Justification Study for a Built-in Imager for the MTG IR Sounding Mission

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William L. Smith, Principal Investigator

H-L. Allen Huang, co-Investigator

Hyperspectral Infrared Sciences (HIS)
Seaford Virginia, 23696

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1.0 Overview

Hyperspectral infrared sounding instruments are providing a revolutionary advance in atmospheric sounding capability as a result of their improved vertical resolution (17). The assimilation of clear-sky radiances from the Aqua Advanced InfraRed Sounder (AIRS) has shown a significant positive impact on the accuracy of global Numerical Weather Prediction, NWP (9). The application of hyperspectral resolution technology to geostationary satellites will permit measurements of vertical wind profiles needed for global NWP, and permit revolutionary advances in nowcasting the development of convective storms, through the observation of water vapor convergence occurring prior to the onset of severe convection (19). The wind profile storm steering observations provided by the geostationary hyperspectral resolution sounder will permit more accurate prediction of the landfall position of tropical storms and hurricanes (20). High spectral and spatial resolution geostationary sounder radiance spectra also permit the observation of chemical pollution episodes and pollutant gas transport as needed for air quality forecasting. Thus, the InfraRed Sounder (IRS) planned for the MTG will advance global and regional weather and air chemistry forecasting.

This is a final report of a study conducted to provide the basis for determining the advantages of using data from a built-in, or companion, imager in the processing of the hyperspectral radiances from the IRS for accomplishing the sounding objectives of the MTG mission. Results are provided for EUMETSAT to make a decision as to whether it is desirable, and/or necessary, to have a built-in imager, or alternatively a separate and independently operated imager, to assist with the interpretation of the IRS data. Since infrared sounding data are affected by cloud(s), the imager data would enable cloud contamination to be detected and their effect on the sounding radiances to be alleviated during the sounding retrieval, or radiance data assimilation, process. Unlike polar orbiting sounding data where the primary use of the observations is to add to the mix of temperature and moisture sounding observations used to initialize global NWP models, the geostationary hyperspectral resolution sounder must observe dynamical features of the atmosphere, such as moisture flux and winds, as well as the transport of pollutants, such as tropospheric dust and toxic trace gases (e.g., ozone and carbon monoxide). In the case of the polar orbiting data, radiance or sounding data, containing errors due to cloud contamination, can be discarded since there is an abundance of spectral and horizontal samples available to select from for the global, relatively low horizontal resolution, NWP model initialization process. However, in order for the geostationary sounder to observe atmospheric dynamical features, spectral radiance measurements with high horizontal resolution and density and high spectral (i.e., vertical) resolution and fidelity are required. These requirements must be met to achieve time and space continuity in the observations of the atmospheric radiance and soundings.

The results of this study illustrate the usefulness of data from a high horizontal resolution imager to support the analysis of the IRS hyperspectral radiance measurements. The most fundamental reason for having an imager is to provide the high horizontal resolution multi-spectral radiance data needed to process the IRS measurements under partly cloudy sky conditions. As a result, the need for the use of imager data is closely associated with the spatial resolution of the sounding instrument, the need increasing with decreasing horizontal resolution of the sounding instrument. Specifications for the imager, in terms of horizontal resolution and spectral channel...
coverage, are developed from scientific studies conducted using actual aircraft and satellite data (i.e., high altitude aircraft NPOESS Airborne Sounder Testbed – Interferometer, NAST-I, and Aqua satellite AIRS and MOderate resolution Imaging Spectroradiometer, MODIS, observations). The results indicate that an imager, with a horizontal resolution of 1 km and possessing six spectral bands, would optimize the use of imager data in the IRS cloud clearing process. The six bands consist of two longwave window channels (11 µm and 12 µm), a shortwave window channel (4 µm), and three weakly absorbing sounding channels (4.5 µm, 7.4 µm, 13.4 µm). It is shown that the value of the use of imager data, for cloud-clearing sounding radiance measurements, increases with increasing horizontal resolution of the imager radiance measurements and decreasing horizontal resolution of the sounder radiance measurements. Thus, the ultimate advantage of using high horizontal resolution imager data, in the sounding retrieval or radiance data assimilation process under partly cloudy conditions, will depend on the horizontal resolution design of the IRS instrument.

The need for a built-in imager also depends upon the spectral channel selection technique used for the IRS. For a dispersion instrument approach, where different detector elements are used to measure different spectral channels, the data from an imager are considered to be important for correcting IRS data for spectral channel field of view co-registration error, which causes pseudo spectral noise in the case of scene non homogeneity (i.e., horizontal variations of cloud or Earth surface conditions). In this case, the spectral radiance noise resulting from detector field of view co-registration errors must be alleviated in order to achieve the high spectral fidelity needed for extracting small vertical scale features of the atmospheric profile from IRS spectra. For the case of a Fourier Transform Spectrometer design for the IRS, there does not appear to be as great a need for a built-in imager for co-registration error correction since the same detector elements are used to obtain the radiance spectrum over broad spectral bands (i.e., all spectral channels within the band have the same optical field of view). If each spectral band of the FTS is designed to cover a window region of spectrum, then the cloud and surface spatial non-homogeneity effects can be handled by processing the spectral bands independently of each other to produce results that are not dependent on band-to-band co-registration.

A built-in imager data can also to enable landmark navigation of the IRS data to improve the accuracy of the absolute location of the radiance spectra and derived soundings. Image to image relative navigation of the IRS data is needed to obtain accurate wind velocity vertical profile estimates by tracing the displacement of features revealed in high-resolution moisture soundings. Improved absolute navigation accuracy would improve the accuracy of the wind velocity field resulting from the continuous assimilation of the moisture sounding data into the NWP model. However, whether a built-in imager is required, to improve the navigation of the MTG IRS data, depends upon the navigation accuracy of the spacecraft and instrument attitude control systems to be employed.

As also discussed here, a built-in imaging capability can be more naturally achieved with the FTS approach for the MTG-IRS instrument. Using a high horizontal resolution (e.g., 1 km) detector array/optical system, both high horizontal/low spectral resolution imagery and high spectral/low horizontal resolution sounding information can be achieved simultaneously with a single instrument, with the signal to noise levels required for both the imagery and sounding application. The two types of radiance information will be naturally co-registered in space and
time. The system can also be operated in a pure low horizontal resolution sounding mode to
decrease the spectral sampling time required, thereby increasing the area coverage or refresh rate
of the imagery. One could also operate the system in a full spectral resolution/full horizontal
resolution sounding mode by simply co-adding multiple interferograms, to improve signal to
noise, before moving the scene mirror, or telescope, of the instrument to view a new Earth
location. The size of the detector array, which can be used, depends upon detector readout
capability. On-board processing is required to minimize the external data rate and downlink
telemetry requirements of the system. Using the same optical/detector system for obtaining the
sounding and imaging information simultaneously, and in a perfectly co-registered fashion, will
optimize the cloud clearing and the sounding retrieval process.

Cloud and detector co-registration effects, together with the potential use of an imager to
improve the navigation accuracy of the derived products, lead to a recommendation for
incorporating available imager data in the routine processing of MTG-IRS data into atmospheric
soundings and radiance data assimilation into NWP models. However, since there are alternate
non-imager methods for treating clouds in the sounding retrieval and radiance data assimilation
process (22), the requirement for a built-in imager component of the IRS instrument system is
ultimately dependent upon instrument/spacecraft design issues, such as the spectral channel co-
registration accuracy and the navigation accuracy permitted by the instrument/spacecraft attitude
control system. Whether or not a built-in imager is required will ultimately depend on how well
the various spectral channel fields of views of the IRS can be optically co-registered with each
other and between time consecutive frames of the sounder radiance data.

In summary, the results of this study are used to determine the requirements for an imager, as
part of the IRS system, for accomplishing the MTG Sounding mission. It is shown that it is
desirable to have a built-in imager, or alternatively a separate and independently operated
imager, to assist with the interpretation of the IRS data. It is concluded that:

(1) A built-in, or companion, multi-spectral imager can provide data useful for optimizing
the extraction of surface and atmospheric information from the MTG-IRS. Data from a multi-
spectral imager can be used to increase the reliability of the sounding information in
meteorologically active areas where clouds and temperature and moisture gradients exist.

(2) It was shown that data from an imager with 1 km horizontal resolution and six spectral
channels can be used to optimize the extraction of clear air radiance information from partly
cloudy hyperspectral sounding observations. However, if the sounding instrument field of view
can be made relatively small, partly cloudy field of view observations can be minimized and the
radiance observations can be treated, without the use of imager data, by using an accurate cloud
radiative transfer model in the sounding retrieval and radiance data assimilation process (22).

(3) In the case of the selection of a dispersion spectrometer approach for the IRS, a built-in
imager may be needed, depending on optical design, to correct the sounding radiances for
artifacts (i.e., pseudo-spectral noise) resulting from the imprecise co-registration of the fields of
view of the various detector elements used to observe the radiance spectrum. An algorithm for
doing this has been formulated but the accuracy of the correction achievable needs to be defined.
The dependence of the accuracy of the co-registration error correction on imager spectral
channel characteristics also needs to be determined.
A built-in imager would enhance the navigation accuracy of the IRS derived product imagery used to define dynamic variables, such as the water vapor flux, wind profile, and the transport of pollutant gases.

A design consideration, which consists of on-board processing of the high horizontal and high spectral resolution interferogram data, has been suggested for providing built-in imager data as part of an FTS instrument approach for the MTG-IRS. This approach has numerous advantages, over the use of a separate imaging instrument to provide the data needed to optimize the IRS sounding data processing for the MTG. The approach may also make it possible to eliminate, or greatly simplify, the requirement for additional imaging instruments to satisfy the High Resolution Fast Imagery (HRFI) and Full Disk High Spectral resolution Imagery (FDHSI) infrared measurement requirements for the MTG.

In summary, the results of this study provide a basis for a decision regarding the need for a built-in, or companion, imaging instrument. Although there is little doubt that the use of high horizontal imager data will improve the accuracy and spatial resolution of the MTG IRS products, there are alternative cloud treatment techniques, which do not depend on the use of imager data (22). Thus, the results of this study do not in themselves justify the need for the use of built-in or companion imager (e.g., FDHSI) data, in order to achieve the objectives of the MTG IRS sounding mission. The decision largely depends on the IRS instrument design, including its horizontal resolution and the spectral selection technique to be used, and instrument and spacecraft navigation accuracy. Consequently, the results of this study alone cannot be used as justification for including, or excluding, a built-in imager as part of the IRS design.

2.0 Background and Objective

The METEOSAT Third Generation (MTG) will carry an instrument to carry out the IRS mission focused on operational meteorology, with some relevance to atmospheric climate. In order to accomplish this mission, the infrared instrument must be capable of providing useful sounding information (i.e., radiances and sounding products) under the cloudy, as well as the clear, atmospheric condition. Clouds act to reduce the IR signal level and may produce noise, dependent on the complexity of the cloud properties and the manner in which they are treated in the profile retrieval process. For atmospheric profile retrieval, there at least three methods to be used to extract profile information from cloud contaminated radiances (22): (1) hole-hunting whereby clear fields of view are selected from a horizontal array of fields of view covering a partly clouded scene, (2) cloud-clearing using two, or more, horizontally adjacent cloud contaminated radiance measurements, and (3) retrieval, or radiance assimilation, using a physically accurate cloud radiative transfer model to account for the absorption and scattering of the radiance observed. The success of hole-hunting depends on both the size of the sounder field-of-view and the ability to distinguish cloud-free from clouded fields of view. Cloud clearing extracts the radiance arising from the clear air portion of partly clouded fields of view permitting soundings to the surface or the assimilation of radiances, as in the clear field of view case. The accuracy of the clear air radiance signal derived by cloud clearing depends upon knowledge of the clear air radiance for one or more spectral channels and the uniformity of the cloud height and cloud and surface optical properties across the multiple fields of view used in the cloud clearing process. The use of a physically accurate cloud radiative transfer model enables reliable retrievals down to cloud top levels and below semi-transparent cloud layers (e.g.,
cirrus), provided that the number of cloud layers seen by the sounder can be independently determined. For a simple one, or possibly two, cloud level condition, it may also be possible to assimilate cloudy radiances directly into the model given a physically accurate cloud radiative transfer model using geometric and microphysical cloud parameters retrieved from high horizontal resolution imager radiometer measurements as initial cloud variables in the radiance assimilation process (7,22). The success of any of these approaches requires that the cloud condition (i.e., height, fractional coverage, uniformity, optical depth, etc.) and the underlying surface properties be properly treated in the data processing. As a result, relatively high horizontal resolution, but moderately low spectral resolution, imagery data can be used to provide the clear air radiance information needed for the reliable treatment of clouds in the sounding retrieval and the radiance data assimilation process.

The objective of this study is to define the need for a built-in imager in order to be able to optimize the use of the MTG IR Sounder radiances in the extraction of the desired geophysical products and the assimilation of the radiances in numerical weather prediction models, the drivers of requirements for highly accurate IRS radiance data and soundings. The study specifically analyzes aircraft and satellite data to determine how data from an imager would improve the handling of clouds for extracting sounding information from the MTG-IRS. Also discussed is the potential use of data from a built-in imager to account for the effects of imperfect co-registration of the fields of view of the different detectors used to observe the radiance spectrum as well as to improve the navigation of the IRS sounding products.

3.0 Study Tasks

Task 1: The first task of this study is to define the need for the use of high horizontal resolution multi-spectral radiance data for transforming MTG IRS geostationary satellite sounding spectrometer observations into atmospheric profiles. The basis for this study is the analysis of NAST-I high horizontal and spectral resolution airborne measurements and joint Aqua satellite MODIS multispectral and high horizontal resolution imager measurements and AIRS hyperspectral resolution sounding measurements. The utility of the imager data, which provides high horizontal resolution multi-spectral radiance data, is defined in terms of spectral radiance accuracy and yield, as they relate to the desired accuracy and horizontal resolution of the derived IRS sounding products and for the assimilation of the IRS radiance spectra into the numerical weather prediction/analysis process.

Task 2: The second task is to define the horizontal resolution and spectral channel alternatives for a built-in, or an independent companion imager to provide simultaneous measurements with the IRS, and estimate their impacts on the spectral radiance and derived sounding accuracy. The trade between accuracy and instrument complexity (i.e., horizontal resolution and the number of spectral channels) is considered.

4.0 Scope of Report

In this report, results from the investigations based on the analysis of experimental aircraft and satellite data are presented in order to provide an assessment of the need for, and the horizontal and spectral design characteristics of, a built-in imager, or an independent companion imager, as
part of the IRS sounding system. Analyses performed, in terms of the use of the imager data for handling clouds associated with the IRS sounding measurements, are outlined as follows:

A. Hole Hunting:
   1. Define the clear field of view yield dependence on the horizontal resolution of the sounder
   2. Specify the ability to define clear sounder fields of view using multi-spectral imager data
   3. Define the capability to use an estimated window radiance threshold, together with the sounder measured window radiance, to detect cloud-free sounder IFOVs, simulating the case when imager data is not available
   4. Using the approaches defined under 2 and 3, above, determine:
      - the % of misclassified IFOVs
      - the % of clear IFOVs classified as being cloudy
      - the % of cloudy IFOVs classified as being clear

B. Cloud Clearing:
   1. Define the use of combined sounder and imager data to obtain cloud-cleared radiances
   2. Define the use of sounder data alone to obtain cloud-cleared radiances
   3. Compare the yields of accurate cloud-cleared radiances for the approaches defined under 1 and 2, above.

Analyses performed to define the optimal horizontal and spectral characteristics of imager and sounder data are:

A. Imager Horizontal Resolution and Spectral Characteristics:
   1. Define cloud-cleared radiance yield dependence on imager horizontal resolution for IRS 3 km and 6 km footprint areas.
   2. Define cloud-cleared radiance accuracy and yield on the spectral channel configuration of the imager.

B. Sounder Horizontal Resolution:
   1. Define the dependence of sounder horizontal resolution on cloud-cleared radiance accuracy and yield.

C. Sounding Retrieval Accuracy:
   1. Define the relative dependence of temperature and moisture sounding accuracy on imager horizontal resolution.
   2. Define the relative improvement of sounding accuracy achieved by using imager radiances directly in the sounding retrieval process.

In addition to the above data analyses, several other topics are discussed as they relate to the built-in imager study. They are:

A. Co-registration Spectral Radiance Noise Correction
B. Landmark Navigation Considerations
C. Optimizing the FTS Approach for built-in imaging
5.0 Data Utilized

5.1 NAST-I

The National Polar-orbiting Operational Environmental Satellite System (NPOESS) Airborne Sounding Testbed-Interferometer (NAST-I) was developed by the NPOESS Integrated Program Office (IPO) to be flown on high altitude aircraft and provide experimental observations especially needed for finalizing specifications and testing proposed designs and data processing algorithms for the Cross-track Infrared Sounder (CrIS), which will fly on NPOESS (5,21,23). 

**NAST-I Measurement Characteristics:** The NAST-I has a spectral range of 3.6–16.1 µm, without gaps, and covers the spectral ranges (Fig. 1) and resolutions of all current and planned advanced high spectral resolution infrared spectrometers to fly on polar orbiting and geostationary weather satellites, including the EOS-AIRS, METOP-IASI (Infrared Atmospheric Sounding Interferometer), the NPP (NPOESS Preparatory Project)/NPOESS-CrIS (Cross-track Infrared Sounder), the GFTS (Geostationary Fourier Transform Spectrometer), the HES (Hyperspectral Environmental Suite) sounder, and the MTG IRS. The NAST-I spectral resolution is equal to, in the case of IASI, or higher than all current and planned advanced sounding instruments. Thus, the NAST-I data can be used to simulate the radiometric observations to be achieved from these advanced sounding instruments. Moreover, the forward radiative transfer models and product retrieval algorithms planned for these satellite systems can be validated prior to launch. Finally, NAST-I can be used for the fundamental purpose of post-launch calibration and validation of sensors and data products for the advanced satellite sounding systems. The NAST-I spatially scans the Earth and atmosphere from an aircraft, such as the high-altitude NASA ER-2 research airplane or the Northrop-Grumman Proteus aircraft. NAST-I provides a vertical resolution of 1–2 kilometers for atmospheric temperature and water vapor, dependent upon altitude. As the aircraft passes over the Earth, NAST-I scans an area at the Earth’s surface collecting data on the properties of the Earth’s surface and atmosphere beneath the aircraft. From an aircraft, the NAST-I provides a field of view size of 130 meters per kilometer of aircraft altitude (e.g., from the NASA ER-2 altitude of 20 km, 2.6 km horizontal resolution is achieved, as shown in figure 2). Thus, NAST-I provides high horizontal resolution three-dimensional hyperspectral images of radiance and derived geophysical products (21) that can be used to assess the utility of an imager component of the MTG IRS system.

**NAST-I Data and Cases:** Measurements made by the NPOESS Aircraft Sounder Testbed Interferometer (NAST-I) have been used to simulate spectral radiance measurements, similar to those to be obtained with the IRS, for a total ground coverage of approximately 40 km x 40 km, which approximates a reasonable sounding resolution for NWP model initialization (3,21). These simulations can be used to represent four potential horizontal resolutions of the IRS, each lower than the horizontal resolution of the original NAST-I data.
Figure 1. Spectrum of radiance showing the spectral coverage for various sounding instruments planned to be flown prior to the launch of the MTG IRS. The NAST-I spectral coverage is the same as that shown for the METOP IASI instrument.

Twelve scan lines of NAST-I data provide a ground coverage of approximately 40 km x 46 km; each scan line of NAST-I data contained 13 footprints with viewing angles from $-45^\circ$ to $+45^\circ$ (with respect to nadir) in $7.5^\circ$ increments. The footprints at the extreme angles of $+45^\circ$ and $-45^\circ$ were discarded and the nadir footprint was duplicated in order to make scan lines with 12 footprints each, which are symmetric with respect to viewing angle. This process forms a 12 x 12 array of NAST-I footprints which have a ground coverage of approximately 40 km x 40 km.

Figure 2. NAST-I scan geometry from the NASA ER-2 high altitude aircraft.
The array of 12 x 12 NAST-I footprints was used to simulate sounding instruments with lower horizontal resolution than NAST-I. The NAST-I nadir footprint is approximately 3 km in diameter, depending upon scan angle. By averaging 2x2, 3x3, 4x4, and 6x6 groups of pixels of the 12x12 array, sounding instruments with approximate footprint diameters of 6 km, 9 km, 12 km, and 18 km, respectively, were simulated. This process is shown in figure 3. Since the simulated sounder data at each reduced resolution have total ground coverage of ~40 km x ~40 km, the number of footprints within the 40 km x 40 km area is different for each resolution as shown in figure 3.

Using the procedures to be presented below, a study of “hole hunting” and “cloud-clearing” accuracy vs. sounder FOV size was conducted using the data available from twelve NAST-I flights whose cloud characteristics are summarized in Table I below. These flights were chosen because they represent the wide variety of cloud conditions to be encountered by a satellite-sounding instrument.

![Figure 3: NAST-I IFOV averaging performed to simulate different IRS sounding instrument horizontal resolutions.](image)

**Table I:** Aircraft NAST-I flight data used for built-in imager study.

<table>
<thead>
<tr>
<th>Date</th>
<th>Mission</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>980826</td>
<td>CAMEX</td>
<td>Tropical ocean cirrus and convection</td>
</tr>
<tr>
<td>980922</td>
<td>CAMEX</td>
<td>Tropical ocean cirrus and convection</td>
</tr>
<tr>
<td>990320</td>
<td>WINTEX</td>
<td>Continental polar alto-cumulus over snow</td>
</tr>
<tr>
<td>990827</td>
<td>Wallops Ferry</td>
<td>Transcontinental convection and cirrus</td>
</tr>
<tr>
<td>010308</td>
<td>W. Pacific</td>
<td>Subtropical oceanic cirrus, altocumulus, marine PBL</td>
</tr>
<tr>
<td>010309</td>
<td>W. Pacific</td>
<td>Subtropical oceanic cirrus, altocumulus, marine PBL</td>
</tr>
<tr>
<td>010310</td>
<td>W. Pacific</td>
<td>Subtropical oceanic cirrus, altocumulus, marine PBL</td>
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<tr>
<td>010312</td>
<td>W. Pacific</td>
<td>Subtropical oceanic cirrus, altocumulus, marine PBL</td>
</tr>
<tr>
<td>010316</td>
<td>W. Pacific</td>
<td>Subtropical oceanic cirrus, altocumulus, marine PBL</td>
</tr>
<tr>
<td>010712</td>
<td>CLAMS</td>
<td>W. Atlantic oceanic cirrus</td>
</tr>
<tr>
<td>07/26/02</td>
<td>Crystal Face</td>
<td>Gulf of Mexico oceanic cirrus</td>
</tr>
<tr>
<td>07/29/02</td>
<td>Crystal Face</td>
<td>W. Atlantic oceanic cirrus</td>
</tr>
</tbody>
</table>
5.2 Aqua AIRS and MODIS

The Aqua satellite is polar orbiting, with an inclination of 98.2 degrees, and sun synchronous, with an ascending node of 1:30 p.m. (descending node 1:30 a.m.) and a period of 98.8 minutes, thereby providing twice per day global coverage of the Earth from an altitude of 705 km. It carries six different instruments of which the AIRS and the MODIS are of interest here.

**AIRS:** The Atmospheric InfraRed Sounder (AIRS) instrument is the first spaceborne spectrometer designed to meet the 1-K/1-km sounding accuracy objective by measuring the infrared spectrum quasi-continuously from 3.7 to 15.4 microns with high spectral resolution (2). The sensitivity requirements, expressed as Noise Equivalent Differential Temperature (NEDT), referred to a 250-K target-temperature, generally ranges from 0.1 K in the 4.2-µm lower tropospheric sounding wavelengths to 0.5 K in the 15-µm upper tropospheric and stratospheric sounding spectral regions. The AIRS Instrument provides spectral coverage in the 3.74 µm to 4.61 µm, 6.20 µm to 8.22 µm, and 8.8 µm to 15.4 µm infrared wavebands at a nominal spectral resolution of $\frac{\nu}{\delta \nu} = 1200$, with 2378 IR spectral samples and four visible/near-infrared (VIS/NIR) channels between 0.41 and 0.94 microns. Horizontal coverage and views of cold space and hot calibration targets are provided by a 360-degree rotation of the scan mirror every 2.67 seconds.

The AIRS footprint size (Fig 4) is relatively large, being approximately 15 km in linear resolution at the satellite nadir. Experience has shown that the yield of clear sky AIRS radiance measurements and associated retrieval products is severely limited by the relatively large footprint size of the AIRS instrument. Fortunately, an Advanced Microwave Sounding Unit (AMSU) and a high horizontal resolution multi-spectral imaging instrument, called MODIS, are also flying aboard the Aqua satellite, whose data can be used to alleviate some of the cloud induced deficiencies in the sounding retrieval process, caused by the relatively low horizontal resolution of the AIRS instrument.

**MODIS:** The Moderate Resolution Imaging Spectroradiometer (MODIS) is a key instrument aboard the Aqua (EOS-PM) satellite which can be used to aid the interpretation of AIRS data (10,14,22) because of its overlapping spectral coverage (see Fig.5 below) and its much higher horizontal resolution. Aqua MODIS views the entire Earth’s surface in 36 spectral bands (4), sixteen of which are contained in the thermal infrared region of the spectrum. The MODIS footprint size ranges from 250 m to 1 km, depending upon spectral channel, with all the IR channels being 1 km horizontal resolution. Cross track scanning of 10 along-track detectors per spectral band is used to collect 1354 cross track samples to provide a cross track scan swath of ~2320 kms. The MODIS channels used in this study are listed in Table II below. Since MODIS flies on the Aqua satellite alongside the AIRS instrument, combined Aqua AIRS/MODIS data sets are used here to define the usefulness of data from an imager for the processing of the MTG sounding data.
Collocation of MODIS and AIRS measurements: The initial step for the use of MODIS and AIRS data for this study is the collocation of the pixels, with 1 km horizontal resolution, within the AIRS footprint. Several collocation algorithms have been developed that are based on the scanning geometry of two instruments flown on the same satellite (6,12). With a set of AIRS earth-located observations, the footprint of each AIRS observation describes a figure that is circular at nadir, quasi-ellipsoidal at intermediate scan angles, and ovular at extreme scan angles. The diameter of the AIRS footprint at nadir is approximately 13.5 km. Depending on the angular difference between the AIRS and MODIS slant range vectors, a weight, referred to as $\omega$ below, is assigned to each MODIS pixel collocated to AIRS (i.e., the weight is unity if the MODIS pixel lies at the center of the AIRS oval, and zero if it lies beyond the outer edge). The collocation algorithm provides co-location accuracy better than 1 km, provided that the geometry information from both instruments is accurate.
**Figure 5:** Infrared spectral bands for MODIS and AIRS.

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Band</th>
<th>Bandwidth (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Surface/Cloud Temperature</strong></td>
<td>20</td>
<td>3.66 - 3.84</td>
</tr>
<tr>
<td></td>
<td>21</td>
<td>3.94 - 4.02</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>3.93 - 4.02</td>
</tr>
<tr>
<td></td>
<td>23</td>
<td>4.02 - 4.11</td>
</tr>
<tr>
<td><strong>Atmospheric Temperature</strong></td>
<td>24</td>
<td>4.40 - 4.50</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>4.48 - 4.57</td>
</tr>
<tr>
<td><strong>Cirrus Clouds, Water Vapor</strong></td>
<td>27</td>
<td>6.69 - 6.88</td>
</tr>
<tr>
<td></td>
<td>28</td>
<td>7.19 - 7.51</td>
</tr>
<tr>
<td><strong>Cloud Properties</strong></td>
<td>29</td>
<td>8.40 - 8.70</td>
</tr>
<tr>
<td><strong>Ozone</strong></td>
<td>30</td>
<td>9.58 - 9.89</td>
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<tr>
<td><strong>Surface/Cloud Temperature</strong></td>
<td>31</td>
<td>10.76 - 11.30</td>
</tr>
<tr>
<td><strong>Atmospheric Temperature</strong></td>
<td>32</td>
<td>11.78 - 12.31</td>
</tr>
<tr>
<td></td>
<td>33</td>
<td>13.21 - 13.52</td>
</tr>
<tr>
<td></td>
<td>34</td>
<td>13.51 - 13.86</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>13.76 - 14.09</td>
</tr>
<tr>
<td></td>
<td>36</td>
<td>14.06 - 14.39</td>
</tr>
</tbody>
</table>
**AIRS cloud masking from MODIS:** Once the MODIS pixels are collocated to the AIRS fields of view, the cloud properties within the AIRS sub-pixel can be characterized using the MODIS cloud mask (1,11,13,14). The AIRS cloud mask is generated from the MODIS cloud mask, which has 1 km horizontal resolution. For each AIRS footprint, a fractional cloud coverage (0 ~ 1) is obtained as the percentage of MODIS pixels with confident clear within the AIRS footprint. The averaged MODIS clear radiance for a given spectral band $i$ within an AIRS footprint is then obtained by

$$
\overline{R}_{M_i}^{clr} = \frac{\sum_{l=1}^{np} \omega_l R_{M_i}^{clr,l}}{\sum_{l=1}^{np} \omega_l},
$$

where $R_{M_i}^{clr,l}$ is the radiance of confident clear pixel $l$, $np$ is the number of confident clear pixels within the AIRS footprint, and $\omega_l$ is the weight of pixel $l$ within the AIRS footprint as described above.

**AIRS Convolution to MODIS Channels:** In order to use high horizontal resolution multi-spectral channel imager data to alleviate the effects of clouds on hyperspectral sounder products, it is desirable to create pseudo-imager channel radiances by spectrally convoluting the sounder’s high spectral resolution radiance observations using the spectral response functions (SRFs) of the imager. The sounder’s low horizontal resolution pseudo-imager channel radiances can then be compared with the actual high horizontal resolution imager radiances to determine the field of view cloud condition of the sounder (i.e., clear, overcast, or cloudy). The AIRS radiance spectra are spectrally convoluted to the MODIS channels for the cloud detection and clearing process. The sounder simulated and actual imager radiances are used to cloud-clear the sounding instruments high spectral resolution cloud-contaminated radiance measurements using methods described below.

It is noted here that the NAST-I airborne sounding radiance data has also been spectrally convoluted to the MODIS spectral channels enabling analyses similar to those conducted with the AIRS/MODIS satellite data. Thus, the NAST-I airborne data analysis results can be directly related to the AIRS/MODIS satellite data analyses performed for this study.

Figure 6 shows the MODIS SRFs overlaid with an AIRS BT spectrum. MODIS radiance SRF and calibration errors have been determined through direct comparison of the spectrally convoluted AIRS pseudo-MODIS radiances with actual co-located and spatially convoluted MODIS channel radiances for uniform scene conditions (25). These comparisons show that the differences between the AIRS pseudo-MODIS brightness temperatures and the actual MODIS channel brightness temperatures are generally within 0.3 K, with the exception of three channels where the differences are close to 1 K. Corrections for the MODIS SRFs and calibration uncertainties have been determined from these comparisons and are accounted for in the creation and use of the AIRS pseudo-MODIS channel radiances for cloud detection and cloud-clearing. In this study, 9 MODIS spectral bands (i.e., 22, 24, 25, 28, 30, 31, 32, 33, and 34) of the 16 available MODIS IR spectral bands are used for cloud detection and cloud clearing of AIRS data. Several MODIS IR spectral bands are not used due excessive detector noise and due to the convolution error introduced by the spectral gaps of AIRS measurements. MODIS IR spectral
bands 20 and 21 are not used due to the large detector noise while MODIS IR spectral IR bands 35 and 36 are not used due to their SRF convolution error.

**AIRS/MODIS Cases:** In this study, AIRS and MODIS data for three different Aqua data granules are used to define the importance of multi-spectral imager data in the processing of MTG IRS hyperspectral data. The cloud characteristics for the three granules of data used for this study are shown in figure 7. They contain typical cloud situations to be sampled by the MTG IRS sounder. The land conditions are particularly relevant for the observation of convective storm development whereas the ocean case (i.e., hurricane Isabel) is most relevant for the observations of the steering currents associated with tropical storms and hurricanes (figure 7).

![Sample AIRS spectrum with MODIS IR channel Spectral Response Functions](image)

**Figure 6.** Sample AIRS spectrum with MODIS IR channel Spectral Response Functions

### 6.0 Handling the Effects of Clouds

#### 6.1 Hole Hunting Technique

**NAST-I:** The hole hunting technique used for the NAST-I data flights is a threshold technique using three “imager” window channels, 10 µm, 11 µm, and 12 µm. Three tests must be passed before a given sounder FOV is considered to be clear; the 11 µm brightness temperature must be greater than a threshold based on the expected clear sky brightness temperature, including the
effects of measurement noise, and the differences between the 10 µm and 11 µm brightness temperatures and the 11 µm and 12 µm brightness temperatures must be less than those differences expected for clear sky conditions, including the effects of instrument noise. As discussed earlier, in the case of the NAST-I study, the objective was to determine the yield of clear air measurements and the accuracy of cloud clearing with and without the use of a multi-spectral imaging instrument as a function of IRS IFOV field of view size. In this case, the statistics are computed only for 40 x 40 km Field of Regards (FORs), which contain at least one clear NAST-I observation, at its nominal 3 km horizontal resolution. Only partly cloudy FORs are considered since an imager is of little value for either hole hunting or cloud clearing when the FOR is entirely clear or entirely overcast with clouds.

Table III below shows the results of the “hole hunting” statistics for the 12 flights considered (see Table I). Table III also includes statistics computed using global MODIS data, based on the use of the MODIS cloud mask for determining clear IFOVs as a function of IFOV size. As can be seen from Table III, the success of obtaining cloud-free fields of view within a partly cloudy area diminishes quickly with increasing field of view size. The reason for the discrepancy between the NAST and MODIS statistics, for the sample means of % FORs with one or more clear fields of view, is believed to be due to the fact that only partly cloudy fields of regard are considered in the NAST statistics whereas all fields of regard (clear, partly cloudy, and cloud overcast) are considered for the generation of the MODIS statistics. There is, however, excellent agreement between the mean percentage of clear fields of view per FOR computed from the NAST-I data and the probability of achieving one or more clear fields of view.

\[ \text{Table III} \]

Table III below shows the results of the “hole hunting” statistics for the 12 flights considered (see Table I). Table III also includes statistics computed using global MODIS data, based on the use of the MODIS cloud mask for determining clear IFOVs as a function of IFOV size. As can be seen from Table III, the success of obtaining cloud-free fields of view within a partly cloudy area diminishes quickly with increasing field of view size. The reason for the discrepancy between the NAST and MODIS statistics, for the sample means of % FORs with one or more clear fields of view, is believed to be due to the fact that only partly cloudy fields of regard are considered in the NAST statistics whereas all fields of regard (clear, partly cloudy, and cloud overcast) are considered for the generation of the MODIS statistics. There is, however, excellent agreement between the mean percentage of clear fields of view per FOR computed from the NAST-I data and the probability of achieving one or more clear fields of view.
view, per FOR, as computed from MODIS data. This result may indicate that there is about an
equal number of completely cloud overcast NAST FORs and completely cloud-free NAST
FORs, which are discarded in computing the partly cloudy FOR statistics.

Table III is important for defining the IFOV size of the imager to be used to cloud-clear IRS
radiance data since the ability of cloud clearing relies on having at least one clear field of view
for the imaging instrument within the partly cloudy region of interest. It can be seen that the
highest achievable imager resolution is desired to optimize the ability to sound down to the
Earth’s surface under partly cloudy sky conditions.

### Table III. Hole hunting statistics for twelve NAST flights as a function of IFOV size

<table>
<thead>
<tr>
<th>Resolution</th>
<th>1km</th>
<th>3 km</th>
<th>6 km</th>
<th>9 km</th>
<th>12 km</th>
<th>18 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAST Mean % ≥ 1Clear / FOR</td>
<td>-</td>
<td>100%</td>
<td>85</td>
<td>67</td>
<td>54</td>
<td>34</td>
</tr>
<tr>
<td>NAST Mean % Clear / FOR</td>
<td>-</td>
<td>52</td>
<td>41</td>
<td>33</td>
<td>25</td>
<td>16</td>
</tr>
<tr>
<td>MODIS Mean % ≥ 1Clear / FOR</td>
<td>75</td>
<td>55</td>
<td>42</td>
<td>31</td>
<td>25</td>
<td>-</td>
</tr>
</tbody>
</table>

1 Based on partly cloudy fields of regard
2 Based on a global average for all fields of regard (i.e., clear, partly cloudy, and overcast FORs)
for August 24, 2002 using the MODIS cloud mask to determine clear IFOVs.

**AIRS/MODIS:** Figure 8 below shows an example of the MODIS cloud mask extracted for a
sample of AIRS fields of view for one of the AIRS granules (193 as shown in Fig. 7) considered
in this study. It can be seen that the 1 km resolution MODIS data can be used to describe the
details of the cloudiness within each AIRS field of view.

![Figure 8. Example MODIS classification for AIRS fields of view observed in granule 193 on September 6, 2002.](image)
It is of interest to estimate the difference between the skill in the cloud/clear classification of sounder fields of view, with and without the benefit of data from an imaging instrument. In this study, AIRS is used as the hyperspectral sounder and MODIS is the multi-spectral imager, although, for the MTG, an imager with fewer spectral channels than those observed with MODIS will be considered. As an example of the potential inability to “hole hunt” with the hyperspectral sounder, without the benefit of an imaging instrument, a simple cloud threshold test comparing AIRS 11 µm window channel brightness temperature data (as determined by spectral convolution with the MODIS band 31 SRF) with a MODIS 11 µm window channel, simulated from a sea surface temperature analysis and a forecast atmospheric state. For this purpose it is assumed that the simulation error of MODIS 11 µm window channel radiance is guassian, with a mean of zero and a standard deviation of 2% (typical of ocean), 4% (typical of land nighttime observations), and 8% (typical of land daytime observations). If the AIRS radiance exceeds a threshold defined as the simulated radiance minus one-half the expected error (i.e., 1%, 2%, or 4%, depending on the surface observing situation being simulated), then the AIRS FOV is declared to be clear. Otherwise the AIRS FOV is presumed to be cloud contaminated.

Table IV below shows the classification error statistics, for three of the four granules (126,184, and 193) shown in Figure 7, for the case where simulated, rather than actual, MODIS data is used for AIRS FOV cloud contamination determination (i.e., hole hunting). As can be seen, without the benefit of high horizontal resolution window channel data, a large percentage of sounder FOV misclassifications occur if only a simple window threshold test is used. These errors will be smallest for ocean, where the simulated window channel radiance threshold errors are generally about 2%, and poorest over land regions during the day, where the simulated window channel threshold errors are typically about 8% . Most damaging is the number of cloudy fields of view mistakenly classified as clear, since for the radiance spectra for cases will produce erroneous atmospheric profile retrievals.

<table>
<thead>
<tr>
<th>Case</th>
<th>G126-Africa (9/2/02)</th>
<th>G193-USA (9/2/02)</th>
<th>G184-W.Atl. (9/17/03)</th>
<th>3 Granule Average</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>32% Clear</td>
<td>35% Clear</td>
<td>24% Clear</td>
<td>30% Clear</td>
</tr>
<tr>
<td>% Clear as Clear</td>
<td>79</td>
<td>77</td>
<td>74</td>
<td>77</td>
</tr>
<tr>
<td>% Cloudy as Cloudy</td>
<td>77</td>
<td>73</td>
<td>58</td>
<td>69</td>
</tr>
<tr>
<td>% Clear as Cloudy</td>
<td>21</td>
<td>23</td>
<td>26</td>
<td>23</td>
</tr>
<tr>
<td>% Cloudy as Clear</td>
<td>23</td>
<td>27</td>
<td>42</td>
<td>30</td>
</tr>
<tr>
<td>Average % Misclassified</td>
<td>22</td>
<td>25</td>
<td>34</td>
<td>27</td>
</tr>
</tbody>
</table>

It is emphasized that Table IV is presented as an example of the degree of field of view misclassification that could result with the absence of imager data if only a window channel radiance threshold was used for determining whether or not the sounder data fields of view are cloud contaminated. These results are not representative of the case where more sophisticated sounder spectral radiance signature and multi-spectral window difference threshold tests would be employed to define the existence of cloud within the sounder field of view, assuming imager data is unavailable. The purpose here was merely to show that a simple window threshold test
for surface temperature and atmospheric profile estimates alone are insufficient for the detection of clouds within the sounder field of view.

The built-in imager specified for the MTG IRS possesses a visible (0.6 µm) channel, a 3.8 µm channel, in addition to an 11.4 µm channel. Comparing clear air window radiances with these three window channels estimated from the IRS radiance spectra would eliminate most of the misclassifications resulting from the use a single sounder window channel brightness temperature measurement with a threshold brightness temperature based on estimates of forecast surface temperature and atmospheric profiles.

The net result of the “hole hunting” statistics performed with both NAST-I aircraft data and AIRS satellite data is that: (1) the reliability of sounder field of view cloud condition (i.e., ”hole hunting”) improves rapidly with the horizontal resolution of the sounding instrument, and (2) the sounder field of view cloud condition (i.e., “hole hunting”) can benefit from the use of a high horizontal resolution radiometer data, especially over land areas, where the surface background radiance uncertainty is high.

6.2 Cloud Clearing Algorithm

The “paired field of view cloud-clearing technique” (15,16, 22), is used to calculate clear column radiance estimates from measurements that were made over partly cloudy regions. The clear column radiance estimates are to be used to retrieve temperature and water vapor profiles.

**Analytical Formulation:** Let $R_1(\nu)$ and $R_2(\nu)$ be sounder radiance spectra, where $\nu$ denotes wavenumber, observed for two adjacent fields of view (field of view 1 and field of view 2). Assume that the two adjacent fields of view have: (a) the same atmospheric temperature and moisture profiles, (b) the same surface skin temperatures and surface IR emissivity spectrum, and (c) the same cloud-top height. Assuming that the difference in radiance observed is solely due to a difference in the fractional cloud coverage, $N$, then the radiance spectra for the two adjacent fields of view can be expressed as

$$R_1(\nu) = (1-N_1)R_c(\nu) + N_1R_{cd}(\nu)$$

$$R_2(\nu) = (1-N_2)R_c(\nu) + N_2R_{cd}(\nu)$$

where the $R(\nu)$ subscript $c$ and $cd$ denotes the clear and cloud radiance, respectively, assumed to be the same for both fields of view 1 and 2 (i.e., the two fields of view have the same cloud height and cloud, surface, and atmospheric radiative properties). It then follows from 1 and 2 that

$$R_c(\nu) = \frac{R_1(\nu) - N^*R_2(\nu)}{1-N^*}$$
where \( N^*(\nu) = \frac{N_1}{N_2} \). From (3), it follows that estimates of \( N^* \) can be obtained from “window” spectral region, radiance measurements, calculated as

\[
N^* = \frac{R_1(w) - R_2(w)}{R_z(w) - R_c(w)},
\]

(4)

where \( R_1(w) \) and \( R_2(w) \) are radiance spectra from the sounder spectrally convoluted to a imaging radiometer window spectral band, \( w \), for FOVs 1 and 2 and \( R_c(w) \) is a simultaneous measurement of the clear column window radiance made by the imaging radiometer, which has much higher horizontal resolution (e.g., 1 km) than the sounder.

In the process of cloud clearing of hyperspectral sounding data, the quality control of the results is most important. This is because the assumption used to obtain equations (3) and (4) will often be violated. That is, if the heights of the clouds differ between FOVs 1 and 2, and/or the clear air radiance is not constant over the area covered by the two FOVs (i.e., the surface temperature and the temperature and moisture profiles are not horizontally homogeneous), and/or the radiance for the cloud covered columns differs between the two FOVs (i.e., the cloud emissivity is not horizontally uniform) then equations (3) and (4) are invalid. As a consequence, erroneous clear air radiance spectra will result causing errors in the atmospheric profiles to be derived from them. Thus, the main advantage of a high horizontal resolution multi-spectral imager is that the correct clear air radiance can be measured for the cloud-contaminated field of view of the sounder, at the spectral resolution of the imager. If the imager channels cover the spectral domain of the sounder, than an excellent estimate of the accuracy of the derived clear air radiance spectra can be obtained from the root mean square difference between the actual radiances observed with the imager and those simulated by spectral convolution of the derived clear air radiance spectrum of the sounder. That is, one can filter erroneous cloud-cleared radiance estimates using the criterion

\[
\Sigma \{ \text{sr}[R_c(\delta\nu_j)] - R_c(\delta\nu_j) \}^2 \leq \varepsilon
\]

(5)

where the summation, \( \Sigma \), is over all the useful infrared spectral channels of the imager, \( \delta\nu_j \), \( \text{sr}[R_c(\delta\nu_j)] \) is the spectral convolution of derived clear air radiance of the sounder obtained using the spectral response function for the imager channel, \( \delta\nu_j \), \( R_c(\delta\nu_j) \) is the sounder FOV average of all the clear air radiances observed with the imager for spectral channel, \( \delta\nu_j \), and \( \varepsilon \) is an error limit criterion (e.g., \( \Sigma [0.005 R_c(\delta\nu_j)]^2 \)) which is equivalent to a root mean square brightness temperature discrepancy over all imager channels of approximately 0.5 K. Figure 9 provides a schematic illustrating the concept for using high horizontal resolution imaging radiometer data to calculate clear air spectra from partly cloudy hyperspectral resolution sounding radiances.
\[ R_c(\nu) = \frac{R_i(\nu) - N^* R_c(\nu)}{1 - N^*} \]

Where, \( N^* = N_1/N_2 \).

\[ N^* = \frac{srf[R_i(w)] - R_c(w)}{srf[R_c(w)] - R_c(w)} \]

\[ srf[R_i(w)] = \int \theta(w, \nu) R_i(\nu) d\nu \]

\[ \Sigma \{srf[R_c(\delta \nu)] - R_c(\delta \nu_j)\}^2 \leq \varepsilon \]

**Figure 9.** Schematic showing the methodology used to calculate clear air radiances from cloud contaminated sounding radiances. The variables are defined in the text.

**NAST I:** Tables V and VI below show the results of applying the cloud clearing technique to hyperspectral sounding data for different FOV sizes as simulated from NAST-I data (3). In this case the multi-spectral imager data was simulated from the NAST-I radiance spectra by spectral convolution to the MODIS channels. However, for NAST-I the highest horizontal resolution of the data is nominally 3 km so the results reflect those which would be achieved with an imager of this same horizontal resolution but with spectral channels similar to the MODIS infrared channels. Only clear and partly cloudy scenes are considered whereby the true sounder clear column radiance spectrum is known from the clear highest horizontal resolution (i.e., 3 km) hole hunting results discussed above.

As shown in Table V the accuracies of the cloud-cleared radiances are highly dependent on the availability of a multi-spectral imager for use in the cloud clearing process. Also, without the availability of simultaneous imager data, the accuracy of the result is highly dependent on the horizontal resolution of the sounding instrument, the accuracy degrading by a factor of 2 with a horizontal resolution decrease from 6 km to 18 km. The increasing accuracy of the cloud-cleared NAST radiances is primarily due to the effectiveness of the quality control of the results using the MODIS-like imager channel radiances. As can be seen from Table VI, even though the filtering procedure improves the accuracies of the cloud-cleared radiances by a factor 3-5, depending on spectral region and sounder horizontal resolution, the total yields are only reduced by about 20%. Thus, it appears that only erroneous radiances are being filtered using the high horizontal resolution MODIS-like imager data. Considering that high vertical resolution sounding requires a radiance accuracy on the order of 0.1 K, or better, (i.e., equivalent to ~ 0.1 mw/m²-str-cm⁻¹ in the longwave band), the results shown in Table IV indicate that useful cloud cleared radiance accuracy can only be consistently achieved if simultaneous high horizontal...
resolution multi-spectral infrared radiance data are available for use in the hyperspectral sounding radiance data processing.

**Table V.** Cloud Clearing Radiance RMS Errors (mw/m$^2$-str-cm$^{-1}$) for 3 sounding spectral absorption regions: (675-751 cm$^{-1}$/1210-1400 cm$^{-1}$/2190-2251 cm$^{-1}$) at full NAST spectral resolution (i.e., 0.25 cm$^{-1}$) for 40 km linear resolution sounding areas (i.e., FORs).

<table>
<thead>
<tr>
<th></th>
<th>6 km</th>
<th>9 km</th>
<th>12 km</th>
<th>18 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without Imager</td>
<td>0.48/0.25/0.026</td>
<td>0.69/0.34/0.035</td>
<td>0.79/0.39/0.041</td>
<td>0.96/0.45/0.054</td>
</tr>
<tr>
<td>With Imager</td>
<td>0.10/0.10/0.014</td>
<td>0.18/0.12/0.016</td>
<td>0.18/0.11/0.016</td>
<td>0.20/0.12/0.020</td>
</tr>
</tbody>
</table>

**Table VI.** Cloud Clearing Yields (%) for 40 km FORs.

<table>
<thead>
<tr>
<th></th>
<th>6 km</th>
<th>9 km</th>
<th>12 km</th>
<th>18 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Without Imager</td>
<td>74</td>
<td>70</td>
<td>66</td>
<td>57</td>
</tr>
<tr>
<td>With Imager</td>
<td>58</td>
<td>52</td>
<td>46</td>
<td>38</td>
</tr>
</tbody>
</table>

**AIRS/MODIS:** Cloud-clearing accuracy was also performed here using the AIRS/MODIS data for the three Aqua satellite granules 126,184, and 193 shown in figure 7. Statistics are presented for two cases; (1) the use of high horizontal resolution MODIS window radiance data for the specification of N*, and (2) using simulated window radiance data which represents the case where only surface temperature and NWP atmospheric analysis/forecast is available to compute N*. In both cases, actual MODIS data was used to quality control the clear column radiance product so that the benefit of the use of the imager data in the cloud clearing process is displayed only in terms of the yields of the cloud-cleared radiance spectra (and therefore derivable soundings) rather than in terms of their accuracy as already displayed in Table V, for different sounding instrument horizontal resolutions.

Figure 10 shows the cloud-cleared radiance yield obtained using the actual MODIS 11 µm window channel (i.e., band 31) radiance data (i.e., the “with MODIS” case) versus the yield obtained using a simulated 11 µm window channel radiance (i.e., the “without MODIS” case) for the determination of the cloud clearing parameter N*. In computing the yields shown in figure 10, the same MODIS acceptance criteria was applied in all cases. In practice, however, if MODIS data were not available then the yields would be higher but the accuracy would be degraded, by adding erroneous cloud-cleared radiance determinations, as shown earlier with the NAST-I data analyses.

The net result of the NAST and AIRS/MODIS cloud clearing studies is that a high horizontal resolution (e.g., 1 km) multi-spectral imager enables reliable determinations of cloud-cleared hyperspectral radiance data. Without a built-in, or companion, multi-spectral imager, the ability to sound to the Earth’s surface, from the MTG spacecraft, will depend heavily on the sounder’s field of view size and the accuracy to which sounder independent quality control criteria can be specified. The results obtained without the use of an imager might be especially problematic over land during the day, thereby severely limiting the use of the MTG IRS for continental convective storm forecasting.
Figure 10. Yield (expressed in terms of % of total partly cloudy fields of view) of accurately determined AIRS cloud-cleared radiance spectra for the cases of using and not using MODIS for defining the N* cloud clearing parameter. The percentage of partly cloudy fields of view is 36%, 42%, and 43%, for granules 126, 184, and 193, respectively.

It is important to note that the results shown here are significant only for the cases where cloud-clearing methodology is used to alleviate the influence of clouds on the sounding retrieval. These results alone do not imply the necessity for a multi-spectral imager for the processing of MTG IRS data, since alternative cloud handling techniques can possibly be used in sounding retrieval and radiance data assimilation (22). However, these results do show that the use of high horizontal resolution multi-spectral imager data can be used effectively to provide a relatively high yield of accurate cloud-cleared radiance spectra.

7.0 Imager Horizontal Resolution and Spectral Sampling Requirements

(a) IRS Imager Clear Field of View Yield Dependence on Horizontal Resolution: In order to determine the dependence of the IRS cloud-clearing capability upon the imager field of view size, statistics were performed with the MODIS cloud mask data at 1 km, 2 km, and 3 km resolution within the 3 km midwave and shortwave channels, and 6 km longwave channel footprint sizes specified for the IRS. As described above, at least one cloud-free imager field of view, within the area domain of two adjacent sounding footprints, is required for cloud clearing. Because the accuracy of the cloud-cleared radiance depends upon the accuracy of the imager defined clear air radiance, the accuracy of the cloud-cleared radiance will improve proportionately with the yield of clear imager fields of view within the IRS adjacent footprint area.
Table VII below shows the results of the MODIS cloud mask analysis for two different portions of the hurricane Isabel case (cloud mask shown in Figure 7). Since adjacent IRS fields of view must be used for cloud-clearing, the areas covered by the IRS 3 km midwave and shortwave channels and 6 km longwave channel field of views are 3 km x 6 km and 6 km x 12 km, respectively. As can be seen, for the relatively cloudy region in the hurricane storm region, there is a strong dependence of the cloud-clearing yield on the imager field of view size.

Table VII. Clear imager field of view yields for two different IRS horizontal resolutions.

### a. Hurricane Isabel Storm Area

<table>
<thead>
<tr>
<th>Configuration</th>
<th>3-km FOV Sounder</th>
<th>6-km FOV Sounder</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3-km FOV Sounder</td>
<td>6-km FOV Sounder</td>
</tr>
<tr>
<td></td>
<td>Pair (3-km by 6-km) C.C. Processing Domain</td>
<td>Pair (6-km by 12-km) C.C. Processing Domain</td>
</tr>
<tr>
<td>Imager Clear FOV Number</td>
<td>Imager Resolution</td>
<td>Imager Resolution</td>
</tr>
<tr>
<td></td>
<td>1-km</td>
<td>2-km</td>
</tr>
<tr>
<td>≥ 1</td>
<td>14.4</td>
<td>---</td>
</tr>
<tr>
<td>≥ 2</td>
<td>13.0</td>
<td>---</td>
</tr>
<tr>
<td>≥ 3</td>
<td>12.0</td>
<td>---</td>
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<tr>
<td>≥ 4</td>
<td>10.9</td>
<td>---</td>
</tr>
<tr>
<td>≥ 5</td>
<td>10.2</td>
<td>---</td>
</tr>
</tbody>
</table>

### b. Hurricane Isabel Environment

<table>
<thead>
<tr>
<th>Configuration</th>
<th>3-km FOV Sounder</th>
<th>6-km FOV Sounder</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>3-km FOV Sounder</td>
<td>6-km FOV Sounder</td>
</tr>
<tr>
<td></td>
<td>Pair (3-km by 6-km) C.C. Processing Domain</td>
<td>Pair (6-km by 12-km) C.C. Processing Domain</td>
</tr>
<tr>
<td>Imager Clear FOV Number</td>
<td>Imager Resolution</td>
<td>Imager Resolution</td>
</tr>
<tr>
<td></td>
<td>1-km</td>
<td>2-km</td>
</tr>
<tr>
<td>≥ 1</td>
<td>31.0</td>
<td>---</td>
</tr>
<tr>
<td>≥ 2</td>
<td>30.1</td>
<td>---</td>
</tr>
<tr>
<td>≥ 3</td>
<td>29.4</td>
<td>---</td>
</tr>
<tr>
<td>≥ 4</td>
<td>28.6</td>
<td>---</td>
</tr>
<tr>
<td>≥ 5</td>
<td>28.0</td>
<td>---</td>
</tr>
</tbody>
</table>
Although, the total yield of clear fields of view within the cloudy storm region is relatively low, the yield improves by a factor of two, or more, for an imager horizontal resolution improvement from 3- to 1-km. The yield of clear fields of view, when expressed as a percentage of the total number of possible, does not decrease significantly when transitioning from the IRS 6 km resolution down to its 3 km sounding resolution. This is significant in that there are four times as many fields of view for the 3 km resolution case than for the 6 km resolution case. Thus, there will be nearly a four times greater density of clear and cloud-cleared radiance spectra and soundings when operating the IRS at the 3 km midwave and shortwave channel horizontal resolution rather than when operating it at the 6 km longwave horizontal resolution. Note also that the improvement in imager clear radiance yield for the 6 km sounder resolution case increases more when the imager resolution transitions from 2 km to 1 km, than it does when the resolution transitions from 3 km to 2 km. This result indicates that it is desirable to have the highest horizontal resolution imager achievable is desired.

(b) Cloud-clearing Accuracy Dependence on Imager Spectral Characteristics: The minimum number of spectral channels desired for the imager is defined here using AIRS spectra, as a surrogate for IRS spectra, and different MODIS channel combinations to simulate different possible MTG IRS imager channel characteristics. Here, seven possible imager channel configurations are considered, as shown in Table VIII below.

<table>
<thead>
<tr>
<th># of Bands</th>
<th>MODIS Channels</th>
<th>Channel Central Wavelengths (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>22, 31, 33</td>
<td>4.0, 11.0, 13.4</td>
</tr>
<tr>
<td>4</td>
<td>22, 25, 31, 33</td>
<td>4.0, 4.5, 11.0, 13.4</td>
</tr>
<tr>
<td>5</td>
<td>22, 25, 28, 31, 33</td>
<td>4.0, 4.5, 7.4, 11.0, 13.4</td>
</tr>
<tr>
<td>6</td>
<td>22, 25, 28, 31, 32, 33</td>
<td>4.0, 4.5, 7.4, 11.0, 12.0, 13.4</td>
</tr>
<tr>
<td>7</td>
<td>22, 24, 25, 28, 31, 32, 33</td>
<td>4.0, 4.4, 4.5, 7.4, 11.0, 12.0, 13.4</td>
</tr>
<tr>
<td>8</td>
<td>22, 24, 25, 28, 31, 32, 33, 34</td>
<td>4.0, 4.4, 4.5, 7.4, 9.7, 11.0, 12.0, 13.4, 13.7</td>
</tr>
<tr>
<td>9 (Reference)</td>
<td>22, 24, 25, 28, 30, 31, 32, 33, 34</td>
<td>4.0, 4.4, 4.5, 7.4, 11.0, 12.0, 13.4, 13.7</td>
</tr>
</tbody>
</table>

The strategy for performing clear column radiance calculations is to use imager window channels to define the cloud clearing parameters, \(N^*\), and weakly absorbing sounding channels to quality control the cloud-cleared radiance spectra, as was described in section 6.2. The paired field of view sampling strategy, which was used here with AIRS, and would most likely be similar to that to be used with the MTG IRS, is depicted in Figure 11, below. As shown in Figure 11, a 3 x 3 array is used to estimate a central sounder field of view clear sky radiance, using its eight closest neighbor fields of view to form eight adjacent pairs for the cloud clearing. Thus, up to eight independent estimates of the clear sky radiance are obtained for each sounder field of view. Each adjacent pair estimate is evaluated by comparing the observed imager radiances with those obtained by SRF convolution of the cloud-cleared spectrum for each adjacent pair. That pair which provides the closest agreement between the observed imager and sounder predicted imager clear sky channel radiances, in a RMS difference sense, is taken as the optimal pair for specifying the clear sky radiance spectrum for the central field of view of the sounder.
Figure 11. Sounder field of view configuration used for cloud clearing.

The Quality Control (QC) criterion used for cloud clearing was described in section 6.2. For a cloud-cleared radiance spectrum to be considered acceptable, the RMS difference between the sounder cloud-cleared radiances, spectrally convoluted to imager spectral channels, and the observed imager clear air radiances must be less than that difference expected to result from measurement noise. The quality control use of the imager data is most important for defining accurate clear radiance spectra from which high quality soundings can be determined. The importance of QC is shown in Figure 12, which shows difference in the scatter of AIRS predicted, using the “operational” microwave (AMSU) based cloud clearing radiance scheme, vs. MODIS observed clear sky brightness temperature for the AIRS fields of view. The two cases illustrated are, (1) where MODIS 11 µm window radiance QC control is imposed and (2) where no imager radiance QC is imposed on AIRS cloud-cleared brightness temperature spectra. As can be seen from Figure 12, the scatter between observed and estimated (i.e., cloud-cleared) clear air brightness temperature for water vapor and temperature sounding channels are greatly reduced using the imager window radiances to QC the cloud-cleared radiance product. In the case of the MTG, which will not possess a microwave instrument for the determination of N*, imager window channels will be used to define N* and weak absorption sounding channels will be used to QC the cloud-cleared radiance spectra results. In either case, it is obvious that using imager radiances to QC the derived sounder cloud-cleared radiance spectra is essential for producing reliable sounding products from a hyperspectral infrared sounder under partly cloudy sky conditions.

Figure 13, below shows, for each of the four AIRS/MODIS data granules shown in Figure 7, the results obtained from cloud clearing AIRS data using the 7 different MODIS channel configurations considered here for the MTG IRS built-in, or companion, imager (Table VIII). The results are presented for the AIRS central field of view used for the cloud clearing (see Figure 11), in terms of the standard deviation of the brightness temperature difference between
the AIRS spectrally convoluted cloud-cleared radiance, for each MODIS channel, and the actual MODIS observed clear radiance, for each channel.

Figure 12. Comparison of the scatter of operational AIRS cloud cleared brightness temperature vs. MODIS observed clear sky sounding channel brightness temperature, “without” (left side of Figure 12) and “with” (right side of Figure 12) MODIS 11.0 µm window channel QC of the AMSU enabled cloud-cleared AIRS radiance results.

The results shown in Figure 13 indicate that, as a minimum, a 4-band IR imager is desired for the MTG IRS imager. More accurate cloud-clearing results are achieved with a 5-band or 6-band imaging radiometer. The three-band configuration produces excessive cloud-cleared radiance errors across most of the spectrum, particularly for the shortwave spectral regions where there is a lack of a sounding channel for QC. One can see from Table VIII why the four-band configuration performs quite well. In this configuration both shortwave and longwave window channels are available for the determination of a longwave and shortwave band cloud clearing parameter, N*, as well as the availability of weak absorption sounding channels in both the shortwave and longwave spectral regions to QC the final cloud-cleared radiance spectrum product. However, there is a considerable improvement in the water vapor spectral region using the 5-band or 6-band configuration since, in this case, a sounding channel is also available to QC the midwave water vapor region of the spectrum. The improvement in the midwave spectral region would presumable enhance the retrieval of water vapor profiles, as shown below.
Figure 13. The standard deviation between AIRS cloud-cleared brightness temperature, spectrally convoluted to MODIS channels, and actual MODIS observations of clear air brightness temperature.

(c) Sounding Retrieval Accuracy Dependence on Imager Spectral Characteristics: In order assess the impact of the imager spectral characteristics, the cloud-cleared radiance results for the four AIRS/MODIS data granules considered here were used to produce atmospheric soundings using the statistical Eigenvector retrieval method. Here, the retrievals were validated using the retrieval obtained from the closest neighboring AIRS clear sky radiance spectrum. Figures 14 and 15 show the results of the cloud-cleared radiance derived temperature and moisture profile retrievals, respectively, for the four different AIRS/MODIS data granules. For both temperature (Figure 14) and water vapor (Figure 15), the 6-band configuration, which includes two longwave window channels (11 µm and 12 µm), a shortwave window (4 µm), and three weak absorption sounding channels (4.5 µm, 7.4 µm, and 13.4 µm) produces consistently good results in all cases, with the 4 and 5 band configurations giving somewhat erratic, case dependent, results. If one is limited for other reasons to either a 4 or 5-band configuration imager, there does not seem to be any strong basis, from the temperature and moisture profile retrieval results, to select a 5-band instrument over a 4-band instrument.

Note that the sounding retrieval accuracy under partly cloudy (i.e., for cloud-cleared radiance spectra) conditions is relatively poor (i.e., temperature errors exceed 1 K) within the surface boundary layer below the 3 km (i.e., 700 mb) level. This is particularly true for the South African land scene (G-126). This is due in part to the fact that there are near surface gradients of temperature and moisture between the geographical positions of where the cloud-cleared radiances were determined and the locations of the cloud-free radiance measurements used to
Figure 14. RMS deviation between temperature profile retrievals obtained using AIRS cloud-cleared radiances from AIRS retrievals obtained from neighboring clear air radiance spectra.
Figure 15. RMS deviation between water vapor absolute humidity profile retrievals obtained using AIRS cloud-cleared radiances from AIRS retrievals obtained from neighboring clear air radiances spectra.
validate the retrievals. Another likely reason for the relatively large discrepancy near the surface is that the cloud clearing process tends to inflate radiance measurement noise to a degree dependent on the sensitivity of the sounder spectral channel’s radiance to cloud contributions. However, the direct use of the imager’s cloud-free radiances directly in the sounding retrieval process might reduce these errors to a tolerable accuracy. The degree to which near surface retrieval errors can be minimized through the direct use of the imager’s cloud-free radiances in the sounding retrieval process is discussed further below.

Since the 6-band MODIS AIRS profile retrieval results (Figures 14 and 15) are consistent with the MODIS clear air brightness temperature validations (Figure 13), it is recommended here that the imager to be used with the IRS include, at least, 6 infrared channels: 4.0 µm, 4.5 µm, 7.4 µm, 11.0 µm, 12.0 µm, and 13.4 µm. It is important to note that this configuration is also useful for nowcasting applications of the data at the full 1 km imager horizontal resolution. For example, the 6-band imager is composed of a longwave split window (i.e., 11.0 µm and 12.0 µm) used for surface temperature retrieval, the 11.0µm window and 13.4µm CO₂ channel combination used for cirrus cloud motion wind vector altitude assignment, and the low level temperature channels (4.5µm and 13.4µm), which when combined with the mid-level water vapor channel (7.4 µm), provides convective instability indices, all at the very high imager horizontal resolution. The simultaneous use of the shortwave and longwave window channels (4.0 µm and 11.0 µm) also enables the detection of high altitude thin cirrus and low altitude stratus cloud contamination of the imager’s 1 km field of view. Such cloud contamination is difficult to detect without simultaneous measurements in these two spectrally separated infrared window regions of the spectrum. Thus, the 6-bands used for the MTG IRS cloud clearing can also contribute to the achievement of the entire meteorological mission objectives of the MTG.

In order to investigate the accuracy and yield dependence of cloud clearing accuracy on the horizontal resolution of the imager and sounder, MODIS data was spatially convoluted to different field of view sizes. The optimal 6 0-band imager configuration defined above was used for the cloud clearing. Here channels 22 (4.0 µm) and 31 (11.0 µm) are used to obtain a shortwave and longwave spectral region N*, respectively, and MODIS channels 24 (4.4 µm), 25 (4.5 µm), 28 (7.4 µm) 32 (12.0 µm), and 33 (13.4µm) were used for quality control. Thus, in the results to be shown, channels 27 (6.8 µm), 29 (8.6 µm), 30 (9.7 µm), 34 (13.7 µm), 35 (13.9 µm), and 36 (14.2 µm) are independent spectral channels used here for validating the accuracy of the cloud clearing process.

Figure 16 shows the accuracy for cloud clearing radiances using a 6-channel imager, at various horizontal resolutions, for the IRS 6 km horizontal resolution. As can be seen the biggest impact of horizontal resolution is on the yield of sounder cloud-cleared radiances, increasing from 5 %, for the 3-km resolution imager, to 16 %, for the 1 km resolution imager. Thus, a three-fold increase is observed. Although the total yield of successful cloud-cleared radiance is relatively small, even for 1 km resolution imager (i.e., ~16%), these partly cloudy fields of view are presumably important, considering that they are observed in the hurricane environment. It is also seen that there is little dependence of the accuracy of the cloud-cleared radiances on imager horizontal resolution. Thus, the quality control exercised in the cloud-clearing process preserves the accuracy of the cloud-cleared radiance results for the poorer imager resolution case, although at the expense of the yield of accurate cloud-cleared radiances.
Figure 16. Cloud-cleared radiance accuracy and yield dependence on imager horizontal resolution.

Figure 17 shows the cloud-cleared brightness temperature accuracy and yield dependence on sounder horizontal resolution assuming the use of the optimal six-channel 1 km horizontal resolution imager for the sounder radiance cloud-clearing process. As can be seen, the quality control exercised in the cloud-clearing process tends to preserve the accuracy of the results, independent of sounder field of view size. Here, the percentage yields of accurate cloud-cleared radiance, relative to the number of FOV pair attempts, increase from about 13% for a 4 km resolution sounder, to 20% for a 10-km resolution sounder. This result is expected because the probability of a sounder FOV being partly cloudy, as well as the probability of obtaining cloud-free imager radiances within a partly cloudy sounder field of view, increases with sounder field of view size. However, what is important in this case is that the actual density of accurate cloud-cleared sounding radiances increases rapidly with the horizontal resolution of the sounder, at a
rate equal to that expected for completely cloud-free conditions (i.e., a rate inversely proportional to the square of the instrument’s linear horizontal resolution). For example, in the hurricane Isabel storm area, there are only 57%, 35%, and 26% of the cloud-cleared radiance soundings possible for the 6-km, 8-km, and 10-km field of view cases as there are available for the 4-km sounder resolution case. As a consequence, even though the percentage of accurate cloud-cleared radiances, relative to the total number of FOV pairs, decreases with increasing sounder horizontal resolution, the sounding density still increases inversely with the FOV size. Thus, in addition to the fact that the percentage yield of direct observations of clear sky observations with the sounder will result from a smaller sounder field of view size, as shown earlier in this report, the resulting density of cloud-cleared radiance soundings also increases dramatically with increasing sounder horizontal resolution. Thus, it is desired that IRS sounder horizontal resolution be as high as is practical.

(d) Use of Imagery Radiances in Cloudy Sounding Retrieval: As can be seen from the “hole-hunting” statistics (Table III and VII) and the cloud-cleared radiance yield statistics (Figs 10 and 17), there will be many cloud situations for which accurate clear radiances for the IRS cannot be defined. In these cases, an algorithm is required, which treats the cloud explicitly in the sounding retrieval process (22). With the treatment of cloud explicitly in the sounding retrieval process, the cloud height is determined and the retrieval is obtained accurately down to the cloud top level and below an optically thin or broken cloud (effective cloud optical depth less than 1). The actual microphysical properties of the cloud are also taken into account by the cloudy sky forward radiative transfer model used in the retrieval process. This retrieval methodology has been validated using NAST-I data (22) and is considered to be very important for being able to achieve sounding retrievals for every IRS field of view, regardless of cloud cover and complexity, so that dynamic variables of the atmospheric state (e.g., water vapor flux and wind velocity profiles) can be determined. In the case of the explicit cloud retrieval, there will be two extreme cases, the opaque cloud overcast case and the case where broken cloud exists in which case imager sounding channel radiances could be used as part of the retrieval process to provide information below cloud level. These two extreme cases have been simulated for a very diverse global annual set of sounding conditions for the AIRS and MODIS spectral measurement characteristics, which closely represent the spectral measurement characteristics of the MTG IRS and Full Disk High Spectral resolution Imager (FDHSI). Figure 18 shows the results of eigenvector regression retrievals performed with this set of radiances for the cases where the clear sky imager radiances are used, and not used, in the retrieval process, which simulates complex broken cloud and overcast cloud conditions, respectively. It is important to note that RMS errors shown here for the clear and broken cloud cases are at least 50% larger than those which would be obtained if regionally and seasonally stratified statistics, rather than global annual statistics, were used for the EOF retrievals. Also, the retrieval error can be reduced further by employing a non-linear variational (i.e., physical matrix inverse) retrieval step in the retrieval process (26). In spite of the limitation of the retrieval method used here, the clear sky retrieval accuracy, for this diverse set of atmospheric conditions, serves as a reference to judge the relative accuracy of the cloudy sky retrievals. Also, it is important to note that the retrieved profiles below the overcast cloud (i.e., as shown in the AIRS only retrievals) result solely from a
statistical extrapolation provided by the eigenvector regression method.

Figure 18. Errors of soundings obtained from radiances simulated for broken cloud (AIRS plus MODIS) and opaque overcast cloud (AIRS only) conditions, obtained using the cloud explicit retrieval method. Results for different cloud altitudes and for clear sky conditions are shown.

As expected, for broken cloud conditions there is considerable improvement in the accuracy of the retrieval below cloud level when the clear sky imager radiances are used, in addition to the cloud contaminated sounding instrument radiances, in the retrieval process.

In summary radiances observed with a high horizontal resolution imaging radiometer can help improve the coverage, yield, and accuracy of the soundings to be obtained from the IRS in several ways: (1) detecting cloud contaminated sounder fields of view, (2) providing cloud free window and broad band atmospheric sounding channel radiances as needed to cloud-clear partly clouded sounding field of view radiances, (3) provision of clear sky sounding radiances under complex broken cloud conditions, which can be used with cloud contaminated sounding instrument radiances to produce accurate profiles down to cloud level and to extend the soundings below a level of broken cloud. The quality of the soundings below cloud level will depend on the fraction and optical depth of the cloud cover. It is also important to note that an imager, such as the MTG FDHSI, can also be useful for defining the surface skin temperature and emissivity and cloud height and cloud optical property conditions as needed for optimizing the sounding retrieval accuracy for cases where cloud clearing cannot be used.

8.0 Co-registration Correction

The data from an imager might also be used to correct the hyperspectral sounder data for pseudo-noise resulting imprecise co-registration of the detector elements used to obtain the different spectral radiance measurements.

Background: High vertical resolution sounding, using hyperspectral radiance observations, depends upon having very high spectral fidelity in the measurement of the spectrum of Earth
outgoing radiance. Vertical variations in atmospheric temperature and moisture produce very small subtle variations in the spectrum of Earth outgoing radiance, the narrower the vertical layer over which these variations occur, the smaller the feature in the measured radiance spectrum. Also, because the retrieval of atmospheric profiles from Earth outgoing radiance measurements is an inherently unstable numerical process, small amounts of noise on the observed spectrum must be dampened to avoid erroneous oscillatory structure in the retrieved profiles, the degree of dampening required being dependent on the degree of spectrally random radiance noise. The dampening of spectral radiance noise also acts to dampen small spectral signatures of atmospheric vertical structure. As a consequence, the retrieval of small vertical scale atmospheric features depends upon having very high spectral radiance measurement precision in the observation of the Earth outgoing radiance spectrum.

Besides the spectrally random component of detector noise and radiometric calibration error, the greatest potential source of spectral radiance noise, which can result in a dispersion spectrometer, is the pseudo-noise resulting from the use of different detector elements for observing different spectral radiances. The pseudo-noise results from the fact that the fields of view of different detector elements cannot be perfectly co-registered due to the spectral dependence of optical distortion and practical limitations of detector element placement, both of which impact the alignment of the effective optical axes of the different spectral channels.

As an example, the AIRS is a very well calibrated and stable hyperspectral resolution spectrometer designed to provide high vertical resolution sounding information from the Aqua Polar orbiting satellite for the purpose of improving global numerical weather prediction. However, a problem with the spectral fidelity of AIRS exists when viewing non-uniform scenes as a result of using multiple detectors for observing the atmospheric radiance spectrum. Because the fields of view of the various detector elements are not perfectly co-registered, noise is introduced into the AIRS spectra when viewing non-uniform scene conditions (e.g., clouds, land surface features, and strong atmospheric gradients) since the spectral radiances observed do not arise from exactly the same scene.

In the case of AIRS, the fields of view (FOV) observed by the various detectors used for constructing the spectrum can be displaced from each other by significant percentages of a FOV size. The AIRS optical axis data shown in Figure 19 below implies that up to 15 % co-registration error, along a single direction, can occur. For uniform scene conditions (i.e., open ocean), imprecise co-registration of the various spectral channels is not a problem, but for non-uniform scenes (i.e., land, clouds, fronts., etc.) errors can result which are much larger than the very small detector noise required for high vertical resolution sounding retrieval. Examples of spectral artifacts in several AIRS observed radiance spectra are shown in Figure 20 below. Although the effects of co-registration errors might be minimized by horizontal re-sampling, or averaging, the data, these processes inherently reduce the horizontal resolution of the data, a very undesirable impact for the geostationary sounder where the highest achievable horizontal resolution is desired. In the case of AIRS data being used to initialize a relatively coarse resolution numerical model, data where significant horizontal radiance gradients exist due to clouds or surface feature variations can be discarded, assuming these condition can be detected (e.g., using MODIS data). However, for the geo-sounder (i.e., the MTG-IRS), the lack of co-registration between spectral channels, if uncorrectable, would cause severe limitations of the
applications of the data. Soundings are needed for nearly every FOV in order to meet the objective to observe atmospheric dynamics using time animated 3-dimensional images of the atmosphere. Most important, the geostationary sounding observations are most useful in the strong horizontal gradient regions where weather is occurring or about to develop. Thus, if the co-registration pseudo-noise cannot be accurately corrected, the dispersion spectrometer design for an IRS cannot be used to meet the objectives of the MTG atmospheric sounder.

The imaging FTS approach (e.g., GIFTS) does not have a co-registration problem with the severity of that encountered for the dispersion instrument. With an imaging FTS, each detector element of a focal plane defines a different geographical field of view rather than a different spectral channel, as in the case of the dispersion spectrometer. With the imaging FTS, large portions of the same spectral region (i.e., very broad spectral bands) are observed with each detector element of the focal plane, thus, all the spectral measurements obtained with the same detector element, within a focal plane, possess the same geometric FOV. However, the co-registration of the several focal planes used to cover the entire spectral domain desired is an issue for cloud-clearing and subsequent atmospheric profile retrieval. In the absence of a means to correct the data for radiance variations due to FTS focal plane co-registration error, the focal planes for each spectral band should contain semi-transparent spectral regions, from which the observed “window” radiances can be used to cloud clear each spectral band independently. The window data from each spectral band can be used to account for spectral band radiance differences resulting from strong horizontal variations in surface temperature, and/or emissivity, in the sounding retrieval or radiance assimilation process.

Figure 19: Optical axes for the AIRS detectors obtained from pre-launch characterization measurements. The nominal FOV size of the AIRS is about 1100 millidegrees (i.e., 1.1 degrees).
Figure 20. Examples of spectral artifacts in AIRS spectra resulting from detector co-registration errors when observing a non-uniform atmospheric scene.

**Co-registration Error Correction Algorithm:** Space and time simultaneous radiance observations from a high horizontal resolution multi-spectral imager, which possess spectral channels across the spectral domain of the sounder, might be used to correct the sounding spectrometer data for the different fields of view observed by each spectral channel (e.g., as obtained with a dispersion instrument) or spectral band (e.g., as obtained with an imaging FTS). For example, in the case of AIRS, MODIS data might be used to correct for such errors. As was shown previously in Figure 6 (section 5.2), the MODIS channels cover most of the spectral domain observed with the AIRS. Since the MODIS possesses 1 km horizontal resolution, as opposed to the nominal 15 km horizontal resolution of the AIRS, the MODIS data might be used with the pre-launch characterization of the AIRS detector optical axes to estimate the variation on the AIRS radiances due to the co-registration differences of the various AIRS detectors (Figure 19). The Algorithm for performing this correction consists of spatially convoluting the MODIS data using the AIRS spatial response functions determined from pre-launch characterization measurements. Using regression relations, derived from theoretical simulations of AIRS and MODIS spectral channel radiances for representative surface and atmospheric conditions, horizontal variations of AIRS spectral channel radiances can be predicted from observed horizontal variations of the multi-spectral MODIS channel radiances, which have been spatially convoluted to the AIRS FOV. In order to use these relations to correct the actual AIRS spectral channel radiance co-registration error for a particular scene condition, MODIS radiances, spatially convoluted to the nominal AIRS FOV, are obtained by shifting the AIRS FOV by one, or more, MODIS scan line forward and one, or more, MODIS scan line behind (i.e., a MODIS scan line shift along the Y-axis of the AIRS instrument) and one, or more, MODIS scan element to the left and one, or more, MODIS scan element to the right (i.e., a MODIS scan element shift along the X-axis of the AIRS instrument) thereby providing spatial derivatives of the spatially convoluted MODIS radiances along both the X and Y axes of the
AIRS instrument. An estimate of the spatial derivatives of the actual AIRS measurements for each AIRS spectral channel is then obtained by applying the predetermined regression relationship between the AIRS spectral radiances and MODIS spectral channel radiances. Thus, the derivative of the AIRS spectral radiance with respect to the X and Y optical axes can estimated, for each AIRS spectral channel, from the MODIS high horizontal resolution radiance observations. A co-registration error corrected AIRS spectral radiance is then determined by adjusting the measured AIRS radiance for each spectral channel using the MODIS observed X and Y axis derivatives and the pre-defined optical axis displacement data.

It is noted that a potentially improved alternative to using the pre-launch optical axis displacement data shown in Figure 19, is to use an empirically determined effective optical axis displacement for each AIRS spectral channel. The effective optical axis displacement can be specified empirically from a statistical analysis of global samples of AIRS and spatially convoluted MODIS data that is shifted in steps of one MODIS scan line and/or scan element along the X and Y-axes of the AIRS instrument. The effective optical axes for each AIRS spectral channel is defined as that MODIS displacement, from a nominal optical axis, which minimizes the difference between the actual AIRS radiances and the MODIS predicted AIRS channel radiances over the global population of measurement samples.

Analytically, the AIRS data corrected for spatial co-registration errors is given by,

\[ R_{\text{airs}}(\nu_j,x_o,y_o) = R_{\text{airs}}(\nu_j,x,y) - \sum a_{ij} [(x-x_o)dR_{\text{MODIS}}(\delta
\nu_i)/dx +(y-y_o)dR_{\text{MODIS}}(\delta
\nu_i)/dy] \]

(7)

where \( R_{\text{airs}}(\nu_j,x_o,y_o) \) is the spatially corrected AIRS spectral radiance for the spectral channel \( \nu_j \), \( R_{\text{airs}}(\nu_j,x,y) \) is the original AIRS spectral radiance measurement, \( a_{ij} \) is regression coefficient relating the MODIS radiance for spectral channel, \( \delta
\nu_i \), to the AIRS spectral channel \( \nu_j \), \( x-x_o \) and \( y-y_o \) are the effective X and Y axis displacements (i.e., co-registration errors) for the AIRS spectral channel \( \nu_j \), and the summation (i.e., \( \sum \)) is to be taken over all appropriate MODIS channels.

Although this methodology is computationally intensive, the corrections may not provide the accuracy needed as a result of the finite spectral and horizontal resolution of the imaging radiometer. However, it is worth investigating this approach as a potential means to alleviate the otherwise negative impact of pseudo-noise caused by imperfect co-registration of detector elements in a dispersion instrument approach for the MTG IRS. AIRS and MODIS observations can be used to develop and validate the algorithm described here. The dependence of the accuracy of the co-registration noise correction on the number and spectral characteristics of the imager channels needs to be investigated in order to properly specify the requirements for the MTG.

It is also re-emphasized that even though co-registration error is not a serious issue for an imaging FTS approach for the MTG IRS instrument, the high horizontal resolution imaging instrument data is still needed for accurate hole hunting and cloud-clearing, as discussed earlier.
9.0 Landmark Navigation

Precise geostationary satellite orbit and attitude determination is required to estimate water vapor flux, wind velocities, and gaseous pollution transport from a time sequence of cloud and water vapor imagery. The orbit and attitude determinations are made using range, star, and landmark measurements. The imager can make landmark navigation observations during its normal scan of the Earth. The instrument attitude is determined from the landmark and star observations. The precision to which imagery products can be navigated, using landmarks, is a function of the horizontal resolution of the instrument, as well as the knowledge of the spacecraft orbit and attitude. A model is used to predict the spacecraft and instrument orbit and attitude parameters for the navigation of future imagery. The satellite and instrument orbit and attitude model parameters are normally updated and transferred to the spacecraft on a daily basis. As a consequence, it may be highly desirable for the MTG-IRS to possess a high horizontal resolution built-in imager to enable precise landmark navigation of the sounding products for the purpose of determining dynamical atmospheric variables. However, the requirement for a built-in imager for this purpose ultimately depends on the quality of the instrument and spacecraft attitude control system.

10.0 An optimized FTS Approach for obtaining the “Built-in Imager” Data

An FTS design approach provides an efficient means for obtaining imager data within the IRS system. For this purpose, the instrument is designed to use a large area format IR detector array with a large diameter imaging telescope from which both a high spectral resolution sounding and high horizontal resolution imaging data is achieved simultaneously with the same instrument. On-board processing enables the external imaging and sounding data rate to be an order of magnitude, or more, lower than the internal data rate, as needed for telemetry of the data to the ground. The detector readout system would be designed to send the interferogram data for all the high horizontal resolution pixels to an onboard processor where they would be spatially averaged for providing the high spectral resolution sounding information. The single spatial sample/single spectral sample signal to noise of the spatially averaged high spectral resolution radiance data would be enhanced by the square root of the number of detector pixels averaged to produce the lower horizontal resolution sounding radiance spectra. The imaging data would be analyzed for every detector pixel but only for a small interval of the interferogram near Zero optical Path Difference (ZPD). The single spatial sample/single spectral sample signal to noise ratio for the imaging spectral channel radiances would be enhanced as a result of the lower spectral resolution of the imagery radiances achieved by limiting the interferogram length used to determine the radiance spectrum. For example, the sounding observations could be produced with an interferogram length extending between ± 0.8 cm (δν = 0.6 cm\(^{-1}\)) with the interferogram signals being averaged over a 4 x 4 (=16) array of detector array pixels. The imagery observations could be produced with an interferogram length of ± 0.05 cm (δν = 10 cm\(^{-1}\)) sampled at the full horizontal resolution of the detector array. For this case, exactly the same signal to noise will be achieved for the high spectral resolution, but low horizontal resolution, sounding radiances as is achieved for the high horizontal resolution, but low spectral resolution, imaging radiances. Both the imagery and sounding data are provided simultaneously during a signal scan of the Michelson mirror. If each detector element resolves a 1 km field of view, then for this case the imaging radiances would have 1 km horizontal resolution while the sounding
radiances would have 4 km horizontal resolution. If it desirable to increase the area coverage per unit time or the refresh rate of the imaging and/or sounding data (e.g., to obtain full disk imagery and/or to obtain wind profiles for global NWP model initialization), this can be accomplished by merely shortening the length of the interferogram scan. On the other hand, if it is desirable to obtain full spectral resolution radiance spectra with the full 1 km horizontal resolution of the sensor (e.g., for atmospheric chemistry measurements), this can be done by merely leaving the scene scan mirror in a fixed position for multiple scans of the Michelson mirror (16 in this example in order to preserve signal to noise), co-adding all the interferograms obtained during the enhanced dwell time of the system. For rapid scan imagery, the interferogram length can be made as short as necessary in order to achieve very rapid partial, or full disk, coverage, the time required to sample the Earth’s disk being limited by the step time of the scene mirror.

The IRS could be designed with the flexibility needed to trade spectral resolution with horizontal resolution dynamically in orbit, rather than possessing one fixed trade as described here. This flexibility would optimize the IRS performance for a wide variety of applications. These applications range from localized storm development or pollution episode detection and dynamics to global wind profile measurements for the initialization of global numerical weather prediction models.

11.0 Summary and Recommendations

**Summary:** This report presents results of trade studies conducted to define the dependence of MTG IRS cloud-cleared radiance accuracy and sounding retrieval accuracy on imager horizontal resolution and infrared spectral characteristics, as well as the horizontal resolution of the IRS. The study was performed using both aircraft NAST and Aqua satellite AIRS and MODIS instrument data. The yield of cloud-cleared radiances was determined as a function of imager horizontal resolution for both the 3 km and 6 km horizontal resolutions defined for the IRS. In order to determine the appropriate spectral channels required for an IRS built-in imager, AIRS/MODIS cloud clearing was performed for seven different infrared channel options of the MODIS, ranging from a minimal three IR channel imager to a full nine IR channel imager. The accuracy dependence of the cloud-cleared radiances was assessed on the basis of comparisons of cloud-cleared AIRS radiance spectra, convoluted to MODIS spectral channels, with actual observed clear MODIS radiance observations. The sounding accuracy dependence on imager channel characteristics was defined by performing temperature and moisture profile retrievals with the AIRS cloud-cleared radiances, obtained for the different imager options. The retrievals were compared with soundings derived from neighboring cloud free AIRS radiances. MODIS data was also used to define the horizontal resolution requirements for the imager to be used to assist the IRS data processing. Here the performance and yield of cloud-cleared radiances as a function of imager field of view size was defined assuming sounder linear horizontal resolutions of 3 and 6 km. As expected, the yield of reliably determined cloud-cleared radiances increased with the imager’s horizontal resolution. For a relatively cloudy hurricane atmospheric scene, the yield of accurate cloud-cleared radiances improved by a factor of 2, or more, as the imager’s linear horizontal resolution improved from 3 km to 1 km. Next, assuming the adoption of a 1 km horizontal resolution imager, the impact of sounder horizontal resolution on cloud-clearing accuracy and yield was defined. Here, MODIS sounding channel data was spatially convoluted to 4 km, 6 km, 8 km, and 10 km to simulate IRS measurements at these different horizontal resolutions.
resolutions. It was shown that the accuracy of the product was relatively independent of sounder horizontal resolution, given 1 km horizontal resolution imagery data for the processing. Although the percentage yield of accurate cloud-cleared radiance determinations decreases with increasing sounder horizontal resolution, since the probability of obtaining clear field of view imager data required for the cloud clearing process decreases with increasing sounder horizontal resolution, the total density of cloud-cleared radiance soundings increases greatly with increasing sounder horizontal resolution. Finally, it is shown by way of radiance simulation, that for the cases of complex partly cloudy cloud sky conditions, where the cloud-clearing process fails, cloud-free radiances observed with a high horizontal resolution imager can be used directly with cloud contaminated sounding instrument radiances (i.e., without cloud-clearing) in the sounding retrieval process to retrieve atmospheric profile information below cloud level. However, the vertical resolution of the profile retrieval achieved below cloud level will depend on the number of imager sounding channels available to be used in the sounding retrieval process, as well as the height and fractional cloud cover of the partially clouded scene.

The results of this study show that an imager, to provide data useful for cloud-clearing IRS radiance measurements, should possess as high a horizontal resolution as practically possible, preferably 1 km, or smaller, in footprint diameter, and contain both broad spectral band absorption, as well as “window” channels. The number of IR spectral channels desired is six, consisting of two longwave window channels (11 µm and 12 µm), a shortwave window channel (4 µm), and three weakly absorbing sounding channels (4.5 µm, 7.4 µm, and 13.4 µm). These channels enable accurate definition of the cloud clearing parameter, N*, for both the longwave and shortwave spectral regions, and provide effective quality control of the derived cloud-cleared radiance spectra, as needed to produce reliable atmospheric soundings under partially clouded sky conditions. As expected, the relatively large profile retrieval errors occur below cloud levels in the surface boundary layer below an altitude of 3 km (i.e., 700 mb). These profile retrieval errors, believed to result from noise amplification produced by the cloud-clearing process, can be minimized by including the 6-band imager observed clear sky radiances directly into the IRS sounding retrieval process. Also important, the radiance data provided by the 6-band imager will permit the specification of cloud height, surface temperature, and convective instability, at 1 km horizontal resolution, for nowcasting applications of the MTG IRS/imager data.

**Recommendations:**

1. A built-in, or companion, multi-spectral imager can provide data useful for optimizing the extraction of surface and atmospheric information from the MTG-IRS. Data from a multi-spectral imager can be used to increase the reliability of the sounding information in meteorologically active areas where clouds and temperature and moisture gradients exist. **It is recommended that the data from a built-in, or companion, imager be considered for use in the processing of MTG IRS data.**

2. It was shown that data from an imager with 1 km horizontal resolution and six spectral channels could be used to optimize the extraction of clear air radiance information from partly cloudy hyperspectral sounding observations.
It is recommended that the imager, used to support the MTG IRS data processing, possess at least six (6) appropriate spectral channels and have a 1 km horizontal resolution.

(3) In the case of the selection of a dispersion spectrometer approach for the IRS, a built-in imager may be needed to correct the sounding radiances for artifacts (i.e., pseudo-spectral noise) resulting from the imprecise co-registration of the fields of view of the various detector elements used to observe the radiance spectrum. An algorithm for doing this has been formulated but the accuracy of the correction achievable needs to be defined. The dependence of the accuracy of the co-registration error correction on imager spectral channel characteristics also needs to be determined.

It is recommend to investigate the use of multi-spectral radiance data from a built-in, or companion, imager for reducing the pseudo-spectral radiance noise associated with a dispersion spectrometer approach for the IRS.

(4) A built-in imager would enhance the navigation accuracy of the IRS derived product imagery used to define dynamic variables, such as the water vapor flux, wind profile, and the transport of pollutant gases. The ultimate requirement for a built-in imager for this purpose depends upon the MTG IRS instrument and spacecraft attitude control capability.

It is recommended to investigate the need for a built-in imager to enhance the navigation accuracy of the IRS data.

(5) A design consideration, which consists of on-board processing of the high horizontal and spectral resolution interferogram data, has been suggested for providing “built-in imager” data as part of an FTS instrument approach for the MTG-IRS. This approach has numerous advantages, over the use of a separate imaging instrument to provide the data needed to optimize the IRS sounding data processing for the MTG. The approach may also make it possible to eliminate, or greatly simplify, the requirement for additional imaging instruments to satisfy the High Resolution Fast Imagery (HRFI) and Full Disk High Spectral resolution Imagery (FDHSI) infrared imaging measurement requirements for the MTG.

It is recommended that a high horizontal resolution/high spectral resolution imaging FTS be considered for the IRS, potentially eliminating the need for an additional large telescope infrared imager to satisfy the HRFI and FDHSI MTG mission objectives.

The results of this study provide a basis for a decision regarding the need for a built-in imaging capability. There is little doubt that the use of high horizontal imager data will improve the accuracy and spatial resolution of the MTG IRS products obtained under partly cloudy conditions, however, there are alternative cloud treatment techniques, which do not depend on the use of imager data (22). Also, for cloud clearing applications of imager data, a built-in imaging component may not be necessary since imager and sounder co-registration is not critical. This is because clear air radiance signal, used in the cloud clearing process, is slowly varying in space in time, relative to the variation of the cloud signal. As a result, data from a companion imager (e.g., the FDHSI) could be used for cloud clearing MTG IRS observations.
with partially clouded fields of view. However, a built-in imager may be needed for product image navigation and/or for co-registration of spectral channels. Consequently, the requirement for a built-in imager ultimately depends on the IRS instrument and MTG spacecraft design, including the IRS horizontal resolution and the spectral selection technique and the instrument and spacecraft attitude control and measurement capability.

Finally, it needs to be emphasized that the employment of a hyperspectral sounder on the MTG will lead to revolutionary improvements in regional and global weather forecasting, regardless of whether data from a built-in, or companion, imager is available to enhance the quality of the sounding products. Thus, the hyperspectral resolution sounding capability is important for satisfying the MTG mission requirements, independent of any consideration for the possible inclusion of a built-in imaging capability within the IRS instrument.

12.0 References


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