vertical resolution.

Thirdly, information content studies can be used to address questions of channel selection, and to choose combinations of channels for retrieving information in the most economical way.

Fourthly, such studies can be used to quantify the sensitivity of IASI to different components of the atmosphere's vertical structure. Of particular interest are structures describing typical short-range forecast errors in baroclinic zones, from which serious forecast errors tend to grow. The expected impact of IASI data in NWP will depend, to a large extent, on its ability to detect and improve the analysis of such structures.

4.7.1.4 Data compression

As mentioned in Section 4.7.1.2, although a strictly optimal system would use IASI data at full resolution in all channels, it is probable that almost all the information in the IASI spectra can be conveyed by a much smaller number of radiance values in a set of "pseudo-channels" (e.g. linear combinations of the original channels). Through such methods it is likely that considerable data compression can be achieved. This would reduce computational costs in the data processing, whether through independent retrievals or direct assimilation of radiances. Data distribution and storage requirements would also be reduced. Studies are required to examine the trade-off between data compression achieved and information content retained.

4.7.1.5 Radiance tuning

It is expected that fast, accurate RTMs will be developed, through progress in the areas described in Section 4.2.2. However, NWP analyses can easily be degraded by small biases that remain between measured radiances and those calculated from model fields (or by equivalent biases in independent retrievals). "Radiance tuning" schemes will probably be required in order to reduce these biases to acceptable levels.

The inputs to such tuning schemes - large ensembles of differences between measured and calculated radiances - are also useful for other purposes: for real-time quality control and monitoring and, through the standard deviations of such data, for assessing forward model errors and for deciding which channels should be selected/rejected.

4.7.1.6 Assimilation of quasi-passive tracer information

IASI data will provide information on 3-D fields of quasi-passive tracers such as WV and ozone. Where these are carried as variable fields of the NWP model (i.e. certainly for WV, possibly for ozone), it is feasible in principle within advanced data assimilation systems to improve the analysis of the model's wind field through assimilating passive tracer information over a period of time. The sensitivity of analyses to such information has already been demonstrated with both TOVS and SSM/I data. Further work is required to develop such techniques and to explore their potential application to IASI data.

4.7.1.7 Extensions to regional and mesoscale Numerical Weather Prediction

The primary focus in the rationale for IASI has been on global NWP, and most of the NWP development activities will take place in this context. However IASI data also have potential for exploitation in regional and mesoscale NWP, if the data can be made available in near real-time (within two hours of the measurement). With measurements at each location only twice a day (although four times a day, given a similar instrument on a second polar satellite, and more frequently at high latitudes), they are not ideally suited to mesoscale applications. However they offer information on temperature and humidity at high vertical resolution, which should complement more frequent data from geostationary satellites. Enhanced information from IASI on cloud may also be valuable in mesoscale NWP. Work is needed on the specific requirements of mesoscale NWP if IASI data are to be exploited effectively in this area.

4.7.1.8 Other applications in operational meteorology.

Some forecast centres use retrievals independent of NWP models as additional information to forecasters. One possible use of IASI products in this context is to help forecasters identify early signs of error in NWP products. The detailed requirements for IASI products in this area need further attention.

IASI will provide information on cloud at only moderate horizontal resolution (25 km) but with high accuracy in cloud top height assignment. This will complement information from other instruments for use in synoptic meteorology, particularly at high latitudes where the frequency of IASI data will be high and where geostationary imagery is less useful.

In particular, synergy between IASI and MSG could be very useful for cross-calibration studies of both instruments.

IASI will provide improved information for ozone analysis, particularly at high latitude in winter (polar night), where ultraviolet (UV) instruments cannot be used. At all latitudes, such information has application in operational UV forecasting.

4.7.2 Climate and global change studies

4.7.2.1 Complementarity between models and space measurements

A number of products generated by IASI will be extremely valuable for climate and global change studies. Careful studies are needed, however, to define the type of average of the IASI retrieved variables or the further processing of some of the IASI products to be useful for climate and global change studies. Several scale integration issues have also to be considered as IASI will have its own space and time sampling specificities.

NWP models are ingesting on a real time basis (or will be, when IASI data are available) highly variable geophysical fields (temperature/humidity profiles from clear sky radiances, cloud type/cloud top altitude for overcast scenes, possibly ozone). However climate models, usually general circulation models (or GCM) of various degree of sophistication, are designed to be representative only "in the average" of the natural short term, small scale variability of the atmospheric system. Although they run with time-steps comparable to those of NWP models, the usual GCM averaging period is often one month and the horizontal and vertical resolution are often reduced as compared to NWP models. Also because of constraints on data volumes various averaging strategies are designed (zonal averages, running means, etc.) to store the data of a model run (typical integration time of five years to reach equilibration at the end of the simulation). It is only by careful comparison of model results with actual observations having comparable time/space resolution and statistical properties that GCM are tested, improved and validated to be accepted for making reliable predictions of the future climate. In any case, present GCM are deeply affected by our lack of knowledge regarding several basic physical processes which strongly impact climate modelling such as the WV cycle and cloud formation.

Hence, there is a permanent cross-fertilisation of model simulations and space measurements. No single instrument, however sophisticated one can imagine it, will globally cover any relevant atmospheric variable at the appropriate space and time scales. As an example, even for a simple variable such as the average daily Earth surface temperature, one can speculate on what is the best strategy for global change monitoring: Use IASI retrieved surface temperatures with their possibly uneven or incomplete sampling and perform daily averages, or use surface temperatures generated by a NWP model assimilating IASI data (and many other measurements from various satellite and other non-space sensors) and integrate (an easy operation on a model) over the globe, with the risk of possible bias and model deficiencies . Such considerations are to be expanded on a case by case basis for each variable measured by IASI or each IASI product that could contribute to climate and global change monitoring.

NWP models are leading the way by using modern data assimilation techniques, but climate and global change models will progressively evolve from completely off-line (past or future) simulations to be compared with observed climatologies (in general the most popular but not always the most recent datasets) to more interactive runs where observed parameters will "force" (with appropriate weighting) the corresponding parameters generated by the models. Many research groups are proceeding along those lines, generally with many more than just one instrument or platform, which explain why IASI data may be only one of their input. On the other hand the combination of IASI data with data produced by other sensors to generate datasets which are of interest for climate change should also be examined. See as an example of expected synergies between instruments the combination of radiometers, lidar and radar measurements discussed in the ESA release "Earth Radiation Mission" (ESA, 1996a) for this aspect of global change to be discussed below in Sections 4.7.2.4 and 4.7.2.5.

On the other hand some IASI products can be considered as almost stand alone (with no extensive parallel modelling and/or large input from another sensor) and could be used as climatologies after proper sampling and averaging. All these options need careful consideration. The corresponding data products are examined in the order of increasing interaction with models. It is assumed that climate and global change issues related to atmospheric chemistry are not discussed here but gathered in Section 4.7.3.

4.7.2.2 IASI data for re-analysis projects

Recently the ECMWF Re-Analysis Project (ERA) processed 15 years of TOVS data along with many other conventional and satellite observation types to provide a consistent description of the atmospheric state once every six hours for 15 years. This important dataset is now available for climate studies and for the validation of GCMs. Also monitoring changes in the quality of the various observing systems during this 15 years period has been a very useful by-product of these studies, providing guidance for the future. Analogous re-analyses including IASI data will be extremely valuable to better characterise actual temperature, humidity and ozone fields (and possibly other surface and cloud fields) affording very useful datasets for comparison with models. Analogous re-analyses have also been performed in the US by the NCEP NCAR and GSFC DAO projects.

It is not clear at this stage whether radiances or retrieved geophysical parameters (including profiles) would be used and so it is important to maintain a complete archive of both the raw radiances and the retrievals and a record of any changes made to the processing of the data. Experience gained with ERA demonstrated the importance of the latter when sudden changes in the processed radiances were observed. Also the ability to go back and reprocess all the data with a consistent processing algorithm can improve the use of these data in re-analyses.

4.7.2.3 IASI products and climate studies

Numerous climate datasets have been (or are being) produced covering several aspects of the climate system. The ISCCP dataset for clouds, the ILSCP dataset for land surface properties and the ATSR SST archive are examples of datasets that IASI will enrich and help maintain. Careful coordination is needed for proper archiving and updating of these past and of the future satellite climate archives to which IASI input will be of prime importance. The following paragraphs will cover specific examples.

4.7.2.4 Radiation budget studies

The direct product from IASI will be TOA spectral radiances. For clear sky pixels, with minimal RT modelling (assumption of near isotropy of the radiation field) the TOA spectral radiances can be converted to TOA upward flux and spectrally integrated over the IASI spectral domain (645 to 2760 cm^{-1}). This part of the spectrum covers the thermal IR where a large proportion of the longwave (LW) flux is radiated to space. The two wings of the LW spectrum are incompletely covered however:

1. The far IR region (10-500 cm^{-1}) and the "dirty window region" (500-600 cm^{-1}) where contribution of the pure rotation band of WV is dominant

2. The end of the thermal IR above 2760 cm^{-1} where some of the atmospheric back scattered solar flux will be mixed with surface/atmospheric emission during the day.

After proper validation, however, it is expected that clear sky RTMs will provide high enough accuracy, to calculate the missing contribution (knowing either the IASI radiances over its measured range, or the vertical temperature and humidity profiles measured by IASI and also the other trace species as far as they contribute) to correct the IASI measured TOA flux and to derive the total outgoing long-wave radiation (OLR) flux at the pixel level. Climatologies are then available following methods of resampling/averaging developed for previous earth radiation budget (ERB) sensors (ERBE, ScaRab), the operational algorithms of which could be tailored to the IASI specificities (see cloudy sky case below).

A possible alternative to overall spectrally integrated OLR fluxes is to consider separately the contribution of different radiative species. IASI spectral radiances in selected channels (say around a well chosen CH_4 spectral feature) could be used as a proxy to deduce, through an appropriate RTM, the contribution of a given species to the overall radiative forcing (in W/m^2) once a pre-calculated regression has been established (and hopefully validated).

Still under the same heading the LW radiative cooling/heating at any level of the atmosphere can be computed rather accurately with LBL codes or with their fast variants, using the IASI measured vertical distribution of H_2O and temperature together with CO_2 and the distribution of the minor constituents (CH_4, N_2O, greenhouse gases) and ozone for which IASI also provide height resolved information. As for the overall (or TOA) radiative forcing, one could consider to retrieve these altitude dependent cooling/heating rates, from pre-calculated regressions, directly from the measured radiances in appropriate channels. An example for radiative forcing due to methane is shown in Figure 5.

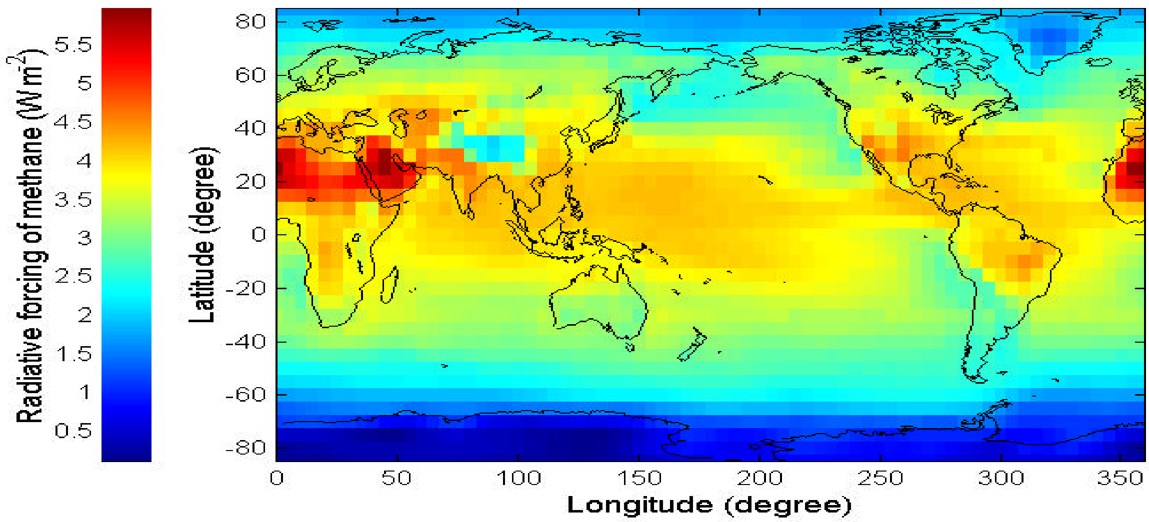

Figure 5 Radiative forcing due to methane computed by a LBL RTM for summertime with the IMAGES model outputs. (Chazette et al., 1998).

Again various averaging strategies should be designed to produce LW radiative cooling/heating products that could be used either to validate the corresponding radiation modules used by the NWP models themselves or in other applications (chemistry transport models (CTMs) for chemistry studies) which need to combine the LW flux discussed here with the solar short-wave (SW) flux to be calculated by appropriate radiation modules and/or measured by other instruments. Specific studies on the potential to couple the production of such data with some of the computational tasks needed to perform IASI retrievals should be considered. But the approach suggested here ("satellite-to-model") may be too indirect or complicated to implement and a better strategy to fully exploit the potential of IASI, could be to validate the TOA spectra calculated from the models directly against IASI spectra ("model-to-satellite" approach). This will hopefully be possible with the improvement of computational speed and capabilities combined with the approach of variational assimilation of composite products. Clearly more research studies are needed in this field.

4.7.2.5 Cloud radiative forcing

With our present knowledge of climate processes, very large uncertainties remain regarding the WV cycle. This is particularly true for cloud formation and the effect of clouds on the earth radiation budget. Cloud clearing techniques can therefore be very useful in order, first, to retrieve cloud cleared radiation fields and, then, to improve our knowledge of cloud radiative forcing. Cloud clearing requires very robust cloud detection schemes. From present experience, it is to be expected that cloud detection would be greatly improved if AVHRR data could be included in operational detection schemes. A good estimation of the cloud radiative forcing requires that no bias affect cloud cleared fields. This could be achieved through the combined use of AMSU and IASI data. In fact AMSU channels which are not affected by clouds, can be used to retrieve the cloud cleared radiation field evolution in space and time. On the other hand interpolation techniques (e.g. N*, radial basis functions, kriging) can be used to interpolate IASI cloud cleared fields around clear IASI FOVs.

In addition to cloud coverage and cloud top pressure level IASI could also allow a refined determination of cloud properties as the nature of the water phase and possibly the different levels in case of multi-layer clouds. This would lead to improved cloud climatologies in which the actual physical cloud properties are coupled to their radiative forcing as deduced from the radiances measured in the spectral domain covered by IASI. Such databases would provide a very important input to improve RTMs in cloudy conditions and to validate the corresponding radiation modules in NWP and GCM models.

Along these lines it would become possible to calculate physical LW fluxes (as opposed to statistically deduced) in any weather conditions. As a result the precise estimation of the Earth radiation budget in cloudy as well as clear sky conditions would be possible with a corresponding improvement in our understanding of the atmospheric energy budget. Of course the availability of simultaneous ground based measurements of cloud properties from selected well instrumented test sites (mainly using cloud radar but possibly with lidar) would enhance the scientific return of the IASI measurements in the field of cloud climatologies and radiation budget.

4.7.2.6 Studies of water vapour and cirrus

As well as contributing to global climate datasets, such as those described above, it is likely that exploitation of the high spectral resolution of IASI data will allow more detailed studies of some of the physical aspects of the climate system that are yet poorly understood. In particular, it should prove possible to test some of the assumptions behind current theories of the absorption and scattering of IR radiation by cirrus cloud and also by WV in the window regions. By enhancing the theoretical basis of these processes, such studies will allow a better understanding of their role in climate and thus prediction of their effects and representation in climate models.

Present theoretical models and laboratory studies describe the continuum absorption by WV as due to contributions of the far wings of spectral lines. Accordingly foreign-broadened lines (i.e. due to collisions with air molecules) enhance emission from the cooler regions of the atmosphere (the upper troposphere and the polar regions). The only current alternative theory, that the continuum results from absorption by water dimers/multimers, does not support such an interpretation of the continuum emission. Studies of IASI spectra in the window regions, together with the associated humidity and temperature profiles, could contribute to resolve this issue although care will have to be taken to separate the continuum signal from other contributions in the window regions (particularly aerosol - see Section 4.7.2.7).

The presence of cirrus cloud has a marked impact on the Earth's radiation budget. Understanding the interaction between IR radiation and the cirrus ice crystals is fraught with difficulty, however, because of the complexity of crystal shapes and sizes and no single theoretical/modelling approach has been found to be successful under all circumstances. Airborne IR spectra (particularly from the University of Wisconsin HIS instrument (Knuteson, 1997)) show interesting spectral features over a variety of cirrus clouds. Analysis of these, together with IASI spectra, should help to identify the more appropriate theoretical treatments and subsequently lead to the possible development of algorithms for the retrieval of cirrus properties (temperature, optical depth, crystal shape/size) from IASI data.

4.7.2.7 Other climatologies

Aerosols are an important variable component in climate and global change studies. They present a broad continuous absorption which covers all the spectral range. However, their properties are often derived from measurements in the near IR and visible part of the spectrum and then extrapolated to the mid and thermal IR region. For climate change studies it is important to understand how well this extrapolation works. IASI IR window channels will provide, then, a global data set to study, understand and refine aerosol models. Proper combination will be needed between measurements from space sensors operating in the IR (IASI) and in the visible (AVHRR, POLDER, SAGE2/3, etc.) as well as from the ground with lidars (including depolarisation measurements) to improve aerosol models for all types and sizes and provide a unified picture of their optical properties (absorption, emission, diffusion, etc.) from the IR to the visible-UV.

It should be stressed, however, that it is only when these models are improved and validated that we can use, with confidence, the window channels to address the problem of the WV continuum. Aerosol absorption and WV continuum overlap in the thermal and mid IR region.

Observations of spectral IR radiances are needed in order to understand how these two effects can be distinguished between each other.

But even with incomplete knowledge of aerosol properties IASI will be an extremely useful tool, because of its wide swath and imaging capabilities, to follow in space and time large aerosol episodes and plumes (volcanic eruptions, fires of natural or man-made origin, dust storms, etc.) which, contrary to the background aerosol (with generally moderate optical depth in the IR, hence their importance in the windows only, see discussion above), will strongly affect, when they occur, the radiances measured by the IASI instrument.

These IR studies will certainly complement in a very interesting manner climatological studies already undertaken with visible (AVHRR) or UV (TOMS) sensors for problems like Saharan dust transport or volcanic SO_2 dispersion and conversion to H_2SO_4/H_2O droplets. The last possibility would be particularly valuable if the gas phase column of SO_2 could be deduced from the IASI spectra (this is expected to be the case for major eruption only, but the decay of the aerosol/SO_2 burden will then be very interesting to follow).

There is still the possibility that land/ocean process and climatology studies could be performed with IASI from surface spectral emissivity measurements. Coupling with the IASI boundary layer humidity and temperature measurements would certainly enhance the interest of surface measurements in the fields of soil/vegetation interaction, hydrological cycle and ocean productivity studies. The horizontal resolution of IASI will not compete with the spatial resolution of the best multi-spectral imagers (VEGETATION, MODIS, OCTS, etc.) but the much higher spectral resolution and spectral coverage of IASI will certainly provide interesting new results. But as for TOA products one may question the "satellite-to-model" approach and better benefit from the "model-to-satellite" approach, where coupling with models which have assimilated IASI data, could be better to resolve the details of the boundary layer profile that control surface interactions. Many feasibility studies are still needed in this respect, once the atmospheric signal itself is properly accounted for, to consolidate these potential capabilities for land/ocean studies.

4.7.3 Atmospheric chemistry monitoring and research

The main objective of IASI on board Metop is to improve the accuracy and vertical resolution of temperature and humidity soundings from space. But to fulfil this operational task, as part of NWP models, the instrument developed also has capabilities to contribute to atmospheric chemistry monitoring and research. The spectral resolution and radiometric accuracy of IASI indeed provide sufficient sensitivity to discriminate between the spectral signatures of several trace species (in much lower abundances than H_2O and CO_2) which are involved in atmospheric chemistry.

As a continuation of previous satellite measurements of trace gases, including most recently those by the Upper Atmospheric Research Satellite (UARS), several research instruments have been specially designed to contribute to stratospheric and tropospheric chemistry studies from space (GOME, ILAS, IMG, etc.), others are under development (GOMOS, MIPAS, SCIAMACHY on ENVISAT, TES, MLS, HRDLS on CHEM-1) and others are in project (see Megie *et al*., 1995; also ESA, 1996). IASI will not have the full capabilities to measure reactive and other less abundant species of some of the future atmospheric chemistry instruments, but IASI can contribute by obtaining information on ozone in the troposphere and in the lower stratosphere as well as by measuring the tropospheric source gases CH_4, N_2O and CO. Information on other less abundant chemical species is also potentially available in the IR spectra recorded by IASI.

4.7.3.1 Climatologies

4.7.3.1.1 Ozone

The role of ozone as a filter of UV radiation reaching the ground (WMO, 1995a) and as a significant contributor to radiative forcing of the whole atmosphere (IPCC, 1996) makes it a species of prime importance for monitoring climate-chemistry interactions. In parallel with other dedicated ozone sensors (TOMS, SAGE, GOME, GOMOS, GOME-2, etc.) the IASI instrument has the capability to enhance global ozone monitoring since it covers the strong 9.6 µm band as well as the weaker 4.7 µm band of O_3 at rather good spectral and spatial resolutions.

As compared to the single rather wide channel 9 of HIRS/TOVS on the NOAA satellites the much higher spectral resolution and coverage together with improved radiometric accuracy of IASI may allow us to extract at least 3 pieces of information on the vertical distribution of O_3 at high horizontal resolution. The capability to quantify the tropospheric column independently of the lower and upper stratospheric columns affords interesting possibilities for IASI to contribute to the improvement of our understanding of the ozone concentration in the most critical region of the upper troposphere/lower stratosphere.

In particular, to improve the vertical resolution of the ozone distribution it would be useful to combine the radiance measurements of both GOME-2 and IASI. Also for later use in the validation process as well as to obtain robust climatologies, total ozone retrieved from the GOME-2 instrument, might be mapped to the IASI sub-pixels. This could be a step separate from the retrieval part because processing time constraints might play a role.

These observations will contribute to monitoring the formation of the Antarctic ozone hole and its subsequent recovery as well as monitoring the decrease of ozone in the Arctic in the cold winter period followed by the expected reduction of ozone due to transport and dispersion of processed air at mid-latitudes.

Pre-launch scientific studies necessary to consolidate the expected capabilities of IASI have already started (Figure 6 for example) and should include careful simulation studies to validate the possibility of retrieving independently the tropospheric and stratospheric distribution of O_3 and to quantify the expected vertical resolution and precision in various geographical and geophysical situations.

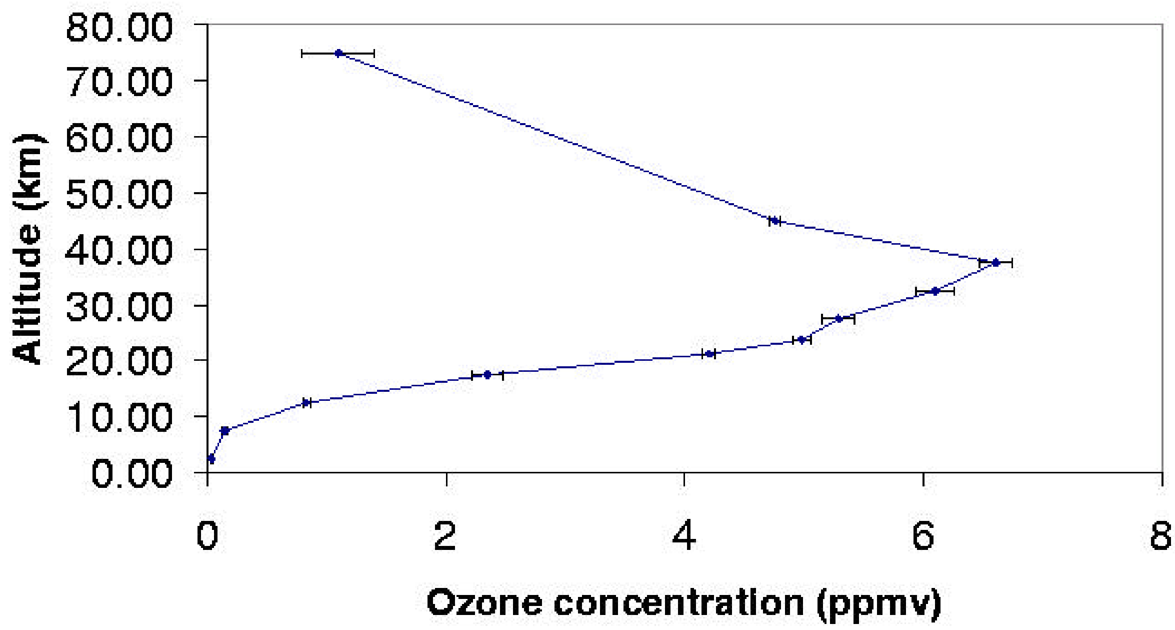

Figure 6 Ozone profile retrieved from IMG radiances processed at IASI resolution of 0.5 cm^{-1}. The inversion was performed on 37 atmospheric layers and reduced to the 11 layers plotted here.

(Serio, 1998).

4.7.3.1.2 The source species CH_4, N_2O and CO

The source species CH_4, N_2O and CO released at the surface by natural/biological processes and anthropogenic activities are affecting both atmospheric chemistry and climate. IASI will be able to monitor them globally (because of the polar orbit) by measuring the tropospheric column of these species at very high horizontal resolution (12 km at one pixel spatial resolution, about 50 km using four pixel averages). Except for AIRS, a meteorological sounder comparable to IASI, only IMG and MOPITT (for CO and CH_4) are expected to yield similar data before IASI is in orbit.
In order to quantify the scientific approach of the measurements, pre-launch studies are needed for:

- The assessment of the precision of the retrieved products (CH4, N2O and CO columns)
- The sensitivity of the retrieved column to the shape of the assumed vertical profile and/or the possibility to extract more than one piece of information about the vertical distribution of the corresponding species
- The expected information available in case of partly cloudy or cloudy pixels

- The problem of spatial averaging versus spatial inhomogeneity of the horizontal distribution of the source species

Future studies to be undertaken as the launch date is approaching should include the preparation of cross-validation and cooperation with other projects devoted to the monitoring of the source species, i.e. the tropospheric (ALE/GAGE, CMDL, etc.) and stratospheric (NDSC, etc.) networks and the other satellite instruments (not to mention the validations appropriate to IASI, discussed in Sections 4.6.2 and 4.9.4). Among the ground-based instruments, IR Fourier transform spectrometers operating in the same spectral region and covering the same spectral features as IASI, will be measuring from below columns directly comparable to the columns measured by IASI from above.

4.7.3.1.3 Other species

The possibility of retrieving from IASI data the column amounts of other species of interest to atmospheric chemistry will be confirmed by additional studies and validation of the proposed retrieval schemes (with available aircraft, balloon or satellite data sets). Among the species that IASI could potentially retrieve are two of the CFCs ($CFCl_3$ and CF_2Cl_2), the monitoring of which is important to confirm the effect of the phasing out of these species following the Montreal protocol as well as HNO_3, a lower stratospheric species, related to the chemistry of the NO_x family and to aerosol formation/evaporation. SO_2 and NO_2 may also be observable during special geophysical events such as volcanic eruptions, strong pollution by aircraft, natural/man induced fires and intense lightning.

4.7.3.2 Process studies

IASI does not have the extensive potential of other instruments dedicated to atmospheric chemistry. But its high horizontal resolution, combined with its capability to provide high vertical resolution temperature and WV profiles and to resolve the ozone column in at least 3 partial columns (tropospheric, lower and upper stratospheric), makes it very interesting to perform specific case studies on important atmospheric issues. Feasibility studies are needed to examine how this can be implemented, mainly as an off-line research activity, since full documention of these specific cases will often combine the information provided by other sensors or platforms into sophisticated high resolution (both spatial and temporal) chemical models. Such studies could address:

- The quantification of stratospheric ozone transport to the troposphere through extended and intense tropopause foldings (cut-off lows) and the subsequent evolution of ozone in the lower atmosphere

- The chemical sources of tropospheric ozone including the monitoring of strong and extended photochemical smog episodes (Mexico City, Los Angeles, etc.) when the concentration of O3 and CO will reach many times the background level on geographic areas that can be resolved at the size of the IASI pixels

- Heterogeneous chemistry models of ozone depletion that are being tested and improved, but these chemistry studies will benefit from the synergy between the temperature information (critical for polar stratospheric cloud (PSC) formation), cloud/aerosol information (possibly type, size, optical depth, etc.) and ozone information all provided by IASI in the same geometry over a large scene viewed at high horizontal resolution along the track

- Through atmospheric chemistry modelling, the spatial distribution, intensity and temporal evolution of the sources of trace gases such as CH4 and CO that IASI is measuring and ways to constrain, with additional information on the NOx species, the tropospheric distribution of OH

- Methods for incorporating the IASI radiances directly or the trace gas retrievals into on-line meteorological models with refined transport (but simplified chemistry) in order to improve the transport estimates. Such models would parallel the data assimilation models which will be used to assimilate the IASI temperature and humidity measurements.

4.8 Needs of direct read-out users

Direct read-out users receive the data stream at level 0. They need to perform the whole data processing chain from end-to-end in a timely manner.

In addition to the pre-processor outlined in Section 4.4 and the subsequent retrieval step, they will need ingest software. It needs to be simple, modular and transportable to various user platforms. It is anticipated that the approach to the processing will be based mostly on the existing ATOVS local processing chain (which is based on the NOAA-KLM use, but it will be required to modify the processing for Metop) (Klaes, 1997). The focus must be on the clear definition of the interfaces between the modules. It is desirable to leave the IASI and ATOVS ingest-chains separated, as the HRPT down links are separated as well. The possible co-processing will then be integrated by the respective pre-processors.

The ingest should be based as far as possible on the global processing. It includes:

- Decommutation

- Calibration

- Navigation

Reference spectra need to be made available to the local users, together with ISRF data for the spectral calibration.

The pre-processor used for global processing should also be made available to local users. As the processing resources of local users are likely to be more limited than those of the central facilities, the pre-processor should be designed to include modes giving useful (but perhaps less extensive) results without computational intensive operations on the full IASI spectrum.

The retrieval steps will have to be defined depending on the needs of the respective local user.

4.9 Spectroscopy

4.9.1 Importance of spectroscopic parameters

IASI is an instrument relying heavily on the quality of spectroscopic parameters involved as input of the forward models used to calculate the radiance spectra at the top of the atmosphere. As an intrinsic part of the retrieval process these calculated spectral radiances will be compared to the radiances actually measured by the IASI instrument at any given time and location to improve upon the initial guess of the atmospheric state vector (vertical distribution of temperature, humidity, ozone, etc.) by minimising the residuals between observed and calculated spectra. This is the general principle of the retrieval or inversion process. The various implementations of the corresponding algorithms have been discussed in Section 4.2.2.

But the accuracy of the fast (or hyper-fast) models, used in the IASI operational retrievals, will eventually depend on the accuracy of the LBL forward model used to generate the so-called training set of atmospheric spectra on which they have been parameterised. Hence the importance of:

- The quality of the spectroscopic databases
- The supporting laboratory studies (both experimental and theoretical) used to generate them
- The validation of the spectroscopic parameters in the most extended range of temperature, pressure and absorber amounts appropriate to the nadir viewing geometry of IASI

4.9.2 Spectroscopic databases

The present status of the atmospheric databases is the result of numerous studies performed during the last 20 years in several dedicated spectroscopic laboratories all over the world. International cooperation contributed to the establishment of widely used spectroscopic databases for atmospheric applications, two of which are of prime importance for IASI:

- HITRAN under the responsibility of Phillips Laboratory, Cambridge, USA (Rothman et al., 1992, Rothman et al., 1997)
- GEISA under the responsibility of LMD, Palaiseau, France (Husson et al., 1992, Jacquinet-Husson et al., 1998)

Further studies in the framework of the ISSWG will assess the need for a dedicated database for IASI, and comparisons of the present databases are ongoing. In any case, the need will remain to improve and consolidate the spectroscopic parameters and the RTMs that use them through careful studies in the laboratory and in well-documented atmospheric conditions. The reason for this is the increased spectral resolution and radiometric accuracy of a new atmospheric sounder like IASI which has been designed to improve upon satellite sounders of the previous generation, such as TOVS and ATOVS, as far as vertical resolution and accuracy of temperature and humidity retrievals are concerned.

However, the new instrumental capabilities will only be fully exploited if the accuracy and reliability of the forward modelling is improved in parallel. Analogous considerations also apply to other high resolution IR instruments (IMG, TES, AIRS, etc.).

4.9.3 Spectroscopic parameters

Several types of spectroscopic parameters are needed by forward models depending on the absorbing molecule. They are listed here in order of decreasing contribution to the IASI radiances:

1. LBL parameters for the molecules having an IR spectrum which can be described in terms of line spectrum (CO_2, H_2O, O_3, CH_4, N_2O, CO, etc.)

2. Far wing absorption and continuum data for H_2O

3. Far wing absorption and line interference effects data for CO_2

4. Cross-section parameters for heavy molecules (CFCs, etc.) or for the major constituents O_2 and N_2 presenting a collision-induced absorption spectrum for which the LBL approach is unpractical or improper.

The line parameters (position, intensity, width/shift and temperature dependence) are usually obtained through experimental studies of pure gas and mixtures (with O_2, N_2 or synthetic air) using very high resolution laboratory instruments (typically 0.002 cm^{-1}) and various absorption cells (with controllable path length, temperature and pressure conditions). At high resolution the number of lines to be considered (more than 10000 for the 9.6 µm band of ozone) prevents a purely empirical approach however, and theoretical analysis and modelling of the experimentally acquired spectra using vibration-rotation Hamiltonian and dipole moment operators is always necessary, firstly to check the consistency of the assignments/measurements, secondly to interpolate and to extrapolate the model parameters to lines which are unobserved (too weak) or unusable (blend) in the accessible experimental conditions.

Appropriate theoretical (quantum mechanical) models involving a precise description of the influence of molecular interactions (of the IR active molecule with collision partners i.e. N_2, O_2 and H_2O) are also needed for collision-induced, line interference, far wing and continuum parameterisation in connection with appropriate experimental measurements. In any case a validated theoretical spectroscopic model makes possible calculation of the absorption properties of atmospheric species for temperature, path length, pressure conditions for which a direct laboratory experiment is not practical. Although the available spectroscopic data are rather extensive on the two most prominent absorbers (H_2O and CO_2) in the spectral region covered by IASI, the importance of these two species as a probe of the surrounding temperature (for CO_2) and as a tracer of humidity (for H_2O) not to mention their radiative effect, is justifying further studies. This is especially true for:

- The intensities and widths of the weak H_2O lines and the continuum of WV in the window regions. Long paths with relatively cool temperatures (e.g. around 260K) are common in the atmosphere but are difficult to simulate in the laboratory as comparable column amounts of WV have to be produced in a smaller volume with practical limitations due to liquid water condensation.

- The consistency of line intensities of several weak CO_2 hot bands or isotopic bands which are contributing in the wings of the strongest bands

- The contribution of line interference effects around several CO_2 Q-branches which look very promising for improving the temperature retrievals

Other species with a more localised contribution in the IASI spectral domain also need additional laboratory studies, namely:

- The absolute intensities of ozone in the 9.6 µm region to match the 5% accuracy requirement on the O3 column

- The methane width and line shape studies in several absorption regions where this important tropospheric species contributes and can be retrieved (at least a column)

Several laboratory investigations covering some of these specific topics have been initiated as a result of project selection following the IASI Announcement of Opportunity. They will be coordinated in the framework of the ISSWG and more focused studies will be recommended and undertaken as a result of sensitivity and validation studies.

5 PRIORITIES FOR IASI RESEARCH AND DEVELOPMENT

5.1 Introduction

Section 4 has provided an overview of the scientific activities which need to be undertaken in preparation of the IASI mission on the EPS/Metop satellites. The steps which are necessary to process IASI data to geophysical products and to use data and products for different applications (meteorology, climate monitoring and atmospheric chemistry) have been discussed.

Based on this discussion, and taking into account the current status of scientific activities within and outside the ISSWG (see Annex 3 for ISSWG projects and Annex 7 for related publications), priorities for further scientific research and development will be identified in this section. The priority is linked to the relevance of a scientific study for the for the development of operational processing chains for IASI data in the EPS Ground Segment. Emphasis is also placed on studies which support the efficient exploitation of IASI data and products by the various user communities.

5.2 Earth/atmosphere radiative transfer

5.2.1 Atmospheric and surface variables

For the operational processing and use of IASI data, databases of various atmospheric and surface variables are needed. Work in this area includes both the critical analysis and possible collation of available data in suitable databases, but also the promotion of additional measurements in case existing data are not sufficient.

Global databases exist for temperature and WV profiles. While the temperature databases (e.g., that at ECMWF) are probably sufficient, it has been recognised that the quality of the stratospheric WV data is in general unsatisfactory. Ozone data have been collected in databases which, however, do not yet include the most recent measurements from sensors such as UARS or GOME. A database is available for CH_4 and N_2O from 0.5 to 20 mb, but again this is out of date and does not reflect the latest measurements. No global database is available for trace gas concentrations, but efforts, coordinated with the Committee on Space Research (COSPAR) are being undertaken to assemble improved sets for O_3, CH_4, N_2O, and CFCs. Information about clouds is given in the International Satellite Cloud Climatology Project (ISCCP) database; aerosol parameters have been derived from SAGE. The land and sea surface emissivity is not adequately characterised for the use of IASI data in the spectral window regions. Current databases for sea and land surface temperature appear to be adequate but it appears that the required information for retrieval and assimilation is the error covariance between initial estimates of skin and surface air temperature rather than simply the land skin temperature, for which no suitable database currently exists.

The following need for studies related to the provision of climatologies has been identified.

High priority:

- Characterisation of the land surface emissivity in the IASI spectral windows for several generic surface types (including the effect of surface moisture)
- Evaluation of data for WV between 300 and 100 mb from aircraft measurements (including lidars) and other sources and add to existing databases, if adequate

Further useful studies or activities:

- Investigation of the availability of a database with the required information for land skin temperatures. Exploration of the possibility to derive this information making use of a surface temperature database if no suitable land skin temperature database exists.
- Establishment of contacts to potential providers of data about trace gas distributions (MOPITT team, NDSC operators, etc.). Acquisition of suitable trace gas databases or, if not available, support of the generation of new databases.

5.2.2 Radiative transfer modelling for IASI

IASI will have to rely on fast and hyper-fast RT modelling for proper processing of the recorded spectral radiances. Several models are currently being developed within the ISSWG and further activities are being undertaken by external groups. LBL models will be the reference against which these fast and hyper-fast models will be evaluated. A variety of LBL models exist which need however to be improved by integrating updated spectroscopic parameters. The further development of LBL models and fast and hyper-fast models will require a continued effort, in particular for the validation of models through intercomparison with other models and through comparison with collocated measured spectra and ground truth measurements.

The following requirements for studies related to RT modelling have been identified:

High priority:

1. LBL models:

    - Integration of updated spectroscopy (line positions, intensities, widths, etc., modelling of the line mixing, including temperature dependence, WV continuum, etc.)
    - Validation of LBL models and characterisation of model errors through intercomparison with other LBL models and comparison with collocated measured spectra and ground truth measurements in different atmospheric conditions but in particular with high total precipitable water (improvements expected in CO_2 Q branches and continuum of H_2O and O_2)

- Continuation of the derivation of analytic Jacobians (for all relevant parameters) for the IASI spectral resolution.

2. Fast and hyper-fast models:

  - Improvement of methods for fast and hyper-fast RT calculations (transmittances, Jacobians (analytic rather than through perturbation), brightness temperatures)

  - Assessment of the accuracy of fast and hyper-fast calculations by comparison with LBL calculations

  - Validation of fast and hyper-fast models and characterisation of model errors through intercomparison with other models of the same type and comparison with collocated measured spectra and ground truth measurements in different atmospheric conditions but in particular with high total precipitable water

  - Assessment of the performance in terms of rapidity and accuracy

Further useful studies or activities:

- Improvement of the geophysical climatology used in RTMs (see also Section 5.1)
- Development of a method for the generation of Jacobians in the presence of clouds
- Continuation of forward modelling in the MW (AMSU-A like channels)

5.3 IASI instrument and ingest processes

CNES has developed a model to describe instrument processes which is expected to be further refined at later stages of the project taking evolutions of the IASI instrument into account (Tournier and Hebert, 1996). This model will be available to generate appropriate instrument characterisation and parameterisation (IPSF, ISRF, noise characteristics, etc.). The majority of the ingest algorithms for the processing up to level 1c have already been defined and validated against IASI breadboard measurements.

The following points remain which should be investigated with priority:

- Verification and validation of the chosen algorithms on real atmospheric spectra (both from the breadboard and other instruments)
- Establishment of the instrument noise covariance matrix (apodised, unapodised, etc.)
- Development of further methods for the parameterisation of the ISRF (including assessment of impact of instrument defects, robustness, etc.)

5.4 Data pre-processing

Data pre-processing for IASI will comprise several steps: mapping to a common grid, co-registration with AVHRR, radiance cluster analysis using AVHRR, cloud detection and cloud clearing. Co-registration and radiance cluster analysis will be under the responsibility of CNES, the latter possibly making use of software developed for MSG. Different combinations of instruments on Metop have to be exploited for cloud detection and cloud clearing algorithms. Work has already been initiated within the ISSWG but further studies seem necessary.

The following studies for the pre-processing of IASI data have been identified:

1. Cloud detection:

    - Improvement of the knowledge of the spectral signatures of clouds and relate the spectral properties to the cloud structure (i.e. the presence of water or ice particles). Analysis for this purpose of data from new instruments launched before IASI (MODIS, AMSR, MERIS, AATSR and AIRS).
    - Application of existing cloud detection schemes for HIRS/MSU to IASI/AMSU-A
    - Assessment of the role of AVHRR for cloud detection
    - Development of methods for cloud detection based on IASI sounding data alone by exploiting the full spectral range of IASI
    - Development of a cloud detection algorithm suitable for operational applications based on results from these preceding studies

2. Cloud analysis:

    - Development of methods for the analysis of AVHRR radiances in the IASI pixel

3. Cloud clearing:

    - Intercomparison of different existing methods for cloud clearing
    - Assessment of the impact of cloud detection schemes on cloud clearing (use of AVHRR, use of IASI alone, etc.)
    - Development of a cloud clearing algorithm applicable to operational or research applications as required based on results from these preceding studies

5.5 Retrieval of geophysical parameters

On-going work within the ISSWG comprises several studies for retrievals of temperature and WV profiles, of minor constituents and of cloud parameters from IASI data. Not covered is the retrieval of some "secondary" parameters which have however lower priority for the IASI mission on Metop. These include, for example, surface temperature and spectral emissivity with a quality adequate for climate monitoring, aerosol properties and radiation budget parameters. For all retrievals the synergism between different instruments on Metop has to be exploited.

The following additional activities concerning retrieval algorithms should be initiated with high priority:

- Development and improvement of further retrieval methods (including improvement of the convergence of the inversion by using the Hessian and a non-linear inversion scheme)

- Exploration of the impact of a synergistic use of data from other instruments (AMSU-A, GOME-2, etc.) on retrievals

- Validation and testing of retrieval algorithms, using both clear and cloudy radiances (simulated and observed). Testing with quasi-real inversions using a large set of profiles with associated errors.

- Intercomparison of different retrieval schemes (including the comparison between global retrievals with sequential retrievals, use of different subsets of IASI data). Testing with AIRS data when available.

- Comparison of the impact of the use of IASI retrieved parameters vis-à-vis the use of IASI radiances (for different subsets) on assimilations (including so-called profile independent retrievals). See also Section 5.7.1.

5.6 Monitoring and validation of IASI data/products

Methods need to be developed for the on- and off-line monitoring and quality control of instrument performance, and the different processing steps of IASI measurements to calibrated radiances and retrieved products. Envisaged methods include consistency checks for radiances, comparison of radiances with RTM output, cross validation of HIRS against IASI, etc.. In particular, the comparison to the output of RTMs is required to enable the tuning of biases between measured and calculated radiances.

Concerning pre-launch and post-launch validation campaigns, EUMETSAT, CNES and the ISSWG have to assess the need for special campaigns in due time. This is not discussed further at this stage.

For the monitoring of the instrument and the on-ground processing, the following further studies need to be undertaken:

- *Instrument performance*: Development of methods for the monitoring of the co-registration IASI sounder/IASI imager and the co-registration IASI imager/AVHRR, for the monitoring of the IASI spatial IPSF, and for the evaluation of the quality of the actual ISRF.

- *Data Processing*: Development of methods for the monitoring of the on-ground processing steps up to geophysical products.

5.7 Applications of IASI products

5.7.1 Operational meteorology

Several parallel activities are currently being undertaken by members of the ISSWG to study the information content of IASI data for NWP and to develop a suitable interface to existing NWP systems, mainly using cloud-cleared radiances and, to a lesser extent, retrieved products. The use of cloud-affected radiances is not foreseen at this time within the planned work of the ISSWG. The use of WV and ozone distributions derived from IASI for the analysis of wind fields is also the subject of a study.

In the context of operational meteorology, the following activities need to be continued or initiated with high priority:

- Extension of fast RTMs to include the tangent-linear and the adjoint

- Enhancement of the IASI Observing System Simulation Experiments (OSSE) database by including other observations to allow meaningful forecast impact studies

- Development of suitable interfaces for NWP (i.e. observation operators for IASI radiances and retrieved products). This includes the determination of an optimal radiance set (< 200 channels) for assimilation, through the selection of pseudo-channels, super-channels or a subset of individual channels.

- Development of methods for the monitoring of IASI radiances and retrievals by use of NWP fields

- Comparison of the impact of assimilation of retrievals versus radiance subsets in 3-D or 4-D VAR on temperature, WV and ozone analyses and on forecast performances, testing with AIRS data on suitable case studies

- Investigation of the use of window and lower tropospheric channels over land with surface emissivity parameterisation

- Formulation of a plan for assimilation of cloudy radiances in NWP (e.g., determination of cloud top pressure, phase, etc.), using the synergy with AMSU-A

5.7.2 Climate monitoring and global change

Activities undertaken in the context of the ISSWG for climate monitoring comprise studies of the information content of IASI data and products, in particular the use of IASI for the study of the radiation budget and radiative forcing, and the development of assimilation schemes (both for radiances and retrieved products). Methods for the generation of trace gas climatologies based on measurements with IASI, companion instruments and other sensors will be developed in a form which is adequate for climate monitoring, i.e. space and time averaged.

Further studies should focus on:

High priority:

- *IR radiation budget*: Development of an approach to construct the global IR radiation budget. Assessment of the effect of clouds (all levels) and upper tropospheric humidity on the IR radiation budget (including the seasonal variation). Investigation of indicators for the spectral signature of climate change

- *Heating rates*: Development of methods for the retrieval of heating rate profiles from IASI radiances

- *Cirrus properties*: Development of methods to retrieve cirrus cloud temperature, cloud top pressure, optical depth and effective crystal size

Lower priority:

- Development of methods for the generation of climatologies: WV profile (particularly upper troposphere humidity), column amounts of O3, total column amounts of CH4, N2O, CO and CFCs, and cloud parameters (cloud cover, cloud top pressure, phase and drop size, in particular for multilayer clouds)

- Radiative forcing: Separate tropospheric and stratospheric contributions by ozone in both IR and UV/visible (including latitudinal and seasonal variation); investigation of the impact of the latitudinal and seasonal variation for other trace gases; study of the impact of cloud clearing schemes and the spectral signature of clouds on the derived cloud radiative forcing

- *Aerosol properties*: Development of methods to retrieve aerosol optical depth, surface temperature and emissivity.

5.7.3 Atmospheric chemistry

Studies are being carried out within the ISSWG to assess the information content of IASI data for applications in the area of atmospheric chemistry. Assimilation schemes for CTM and regional pollution models will be developed, and the use of IASI data for the characterisation of sources, sinks and the temporal evolution of trace gases (O_3, CH_4, N_2O and CO) will be explored. The possibility of constraining the distribution of the OH radical based on this information will be investigated. One study within the ISSWG is dedicated to the use of IASI data for the monitoring of volcanic plumes.

To prepare the use of IASI data for atmospheric chemistry the following activities should be continued or initiated.

High priority:

- A study of the information content for atmospheric chemistry (identification of retrievable species, selection of relevant IASI channels for use in retrieval schemes)

- Sensitivity studies to noise, spectral resolution, temperature/surface properties, cloudiness, etc.

Lower priority:

- Use of IASI data in conjunction with CTMs or regional pollution models (data assimilation or retrieved products) to understand chemical processes, characterise sources and sinks (CO, CH_4, O_3) and to infer the OH concentration

- Development of methods to study polar ozone destruction, troposphere/stratosphere exchange, biomass burning, smog episodes, aerosols, HNO_3 and SO_2 by using IASI data and data from other instruments

5.8 Needs of direct read-out users

The development of software for direct read-out users will benefit from the work undertaken in the ISSWG for the processing of global IASI data and also from the on-going development of ATOVS software for local users. The latter includes at this time ingest and pre-processing steps, but the inclusion of retrieval algorithms is anticipated. The provision of IASI processing software for local users could possibly be covered in the form of an extension of the ATOVS software.

The following steps need to be undertaken:

- Extension of the existing ATOVS processing software to include ingest and pre-processing of IASI data upon consolidation of the IASI ingest and pre-processing methods

- Adjustment of IASI global retrieval algorithms after their development for the needs of local users, taking into account possibly limited computing resources, availability of data bases, etc.

5.9 Spectroscopy

Several studies, partially overlapping, partially complementary, are currently being undertaken within the ISSWG to improve the quality of spectroscopic parameters which are needed as input to RTMs. They include measurements of line parameters for H_2O, O_3, CH_4 and other trace gases; and cross-section measurements for CFCs, O_2 and N_2. The WV continuum will also be modelled. Further modelling covers line interference, collision effects and the parameterisation of far wing effects. The evaluating of existing spectroscopic databases (GEISA and HITRAN) and their update with the latest spectroscopic data requires a continuing effort.

Regarding the measurement of spectroscopic parameters and their modelling, the following high priority studies have to be undertaken.

1. Data bases:

   - Validation and systematic intercomparison of the existing databases (HITRAN, GEISA) for the stronger absorbers H_2O, CO_2, CH_4, O_3, N_2O. Comparison with real atmospheric spectra recorded in well documented conditions in order to locate deficiencies. Correction of known inadequacies observed when modelling high resolution atmospheric spectra (H_2O, CO_2, CH_4) recorded from the ground, from balloon or from space

   - The combination of existing and new laboratory data in a consistent manner using suitable theoretical models for the calculation of line positions, intensities and widths. (Note that patches and add-ons can degrade the database consistency by duplicates or missing lines).

   - Provision of improved and more realistic estimates for spectroscopic errors. (The coding of uncertainties by an index is insufficient for proper use in the F (forward model) variance-covariance matrix).

2. WV continuum studies (foreign and self) and temperature dependence:

   - Performance of long path laboratory measurements

   - Performance of real atmospheric measurements along horizontal paths in well documented conditions

   - Improvement of existing parameterisations

   - Elaboration of new theoretical models

3. Further measurements and modelling of spectroscopic parameters:

   (a) H_2O:

   - Weak lines in the 650-1200 cm^{-1} still have incorrect positions and intensities. Need for both measurements and improvement of theoretical calculations

   - Widths (foreign and self) have not been validated by enough systematic laboratory work; very strong variations from line to line

   - Temperature dependencies of widths are poorly measured or calculated

   - Pressure shifts can be important in the lower troposphere

   - Some lines recorded at high resolution in ground based solar spectra show profiles inconsistent with current line shape formalisms

- More detailed line shape measurements and modelling needed for H_2O (in connection with continuum studies)

(b) CO_2:

- Validation of line intensities for the isotopomers in ^{13}C, ^{18}O and ^{17}O needed

- New line shape studies needed in the 15 µm band (laboratory and theoretical)

(c) O_3:

- For lower stratospheric and tropospheric ozone retrievals, a better knowledge of the temperature dependence of the line widths needed

(d) Collision induced spectra:

- More atmospheric validations of O_2 and N_2 collision induced spectra still needed.

In addition, there are the following further needs of lower priority:

1. Measurements and modelling of spectroscopic parameters:

(a) CH_4:

- Intensive laboratory and theoretical work still needed for air-broadened widths

- Line shape studies needed including line interference effects in multiplets and Q-branches

(b) HNO_3:

- Potential contribution in the IASI spectra (in the window regions); work on absolute line intensities still needed

(c) Heavy molecules (described in terms of cross section instead of line by line parameters):

- Establishment of a priority list with the known scenarios for man-made species (CFCs, HCFCs, perfluorinated compounds) based on existing cross section data

- Performance of new measurements and establishment of smooth parameterisations (as a function of temperature and total pressure) to avoid the use of just empirically measured cross sections

(d) Aerosols:

- No validated database for extinction coefficients in the thermal IR is available. Temperature dependence of the optical properties of binary (H_2SO_4/H_2O) and ternary ($H_2SO_4/H_2O/HNO_3$) solutions, as applicable to atmospheric aerosols, should be measured and parameterised.

A1 IASI INSTRUMENT DESIGN

The IASI instrument functional break-down is given in Figure 7. The instrument is separated into three modules. This separation is dictated by the fact that due to limitation of allocated data rate on Metop the conversion of interferograms to spectra is performed onboard. The instrument includes an important Data Processing System which accounts for a substantial part of the electric power budget, so, in order to avoid too high a temperature in the instrument, electronic boxes have been separated from the optics whenever possible and arranged in two electronic modules, the optics and non-separable electronics forming the sensor module. The following paragraphs briefly describe the contents of the functional boxes of Figure 4.

Scan unit: This unit is common to sounder and imager. It consists of a mirror containing the velocity axis and rotating round it (Figure 8). This mirror works with a varying incidence for different scan positions. Instrument layout has limited the maximum incidence angle.

Afocal telescope: This telescope is made of confocal parabolic mirrors.

Interferometer: The interferometer is described in Figure 9. Its OPD range is -2 to +2 cm. The pupil diameter is 80 mm; reflectors are lightweight (300 g) cube corners made in silicon carbide; the auxiliary interferogram is produced through dedicated portions of the pupil.

Laser reference: Frequency controlled laser diode, the control loop very accurately ($\delta\sigma/\sigma < 10^{-7}$) locks the emission frequency to an absorption line of C_2H_2.

Cooler: The cooler is a three-stage passive cooler. End of life equilibrium temperature is required to be below 100 K. It must have the capability of heating to 60°C for decontamination purposes.

Spectral separation and detection: The spectral separation in three bands is made through dichroics with:

band 1:	645 cm^{-1}	$\leq \sigma <$	1210 cm^{-1}
band 2:	1210 cm^{-1}	$\leq \sigma <$	2000 cm^{-1}
band 3:	2000 cm^{-1}	$\leq \sigma <$	2760 cm^{-1}

Detection is by HgCdTe photoconductor in band 1, HgCdTe photovoltaic in band 2 and InSb photovoltaic in band 3. In order to minimise electromagnetic susceptibility effects in bands 2 and 3 which are using high impedance detectors, the corresponding pre-amplifiers have been placed in the cold area.

Other boxes for the signal processing: Classical electronic circuitry with anti-aliasing filter, Sample and Hold driven by the auxiliary interferogram and 16-bit Analog to Digital Converter are used along the analog signal processing chain.

The processes in the rest of the digital path are described in detail in document "Data processing algorithms in on-board and Ground Segment". They are implemented using the hardened version of the digital signal processor ADSP 21020.

The imager chain: The imager chain shares the scan mirror with the interferometer system. The following optics are dioptric and image the IFOV through a bandpass filter on a 64 by 64 pixels pyroelectric detector matrix . The signal is amplified then digitised and corrected for detector dark current. The raw digital image is transmitted to the Ground Segment for further processing.

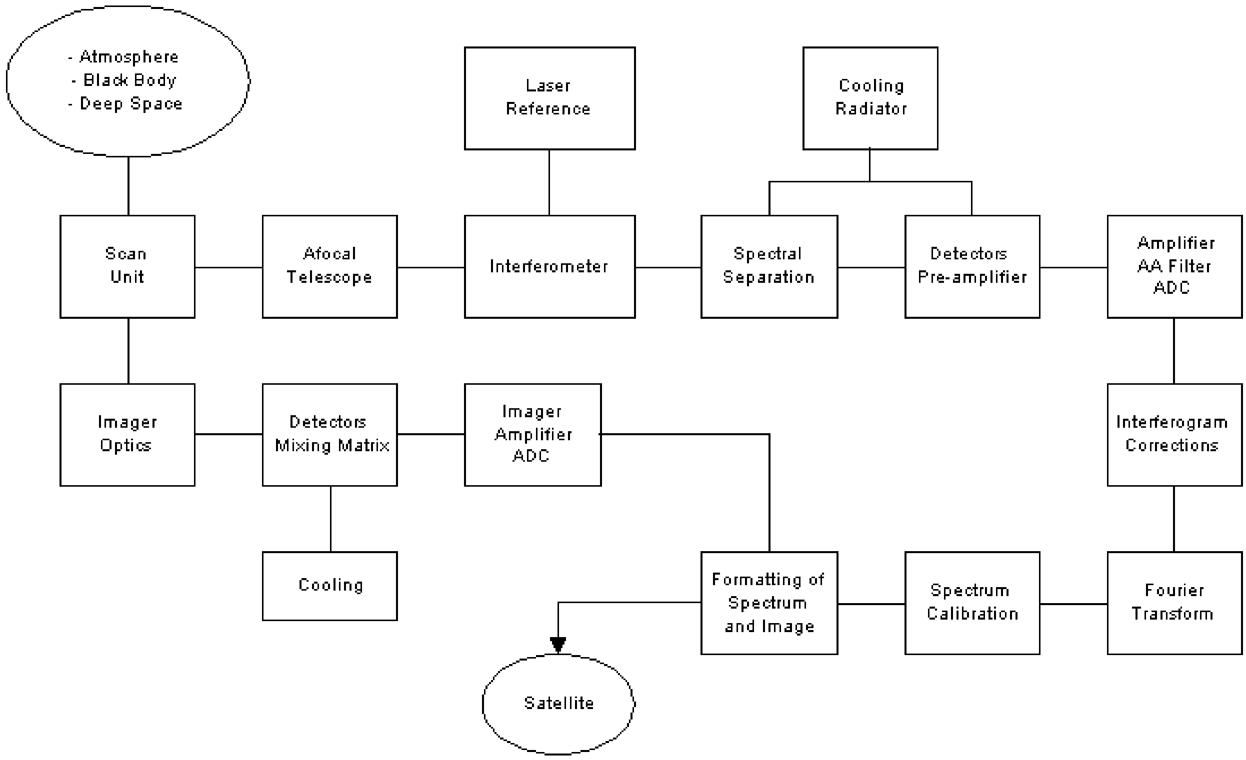

Figure 7 Functional chains in IASI

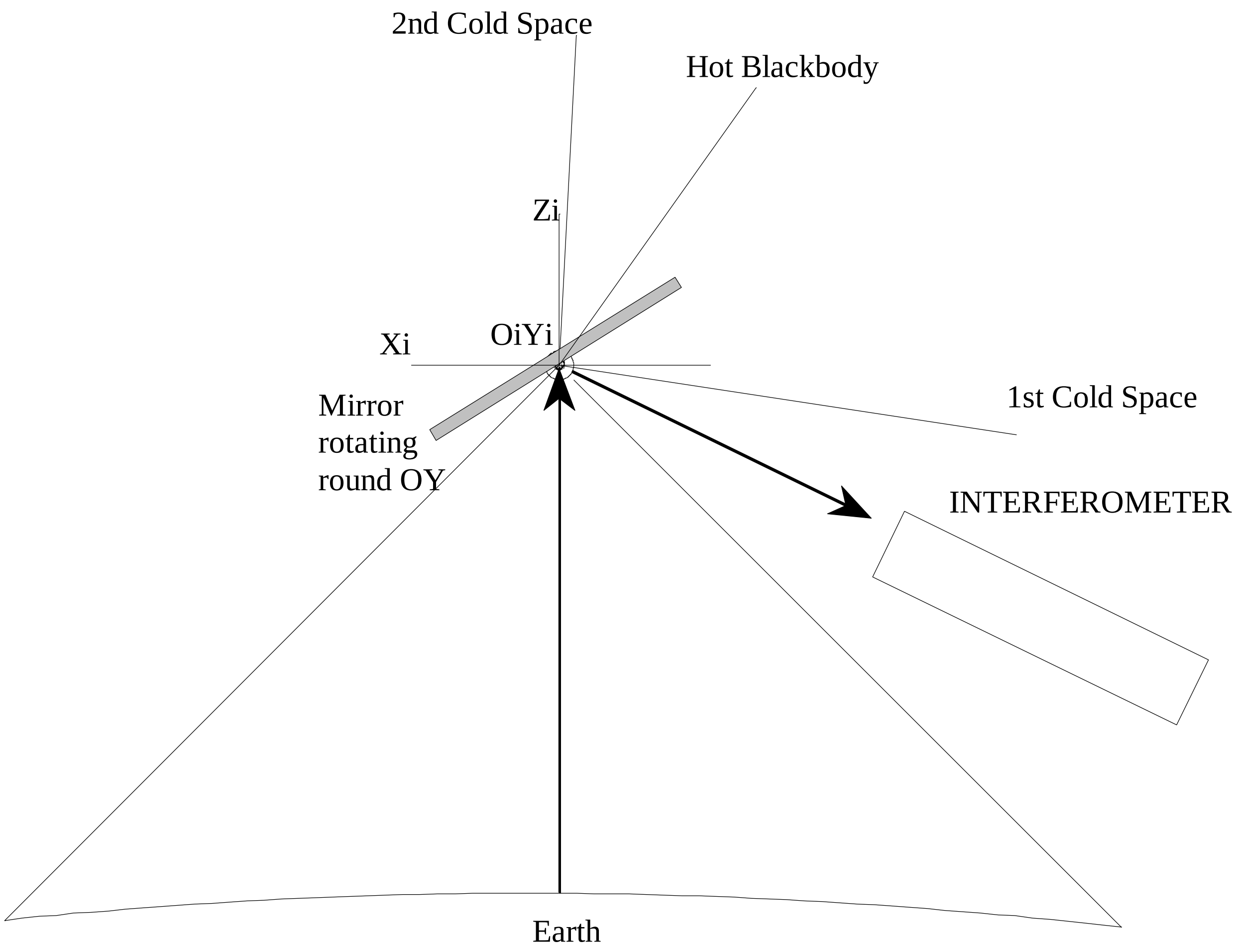

Figure 8 Scan subsystem

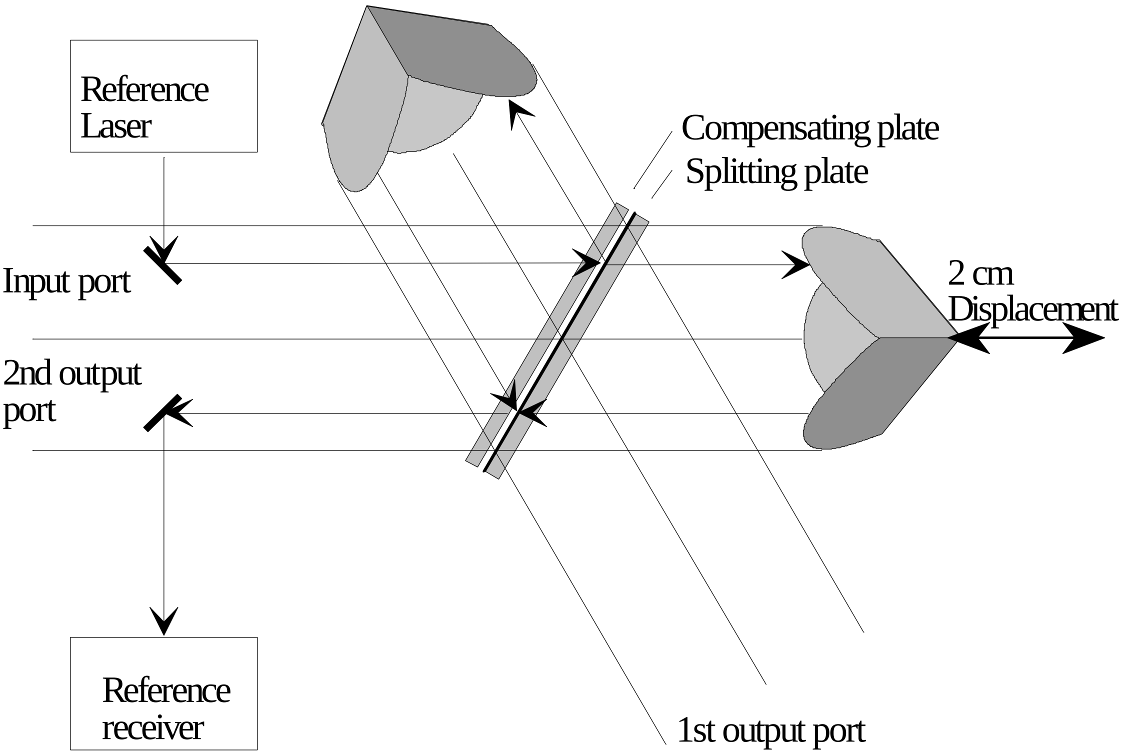

Figure 9 The interferometer

A2 METOP INSTRUMENT CHARACTERISTICS

A2.1 Advanced Very High Resolution Radiometer (AVHRR)

The Advanced Very High Resolution Radiometer (AVHRR) is a multi-purpose imaging instrument used for global measurement of cloud cover, sea surface temperature, ice, snow and vegetation cover and characteristics. This instrument is currently flying on the NOAA series of spacecraft in a five-channel version (no channel 3a present). AVHRR has six channels in the visible and IR between 0.63 and 12.0 µm, with an instantaneous footprint of 1.1 km at the sub satellite point. The internal rotating scan mirror also views deep space and a thermal calibration source on each rotation. Scanning is cross-track with a range of ±55.37° about nadir.

Calibration of the IR channels is performed with four internal black bodies every scan line. The calibration coefficients for the visible channels are determined pre-launch.

AVHRR scans across track of the satellite path in continuous scan. There are 2048 Earth views per scan over a swath of ± 1447 km. The squared instantaneous field of view has a size of 1.1 km at nadir.

AVHRR/3 Channel Characteristics

Channel	Central wavelength (µm)	Half Power Points (µm)	Channel Noise Specifications
1	0.630	0.58 - 0.68	S/N 9:1 @ 0.5 % Albedo
2	0.865	0.85 - 0.88	S/N 9:1 @ 0.5 % Albedo
3a	1.61	1.58 - 1.64	S/N 20:1 @ 0.5 % Albedo
3b	3.74	3.55 - 3.93	0.12 K @ 300 K
4	10.8	10.30 - 11.30	0.12 K @ 300 K
5	12.00	11.50 - 12.50	0.12 K @ 300 K

Table 2 AVHRR/3 channel characteristics

A2.2 High Resolution Infrared Radiation Sounder (HIRS)

The High Resolution Infrared Radiation Sounder (HIRS/4) will fly on NOAA-K to NOAA-N and provides the basic 20 channel IR temperature and humidity soundings of the ATOVS system. All HIRS/4 channels will be used to provide information on temperature and humidity profiles, surface temperature, cloud parameters and total ozone.

Calibration of HIRS/4 is performed every 40 scan lines, there will be a gap of two scan lines in data coverage. Calibration repeatability is specified to be better than 0.3 K and inter channel accuracy better than 0.2 K.

HIRS scans across track in a ‘stop and stare’ mode at a scan rate of 6.4 sec. There are 56 Earth Views per scan. The circular field-of-views have a diameter of 10 km at nadir. The swath covers ± 1080 km.

Channel	Centre wave number (cm^{-1})	Centre wavelength (µm)	Half Band-width (cm^{-1})	Anticipated Max. Scene Temperature (K)	Specified NEΔN ($mW/m^2/sr/cm^{-1}$)
1	668.5 ±1.3	14.959	3.0 + 1/-.5	280	3.00
2	680.0 ±1.8	14.706	10.0 + 4/-1	265	0.67
3	690.0 ±1.8	14.493	12.0 +6/-0	240	0.50
4	703.0 ±1.8	14.225	16.0 +4/-2	250	0.31
5	716.0 ±1.8	13.966	16.0 +4/-2	265	0.21
6	733.0 ±1.8	13.643	16.0 +4/-2	280	0.24
7	749.0 ±1.8	13.351	16.0 +4/-2	290	0.20
8	900.0 ±2.7	11.111	35.0 ± 5.0	330	0.10
9	1030.0 ±4.0	9.709	25.0 ± 3.0	270	0.15
10	802.0 ±2.0	12.469	16.0 +4/-2	300	0.15
11	1365.0 ±5.0	7.326	40.0 ±5.0	275	0.20
12	1533.0 +2/-6	6.523	55.0 ±5.0	255	0.20
13	2188.0 ±4.4	4.570	23.0 ±3.0	300	0.006
14	2210.0 ±4.4	4.525	23.0 ±3.0	290	0.003
15	2235.0 ±4.4	4.474	23.0 ±3.0	280	0.004
16	2245.0 ±4.4	4.454	23.0 ±3.0	270	0.004
17	2420.0 ±4.0	4.132	28.0 ±3.0	330	0.002
18	2515.0 ±5.0	3.976	35.0 ±5.0	340	0.002
19	2660.0 ±9.5	3.759	100.0 ±15.0	340	0.001
20	14500 ±220	0.690	1000	100 %	0.10 %

Table 3 HIRS/4 sounder channel characteristics

A2.3 Microwave Humidity Sounder (MHS)

The Advanced Microwave Sounding Unit-A (AMSU-A) and the Advanced Microwave Wave Sounding Unit B are planned for NOAA-K, -L and -M. AMSU-A, a US instrument, and an upgrade of AMSU-B, the Microwave Humidity Sounder (MHS), procured and developed by EUMETSAT, are planned to fly on Metop. The prime role of these MW sounders is to provide temperature and humidity sounding under completely overcast conditions and to aid the cloud detection for the companion IR sounding instrument. The temperature sounding mainly exploits the band of oxygen at 50 GHz.

MHS is a five-channel MW radiometer. The channels in the frequency range 89 to 190 GHz provide a humidity profiling capability. The measured signals are sensitive to liquid water in clouds and hence can be used to measure cloud liquid water content, and are also sensitive to *graupel* and large water droplets in precipitating clouds and so can provide a qualitative estimate of precipitation rate.

The 3 dB instantaneous footprint for AMSU-A channels is 3.3° (45 km) and for MHS is 1.1° (15 km). Calibration repeatability is 0.3 K. The inter channel calibration accuracy for MHS is 0.5 K.

AMSU-A scans across track in a ‘stop and stare’ mode at a scan rate of eight seconds. The circular instantaneous field of view has a diameter of 45 km at nadir. The covered swath is about ± 1027 km. There are 30 mirror positions per scan.

MHS scans across track at a rate of 2 2/3 sec in continuous mode. The circular field of view, of which 90 are sampled per scan line, has a diameter at nadir of about 15 km. The covered swath width is ± 1078 km.

Channel	Centre Frequency (GHz)	Band Width (MHz)	NE∆T (K)	Calibration Accuracy (K)	Polarisation Angle (°)
H1	89.0	± 1400	1.00	1.0	90-θ
H2	157	± 1400	1.00	1.0	90-θ
H3	183.311 ± 1.00	± 250	1.00	1.0	No spec.
H4	183.311 ± 3.00	± 500	1.00	1.0	No spec.
H5	190.311	± 1100	1.00	1.0	90-θ

Table 4 MHS channel characteristics (specification)

Channel	Centre Frequency (GHz)	# of Pass Bands	Band Width (MHz)	NeΔT (K)	Calibration Accuracy (K)	Polarisation Angle (°)
AMSU-A2						
1	23.8	1	± 135	0.3	2.0	90-θ
2	31.4	1	± 90	0.3	2.0	90-θ
AMSU-A1						
3	50.3	1	± 90	0.4	1.5	90-θ
4	52.8	1	± 200	0.25	1.5	90-θ
5	53.596 ± 0.115	2	± 85	0.25	1.5	No Spec.
6	54.40	1	± 200	0.25	1.5	No Spec.
7	54.94	1	± 200	0.25	1.5	No Spec.
8	55.50	1	± 165	0.25	1.5	No Spec.
9	F_{LO} = 57.290344	1	± 165	0.25	1.5	No Spec.
10	F_{LO} ± 0.217	2	± 39	0.4	1.5	No Spec.
11	F_{LO} ± 0.3222 ± 0.048	4	± 18	0.4	1.5	No Spec.
12	F_{LO} ± 0.3222 ± 0.022	4	± 8	0.6	1.5	No Spec.
13	F_{LO} ± 0.3222 ± 0.010	4	± 4	0.8	1.5	No Spec.
14	F_{LO} ± 0.3222 ± 0.0045	4	± 1.5	1.2	1.5	No Spec.
15	89.0	1	± 3000	0.5	2.0	90-θ

Table 5 AMSU-A channel characteristics (specification)

A2.4 Global Ozone Monitoring Experiment (GOME)

The Global Ozone Monitoring Experiment, GOME-2 is a descendant of GOME flying on ERS-2 in the sense that it will be a nadir-viewing spectrometer to measure radiation back scattered from the atmosphere and reflected from the surface in the UV and visible range. The spectral resolution will be moderately high to enable the discrimination of absorption features of various trace gases. The main focus will be on ozone.

GOME-2 will cover the wavelength range from 240 to 790 nm in four channels, with a spectral resolution between 0.2 and 0.4 nm. In addition to ozone the spectral coverage permits the detection of the nitrogen compounds NO, NO_2 and NO_3, the halogen compounds ClO, OClO, and BrO, HCHO and SO_2. On board hardware provides radiometric and wavelength calibration, which enables the utilisation of both the traditional SBUV and the more innovative Differential Optical Absorption Spectroscopy (DOAS) retrieval techniques to be applied.

While GOME has a swath width of 960 km across track, yielding a global coverage of the Earth within 3 days, it is foreseen to double the swath of GOME-2 to obtain coverage in 1 day at polar and mid-latitudes and 2 days in tropical regions. GOME samples adjacent pixels, and the same sampling strategy is likely to apply also for GOME-2.

With the increased swath width and the allocated maximum data rate for GOME-2, nadir ground pixels sizes of typically 80 km (across track) by 40 km (along track) could be achieved. However, the actual pixel size on which measured GOME-2 data will be used for further processing to geophysical products also has to consider required signal to noise ratios. If needed, larger ground pixel sizes could result from increased on-board integration times or from co-adding pixels on the ground.

Based on experience with GOME measurements, it is anticipated that ozone profiles in the middle and upper stratosphere can be retrieved with horizontal scales of about 250 to 500 km (both along track and across track). Ozone total amounts and profiles in the troposphere and lower stratosphere should be available on significantly smaller pixel sizes.

A2.5 GNSS Receiver for Atmospheric Sounding (GRAS)

For the past 25 years, the radio occultation technique has been used with great success by planetary missions to measure vertical profiles of temperature and density for most of the planets of the Solar System. With the advent of Global Navigation Satellite Systems (GNSS), using high performance radio transmitters in suitably high orbits, along with receivers on low Earth orbiting (LEO) platforms, it is now possible to make radio occultation measurements for Earth’s atmosphere with an accuracy useful for applications in operational meteorology and in climate and ionospheric research.

		Temperature	**Humidity**	**Bending Angle**
Horizontal Domain		Global	Global	Global
Horizontal Sampling (1)		< 300 km (2)	< 300 km (2)	< 300 km(2)
Vertical Domain		Surface to 1 hPa (0 – 50 km)	Surface to 300 hPa (0 – 10 km)	Surface to 80 km
Vertical Resolution		0.5 – 1.0 km	0.5 km	< 0.5 km or equivalent in time sampling
Time Resolution		1 - 6 hrs	1 – 6 hrs	1 – 6 hrs
Absolute Accuracy	**0–30 km**	< 1.0 K	<10% or <0.2g/kg (3)	< 1 µrad or 0.4 % (3)
	30–50 km	< 2 K	N/A	< 1 µrad or 0.4 % (3)
Timeliness		2 – 3 hrs	2 – 3 hrs	2 – 3 hrs

Table 6 Generic GRAS requirements for Operational Meteorology

Notes: (1) This would be the mean sampling distance between atmospheric profiles
(2)This assumed 20 to 25 satellites carrying GRAS
(3) which ever is larger

A2.6 Advanced Wind Scatterometer (ASCAT)

The Advanced Wind Scatterometer, ASCAT, is a C-band radar (5.255 GHz) instrument used for global measurement of the sea surface wind vectors. The primary product is the radar backscattering coefficient, which can also be retrieved over land and ice.

The instrument concept uses the antenna geometry of its precursors flying on ERS 1/2 in order to assure continuity to the dataset provided by such satellites (i.e. same model, similar algorithms). This is mainly for the benefit of the Meteorological Services already assimilating the scatterometer products.

The ASCAT will provide backscatter coefficient triplets over two wide swaths of 500 km, positioned at 350 km each side of the Metop spacecraft ground track. The values will be provided on a regular grid (nodes) with an inter-node distance of 25 km (low resolution) and 12.5 km (high resolution). For each node, the backscatter will be measured from three independent viewing directions, oriented at 45, 90 and 135° relative to the ground track. See table below.

ASCAT will be calibrated using an internal calibration unit which monitors the potential variations in the throughput of the instrument as a function of the receiver gain. External calibration using ground transponders and the Amazonian rain forest complement the internal calibration.

Parameter	**Requirement**	**Remarks**
Spatial Resolution	< 50 km	along and across track
Centre Frequency	5.2555 GHz	
Swath Length	Continuous	
Swath Width	2×500 km	
Polarisation	VV	

Table 7 ASCAT characteristics

A3 COMPOSITION OF THE ISSWG AND THE ISUP

Title	**Principal Investigator**	**Affiliation**
Spectroscopic studies in support of IASI	C. Camy-Peyret	Laboratoire de Physique Moléculaire et Application - CNRS, France
Meteorological aspects of studies and simulations for IASI in France	V. Cassé	Météo-France, France
An investigation of methane source regions using EUMETSAT/IASI data	D.M. Cunnold	School of Earth and Atmospheric Sciences, Georgia Tech, U.S.A.
Radial predicting filters and Kriging to recover clear-column from IASI radiances	V. Cuomo	IMAAA - CNR, Italy
NOAA's participation in the preparation of the IASI mission	M.D. Goldberg	NOAA/NESDIS
Simulation and validation of IASI earth radiation budget products and evaluation of their sensitivity to atmospheric conditions	J.D. Haigh	Imperial College, U.K.
The validated GEISA spectroscopic data base as an operational interactive tool for IASI sounding modelling: GEISA/IASI	N. Jacquinet-Husson	Laboratoire de Météorologie Dynamique - CNRS, France
Data assimilation with the IASI instrument for Earth system science	J. Joiner	NASA/Goddard Space Flight Center
Spectral and radiometric calibration for the IASI mission: characterisation and validation	R.O. Knuteson	University of Wisconsin, U.S.A
The use of IASI observations to specify current and future atmospheric state over the Southern Hemisphere - particularly over Australia and Antarctica	J. Le Marshall	Bureau of Meteorology, Australia
Chemistry and climate related studies using the IASI remote sensor	G. Mégie	Service d'Aéronomie - CNRS, France

Table 8 Members of the ISSWG and retained studies

Title	**Principal Investigator**	**Affiliation**
Investigation of optimising the assimilation of IASI data into Numerical Weather Prediction models: the covariance matrices, the interfaces and likely impact	D.R. Pick	Meteorological Office, U.K.
Simulation of IASI radiances in presence of clouds	R. Rizzi	University of Bologna, Italy
Exploitation of IASI data for Numerical Weather Prediction	R.W. Saunders	ECMWF, U.K.
Assessment of IASI data for atmosphere	C. Serio	Università della Basilicata
Retrieval of wind information from IASI data	J.-N. Thépaut	Météo-France, France
IASI: analysis of information content and development of data processing procedures to derive atmospheric minor gaseous constituents vertical profiles and total content	A.B. Uspensky	PLANETA, Russia
AVHRR/HIRS/IASI global cloud mask and cloud property retrieval	R.M. Welch	South Dakota School of Mines and Technology

Table 8 (cont.) Members of the ISSWG and retained studies

Name	**Affiliation**
J.M. Fernandez Serdan	INM, Spain
Y. Fouquart	University of Lille, France
G. Prangsma	KNMI, The Netherlands
B. Ritter	DWD, Germany
W.L. Smith	NASA-GSFC, USA
J. Sunde	DNMI, Norway

Table 9 Members of the ISUP

A4 TERMS OF REFERENCE

A4.1 Terms of reference for the IASI Science Sounding Working Group (ISSWG)

The IASI instrument is part of the core payload of the EUMETSAT Polar System (EPS). The first flight opportunity of the IASI instrument will be the EPS/Metop-1 satellite to be launched 2002 and operated by EUMETSAT. IASI will contribute both to primary mission objectives of the EPS missions in the areas of operational meteorology and climate monitoring and to more research related objectives in the fields of global change and atmospheric chemistry. The objectives of the IASI mission are described in the document "IASI Mission Rationale and Requirements", prepared and approved jointly by EUMETSAT and CNES.

For the scientific preparation of the IASI mission, CNES and EUMETSAT have established the IASI Science Sounding Working Group (ISSWG), following the release of an Announcement of Opportunity in 1995. Principal Investigators of selected proposals are members of the ISSWG which will meet in intervals of typically four months.

One of the primary tasks of this group is the preparation of a Science Plan to detail the scientific work which is needed to meet the IASI mission objectives. This plan will be prepared by the ISSWG, guided by its two chairmen and supported by EUMETSAT and CNES. The Science Plan must especially establish the scientific requirements for the IASI related components of the EPS Ground Segment and for a Technical Expertise Centre at CNES. The plan will be used as reference for scientific activities to be undertaken within and outside of the ISSWG in the coming years.

In particular, the ISSWG should:

- Provide a Science Plan to detail the scientific work which is needed in preparation of the IASI mission, especially also of the EPS Ground Segment and a Technical Expertise Centre at CNES; update this plan when necessary

- Assist EUMETSAT and CNES in the selection of the most suitable methods to be applied for the EPS Ground Segment and a Technical Expertise Centre at CNES

- Advise EUMETSAT and CNES on requirements and methods for instrument calibration and post-launch validation activities

- Advise on the scientific requirements of the IASI system and instrument, taking into account constraints which are imposed by the status of the system and instrument development

- Review the progress and the results of projects initiated under the IASI Announcement of Opportunity; provide recommendations to EUMETSAT and CNES on the direction/focus of the further work to be pursued within these projects

- Provide recommendations for further studies which are needed to supplement these projects in order to fulfil the requirements in the Science Plan; assist in the preparation of work statements and assist in the review of the progress and the results of studies initiated in this context

- Participate in the coordination of the ISSWG activities with external science and user groups

- Participate in technical reviews of the IASI project in order to advise on implications for mission and scientific objectives

- Produce and/or contribute to the production of scientific reports and publications in the framework of the ISSWG activities

A4.2 Terms of reference for the IASI Science and User Panel (ISUP)

EUMETSAT and CNES decided to organise a second group, the IASI Science and User Panel (ISUP), to follow and to contribute to the scientific activities for IASI. This group comprises users and scientists most of which participated on earlier occasions in IASI related activities but are not involved in the work of the ISSWG either as Principal Investigators or as Co-investigators of the retained proposals. To maintain the contact with these users and scientists and to benefit from their expertise the ISUP will be requested to attend the meetings of the ISSWG once a year and to provide their recommendations and observations to the ISSWG, EUMETSAT and CNES. The chairmen of the ISSWG are also members of the ISUP to ensure close coordination between both groups.

In particular, the ISUP should:

- Comment on the contents of the Science Plan as prepared by the ISSWG

- Assist the ISSWG, EUMETSAT and CNES in the selection of the most suitable processing methods to be implemented in the EPS Ground Segment and in a Technical Expertise Centre at CNES

- Assist the ISSWG, EUMETSAT and CNES in the identification of requirements and methods for instrument calibration and post-launch validation activities

- Advise on the scientific requirements of the IASI system and instrument, taking into account constraints which are imposed by the status of the system and instrument development

- Review the progress of projects initiated under the IASI Announcement of Opportunity and of potential supplementary studies and follow the activities of the ISSWG; provide recommendations to the ISSWG, EUMETSAT and CNES on the direction/focus of the further work to be pursued within these projects and the ISSWG

- Provide recommendations for further studies which are needed to supplement these projects in order to fulfil the requirements in the Science Plan and assist in the preparation of work statements

- Support the coordination of the ISSWG activities with external science and user groups

A5 ACRONYMS

3-D	Three-Dimensional
3-D VAR	Three-Dimensional Variational Analysis
3R	A Library Look-Up Model
4A	A Line-By-Line Model
4-D	Four-Dimensional
4-D VAR	Four-Dimensional Variational Analysis
AA	Anti-Aliasing
AATSR	Advanced Along-Track Scanning Radiometer
ADC	Analog to Digital Converter
AFGL	Air Force Geophysics Laboratory
AIRS	Atmospheric Infrared Sounder
ALE	Atmospheric Lifetime Experiment
ALE/GAGE	ALE/Global Atmospheric Gases Experiment
AMSR	Advanced Microwave Scanning Radiometer
AMSU	Advanced Microwave Sounding Unit
AMSU-A	AMSU unit A
AMSU-B	AMSU unit B
AO	Announcement of Opportunity
ARIES	Australian Resource Information and Environment Satellite
ARM	Atmospheric Radiation Measurement Program
ASCAT	Advanced Wind Scatterometer
ASI	Agenzia Spaziale Italiana
ATMOS	Atmospheric Trace Molecules Observed by Spectroscopy
ATOVS	Advanced TIROS Optical Vertical Sounder
ATSR	Along Track Scanning Radiometer
AVHRR	Advanced Very High Resolution Radiometer
CCD	Charge Coupled Device
CCSDS	Consultative Committee for Space Data Systems
CFC	Chlorofluorocarbon
CHEM-1	EOS Chemistry Platform
CIMO	Commission for Instruments and Methods of Observation
CMDL	Climate Monitoring and Diagnostics Laboratory
CMS	Le Centre de Météorologie Spatiale
CNES	Centre National d'Etudes Spatiale
CNR	Consiglio Nazionale delle Ricerche
CNRS	Centre National de la Recherche Scientifique
COSPAR	Committee on Space Research
CTM	Chemistry/Transport Models
DC	Direct Current
DCS	Data Collection System
DNMI	Det Norske Meteorologiske Institutt
DOAS	Differential Optical Absorption Spectroscopy
DWD	Deutsche Wetterdienst
ECMWF	European Centre for Medium-Range Weather Forecasts
ENVISAT	Environmental Satellite
EOS	Earth Observation System

EPS	EUMETSAT Polar System
ER-2	Extended Range U-2 (aircraft)
ERA	ECMWF Re-Analysis Project
ERB	Earth Radiation Budget
ERBE	Earth Radiation Budget Experiment
ERS-1	European Remote-Sensing Satellite-1
ERS-2	European Remote-Sensing Satellite-2
ESA	European Space Agency
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
FAA	Federal Aviation Administration
FASCODE	Fast Atmospheric Signature Code
FWHM	Full Width at Half Maximum
GCM	General Circulation Model
GCOS	Global Climate Observing System
GEISA	Gestion et d'Etude des Information Spectroscopiques Atmosphériques
GENLN2	General Line-by-Line Atmospheric Transmittance and Radiance Model
GNSS	Global Navigation Satellite System
GOES	Geostationary Operational Environmental Satellite
GOES-IR	GOES Infrared
GOME	Global Ozone Monitoring Experiment
GOME-2	Global Ozone Monitoring Experiment - 2
GOMOS	Global Ozone Monitoring by Occultation of Stars
GPS	Global Position System
GPS/MET	GPS Meteorology
GRAS	GNSS Receiver Atmospheric Sounder
GSFC	Goddard Space Flight Center
GSFC/DAO	GSFC Data Assimilation Office
HALOE	Halogen Occultation Experiment
HARTCODE	A Line-By-Line Model
HCFC	hydrochlorofluorocarbon
HIRS	High Resolution Infrared Radiation Sounder
HIS	High Resolution Interferometer Sounder
HITRAN	High Resolution Transmittance Model
HRDLS	High Resolution Dynamics Limb Scanner
HRPT	High Resolution Picture Transmission
IASI	Infrared Atmospheric Sounding Interferometer
IFOV	Instantaneous Field of View
IGAC	International Global Atmosphere Chemistry
ILAS	Improved Limb Atmospheric Spectrometer
ILSCP	International Land Surface Climatology Project
IMAAA	Istituto di Metodologie Avanzate di Analisi Ambientale
IMG	Interferometric Monitor of Greenhouse gases
INM	Instituto Nacional De Meteorologia
IPCC	Intergovernmental Panel on Climate Change
IPSF	Instrument Point Spread Function
ISAMS	Improved Stratospheric and Mesospheric Sounder
ISCCP	International Satellite Cloud Climatology Project
ISRF	Instrument Spectral Response Function
ISSWG	IASI Sounding Science Working Group
ISUP	IASI Science and User Panel

kCARTA	kCompressed Atmospheric Radiative Transfer Algorithm
KNMI	Koninklijk Nederlands Meteorologisch Instituut
LBL	Line-By-Line
LBLRTM	Line-By-Line Radiative Transfer Model
LEO	Low Earth Orbiting
LMD	Laboratoire de Météorologie Dynamique
LOWTRAN	Low Resolution Transmittance Model
LPMA	Laboratoire de Physique Moléculaire et Applications
LRPT	Low Rate Picture Transmission
LW	Longwave
MCT	Mercury Cadmium Telluride
MERIS	Medium Resolution Imaging Spectrometer
Metop	Meteorological Operational satellite
MHS	Microwave Humidity Sounder
MIPAS	Michelson Interferometric Passive Atmosphere Sounder
MLS	Microwave Limb Sounder
MODIS	Moderate Resolution Imaging Spectroradiometer
MODTRAN	Moderate Resolution Atmospheric Transmittance Model
MOPITT	Measurements of Pollution in the Troposphere
MSG	Meteosat Second Generation
NASA	National Aeronautics and Space Administration
NCAR	National Center for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NDSC	Network for the Detection of Stratospheric Change
NEΔR	Noise Equivalent Radiance
NEΔT	Noise Equivalent Temperature
NESDIS	National Environmental Satellite, Data and Information Service
NIMBUS	NASA Meteorological Satellites
NMS	National Meteorological Services
NOAA	National Oceanic and Atmospheric Administration
NOAA-KLM	NOAA-K, NOAA-L and NOAA-M Spacecraft
NSF	National Science Foundation
NWP	Numerical Weather Prediction
OCTS	Japanese Ocean Colour Temperature Scanner
OLR	Outgoing Longwave Radiation
OPD	Optical Path Difference
OPTRAN	Optical Path Transmittance
OSSE	Observing System Simulation Experiments
PI	Principal Investigator
PLOD	A Radiative Transfer Model
POLDER	Polarisation and Directionality of Reflectances
PPMV	Parts Per Million by Volume
PSC	Polar Stratospheric Cloud
RT	Radiative Transfer
RTM	Radiative Transfer Model
RTTOV	Radiative Transfer Model for TOVS
SAGE	Stratospheric Aerosol and Gas Experiment
SAGE-2	Stratospheric Aerosol and Gas Experiment-2
SAGE-3	Stratospheric Aerosol and Gas Experiment-3
SBUV	Solar Backscatter Ultraviolet Radiometer

ScaRaB	Scanner for Radiation Budget
SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Chartography
SSM/I	Special Sensor Microwave/Imager
SST	Sea Surface Temperature
SW	Shortwave
TBC	To Be Confirmed / Completed
TBD	To Be Decided
TEC	Technical Expertise Centre
TES	Tropospheric Emission Spectrometer
TIGR	Thermodynamical Initial Guess Retrieval
TIROS	Television Infrared Observing Satellite
TOA	Top Of the Atmosphere
TOMS	Total Ozone Mapping Spectrometer
TOVS	TIROS Operational Vertical Sounder
UARS	Upper Atmosphere Research Satellite
UCAR	University Cooperation for Atmospheric Research
UKMO	United Kingdom Meteorological Office
UV	Ultraviolet
VIRI	Visible and Infrared Imager
WMO	World Meteorological Organization
WV	Water Vapour
WWW	World Weather Watch
ZPD	Zero Optical Path Difference

A6 REFERENCES

Berk, A., L.S. Bernstein, and D.C. Robertson, 1989, "MODTRAN: A Moderate Resolution Model for LOWTRAN 7", Air Force Geophysics Laboratory, Technical Report, F19628-86-C-0079, Hanscom AFB, MA, USA.

Camy-Peyret, C., P. Jeseck, T. Hawat, G. Durry, S. Payan, G. Berubé, L. Rochette and D. Huguenin, 1995, "The LPMA balloon-borne spectrometer for remotes sensing of atmospheric constituents", ESA Publications, SP-370, 232-328

CEOS, 1992, "The relevance of satellite missions to the study of the global environment", UNCED Conference, Rio de Janiero, 1992.

CEOS, 1995, "Committee for Earth Observation Satellites: Manual of the CEOS database on user requirements and space capabilities", Version 1.1, September 1995.

CEOS, 1997, "Towards an integrated global observing strategy (1997 CEOS Yearbook)", ESA.

Chazette P., C. Clerbaux, and G. Megie, 1998, "Direct estimate of the methane radiative forcing using nadir spectral radiances", *Appl. Optics*, **37** (15), 3113-3120.

Chedin, A., N. A. Scott, C. Wahiche, P. Moulineier, 1985, "The Improved Initialization Inversion Method: A high resolution physical method for temperature retrievals from satellites of the TIROS-N series", *Journal of Climate and Applied Meteorology*, **24**, 128-143.

Clough, S.A., J.L. Moncet, R.D. Worsham, M.J. Iacono, and A. Bianco, 1991, "Radiative transfer model development in support of the Atmospheric Radiation Measurement (ARM) Program", *Proceedings of the Second Atmospheric Radiation Measurement (ARM) Science Team Meeting*, CONF-9110336, U.S. Department of Energy, Washington, D.C., pp 21-24 .

CNES, 1996, "Data processing algorithms in IASI on-board and Ground Segment ",IA-TN-0000-5482-CNE", CNES.

CNES, 1996a, "IASI level 1 data", IA-TN-0000-5479-CNE, CNES.

CNES, 1998, "IASI instrument specification, IA-SP-1000-201-CNE", CNES.

CNES, 1998a, Internal Communication.

CNES/EUMETSAT, 1995 "Announcement of Opportunity: Preparation of the IASI mission on the EUMETSAT Polar System", EPS/IAS/DOC/95097.

CNES/EUMETSAT, 1996, "IASI mission rationale and requirements, IA-SM-0000-10-CNE/EUM".

DOE, 1996, “Science Plan for the Atmospheric Radiation Measurement (ARM) Program”, U.S. Department of Energy, Washington, D.C., DOE/ER-0670.

Edwards, D.P., 1982, “A general Line-By-Line atmospheric transmittance and radiance model”, *NCAR Technical Note NCAR/TN-367+STR*.

ESA, 1996, “ESA SP-1196(6), Atmospheric Chemistry Mission”.

ESA, 1996a, “the nine candidate earth explorer missions: reports for assessment (April 1996): VOL. 3: Earth radiation mission”, ESA SP-1196.

Eyre J.R.,1991, “A fast radiative transfer model for satellite sounding systems”, ECMWF Research Dept.Tech. Memo. 176, (available from the librarian at ECMWF).

Fischer, H., and H. Oelhaf, 1996, “Remote sensing of vertical profiles of atmospheric trace constituents with MIPAS limb-emission spectrometers”, *Appl. Opt*., **35**, 2787-2796.

Francis, P.N., A. Jones, R.W. Saunders, K.P. Shine, A. Slingo and Z. Sun, 1994, “An observational and theoretical study of the radiative properties of cirrus: Some results from ICE'89'”, *Quart. J. Roy. Meteorol. Soc*., **120,** 809-848.

Goodrum, G., K.B. Kidwell and W. Winston (eds.), 1998, “NOAA KLM User's Guide”, National Climatic Data Center, National Oceanic and Atmospheric Administration, U.S. Department of Commerce.

Hannon, S., L. Strow and W.W. Mc Millan, 1996, “Atmospheric Infrared Fast Transmittance models: a comparison of two approaches”, Proceedings of SPIE Conference 2830, Optical Spectroscopic Techniques and Instrumentation for Atmospheric and Space Research 2.

Husson, N., Bonnet, B., Chedin, A., Scott, N.A., 1992, “Management and study of spectroscopic information: the GEISA program. ”, *JQSRT*, **48**, 509-518.

IGAC, 1998, “International Global Atmosphere Chemistry Home Page”, [Online] Available http://web.mit.edu/igac/www/.

IPCC, 1996, “Climate Change 1995. The Science of Climate Change. Contribution of Working Group 1 to the 2nd assessment report of the Intergovernment Panel on Climate Change”, Cambridge Univ. Press.

Jacquinet-Husson, N, N.A. Scott, A. Chedin, B. Bonnet, A. Barbe, VL. G. Tyuterev, J.P Champion, M. Winnewisser, L.R. Brown, R. Gamache, V.F. Golovkom and A.A.Chursin, 1998, “The GEISA system in 1996: Towards an operational tool for the second generation vertical sounders radiance simulation”, *J. Quant. Spectrosc. Radiat. Transfer* Vol 59, Nos 3-5, pp 511-527.

Kaplan L.D., M.T Chahine, J. Susskind and J.E. Searl, 1977, “Spectral band passes for a high precision satellite sounder”, *Appl. Opt*., **16**, 322-325.

Klaes, D., 1997, " ATOVS data processing in Europe", *Tech. Proc. 9th. Intl. TOVS Study Conf.*, Igls, Austria 20-26 February 1997, pp267 - 274.

Kneizys, F.X. E.P. Shettle, L.W. Abreu, J.H. Chetwynd, G.P. Anderson, W.O. Gellery, J.E.A. Selby and S.A. Clough, 1988, " Users Guide to LOWTRAN 7", Air Force Geophysics Laboratory, Report AFGL-TR-88-0177, (NTIS AD A206773), Hanscom AFB, MA , USA.

Knuteson, R.O., 1997, Internal Communication.

McMillin L.M., L.J. Crone and T.J. Kleespies, 1995, "Atmospheric transmittance of an absorbing gas. 5. Improvements to the OPTRAN approach.", *Appl. Optics* **34**, pp 8396-8399.

Megie, G., *et al.*, 1995, "ESA Review on scientific priorities for an atmospheric chemistry mission for the year 2002 and beyond".

Miskolczi F., R. Rizzi, R. Guzzi, M.M. Bonzagni, 1988, "A new high resolution atmospheric transmittance code and its application in the field of remote sensing", in *Proceedings of IRS 88: Current problems in atmospheric radiation*, Lille 18 -24 August 1988, pp 388-391.

Prunet, P., J.-N. Thépaut, and V. Cassé, 1998, "The information content of clear sky IASI radiances and their potential for numerical weather prediction", *Q. J. R. Meteorol. Soc.*, **124**, 211-241.

Rothman, L.S., Gamache, R.R., Tipping, R.H., Rinsland, C.P., Smith, M.A.H., Chris Benner, D., Malathy Devi, V., Flaud, J.-M., Camy-Peyret, C., Perrin, A., Goldman, A., Massie, S.T., Brown, L.R. and Toth, R.A., 1992,"The HITRAN molecular database: Editions of 1991 and 1992. ", *JQSRT*, **48**, 469-507.

Rothman, L.S., R.R. Gamache, A. Barbe, A. Goldman, J.R. Gillis, L.R. Brown, R.A. Toth, J.-M. Flaud and C. Camy-Peyret, 1983, "AFGL atmospheric absorption line parameters compilation: 1982 Edition", *Appl. Opt*. **22**, 2247-2256.

Rothman, L.S., Rinsland, C.P., Goldman, A., Massie, S.T., Flaud, J-M., Perrin, A., Dana, V., Mandin, J.-Y., Schroeder, J., Mc Cann, A., Gamache, R.R., Wattson, R.B., Yoshino, K., Chance, K., Jucks, K., Brown, L.R. and Varanasi, P., 1997, "The HITRAN molecular spectroscopic database and HAWKS (HITRAN Atmospheric Workstation) " , *JQSRT*, submitted for publication.

Serio, C., 1998, Internal Communication

Smith, H.J.P., D.J. Dube, M.E. Gardner, S.A. Clough, F.X. Kneizys, and L.S. Rothman, 1978, "FASCODE- Fast Atmospheric Signature Code (Spectral Transmittance and Radiance)", Air Force Geophysics Laboratory, Technical Report AFGL-TR-78-0081, Hanscom AFB, MA, USA.

Tournier, B. and Ph. Hebert, 1996," IASI Modele numerique de performance niveau 0", Documentation projet IASI, IA-TN-0000P-5553-CNE

WMO, 1995 “Plan for space-based observations”, Global Climate Observing System, GCOS-15, WMO/TD-No. 684.

WMO, 1995a, “World Meteorological Organization, Scientific assessment of ozone depletion”, Global Ozone Research and Monitoring Project, Report n° **37**.

A7 ISSWG BIBLIOGRAPHY

Derber, J.C. and W. Wu, 1998, "The Use of TOVS Cloud-Cleared Radiances in the NCEP SSI Analysis System", *Monthly Weather Review* , **126**, pp2287-2299

Amato, U., and Serio, C., 1996, "Impact of random noise on the performance of the new IASI configuration", *Int. J. Rem. Sens.* , Vol. 18, No. 15, 3135-3143.

Amato, U., Cuomo, V., Rizzi, R., and Serio, C., 1997, "Evaluating the effect of the inter-relationship among the different spectral bands on IASI performances", *Quarterly J. R. Met. Soc.,* Vol. 4, 2231-2244.

Amato, U., D. De Canditiis and C. Serio, 1998, "A new quasi-analytical method for evaluating the coefficients of a linearized R.T.E. model", *SPIE*, **3220**, 148-155.

Amato, U., De Feis, I., and Serio, C., 1996, "Linearization Pseudo-Noise and its Effect on the Retrieval of Atmospheric State from Infrared Spectral Radiances", *Geophys. Res. Lett*. Vol. 23, pp. 2565-2568.

Amato, U., I. De Feis and C. Serio, 1998, "Retrieval of temperature vertical profile from radiance spectra by the inversion of radiative transfer equation", *SPIE*, **3220**, 186-196.

Chazette P., C. Clerbaux, and G. Megie, 1998, "Direct estimate of the methane radiative forcing using nadir spectral radiances", *Appl. Optics*, **37** (15), 3113-3120.

Chu, P.M., S.J. Wetzel, W.J. Lafferty, A. Perrin, J.-M. Flaud, Ph. Arcas and G. Guelachvili, "Line intensities for the 8 µm of SO_2", *J. Mol. Spectrosc*., **189**, 55-63

Chursi, A.A., V.F. Golovko, Vl. G. Tyuterev, N. Jacquinet-Husson, B. Bonnet, N.A. Scott, 1997, "The GEISA-PC software in 1996. Innovations towards the atmospheric optics needs", *Proc. of the 12th International Symposium and School on High Resolution Molecular Spectroscopy*, St Petersburg,, Russie, 1-5 July1996, *Proceedings of SPIE*, **3090**, pp338-343.

Chursin, A.A., V.F. Golovko, A;V.Nikitin, N. Jacquinet-Husson, B. Bonnet, N.A. Scott, and Vl.G. Tyuterev, 1997, "The GEISA-PC software packages for large-scaled spectroscopic data basees management: Current status and perspectives", *Proc. of the first East-European Symposium on Advances in Databases and Information Systems*, St. Petersbourg, Russie, 2-5 September 1997, Vol. 2, pp 70-73.

Chursin, A.A., V.F. Golovko, Vl.G. Tyuterev, N. Husson, B. Bonnet, A. Chedin,N.A. Scott, 1995, "The software package for managing large-scaled spectroscopic databases and its atmospheric applications. GEISA based PC/AT compatible computers version ", *Workshop on Advances in Databases and Information Systems*, vol.2, Phasis Publishing House, Moscow, June 27-30 1995, pp. 9-11.

Clerbaux, C., P. Chazette and G. Megie, 1995, "Tropospheric concentrations of infrared absorbing molecules using a nadir-looking Fourier transform spectrometer", Passive Infrared Remote Sensing of Clouds and the Atmosphere III, SPIE Proceedings Series, **2578**, 148-153.

Cunnold, D.M., H. Wang, W. Chu, and L. Froidevaux, 1997, "Comparisons between SAGE II and MLS ozone measuremnets and aliasing of SAGE II ozone trends in the lower stratosphere", *J. Geophys. Res.*, **101** (D6), 10,061 – 10,075.

Cunnold, D.M., L. Froidevaux, J. Russell, B. Connor and A. Roche, 1996, "An overview of UARS ozone validation based primarily on intercomparisons among UARS and SAGE II measuremnets", *J. Geophys. Res*, **101**(D6), 10,335-10,350.

Cunnold, D.M., R. Weiss, R.G. Prinn, D. hartley, P.G. Simmonds, P.J. Fraser, B. Miller, F.N. Alyea and L. Porter, 1997, "GAGE/AGAGE measurements indicating reductions in global emissions of CCl_3F and CCl_2F_2 in 1992 – 1994", *J. Geophys. Res.*, **102**, 1259-1269.

Gamache, R.R., E. Arié, C. Boursier and J.-M. Hartmann, 1998, "Pressure-broadening and pressure-shifting of spectral lines of ozone", *Spectrochim. Acta*, **A54**, 35-63.

Haigh, J.D. (Ed), 1998, "Satellite remote sensing of clouds and the atmosphere II.", *Proc. SPIE* **3220.**

Hartley, D., T. Kindler, R. Prinn and D. Cunnold, 1996, "Evaluating chemical transport models: Comparison of effects of difference CFC-11 emission scenarios", 1996, *J. Geophys. Res.*, **101**, 14,381 – 14,386.

Hartmann, J.-M., J.-M. Kochel, S. Payan, C. Camy-Peyret and A. Engel, 1997, "CCl_2F_2 mixing ratio profiles in the 1995 late winter arctic vortex from balloon-borne spectra.", *Geophys. Res. Lett.,* **24**, 2367-2370.

Jacquinet-Husson, N., N.A. Scott, A. Chedin, B. Bonnet, A. Barbe, Vl.G., Tyuterev, J.P. Champion, M. Winnewisser, L.R. Brown, R. Gamache, V.F. Golovko and A.A. Chursin, 1997, "The validated GEISA spectroscopic database as an operational interactive tool for IASI sounding modeling:GEISA/IASI", *International Radiation Symposium, " Current Problems in Atmospheric Radiation "*, Fairbanks, Alaska, USA, 19-24 August 1996. A. Deepak Publishing, W.L.Smith and K. Stamnes Eds. pp 993-996.

Jacquinet-Husson, N., E. Arié, J. Ballard, A. Barbe, G. Bjoraker, B. Bonnet, L.R. Brown, C. Camy-Peyret, J.P. Champion, A. Chédin, A. Chursin, C. Clerbaux, G. Duxbury, J.-M. Flaud, N. Fourrié, A. Fayt, G. Graner, R. Gamache, A. Goldman, Vl. Golovko, G. Guelachvilli, J.-M. Hartmann, J.C. Hilico, J. Hillman, G. Lefèvre, E. Lellouch, S.N. Mikhanlenko, O.V. Naumenko, V. Nemtchinov, D.A. Newnham, A. Nikitin, J. Orphal, A. Perrin, D.C. Reuter, C.P. Rinsland, L. Rosenmann, L.S. Rothman, N.A. Scott, J. Selby, L.N. Sinitsa, J.M. Sirota, A.M. Smith, K.M. Smith, Vl.G. Tyuterev, R.H. Tipping, S. Urban, P. Varanasi and M. Weber, 1998, "The 1997 spectroscopic GEISA databank", *J. Quant. Spectrosc. Radiat. Trans,* accepted for publication.

Jacquinet-Husson, N., N.A. Scott, A. Chedin, B. Bonnet, A. Barbe, Vl.G., Tyuterev, J.P. Champion, M. Winnewisser, L.R. Brown, R. Gamache, V.F. Golovko and A.A. Chursin, 1998, "The GEISA system1996: towards an operational tool for the second generation vertical sounders radiance simulations", *JSQRT*, **59**, 511-527.

Joiner, J., "Investigation of systematic errors and correction models", *Tech. Proc. 9th Intl. TOVS Study Conf.*, Igls, Austria, 207-216.

Kochel, J.-M., J.-M. Hartmann, C. Camy-Peyret, R. Rodrigues and S. Payan, 1997, "Influence of line-mixing on absorption by CO_2 Q-branches in atmospheric balloon-borne spectra near 13 µm", *J. Geophys. Res.*, **102**, 12891-12899.

Lafferty, W.J., A.M. Solodov, A. Weber, W.B. Olson and J.-M. Hartmann, 1996, "Infrared collision-induced absorption by N_2 near 4.3 µm for atmospheric applications: Measurements and empirical modeling", *App. Opt.*, **35**, 5911-5917.

Matricardi, M. and R. Saunders, 1998, "A fast radiative transfer model for IASI", *Proceedings of the 9th Conference on Satellite Meteorology and Oceanography*, 25-29 May 1998, Paris. Vol. 2. pp 701-705.

McMillin, L.M., M.D. Goldberg, H. Ding, J. Susskind and C.D. Barnet, 1998, "Forward calculation for interferometers: method and validation", *Appl. Opt.*, **37**, No. 14, p3059-3068.

Perrin, A., J.-M. Flaud, C. Camy-Peyret, D. Hurtmans and M. Herman, 1996, "The {2?$_3$, 4?$_2$, 2?$_2$+?$_3$} and 2?$_3$-?$_3$ bands of $^{14}N^{16}O_2$: line positions and intensities", *J. Mol. Spectrosc.*, **177**, 58-65.

Prunet, P., J.-N. Thépaut, and V. Cassé, 1998, "The information content of clear sky IASI radiances and their potential for numerical weather prediction", *Q. J. R. Meteorol. Soc.*, **124**, 211-241.

Rodrigues, R. and J.-M. Hartmann, 1997, "Simple modelling of the temperature dependence of first-order line-mixing coefficients $Y_1(T)$.", *J. Quant. Spectrosc. Radiat. Trans.*, **57**, 63–73.

Rodrigues, R., B. Kohli, R. Le Doucen, L. Bonamy and J.-M. Hartmann, 1997, "Temperature, pressure and perturber dependencies of line-mixing effects in CO_2 infrared spectra. I. S? ? Q-branches.", *J. Chem Phys.*, **107**, 4118 – 4132.

Rodrigues, R., G. Blanquet, J. Walrand, B, Khali, R. Le Doucen, F. Thibault and J.-M. hartmann, "Line-mixing effects in Q-branches of CO_2. I. Influence of parity in ? - ? bands.", *J. Mol. Spectrosc.*, **186**, 256-268.

Russell J.E., R.J. Bantges, J.D. Haigh, W.L. Smith and H.E. Revercomb, 1998, "Retrieval of cirrus properties from high spectral resolution IR measurements", *Proc. SPIE*, **3220**, 60-71.

Russell, J.E. and J.D. Haigh, 1996, "Retrieval of cirrus cloud temperature and optical depth using the Along-Track Scanning Radiometer", *Proc.SPIE*, **2961**, 2-11.

Strow, L., D.C. Tobin, W.W. McMillan, S.E.Hannon, W.L. Smith, H.E. Revercomb, and R. Kneuteson, 1997, "Impact of a new water vapor continuum and line shape model on observed high resolution infrared radiances", *J. Quant. Spectrosc. Radiat. Trans*., **59**, 303-317.

Strow, L., H.E. Motteler, R.G. Benson, S.E. Hannon, and S.D. Souza-Machado, 1997, " Fast computation of monochromatic infrared atmospheric transmittances using compressed look-up tables", *J. Quant. Spectrosc. Radiat. Trans*., **59**, 481-493.

Thibault, F., V. Menoux, R. Le Doucen, L. Rosenmann, J.-M. Hartmann and C. Boulet., 1997, "Infrared collision induced absorption by O_2 near 6.4 µm for atmospheric applications: Measurements and empirical modeling", *Appl. Opt*., **36,** 1-5

Trotsenko A.N., A.V. Kopylov, A.B.Uspensky, 1998, "Fast radiative transfer model based on the line-by-line calculation look-up tables", *Proc. of the 9th Conf. on Sat. Meteor. and Oceanogr*., v.2. AMS 45 Beacon Street, Boston Mass. USA, 02108-3693. 25-29 May, 1998, pp.686-689.

Uspensky, A.B., A.N. Trotsenko, A.N. Rublev, et al.,1998, " Determination of column amounts of the atmospheric minor gas content using IASI IR-sounder. I. Information content analyses", *Journal of Earth Research from Space,* Russian Academy of Sciences, **2**, pp3-16. (in Russian).

Uspensky, A.B., A.N. Trotsenko, A.N. Rublev, et al.,1998, "Information content and retrieval error analysis for remote sensing of atmospheric trace gases column amounts by IASI", *Proc. of the 9th Conf. on Sat. Meteor. and Oceanogr*., v.2. AMS 45 Beacon Street, Boston Mass. USA, 02108-3693. 25-29 May, 1998, pp.591-593.

Valentin, A., F. Rachet, A.D. Bykov, N.N. Lavrentieva, V.N. Saveliev and L.N. Sinitsa, 1998, "J-dependence of the lineshift corefficients in the $?_2$ water vapor band.", *J. Quant. Spectrosc. Radiat. Trans*., **59**, 165-170.

Wang, H.J., D.M. Cunnold and X. Bao, 1996, "A critical analysis of SAGE ozone trends", *J. Geophys. Res*, **101**(D7), 12,495 – 12,514.

Zhong, W. and J.D. Haigh, 1995, "Improved broadband emissivity parameterization for water vapor cooling rate calculations", *J.Atmos.Sci*., **52**, 124-138.

Zhong, W., R. Toumi and J.D. Haigh, 1998, "Reply to Comments on "Climate forcing by stratospheric ozone depletion calculated from observed temperature trends" by K P Shine, R S Freckleton and P M deF Forster", *Geophys.Res.Lett.*, **25**, 665.

Zhong. W., R. Toumi and J.D. Haigh, 1996, "Climate forcing by stratospheric ozone depletion calculated from observed temperature trends", *Geophys.Res.Lett.*, **23**, 3183-3186.

A8 INTERNET RESOURCES

A8.1 EPS mission

EUMETSAT Polar System (EPS)
http://www.eumetsat.de/en/area4/topic2.html

Infrared Atmospheric Sounding Interferometer (IASI)
http://earth-sciences.cnes.fr:8060/iasi/Mission.html

ATOVS and AVHRR Processing Package (AAPP)
http://www.eumetsat.de/en/area4/aapp/index.html

National Oceanic and Atmospheric Administration (NOAA)
http://www.noaa.gov/

A8.2 ISSWG related activities

LBL intercomparison exercise
Data for the LBL intercomparison exercise can be found at:

ftp://atmos20.df.unibo.it
user name: anonymous
password: username or group identifier

Please inform the contact if you upload data.

Contact: R. Rizzi (rrizzi@atmos20.df.unibo.it)

Retrievals intercomparison exercise
Data for the retrievals intercomparison exercise can be found at:

ftp://cnrm-ftp.meteo.fr/pub-ext/prunet/IASI-EXP/
user name: anonymous
password: your e-mail address

The directory INPUT contains the input files.
The directory OUTPUT is dedicated to receive output files.

Please inform the contacts if you upload data.

Contact: Vincent Cassé(vincent.casse@meteo.fr) or Pascal Prunet (pascal.prunet@meteo.fr)

ISRF and radiative transfer subroutines

Software for the parametric representation of the IASI ISRF and for computing CO_2 line interference effects, as well as O_2 and N_2 collision induced spectra, are available from LPMA/CNRS at:

ftp://batz.lpma.u-psud.fr/pub/
user name: anonymous
password: your e-mail address

Check the Read.Me file for information. The software is located in the ISRF, CO2, N2 and O2 subdirectories.

Contact: Claude Camy-Peyret (camy@ccr.jussieu.fr)

CO Mixing ratio profiles

A collection of representative tropospheric mixing ratio profiles for CO and descriptions of their geographical location for each month are available at:

ftp://ftp.aero.jussieu.fr/pub/data/ISSWG
user name: anonymous
password: your e-mail address

Note: Files should be transferred in ASCII format.

Contact: Cathy Clerbaux (catherine.clerbaux@aero.jussieu.fr)

RTIASI

The code to RTIASI, the fast RTM developed by the ECMWF group will be made available via FTP. Please ask the contact for further information on how to access the FTP server.

Contact: Roger Saunders (sto@ecmwf.int)

Fast RTM

The software for the fast RTM developed by the Planeta-Roshydromet/Kurchatov Institute group will be accessible via the web site:

http://www.imp.kiae.ru/projects/iasi/

Contact: Alexander Uspensky (uspensky@imp.kiae.ru)

GEISA

GEISA97 description files and general information are available from:

ftp://ara01.polytechnique.fr/pub/libgeisa

user name: anonymous
password: your e-mail address

The current version of the GEISA data bank is available for download. Users should register at:

http://ara01.polytechnique.fr/registration
user name: registerme
password: [none]

Once registered, you will then have access to online tools that will allow you to extract the required sections of the GEISA database using the associated GEISA management software.

Contact: Nicole Jacquinet-Husson (husson@ara01.polytechnique.fr)

kCARTA

The most recently released version of the kCompressed Atmospheric Radiative Transfer Algorithm (kCARTA) code is available via:

ftp:// kale.umbc.edu/pub/kcarta
user name: anonymous
password: your e-mail address

The kCompressed database is available on CD-ROM. Requests should include the target machine so that you can be sent the correct big/little endian format for your system.

Future changes to the database and kCARTA code are detailed at:

http://asl.umbc.edu/kcarta/kcarta.html

Contact: Larrabee Strow (strow@umbc.edu)

A8.3 Other infrared instruments

Atmospheric Infrared Sounder (AIRS)

http://www-airs.jpl.nasa.gov/

High Resolution Interferometer Sounder (HIS)

http://cimss.ssec.wisc.edu/his/hishome.html

Interferometric Monitor of Greenhouse gases (IMG)

http://img.ersdac.or.jp