MTG imaging channels in the solar domain and 3.7 microns for retrieval of cloud and aerosol microphysical properties

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1. **INTRODUCTION**

The purpose of this study is:

- to make progress with the channel definition of the imagers proposed for Meteosat Third Generation (MTG): HRFI (High Resolution Fast Imager) and FDHSI (Full Disk High Spectral-resolution Imager), specifically as the new short-wave channels are concerned, that implies:
  - to assess the sensitivities of the proposed channels to the applications intended to be improved:
    - cloud microphysical properties (water phase, optical thickness, drop size, ...)
    - aerosol (type, optical thickness, ...; over sea and land);
  - to re-adjust channel definitions (marginally for central wavelengths and bandwidths, perhaps substantially for SNR).

*Table 1* reports the first-guess short-wave channels definition for HRFI and FDHSI, as proposed as a baseline by a panel of experts. For comparison, Meteosat 1-7 and MSG SEVIRI imagers characteristics are reported too. The approximate positions of FDHSI channel centres are shown in *Fig. 1*.

### Table 1 – Characteristics of solar-reflecting channels of Meteosat 1-7, MSG and MTG.

<table>
<thead>
<tr>
<th>Meteosat 1-7 MVIRI</th>
<th>MSG SEVIRI</th>
<th>MTG HRFI</th>
<th>MTG FDHSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel</td>
<td>SNR / NEΔT</td>
<td>Channel</td>
<td>SNR / NEΔT</td>
</tr>
<tr>
<td>500-900 nm</td>
<td>3 @ 1 % ρ</td>
<td>560-710 nm</td>
<td>30 @ 1 % ρ</td>
</tr>
<tr>
<td>500-900 nm</td>
<td>3 @ 1 % ρ</td>
<td>560-710 nm</td>
<td>30 @ 1 % ρ</td>
</tr>
<tr>
<td>740-880 nm</td>
<td>20 @ 1 % ρ</td>
<td>845-885 nm</td>
<td>10 @ 1 % ρ</td>
</tr>
<tr>
<td>1500-1780 nm</td>
<td>10 @ 1 % ρ</td>
<td>1580-1640 nm</td>
<td>10 @ 1 % ρ</td>
</tr>
<tr>
<td>3.48-4.36 μm</td>
<td>0.2 K @ 300 K</td>
<td>3.5-4.1 μm</td>
<td>0.2 K @ 300 K</td>
</tr>
</tbody>
</table>

*Fig. 1 – E.m. spectrum in the range 0.4-4.0 μm showing the MTG/FDHSI channel positions.*
It is noted that the channel specification for the two MTG imagers are currently tentative, both in terms of channel boundary definitions and (most tentative) radiometric accuracy. Specifically, the SNR values of the short-wave channels have been set to figures that quite safely are sufficient for the general-purpose cloud analysis, but the suitability for improved aerosol and cloud microphysics observation still needs to be assessed.  

This is the purpose of this study.

Preliminary and qualitative considerations that constituted the basis for the first-guess definition of the solar range channels of MTG/FDHSI are listed as follows:

- **443 nm** - The purpose of this new (“blue”) channel is to add information for the aerosol retrieval.
- **645 nm** - By narrowing the bandwidth the sensitivity to O3 absorption decreases.
- **865 nm** - By narrowing the channel compared to the SEVIRI one the residual effects of absorption from the O2 A-band (for shorter wavelength) and water vapour (for longer wavelength) are expected to decreased to a level such that they can be negligible. In particular, absorption in the O2 A-band introduces a dependence of the radiance on the pressure and the aerosol vertical distribution that is particularly difficult to correct in the absence of any information on aerosol vertical distribution.
- **1375 nm** - The major role of this new channel, in a strong H2O absorption band that screens out the surface and the lower troposphere, is to detect thin cirrus and correct for their effect in the retrieval of aerosol properties.
- **1610 nm** - By narrowing the bandwidth of this channel the effect of water vapour absorption decreases.
- **2130 nm** - Important new channel for cloud effective radius retrieval as well as source of information on surface land reflectance properties in the aerosol retrieval.
- **3.7 µm** - By narrowing this channel the effect of residual absorption by several atmospheric gases that absorb in the vicinity of such window decreases.

During this study we will try to confirm the consideration listed above and give a quantified estimation of the impact on the final geophysical products.

This study starts, in Chapter 2, with the assessment of the heritage that led to the current channel selection. For each of the seven candidate channels (443, 645, 865, 1375, 1610, 2130 nm and 3.7 µm) a review is performed of the instruments using them, and specific analysis is performed of the filtering functions of MSG SEVIRI, EOS Terra/Aqua MODIS and GOES-R ABI.

Chapter 3 presents the overall approach used in this study to tune central wavelength, bandwidth and Signal-to-Noise Ratio (SNR) of the various channels so as to optimise the sensitivity to the addressed geophysical parameters. For each channel, the optimisation process is performed in respect of the geophysical parameter best addressed by the channel.

Chapter 4 contains the description of the numerical radiative transfer model used in this study and of the characteristics common to all the numerical experiments.

Chapter 5 describes the work carried out to investigate the optimal channel characteristics to maximise the sensitivity to the geophysical parameters:

- Cloud optical thickness and effective radius
- Cloud Phase
- Cirrus
- Aerosols
- Cloud top drop size for HRFI.

Chapter 6 collects and comments the results in terms of recommended adjustments of central wavelengths and bandwidths and new specifications of SNR.
2. **HERITAGE FOR CHANNEL SELECTION**

2.1 **Introduction**

In this Chapter we review the heritage of the currently selected channels by making reference to the following instruments that have been used or will be used, to a minor or major extent, for cloud microphysics and aerosol evaluation [Note: instruments exploiting multi-polarisation and/or multi-angle viewing have not been included since those conditions cannot be implemented from GEO]:

- NOAA and MetOp AVHRR (reason of selection: historical)
- ENVISAT AATSR (reason of selection: scientific work carried out from)
- EOS Terra and Aqua MODIS (reason of selection: scientific work carried out from)
- ENVISAT MERIS (reason of selection: scientific work carried out from)
- OrbView-2 SeaWiFS (reason of selection: scientific work carried out from)
- NPP and NPOESS VIIRS (reason of selection: future compatibility for cal/val)
- MetOp-3 VIDI-M (reason of selection: future compatibility for cal/val)
- Meteosat 1-7 MVIRI (reason of selection: historical)
- MSG SEVIRI (reason of selection: continuity)
- GOES-R ABI (reason of selection: consistency of instruments in the GOS).

For each MTG solar channel, the characteristics of similar channels from the above mentioned instruments are summarized in a table. Because of the lack of common definition of central wavelength and bandwidth, for a limited set of instruments the channel spectral characteristics have been computed in accordance with the template provided by EUMETSAT (Fig. 2 and Table 2). The computation of central wavelength and bandwidth have been performed by selecting the values that best fit the given channel response and the EUMETSAT-like template. In addition, for such limited set of instruments, the channel response function are plotted together with a transmittance spectra to give an idea of main atmospheric disturbances in the considered wavelength range.

![Fig. 2 - EUMETSAT-provided template for plotting channel boundaries.](image-url)
Table 2 – EUMETSAT-provided template for plotting channel boundaries.

<table>
<thead>
<tr>
<th>Co-ordinates and Amplitudes of Template Points (50 % = ½ Δλ₀ = nominal channel width)</th>
<th>A/A'</th>
<th>B/B'</th>
<th>C/C'</th>
<th>D/D'</th>
<th>E/E'</th>
<th>F/F'</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position [%]</td>
<td>± 50 %</td>
<td>± 30 %</td>
<td>± 30 %</td>
<td>± 20 %</td>
<td>± 20 %</td>
<td>± 10 %</td>
</tr>
<tr>
<td>Position [Width / FWHM]</td>
<td>± 1.0</td>
<td>± 0.6</td>
<td>± 0.6</td>
<td>± 0.4</td>
<td>± 0.4</td>
<td>± 0.2</td>
</tr>
<tr>
<td>Amplitude</td>
<td>2 %</td>
<td>50 %</td>
<td>100 %</td>
<td>0 %</td>
<td>50 %</td>
<td>80 %</td>
</tr>
</tbody>
</table>

The selected instruments, and the reasons for selection, are listed as follows:

- MSG SEVIRI (reason: reference on which to build possible improvements)
- EOS MODIS (reason: reference for maximum possible performance)
- GOES-R ABI (reason: reference for state-of-the-art from GEO in 2015).

It would have been of great interest to analyse also the VIIRS channel characteristics. Unfortunately, they will not be available for more than a year, i.e. sometime before NPP launch (end-2006). The data on the channel filter response of SEVIRI, MODIS and ABI have been obtained from:

- SEVIRI: www.eumetsat.de → MSG → missions → observation;
- MODIS: ftp://ftp.mcs.tasau.aiz/pub/permanent/MCST/FM1 RSR LUT 07-10-01 and, in addition, www.eoc.csiro.au/modis/modis bandpass/rsr.htm [Note: filter functions exist for MODIS on Terra and on Aqua and, for each, 10 functions are available, due to the detector array technique. The first function in the Aqua instrument has been used];
- ABI: document Baseline Version 2.0 417-R-ABIPORD-0017 dated 3 May 2004, page 20-21. Note that for this instrument, being in a phase of definition (as for the MTG radiometer), only a template as for the EUMETSAT MTG is available. As a consequence, the fitted central wavelength will be always the same as the specified one. The main difference in the template is that the lower response curve has a maximum of 70 % compared to 80 % of the EUMETSAT one.

Fig. 3 shows an example of fitted EUMETSAT-provided template: the resulting Central wavelength and the Full Width at Half-Maximum (FWHM) for the “red” channels of the three selected instruments.

Fig. 3 – Example of fitted filter function for the “red” channel (645 nm). SEVIRI-635 (left), MODIS-645 (centre), ABI-640 (right).
2.2 Channels review

2.2.1 The “blue” channel (443 nm)

The purpose of the “blue” channel is to support aerosol estimation, certainly over sea and (more controversial) over land. The channel also is proposed for slant visibility estimate for air transportation. Fig. 1 (previous) and, more in detail, Fig. 4 (to follow) show that this region of the spectrum is relatively transparent and the total transmittance is practically the transmittance due to molecular scattering. This channel is constrained on the short-wave end by increasing atmospheric absorption by O3 and molecular scattering (and decreasing solar energy), whereas on the long-wave end there is the less strong O3 Chappius band. Table 3 reports a review of the characteristics for the MTG FDHSI currently nominal channel, and channels of other instruments at similar wavelengths, including the “green” range. It is noted that the 443 nm channel is a primary channel of the set designed to measure ocean colour. For that purpose, the channel bandwidth is particularly narrow and the radiometric accuracy extremely good. For atmospheric use, bandwidth and radiometric accuracy are less stringent.

Table 3 – Comparative characteristics of “blue-green” channels on several instruments.

<table>
<thead>
<tr>
<th>Satellite / instrument</th>
<th>Central wavelength</th>
<th>Bandwidth</th>
<th>Radiometric accuracy</th>
<th>Intended mission</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTG FDHSI</td>
<td>443 nm</td>
<td>20 nm</td>
<td>10 @ 1 % albedo</td>
<td>Clouds, aerosol</td>
</tr>
<tr>
<td>ENVISAT AATSR</td>
<td>555 nm</td>
<td>20 nm</td>
<td>20 @ 0.5 % albedo</td>
<td>Clouds, aerosol, vegetation</td>
</tr>
<tr>
<td>EOS MODIS</td>
<td>412 nm</td>
<td>15 nm</td>
<td>880 @ 44.9 Wm⁻²μm⁻¹sr⁻¹</td>
<td>Ocean colour</td>
</tr>
<tr>
<td></td>
<td>443 nm</td>
<td>10 nm</td>
<td>838 @ 41.9 Wm⁻²μm⁻¹sr⁻¹</td>
<td>Ocean colour</td>
</tr>
<tr>
<td></td>
<td>469 nm</td>
<td>20 nm</td>
<td>243 @ 35.3 Wm⁻²μm⁻¹sr⁻¹</td>
<td>Clouds, aerosol</td>
</tr>
<tr>
<td></td>
<td>488 nm</td>
<td>10 nm</td>
<td>802 @ 32.1 Wm⁻²μm⁻¹sr⁻¹</td>
<td>Ocean colour</td>
</tr>
<tr>
<td></td>
<td>531 nm</td>
<td>10 nm</td>
<td>754 @ 27.9 Wm⁻²μm⁻¹sr⁻¹</td>
<td>Ocean colour</td>
</tr>
<tr>
<td></td>
<td>551 nm</td>
<td>10 nm</td>
<td>750 @ 21.0 Wm⁻²μm⁻¹sr⁻¹</td>
<td>Ocean colour</td>
</tr>
<tr>
<td></td>
<td>555 nm</td>
<td>20 nm</td>
<td>228 @ 29.0 Wm⁻²μm⁻¹sr⁻¹</td>
<td>Clouds, aerosol, vegetation</td>
</tr>
<tr>
<td>ENVISAT MERIS</td>
<td>412 nm</td>
<td>10 nm</td>
<td>Less than 2% of detected signal, relative to sun</td>
<td>Ocean colour</td>
</tr>
<tr>
<td></td>
<td>422 nm</td>
<td>10 nm</td>
<td>Ocean colour</td>
<td></td>
</tr>
<tr>
<td></td>
<td>490 nm</td>
<td>10 nm</td>
<td>Ocean colour</td>
<td></td>
</tr>
<tr>
<td></td>
<td>510 nm</td>
<td>10 nm</td>
<td>Ocean colour</td>
<td></td>
</tr>
<tr>
<td></td>
<td>560 nm</td>
<td>10 nm</td>
<td>Clouds, aerosol, vegetation</td>
<td></td>
</tr>
<tr>
<td>OrbView-2 SeaWiFS</td>
<td>412 nm</td>
<td>20 nm</td>
<td>499 @ 9.10 mW⋅cm⁻²</td>
<td>Ocean colour</td>
</tr>
<tr>
<td></td>
<td>443 nm</td>
<td>20 nm</td>
<td>674 @ 8.41 mW⋅cm⁻²</td>
<td>Ocean colour, aerosol</td>
</tr>
<tr>
<td></td>
<td>490 nm</td>
<td>20 nm</td>
<td>667 @ 6.56 mW⋅cm⁻²</td>
<td>Ocean colour</td>
</tr>
<tr>
<td></td>
<td>510 nm</td>
<td>20 nm</td>
<td>640 @ 5.64 mW⋅cm⁻²</td>
<td>Ocean colour</td>
</tr>
<tr>
<td></td>
<td>555 nm</td>
<td>20 nm</td>
<td>596 @ 4.57 mW⋅cm⁻²</td>
<td>Clouds, aerosol, vegetation</td>
</tr>
<tr>
<td>NPP/NPOESS VIIRS</td>
<td>412 nm</td>
<td>20 nm</td>
<td>Information not available</td>
<td>Ocean colour</td>
</tr>
<tr>
<td></td>
<td>445 nm</td>
<td>18 nm</td>
<td>Ocean colour</td>
<td></td>
</tr>
<tr>
<td></td>
<td>488 nm</td>
<td>20 nm</td>
<td>Ocean colour, aerosol</td>
<td></td>
</tr>
<tr>
<td></td>
<td>555 nm</td>
<td>20 nm</td>
<td>Clouds, aerosol, vegetation</td>
<td></td>
</tr>
<tr>
<td>MetOp VIRI-M</td>
<td>443 nm</td>
<td>20 nm</td>
<td>20 @ 0.5 % albedo</td>
<td>Clouds, aerosol</td>
</tr>
<tr>
<td>GOES-R ABI</td>
<td>470 nm</td>
<td>40 nm</td>
<td>300 @ 100 % albedo</td>
<td>Clouds, aerosol</td>
</tr>
</tbody>
</table>

Table 4 reports the fitted Central wavelengths and FWHM for:
- the MODIS channels at 469 nm and 555 nm, addressing clouds and aerosol (the channel at 443 nm is not considered, since it is clearly specified for ocean colour);
- the ABI channel at 470 nm.

Table 4 – Central wavelengths and FWHM for “blue-green” channels.

<table>
<thead>
<tr>
<th>Instrument-channel</th>
<th>Central wavelength</th>
<th>Full-Width at Half-Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>nominal</td>
<td>actual</td>
</tr>
<tr>
<td>MODIS-469</td>
<td>469 nm</td>
<td>466 nm</td>
</tr>
<tr>
<td>MODIS-555</td>
<td>555 nm</td>
<td>554 nm</td>
</tr>
<tr>
<td>ABI-470</td>
<td>470 nm</td>
<td>470 nm</td>
</tr>
</tbody>
</table>

Table 4 – Central wavelengths and FWHM for “blue-green” channels.
Fig. 4 reports the filter response of SEVIRI, MODIS and ABI “blue-green” channels plotted over the one-way transmittance spectra as computed for the US 76 standard atmosphere (all spectra reported in Figures 4 to 10 are computed for the same standard atmosphere). It is reminded that, for ABI, the filter responses reported in Figures 4 to 10 are only specified as templates.

2.2.2 The “red” channel (645 nm)

The “red” channel is that one providing maximum contrast against vegetated land (maximum absorption from chlorophyll is at 665 nm). On the long-wave end the channel cannot be extended beyond about 690 nm because of the O₂ band and successively the water vapour band around 730 nm (see Fig. 1 previous and, more in detail, Fig. 5 to follow). On the short-wave end, with increasing bandwidth, the ozone disturbance increases.

Table 5 reports a review of the characteristics for the MTG FDHSI currently nominal channel, and channels of other instruments at similar wavelengths.

<table>
<thead>
<tr>
<th>Satellite / instrument</th>
<th>Central wavelength</th>
<th>Bandwidth</th>
<th>Radiometric accuracy</th>
<th>Intended mission</th>
</tr>
</thead>
<tbody>
<tr>
<td>Meteosat-7 MVIRI</td>
<td>700 nm</td>
<td>400 nm</td>
<td>3 @ 1 % albedo</td>
<td>Multi-purpose</td>
</tr>
<tr>
<td>MSG SEVIRI</td>
<td>635 nm</td>
<td>150 nm</td>
<td>30 @ 1 % albedo</td>
<td>Multi-purpose</td>
</tr>
<tr>
<td>MTG FDHSI</td>
<td>645 nm</td>
<td>50 nm</td>
<td>10 @ 1 % albedo</td>
<td>Multi-purpose</td>
</tr>
<tr>
<td>MTG HRFI</td>
<td>600 nm</td>
<td>200 nm</td>
<td>10 @ 1 % albedo</td>
<td>Multi-purpose</td>
</tr>
<tr>
<td>NOAA + MetOp AVHRR</td>
<td>630 nm</td>
<td>100 nm</td>
<td>9 @ 0.5 % albedo</td>
<td>Multi-purpose</td>
</tr>
<tr>
<td>ENVISAT AATSR</td>
<td>659 nm</td>
<td>20 nm</td>
<td>20 @ 0.5 % albedo</td>
<td>Multi-purpose</td>
</tr>
<tr>
<td>EOS MODIS</td>
<td>645 nm</td>
<td>50 nm</td>
<td>128 @ 21.8 Wm⁻²μm⁻¹sr⁻¹</td>
<td>Multi-purpose</td>
</tr>
<tr>
<td></td>
<td>667 nm</td>
<td>10 nm</td>
<td>910 @ 9.5 Wm⁻²μm⁻¹sr⁻¹</td>
<td>Ocean colour</td>
</tr>
<tr>
<td></td>
<td>678 nm</td>
<td>10 nm</td>
<td>1087 @ 8.7 Wm⁻²μm⁻¹sr⁻¹</td>
<td>Ocean colour</td>
</tr>
<tr>
<td>ENVISAT MERIS</td>
<td>620 nm</td>
<td>10 nm</td>
<td></td>
<td>Ocean colour, vegetation</td>
</tr>
<tr>
<td></td>
<td>665 nm</td>
<td>10 nm</td>
<td>Less than 2% of detected signal, relative to sun</td>
<td>Ocean colour, vegetation</td>
</tr>
<tr>
<td></td>
<td>681.25 nm</td>
<td>7.5 nm</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>705 nm</td>
<td>10 nm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>OrbView-2 SeaWiFS</td>
<td>670 nm</td>
<td>20 nm</td>
<td>442 @ 2.46 mW·cm⁻²</td>
<td>Multi-purpose</td>
</tr>
<tr>
<td>NPP/NPOESS VIIRS</td>
<td>672 nm</td>
<td>20 nm</td>
<td>Information not available</td>
<td>Multi-purpose</td>
</tr>
<tr>
<td>MetOp VIRI-M</td>
<td>670 nm</td>
<td>20 nm</td>
<td>20 @ 0.5 % albedo</td>
<td>Multi-purpose</td>
</tr>
<tr>
<td>GOES-R ABI</td>
<td>640 nm</td>
<td>100 nm</td>
<td>300 @ 100 % albedo</td>
<td>Multi-purpose</td>
</tr>
</tbody>
</table>
Table 6 reports the fitted Central wavelengths and FWHM for:

- the SEVIRI channel at 635 nm;
- the MODIS channel at 645 nm (the channels at 667 nm and 678 nm are not considered, since they are clearly specified for ocean colour);
- the ABI channels at 640 nm.

**Table 6 – Central wavelengths and FWHM for “red” channels.**

<table>
<thead>
<tr>
<th>Instrument-channel</th>
<th>Central wavelength</th>
<th>Full-Width at Half-Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>nominal</td>
<td>actual</td>
</tr>
<tr>
<td>SEVIRI-635</td>
<td>635 nm</td>
<td>641 nm</td>
</tr>
<tr>
<td>MODIS-645</td>
<td>645 nm</td>
<td>645 nm</td>
</tr>
<tr>
<td>ABI-640</td>
<td>640 nm</td>
<td>640 nm</td>
</tr>
</tbody>
</table>

Fig. 5 reports the filter response of SEVIRI, MODIS and ABI “red” channels plotted over the spectrum.

### 2.2.3 The NIR channel (865 nm)

Moving from “red” to NIR the effect of vegetation increases whereas the brightness of aerosol decreases, thus the differential information is important. The window is constrained (see Fig. 1 previous and, more in detail, Fig. 6 to follow) between the O₂ A-band on the short-wave end and a water vapour band on the long-wave end, thus there is a strong interest to have it as narrow as possible. Table 7 provides a synoptic view of characteristics for the MTG FDHSI currently nominal channel and channels at similar wavelengths of other instruments.

**Table 7 – Comparative characteristics of NIR channels on several instruments.**

<table>
<thead>
<tr>
<th>Satellite / instrument</th>
<th>Central wavelength</th>
<th>Bandwidth</th>
<th>Radiometric accuracy</th>
<th>Intended mission</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSG SEVIRI</td>
<td>810 nm</td>
<td>140 nm</td>
<td>20 @ 1 % albedo</td>
<td>Multi-purpose</td>
</tr>
<tr>
<td>MTG FDHSI</td>
<td>865 nm</td>
<td>40 nm</td>
<td>10 @ 1 % albedo</td>
<td>Multi-purpose</td>
</tr>
<tr>
<td>NOAA + MetOp AVHRR</td>
<td>862 nm</td>
<td>275 nm</td>
<td>9 @ 0.5 % albedo</td>
<td>Multi-purpose</td>
</tr>
<tr>
<td>ENVISAT AATSR</td>
<td>865 nm</td>
<td>20 nm</td>
<td>20 @ 0.5 % albedo</td>
<td>Multi-purpose</td>
</tr>
<tr>
<td>EOS MODIS</td>
<td>858 nm</td>
<td>35 nm</td>
<td>201 @ 24.7 Wm²μm²sr⁻¹</td>
<td>Multi-purpose</td>
</tr>
<tr>
<td>ENVISAT MERIS</td>
<td>775 nm</td>
<td>15 nm</td>
<td>Less than 2% of detected signal, relative to sun</td>
<td>Aerosol, vegetation</td>
</tr>
<tr>
<td></td>
<td>865 nm</td>
<td>20 nm</td>
<td>20 @ 0.5 % albedo</td>
<td>Multi-purpose</td>
</tr>
<tr>
<td></td>
<td>890 nm</td>
<td>10 nm</td>
<td>516 @ 6.2 Wm²μm²sr⁻¹</td>
<td>Ocean colour</td>
</tr>
<tr>
<td>OrbView-2 SeaWiFS</td>
<td>865 nm</td>
<td>40 nm</td>
<td>467 @ 1.09 mW.cm⁻²</td>
<td>Multi-purpose</td>
</tr>
<tr>
<td>NPP/NPOESS VIIRS</td>
<td>865 nm</td>
<td>39 nm</td>
<td>Information not available</td>
<td>Multi-purpose</td>
</tr>
<tr>
<td>MetOp VIIR-M</td>
<td>885 nm</td>
<td>20 nm</td>
<td>20 @ 0.5 % albedo</td>
<td>Multi-purpose</td>
</tr>
<tr>
<td>GOES-R ABI</td>
<td>860 nm</td>
<td>40 nm</td>
<td>300 @ 100 % albedo</td>
<td>Multi-purpose</td>
</tr>
</tbody>
</table>
Table 8 reports the fitted Central wavelengths and FWHM for:

- the SEVIRI channel at 810 nm;
- the MODIS channel at 858 nm (the channel at 870 nm is clearly specified for ocean colour);
- the ABI channels at 860 nm.

<table>
<thead>
<tr>
<th>Instrument-channel</th>
<th>Central wavelength</th>
<th>Full-Width at Half-Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>nominal</td>
<td>actual</td>
</tr>
<tr>
<td></td>
<td></td>
<td>nominal</td>
</tr>
<tr>
<td>SEVIRI-810</td>
<td>810 nm</td>
<td>810 nm</td>
</tr>
<tr>
<td>MODIS-858</td>
<td>858 nm</td>
<td>857 nm</td>
</tr>
<tr>
<td>ABI-860</td>
<td>860 nm</td>
<td>860 nm</td>
</tr>
</tbody>
</table>

Table 8 – Central wavelengths and FWHM for NIR channels.

Fig. 6 reports the filter response of SEVIRI, MODIS and ABI NIR channels plotted over the spectrum.

Fig. 6 – Filter response of SEVIRI, MODIS and ABI NIR channels plotted over the spectrum.

2.2.4 The SWIR water vapour channel (1375 nm)

It is a strong absorption band (see Fig. 1 previous and, in more detail, Fig. 7 to follow) that stops radiation from the earth surface, thus enables upper-troposphere clouds to be detected, specifically over land, and enables discrimination against aerosol. It also enables detecting high-level aerosol under certain conditions (e.g., volcanic eruptions). It is a relatively narrow band, thus the channel bandwidth must be narrow. Table 9 provides a synoptic view of characteristics for the MTG FDHSI currently nominal channel and channels at similar wavelengths of other instruments.

<table>
<thead>
<tr>
<th>Satellite / instrument</th>
<th>Central wavelength</th>
<th>Bandwidth</th>
<th>Radiometric accuracy</th>
<th>Intended mission</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTG FDHSI</td>
<td>1375 nm</td>
<td>30 nm</td>
<td>10 @ 1 % albedo</td>
<td>Cirrus and high-level aerosol</td>
</tr>
<tr>
<td>EOS MODIS</td>
<td>1375 nm</td>
<td>30 nm</td>
<td>150 @ 6.0 Wm⁻²μm⁻¹sr⁻¹</td>
<td>Cirrus and high-level aerosol</td>
</tr>
<tr>
<td>NPP/NPOESS VIIRS</td>
<td>1378 nm</td>
<td>15 nm</td>
<td>Information not available</td>
<td>Cirrus and high-level aerosol</td>
</tr>
<tr>
<td>MetOp VIRI-M</td>
<td>1375 nm</td>
<td>30 nm</td>
<td>40 @ 0.5 % albedo</td>
<td>Cirrus and high-level aerosol</td>
</tr>
<tr>
<td>GOES-R ABI</td>
<td>1380 nm</td>
<td>30 nm</td>
<td>300 @ 100 % albedo</td>
<td>Cirrus and high-level aerosol</td>
</tr>
</tbody>
</table>

Table 9 – Comparative characteristics of water vapour channels on several instruments.

Table 10 reports the fitted Central wavelengths and FWHM for:

- the MODIS channel at 1375 nm;
- the ABI channel at 1380 nm.

<table>
<thead>
<tr>
<th>Instrument-channel</th>
<th>Central wavelength</th>
<th>Full-Width at Half-Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>nominal</td>
<td>actual</td>
</tr>
<tr>
<td></td>
<td></td>
<td>nominal</td>
</tr>
<tr>
<td>MODIS-1375</td>
<td>1375 nm</td>
<td>1383 nm</td>
</tr>
<tr>
<td>ABI-1380</td>
<td>1380 nm</td>
<td>1380 nm</td>
</tr>
</tbody>
</table>

Table 10 – Central wavelengths and FWHM for water vapour channels.
**Fig. 7** reports the filter response of MODIS and ABI water vapour channels plotted over the spectrum.

---

**2.2.5 The SWIR channel at 1610 nm**

It is a basic channel both for cloud/surface discrimination (specifically over snow fields) and for cloud microphysical properties. The window is constrained (see Fig. 1 previous and, in more detail, Fig. 8 to follow) between water vapour bands, thus it is important to have a channel narrow enough. **Table 11** provides a synoptic view of characteristics for the MTG FDHSI currently nominal channel and channels at similar wavelengths of other instruments.

**Table 11 – Comparative characteristics of SWIR channels at 1610 nm on several instruments.**

<table>
<thead>
<tr>
<th>Satellite / instrument</th>
<th>Central wavelength</th>
<th>Bandwidth</th>
<th>Radiometric accuracy</th>
<th>Intended mission</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSG SEVIRI</td>
<td>1640 nm</td>
<td>280 nm</td>
<td>10 @ 1 % albedo</td>
<td>Multi-purpose</td>
</tr>
<tr>
<td>MTG FDHSI</td>
<td>1610 nm</td>
<td>60 nm</td>
<td>10 @ 1 % albedo</td>
<td>Multi-purpose</td>
</tr>
<tr>
<td>NOAA + MetOp AVHRR</td>
<td>1610 nm</td>
<td>60 nm</td>
<td>20 @ 0.5 % albedo</td>
<td>Multi-purpose</td>
</tr>
<tr>
<td>ENVISAT AATSR</td>
<td>1610 nm</td>
<td>30 nm</td>
<td>20 @ 0.5 % albedo</td>
<td>Multi-purpose</td>
</tr>
<tr>
<td>EOS MODIS</td>
<td>1640 nm</td>
<td>24 nm</td>
<td>275 @ 7.3 Wm⁻²μm⁻¹sr⁻¹</td>
<td>Multi-purpose</td>
</tr>
<tr>
<td>NPP/NPOESS VIIRS</td>
<td>1610 nm</td>
<td>60 nm</td>
<td>Information not available</td>
<td>Multi-purpose</td>
</tr>
<tr>
<td>MetOp VIRI-M</td>
<td>1610 nm</td>
<td>30 nm</td>
<td>40 @ 0.5 % albedo</td>
<td>Multi-purpose</td>
</tr>
<tr>
<td>GOES-R ABI</td>
<td>1610 nm</td>
<td>60 nm</td>
<td>300 @ 100 % albedo</td>
<td>Multi-purpose</td>
</tr>
</tbody>
</table>

**Table 12** reports the fitted Central wavelengths and FWHM for:
- the SEVIRI channel at 1640 nm;
- the MODIS channel at 1640 nm;
- the ABI channel at 1610 nm.

**Table 12 – Central wavelengths and FWHM for SWIR channels at 1610 nm.**

<table>
<thead>
<tr>
<th>Instrument-channel</th>
<th>Central wavelength</th>
<th>Full-Width at Half-Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEVIRI-1640</td>
<td>1640 nm</td>
<td>280 nm, 224 nm</td>
</tr>
<tr>
<td>MODIS-1640</td>
<td>1640 nm</td>
<td>24 nm, 26 nm</td>
</tr>
<tr>
<td>ABI-1610</td>
<td>1610 nm</td>
<td>60 nm, 67 nm</td>
</tr>
</tbody>
</table>
**Fig. 8** reports the filter response of SEVIRI, MODIS and ABI SWIR-1.6 channels plotted over the spectrum.

2.2.6 The SWIR channel at 2130 nm

This channel is used for the retrieval of droplet effective radius because of the relative maximum absorption of liquid/solid water that occurs mostly outside the water vapour absorption bands. It is also used to retrieve land surface information for aerosol retrieval algorithms. The window is bounded at both ends by strong water vapour absorption bands (see Fig. 1 previous and, in more detail, Fig. 9 to follow). A weak water vapour absorption feature occurs also in the centre of the window. In the shortwave portion of the window, atmospheric transmittance is also limited by the effect of two carbon dioxide bands. **Table 13** provides a synoptic view of characteristics for the MTG FDHSI currently nominal channel and channels at similar wavelengths of other instruments.

**Table 13 – Comparative characteristics of SWIR channels at 2130 nm on several instruments.**

<table>
<thead>
<tr>
<th>Satellite / instrument</th>
<th>Central wavelength</th>
<th>Bandwidth</th>
<th>Radiometric accuracy</th>
<th>Intended mission</th>
</tr>
</thead>
<tbody>
<tr>
<td>MTG FDHSI</td>
<td>2130 nm</td>
<td>50 nm</td>
<td>10 @ 1 % albedo</td>
<td>Cloud microphysics, aerosol</td>
</tr>
<tr>
<td>MTG HRFI</td>
<td>2200 nm</td>
<td>200 nm</td>
<td>10 @ 1 % albedo</td>
<td>Cloud microphysics, aerosol</td>
</tr>
<tr>
<td>EOS MODIS</td>
<td>2130 nm</td>
<td>50 nm</td>
<td>110 @ 1.0 Wm(^{-2})μm(^{-1})sr(^{-1})</td>
<td>Cloud microphysics, aerosol</td>
</tr>
<tr>
<td>NPP/NPOESS VIIRS</td>
<td>2250 nm</td>
<td>50 nm</td>
<td>Information not available</td>
<td>Cloud microphysics, aerosol</td>
</tr>
<tr>
<td>GOES-R ABI</td>
<td>2260 nm</td>
<td>50 nm</td>
<td>300 @ 100 % albedo</td>
<td>Cloud microphysics, aerosol</td>
</tr>
</tbody>
</table>

**Table 14** reports the fitted Central wavelengths and FWHM for:
- the MODIS channel at 2130 nm;
- the ABI channel at 2260 nm.

**Table 14 – Central wavelengths and FWHM for SWIR channels at 2130 nm.**

<table>
<thead>
<tr>
<th>Instrument-channel</th>
<th>Central wavelength</th>
<th>Full-Width at Half-Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>nominal</td>
<td>actual</td>
</tr>
<tr>
<td>MODIS-2130</td>
<td>2130 nm</td>
<td>2112 nm</td>
</tr>
<tr>
<td>ABI-2260</td>
<td>2260 nm</td>
<td>2260 nm</td>
</tr>
</tbody>
</table>
**Fig. 9** reports the filter response of MODIS and ABI SWIR-2.1 channels plotted over the spectrum.

![Fig. 9](image)

2.2.7 The MWIR channel (3.7 µm)

The use of this channel in daylight assumes that the thermal component is measured by means of the TIR channels and subtracted. It is very effective for cloud microphysics (Rosenfeld et al. 2004). The window is surrounded by several absorbing bands on the short-wave end and the strong carbon dioxide band on the long-wave end (see Fig. 1 previous, and, in more detail, Fig. 10 to follow), thus there is an interest for a relatively narrow bandwidth. **Table 15** provides a synoptic view of characteristics for the MTG FDHSI currently nominal channel and channels at similar wavelengths of other instruments.

<table>
<thead>
<tr>
<th>Satellite / instrument</th>
<th>Central wavelength</th>
<th>Bandwidth</th>
<th>Radiometric accuracy</th>
<th>Intended mission</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSG SEVIRI</td>
<td>3.92 µm</td>
<td>0.88 µm</td>
<td>0.2 K @ 300 K</td>
<td>Multi-purpose</td>
</tr>
<tr>
<td>MTG FDHSI</td>
<td>3.80 µm</td>
<td>0.60 µm</td>
<td>0.1 K @ 300 K</td>
<td>Multi-purpose</td>
</tr>
<tr>
<td>MTG HRFI</td>
<td>3.80 µm</td>
<td>0.60 µm</td>
<td>0.2 K @ 300 K</td>
<td>Multi-purpose</td>
</tr>
<tr>
<td>NOAA + MetOp AVHRR</td>
<td>3.74 µm</td>
<td>0.38 µm</td>
<td>0.12 K @ 300 K</td>
<td>Multi-purpose</td>
</tr>
<tr>
<td>ENVISAT AATSR</td>
<td>3.70 µm</td>
<td>0.30 µm</td>
<td>0.08 K @ 300 K</td>
<td>Multi-purpose</td>
</tr>
<tr>
<td>EOS MODIS</td>
<td>3.75 µm</td>
<td>0.18 µm</td>
<td>0.05 K @ 300 K</td>
<td>Multi-purpose</td>
</tr>
<tr>
<td>NPP/NPOESS VIIRS</td>
<td>3.70 µm</td>
<td>0.18 µm</td>
<td>Information not available</td>
<td>Multi-purpose</td>
</tr>
<tr>
<td>MetOp VIRI-M</td>
<td>3.74 µm</td>
<td>0.38 µm</td>
<td>0.1 K @ 300 K</td>
<td>Multi-purpose</td>
</tr>
<tr>
<td>GOES-R ABI</td>
<td>3.90 µm</td>
<td>0.20 µm</td>
<td>0.1 K @ 300 K</td>
<td>Multi-purpose</td>
</tr>
</tbody>
</table>

**Table 16** reports the fitted Central wavelengths and FWHM for:
- the SEVIRI channel at 3.92 µm;
- the MODIS channel at 3.75 µm;
- the ABI channel at 3.9 µm.

<table>
<thead>
<tr>
<th>Instrument-channel</th>
<th>Central wavelength</th>
<th>Full-Width at Half-Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>nominal</td>
<td>actual</td>
</tr>
<tr>
<td>SEVIRI-3.8</td>
<td>3.92 µm</td>
<td>3.92 µm</td>
</tr>
<tr>
<td>MODIS-3.8</td>
<td>3.75 µm</td>
<td>3.70 µm</td>
</tr>
<tr>
<td>ABI-3.9</td>
<td>3.90 µm</td>
<td>3.90 µm</td>
</tr>
</tbody>
</table>
Fig. 10 reports the filter response of SEVIRI, MODIS and ABI MWIR channels plotted over the spectrum.

Fig. 10 – Filter response of SEVIRI, MODIS and ABI MWIR channels plotted over the spectrum.

2.3 Discussion

This Chapter 1 has reviewed the heritage of channels being selected for the MTG imagers. It is confirmed that most instruments make use of substantially narrower channels as compared to those of MSG/SEVIRI (not surprising, since MSG is conditioned by the spin stabilisation). The channels so far defined for MTG FDHSI and HRFI are consistent with the state-of-the-art, also as reflected in the GOES-R ABI.

The templates provided by EUMETSAT have been found useful to ensure that channels nominally similar also are similar when considering the details of the filter functions.

There is a misalignment in the definition of the MTG FDHSI “blue” channel. Instruments that make use of 443 nm (e.g., MODIS, VIIRS) also include a “green” channel at 555 nm. This would stabilise the retrieval process, and also improve the overall earth-radiation mission (e.g., PAR, Photosynthetically Active Radiation) through better spectral coverage, specifically in the region of maximum solar radiation. On the other hand, instruments with only one “blue” channel (most representative: ABI) move the position in the 470 nm region, so as to reduce the gap with the next channel (645 nm) and reduce the retrieval instability.

This sort of option (one or two channels and, if one, in which position) cannot be solved in this study, since we should enter the field of retrieval, whereas the current study is more based on sensitivity of single channels to the addressed parameters.

What can be done at this stage is to study the sensitivity of all three channels, the nominal 443 nm, a possible additional 555 nm channel and a 470 nm channel alternative to the couple 443 + 555.
3. APPROACH TO CHANNEL STUDY

3.1 Introduction

The channels of the MTG images, FDHSI and HRFI, have been preliminary defined by the remote sensing experts in response to the high level user requirements identified in the post-MSG User requirements definition process. The reference document for this study is the issue of the MTG Mission Requirements Document (MRD) valid in October 2004. The channel specifications in terms of position, bandwidth and SNR, defined on the base of existing experience with instruments like SEVIRI, MODIS, MERIS, AATSR, etc., are reported in Table 17 for FDHSI and Table 18 for HRFI.

Table 17 – Description of reference FDHSI solar reflecting channels.

<table>
<thead>
<tr>
<th>Channel name</th>
<th>Central wavelength [µm]</th>
<th>Bandwidth [µm]</th>
<th>Minimum signal</th>
<th>Maximum signal</th>
<th>Reference signal</th>
<th>SNR or NEΔT at reference signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>FD-VIS 0.4</td>
<td>0.443</td>
<td>0.02</td>
<td>1 %</td>
<td>120 %</td>
<td>1 %</td>
<td>10</td>
</tr>
<tr>
<td>FD-VIS 0.6</td>
<td>0.645</td>
<td>0.05</td>
<td>1 %</td>
<td>120 %</td>
<td>1 %</td>
<td>10</td>
</tr>
<tr>
<td>FD-VIS 0.8</td>
<td>0.865</td>
<td>0.04</td>
<td>1 %</td>
<td>120 %</td>
<td>1 %</td>
<td>10</td>
</tr>
<tr>
<td>FD-NIR 1.3</td>
<td>1.375</td>
<td>0.03</td>
<td>1 %</td>
<td>100 %</td>
<td>1 %</td>
<td>10</td>
</tr>
<tr>
<td>FD-NIR 1.6</td>
<td>1.610</td>
<td>0.06</td>
<td>1 %</td>
<td>100 %</td>
<td>1 %</td>
<td>10</td>
</tr>
<tr>
<td>FD-NIR 2.1</td>
<td>2.130</td>
<td>0.05</td>
<td>1 %</td>
<td>100 %</td>
<td>1 %</td>
<td>10</td>
</tr>
<tr>
<td>FD-IR 3.8</td>
<td>3.800</td>
<td>0.06</td>
<td>165 K</td>
<td>450 K</td>
<td>300 K</td>
<td>0.1 K</td>
</tr>
</tbody>
</table>

Table 18 – Description of reference HRFI solar reflecting channels.

<table>
<thead>
<tr>
<th>Channel name</th>
<th>Channel boundaries [µm]</th>
<th>Minimum signal</th>
<th>Maximum signal</th>
<th>Reference signal</th>
<th>SNR or NEΔT at reference signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>HR-VIS 0.6</td>
<td>λmin &gt; 0.5 - λmax &lt; 0.7</td>
<td>1 %</td>
<td>120 %</td>
<td>1 %</td>
<td>10</td>
</tr>
<tr>
<td>HR-NIR 2.1</td>
<td>λmin &gt; 2.1 - λmax &lt; 2.3</td>
<td>1 %</td>
<td>100 %</td>
<td>1 %</td>
<td>10</td>
</tr>
<tr>
<td>HR-IR 3.8</td>
<td>λmin &gt; 3.5 - λmax &lt; 4.1</td>
<td>165 K</td>
<td>450 K</td>
<td>300 K</td>
<td>0.2 K</td>
</tr>
</tbody>
</table>

The general objective of this study is to consolidate and somehow to optimise these preliminary channels definition in terms of user needs, also taking into account technical constraints. In order to optimise the channel definition v/s the user needs we started analysing from the MTG MRD:

- for the FDHSI mission: Tables 6 (page 33) and 7 (page 39) reporting the “FDHSI Mission versus User Needs” and the “Link between FDHSI ‘core’ channels and tentative level-2 products in support of user/service needs” respectively;
- for the HRFI mission: Table 2 (page 17) reporting the “HRFI Mission versus User Needs”.

From such analysis a set of numerical experiments was defined in order to have a data base to develop and test a methodology for the optimisation of the proposed channels. The experiments are:

- CLM - Cloud microphysical properties: optical thickness \( \tau_c \) and effective radius \( r_e \) (FDHSI);
- CLP - Cloud phase, that contributes also to the cloud type product (FDHSI);
- CIR - Definition of the 1375 nm channel for cirrus detection, that contributes to different products such as cloud type, aerosol optical properties (as correction for the cirrus effect) and possibly to the cloud microphysical properties both by correcting for cirrus effects and for estimation of cirrus microphysical properties (FDHSI);
- AER - This set of experiments is designed to optimise the visible channels selection to retrieve aerosol optical thickness and aerosol type (FDHSI);
- CLM F - Cloud top drop size (HRFI);

\[ \text{Available at www.eumetsat.int → Preparation of Future Programmes → MTG.} \]
In the above list the order corresponds roughly to the priority ranking given by the EUMETSAT MTG-MRD document. The list reports, for each set of numerical experiments, the acronym (for example: CLP) used in the rest of the study to identify the numerical experiment.

Note that there are two set of experiments (CLM and CLM F) that apparently deal with the same geophysical variables: the cloud top drop size. Nevertheless, due to the different purposes of the two missions (FDHSI or HRFI), different requirements have been assumed, that generated two separate sets of numerical experiments as it will be better explained in the specific sections.

An additional set of numerical experiments defined as clear sky [CSKY] has been run by simulating scenarios with atmospheres containing no scatterers apart from gas molecules. This would give a reference clear sky variability.

As a first approach, each single channel has been optimised by maximising its response for a single product. FDHSI channels have been optimised according to the priority in the considered product missions, as summarised in Table 19. HRFI channels (HR-VIS 0.6, HR-NIR 2.1 and HR-IR 3.8) have been optimised for the use of the cloud top drop size product in nowcasting.

### Table 19 – Priority associated within each simulation experiment to the single FDHSI channels (FD-).

The last line reports for each channel the experiment results used for the optimisation.

<table>
<thead>
<tr>
<th>VIS 0.4</th>
<th>VIS 0.6</th>
<th>VIS 0.8</th>
<th>NIR 1.3</th>
<th>NIR 1.6</th>
<th>NIR 2.1</th>
<th>IR 3.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLP</td>
<td>6</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>CLM</td>
<td>5</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>CIR</td>
<td>5</td>
<td>2</td>
<td>4</td>
<td>1</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>AER</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>AER</td>
<td>AER</td>
<td>AER</td>
<td>CIR</td>
<td>CLP</td>
<td>CLM</td>
<td>CLM</td>
</tr>
</tbody>
</table>

### 3.2 Description of the approach

The aim of this study is to give for each channel of Tables 17 and 18:

- the spectral characteristics: central wavelength and bandwidth;
- the SNR at a reference scenario (for example: 1 % albedo).

We started by splitting the search for the channel characteristics into two separate problems and as a consequence separate procedures were developed. In addition, depending on the geophysical product considered, two different types of retrieval were identified:

- quantitative retrieval, when the mission is expected to give a quantitative estimate of the geophysical variable of interest (with associated expected accuracy). This is the case for example of the retrieval of cloud microphysical properties;
- a classification-like retrieval when the satellite product is rather a yes-no product as for example for the retrieval of the cloud phase.

As a consequence, four different procedure were defined. Their general bases are reported in the following. The main difficulties in defining such procedures derived from the absence of any information on possible candidate sensors from which a realistic relationship between the Signal and the Noise could be derived. On the other hand, the aim of a similar study is to give SNR requirements independently from currently available sensor performances in order to start a trade-off procedure for a realistic instrument definition. Therefore, in order to overcome the lack of information of possible relationship between the Signal and the Noise, assumptions, documented in the following, were adopted. The use of such assumptions as well as the relatively limited set of cases analysed may limit the validity of the results of this study. Nevertheless, the procedures have been designed as much as possible in a parametric way. This allows, in principle, to produce results with different assumptions or enlarged simulation dataset (see for example the case of number of digits reported in the following of this section).
3.2.1 Selection of central wavelength ($\lambda_0$) and bandwidth ($\Delta\lambda$)

Quantitative retrieval

The procedure developed for the selection of channel spectral characteristics is based on the idea that the radiance $R(\lambda)$ at the Top Of Atmosphere (TOA) depends on the variable of interest ($X$) as well as on a set of other variables ($Y$) called geophysical disturbances, i.e.:

$$R = R(\lambda, X, Y).$$

The selected channel spectral characteristics are the combination of $\lambda_0$ and $\Delta\lambda$ values that better meet the following optimisation requirements:

- maximise the sensitivity to the variable of interest ($X$)
- minimise the sensitivity for the rest of the variables ($Y$)
- as broad as possible to have a sensitivity to the variable of interest above an assumed noise level.

The third condition is needed because a search based only on the first two conditions would give very narrow bandwidth, practically at the resolution of the radiative transfer simulations, that would have relatively low signal level.

For this set of simulations a reference status ($X_0, Y_0$) and a reference observation geometry are defined. Successively, the reference status is perturbed by a quantity $\Delta X$ that is the minimum variation of the geophysical quantity that we would like to be able to detect (practically the sensitivity). Similarly, the reference status is perturbed by a quantity $\Delta Y$ that represents the variability of the other geophysical variables not of interest. In this way, a spectrally detailed database of radiances is produced.

Starting from the spectrally resolved simulation database, for each experiment the spectrum is convoluted with a set of combinations of $\lambda_0$ and $\Delta\lambda$ in order to have the weighed radiance $R_{\text{exp}}(\lambda_0, \Delta\lambda)$ [mW m$^{-2}$ sr$^{-1}$]. We define the signal the variation in the weighed radiance due to the change of the variable of interest $X$ only:

$$\Delta R_{\text{sig}}(\lambda_0, \Delta\lambda) = \min_{\text{exp}} | R_{\text{exp}}(\lambda_0, \Delta\lambda, X_0, Y_0) - R_{\text{exp}}(\lambda_0, \Delta\lambda, X_0 \pm \Delta X, Y_0) |$$

Similarly, the disturbance is defined as the variation in the weighed radiance due to the change of the variables $Y$ only:

$$\Delta R_{\text{dis}}(\lambda_0, \Delta\lambda) = \max_{\text{exp}} | R_{\text{exp}}(\lambda_0, \Delta\lambda, X_0, Y_0) - R_{\text{exp}}(\lambda_0, \Delta\lambda, X_0, Y_0 \pm \Delta Y) |$$

In order to consider the less favourable scenario, for the signal we consider the minimum value while for the disturbance the maximum, where the search is done over the whole set of experiments (exp), based on the assumption that we want:

$$\Delta R_{\text{sig}}(\lambda_0, \Delta\lambda) > \Delta R_{\text{dis}}(\lambda_0, \Delta\lambda).$$

If the quantity to maximise is simply the ratio:

$$\Delta R_{\text{sig}}(\lambda_0, \Delta\lambda) / \Delta R_{\text{dis}}(\lambda_0, \Delta\lambda)$$

as a function of $\lambda_0$ and $\Delta\lambda$, the selected bandwidth value would be, as mentioned above, about the resolution of the simulations. This would be correct from the viewpoint of inversion algorithm, but a too narrow band would give a relatively low signal value that could be close or even lower than the noise level.

Being necessary to introduce somehow the Noise and having no information on its characteristics for the sensors to be simulated, we assume that the most important contribution to the sensor Noise is given by the Shot Noise. As a consequence, this allows us to assume that the Noise, in terms of Digit Number ($DN$), is proportional to the square root of the signal (see for example Boreman 1998):

$$DN_{\text{noise}} \propto (DN_{\text{sig}})^{1/2} \Rightarrow DN_{\text{noise}} = K_{\text{S-N}} \cdot (DN_{\text{sig}})^{1/2}$$

Introducing the noise and converting both signal and disturb in $DN$ the ratio to maximise becomes:

$$RATIO(\lambda_0, \Delta\lambda) = DN_{\text{sig}}(\lambda_0, \Delta\lambda) / [DN_{\text{dis}}(\lambda_0, \Delta\lambda) + DN_{\text{noise}}(\lambda_0, \Delta\lambda)]$$
As an example Fig. 11 shows $\Delta R_{\text{dis}}(\lambda_0, \Delta \lambda)$, $\Delta R_{\text{sig}}(\lambda_0, \Delta \lambda)$ and $\text{RATIO}(\lambda_0, \Delta \lambda)$ as a function of $\lambda_0$ (x-axis) and $\Delta \lambda$ (y-axis). The band considered is the FD-VIS 0.8 and the variable of interest is aerosol. An absolute maximum is easily recognised in the RATIO plot. However, the presence of a distinct maximum, once fixed the assumptions for all channels, is not always found, therefore for some case the position of relative maxima, around reasonable values of the spectral characteristics, has been investigated. To compute the quantity RATIO by eq. (4) it is required:

- a conversion factor ($r_{\text{DN}}$) Radiance → Digit Number
- some assumption on the proportionality coefficient $K_{\text{S,N}}$ in eq. (3).

![Fig. 11 – Example of variables used in the optimisation process as a function of $\lambda_0$ (x-axis) and $\Delta \lambda$ (y-axis): $\Delta R_{\text{dis}}(\lambda_0, \Delta \lambda)$ (left panel), $\Delta R_{\text{sig}}(\lambda_0, \Delta \lambda)$ (central panel) and $\text{RATIO}(\lambda_0, \Delta \lambda)$ (right panel).](image)

The factor $r_{\text{DN}}$ to convert spectrally convoluted radiance into digit numbers is obtained considering:

- a calibration function linear with no offset;
- the dynamic range (where the lower limit is fixed to 0 radiance) in order to use the dark sky as possible reference in a calibration procedure and for the upper limit the one given in Tables 17 and 18 for the preliminary channel characteristics;
- the number of digits.

The following iterative approach was used:

a. we start from the assumption that we would like to be sensitive to the minimum signal over the whole set of $\lambda_0, \Delta \lambda$ combinations:

$$1\text{DN} = \min(\Delta R_{\text{exp}}^{\text{sig}}(\lambda_0, \Delta \lambda)) \quad \forall \text{exp}, \lambda_0, \Delta \lambda.$$  

b. we test the number of bits that a similar measurements should have to be sensitive to such radiance variation and to satisfy the requirements on minimum and maximum signal;

c. we compare the obtained number of bits with an assumed one (for example 16);

d. if the number of bits is less than the assumed one we adjust to optimise the range with the assumed one;

e. if the number of required bits is still greater than the assumed one we increase of one step the minimum $\Delta \lambda$ and go to a.

The results reported in this study are obtained assuming:

- a 16-bit digitization level
- the noise radiance proportionality coefficient: $K_{\text{S,N}} = 1$
- a linear calibration with no offset.

However, in the procedure, the above assumptions are parameters that can be easily changed to test different hypothesis. As an example, sensitivity to the proportionality coefficient has been tested (see Fig. 12): further investigations are needed that will be better carried out with more realistic information during the successive phases of the definition of the instrument when more realistic inputs from the industries are expected to be available. Similarly, Fig. 13 shows the sensitivity to the number of bits.
Fig. 12 – Position and upper and lower limits of the FD-VIS 0.8 channel optimised for the aerosol product as a function of the coefficient $K_{S,N}$ (black: $K_{S,N} = 1$, red: $K_{S,N} = 2$, magenta: $K_{S,N} = 0.5$).

Fig. 13 – Lower panel: number of bits needed to resolve with the max and min reflectance fixed, the minimum signal as a function of the width used to integrate the radiance to give the signal. Central panel: as above, for the FD-VIS 0.8 channel width. Upper panel: as above, for the lower, upper and central position of the FD-VIS 0.8 channel.
**Classification retrieval**

For the cases where the product of the retrieval is a classification (CLP, CIR and CLM F), the following approach to optimise the channel spectral characteristics has been adopted.

First, a set of simulations is produced, similarly to what has been described for the case of quantitative retrieval by varying the geophysical disturbances \( Y \) and the variable of interest \( X \) between two classes, i.e.:
\[
X = A \quad X = B.
\]

We start from the assumption that the classification scheme is based on the comparison of a parameter derived from observations (for example ratio of reflectances) against a threshold. Let us define \( K \) the classification parameter and \( K_t \) its threshold value. The classification scheme would be, for example:
\[
K > K_t \Rightarrow \text{Event } A \text{ occurs} \\
K \leq K_t \Rightarrow \text{Event } B \text{ occurs}.
\]

In order to select the channel spectral characteristics, for each combination of \( \lambda \) and \( \Delta \lambda \):

a. the value of \( K_t \) is defined. Within the whole set of experiments:
   - the minimum value of \( K \) corresponding to the occurrence of an event \( A \) is searched (\( K_{A \min} \))
   - the maximum value of \( K \) corresponding to the occurrence of an event \( B \) is searched (\( K_{B \max} \))
   - the threshold value is defined as the average:
\[
K_t = (\lambda, \Delta \lambda) = 0.5 \cdot (K_{A \min} + K_{B \max})
\]

b. using the classification scheme, the False Alarm Rate (FAR) and the Hit Rate (HR) are computed according with the following definition:
\[
\text{FAR} = a / (a + c) \\
\text{HR} = (a + d) / (a + b + c + d)
\]

where the contingency table is:

<table>
<thead>
<tr>
<th></th>
<th>True</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>a</td>
<td>b</td>
</tr>
<tr>
<td>No</td>
<td>c</td>
<td>d</td>
</tr>
</tbody>
</table>

\( \text{FAR} \) and \( \text{HR} \) have been selected among the possible skill scores (see for example Wilks 1995) because they are the skills used in the User Requirement Documents to define the required accuracy of the products;

c. for each \( \Delta \lambda \) value, the \( \lambda \) value that maximises the \( \text{HR} \) and minimises the \( \text{FAR} \) is searched;

d. the dependence of the best \( \text{HR} \) and \( \text{FAR} \) from the channels width is studied and the occurrence of absolute and relative maxima is used to identify the channel spectral characteristics.

### 3.2.2 Estimate of the SNR at a reference scene

In order to obtain the SNR at the reference albedo (for example 1 %) two different procedures were developed depending on the type of retrieval (quantitative or qualitative). They are described in the following.

**Quantitative retrieval**

The proposed way to define the SNR is based on the comparison between the expected sensitivity to the geophysical variable and a maximum allowable noise. Practically, for a set of geophysical scenes, once defined \( \lambda_0 \) and \( \Delta \lambda \), the spectrally integrated radiance is computed for a reference status \((X, Y)\). Then only the variable of interest \((X)\) is perturbed of a quantity given by the required sensitivity; i.e. the perturbed status will be \((X + \Delta X, Y)\). The sensitivity in terms of radiance will be the difference between the two integrated radiances, i.e.:
\[
\Delta R_{(\lambda_0, \Delta \lambda)} = | R_{(\lambda_0, \Delta \lambda)} (X, Y) - R_{(\lambda_0, \Delta \lambda)} (X + \Delta X, Y) |
\]
It is assumed that the maximum allowable noise should be a portion of the $\Delta R$ computed above. For example, a minimum requirement scenario can be obtained by requiring the maximum allowable noise to be less than half of the desired signal, i.e.:

$$NOISE_{0.5} < 0.5 \Delta R_{signal}$$

or a more safe scenario can be obtained requiring the noise to be one order of magnitude less than the signal, i.e.:

$$NOISE_{0.1} < 0.1 \Delta R_{signal}$$

Making this estimation for different reference scenarios, it is possible to obtain SNR estimates at different scene reflectances. This can be used to give two SNR estimates at relatively low and high scene reflectance. If the requirement is for an exact value of the scene reflectance (for example 1%), by fitting the estimated SNR v/s the scene reflectance it is in principle possible to compute the SNR at any required reflectance value.

**Classification retrieval**

The SNR ratio for the channels optimised against classification-like products, has been estimated taking into account the minimum accuracy requirement, in term of $FAR$ and $HR$, commonly used in the User Requirement Documents, i.e.:

$$FAR < 50 \% \quad HR > 50\%$$

Once the channel spectral characteristics were selected, $HR$ and $FAR$ were computed by perturbing the simulated spectrally integrated radiances with an increasing level of Noise. The maximum allowable noise, from which the SNR has been computed, is the Noise level above which the minimum accuracy requirements cannot be met.
4. **ANALYSIS OF THE TOOLS AND EXPERIMENT SETUP**

From the description of the approach adopted in this study, reported in the previous Chapter, it emerges the need to:

- define, for each experiment:
  - the variables to be considered ($X$, $Y$)
  - their reference status ($X_0$, $Y_0$)
  - their range of variability
  - the amount of disturbance ($\Delta X$, $\Delta Y$);
- develop and test, in a relatively short time, a set of computer programs to perform the experiments and optimise the whole simulation process.

In this Chapter the basis for the choice of the variables and their values are described, as well as the process, from the selection of the numerical tool to the description of features characteristics for all experiments, to set up the specific numerical experiments which are described in detail in the next chapter.

4.1 **Generalities on variables**

For each experiment the following variables need to be defined:

- the reference status of the variable of interest and the required sensitivity ($X_0$ and $\Delta X$)
- the nature of the disturbances, their average status and the entity of disturbances ($Y_0$ and $\Delta Y$).

As for the variable of interest ($X$), for the majority of the experiments it was considered a minimum scenario of a reference value ($X_0$) and two perturbed scenarios ($X_0 \pm \Delta X$). The choice of the reference scenario is based as much as possible on existing climatology derived from measurements of the parameter of interest. We considered climatology with the following characteristics:

- the measurement technique must be as much as possible independent from a satellite remote sensing technique;
- large data set with possible information on the interannual and geographical variability, even if the value representative for northern-hemisphere mid-latitude (where most of the MTG users are expected to be) was considered.

The perturbation value ($\Delta X$) is defined on the basis of the use done in the experiments. In fact, $\Delta X$ represents the minimum variation of the geophysical variable of interest that we would like to be able to measure (i.e. the sensitivity). A possible definition could be derived from the User Requirements Documents, however for some parameter the requirements are not clear (for example for the aerosol type) and they differ depending on the user community.

For the geophysical variables for which a quantitative retrieval is expected we consider that once the products will be available their accuracy must be evaluated with a validation exercise. A similar exercise would produce an estimate of the accuracy that cannot be better than the accuracy of ground truth used. As a consequence, for each product we identified possible ground truth sources and assumed their accuracy as expected sensitivity for the satellite retrieved product.

About the geophysical disturbance ($Y$) an average status was selected with the same criteria as for the variable of interest, while for its range of variability ($\Delta Y$) two possible approaches were considered:

- the uncertainties on a known value to be used as correction, for example we assume to know the water vapour to correct for its effects, but an uncertainty (for example 10 %) is associated to the known value;
- some sort of range of variability (for example seasonal) in case no auxiliary data or climatological auxiliary data are used to correct for the effect.
The second option was selected (i.e. the geophysical disturbances were varied within a relatively large interval somehow representative of the range of variability of climatology) for the following reasons:

- The hypothesis of a “real-time” correction (to distinguish from a climatological one) to be applied would need an input at the same space and time resolution. For some variables (for example the water vapour) such input can be derived from the satellite products itself but for others (for example the pressure) the correction would rely on fields from numerical weather forecast models that may not easily be accessible at the space and time scales required.
- Even if the expected accuracy for the geophysical disturbances is reduced compared to the range of variability considered (for example, for the surface pressure an accuracy of 1-2 hPa can be expected while the range used in this study is ±15 hPa) by considering a large interval:
  - somehow we consider the uncertainty for realistic observation geometry still maintaining the observation geometry that minimises the optical path;
  - it is possible, with the assumption of linearity, to estimate the sensitivity of the measured radiances to a variation smaller than the range, minimising possible errors due to round-off.

The detailed description of each experiments is reported in Chapter 5. We give here, in Table 20, a short summary of experiment characteristics: variable and range of variability and resulting number of experiments and the spectral range investigated for each channel.

### Table 20 - Variables and relative range of variability for each experiment.

<table>
<thead>
<tr>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>CLP</td>
<td>998-1028</td>
<td>274-371</td>
<td>0-42</td>
<td>0.05</td>
<td>5,27,36</td>
<td>0.58-1.08</td>
<td>5-8</td>
<td>8.7</td>
<td>W-I</td>
<td>648</td>
</tr>
<tr>
<td>CLM</td>
<td>998-1028</td>
<td>274-371</td>
<td>25-37</td>
<td>0.05</td>
<td>5,27±10%, 36</td>
<td>0.58-1.08</td>
<td>3-6</td>
<td>8.7±10%</td>
<td>W</td>
<td>810</td>
</tr>
<tr>
<td>CIR</td>
<td>1013</td>
<td>274-371</td>
<td>20-38</td>
<td>0.0-0.3</td>
<td>0.02-22.0</td>
<td>0.58-1.08</td>
<td>8-13</td>
<td>8.7</td>
<td>I</td>
<td>1512</td>
</tr>
<tr>
<td>AER</td>
<td>998-1028</td>
<td>274-371</td>
<td>20-38</td>
<td>0.05-0.3</td>
<td>0.04±0.02, 0.2±10%, 0.3±10%</td>
<td>0.58-1.08</td>
<td>-</td>
<td></td>
<td></td>
<td>729</td>
</tr>
<tr>
<td>CLM F</td>
<td>998-1028</td>
<td>274-371</td>
<td>00-35</td>
<td>0.05</td>
<td>40±5</td>
<td></td>
<td>6</td>
<td>10÷18</td>
<td>W</td>
<td>243</td>
</tr>
<tr>
<td>CSKY</td>
<td>998-1028</td>
<td>274-371</td>
<td>25-37</td>
<td>0.0-0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>81</td>
</tr>
</tbody>
</table>

| ρ  | Surface reflectance | τ   | Optical thickness | α   | Angstrom coefficient | re  | Effective radius | WI   | Cloud particle phase | Water/Ice |

### 4.2 RTM selection

In order to perform the numerical experiments it is necessary to simulate the radiance measured by passive radiometer on board of a satellite for variable instrument characteristics and with the possibility to simulate realistically the variability of the geophysical variables of interest. In principle a complete “instrument simulator” coupled with a large database on input variables would constitute the optimal tool for this study.

However, in the short time available it was unrealistic to build a specific MTG instrument simulator especially if we consider that a large part of modelling constituting an instrument simulator are currently included in the majority of the Radiative Transfer Models (RTM) available. As a consequence, the possibility to use a RTM, combined when needed with some model (for example the “Radiometer model”) has been adopted.

In addition, because the objective of this study is not to reproduce exactly realistic radiances to be compared with observations, such as in the development of a retrieval database, but rather to study the sensitivity to the different variables, some constraint on the input may be relaxed; for example, all particles including cirrus can be as a first approximation assumed as spherical.

In order to rapidly select the RTM to be used, the requirements have been collected as follows:

- sufficiently detailed spectral resolution. We are not simulating a spectrometer, nevertheless we should be able to have a sufficiently good spectral resolution to enable to investigate the position of the channel within a spectral interval with sufficient detail;
• the program should be able to solve the Radiative Transfer Equation (RTE) multiple scattering regime in the most accurate, but not computationally heavy way;
• possibility to introduce vertically detailed user-defined profiles of aerosols/clouds;
• relatively fast;
• previous experience in the use of the model in order to avoid the time required for familiarisation.

The MODTRAN 4 [Version 1.0] (Berk et al. 1983, Bernstein et al. 1996) model has been selected as tool to be used in this study. MODTRAN is a relatively fast radiative transfer model developed by the Air Force Research Laboratories (previously Air Force Geophysics Laboratory) and it is probably the most advanced narrow-band radiative transfer programme for computing transmittance in cloudless atmospheres. Band model parameters based on HITRAN data for 12 atmospheric molecular species (H₂O, CO₂, O₃, N₂O, CO, CH₄, O₂, NO, SO₂, NO₂, NH₃ and HNO₃) are included in the model (Kneizys et al. 1988).

Larsen 1994 replaced the two-stream multiple scattering computations in the MODTRAN with a modified version of the Discrete Ordinate Radiative Transfer (DISORT Version 1.3) multiple scattering RTE solver (Stamnes et al. 1988). DISORT is a state-of-the-art, user-friendly discrete ordinate algorithm for radiative transfer in vertically inhomogeneous, non-isothermal, plane-parallel media. It considers scattering, absorption and emission by particles as well as incident radiative sources at boundaries. Given cloud optical properties for each layer, DISORT can generate angular dependent radiances and radiative fluxes profiles within the cloud.

Although MODTRAN can produce spectrally high-resolution clear radiances with excellent accuracy and DISORT can generate reliable cloud radiances at any angle, the present combination of MODTRAN with DISORT is not optimised. In fact, although DISORT with a user specified number of streams is used to compute the multiple scattering, the description of the phase function for any type of scatterer (aerosols, clouds particles and rain) is done internally by approximating the coefficients of the Legendre polynomials, required by DISORT with the term $g^n$ with $n$ the degree of the polynomial series expansion and $g$ the asymmetry factor that corresponds to the assumption of the Henyey-Greenstein functional form for the phase function.

4.3 MODTRAN and common experiment features

In this section the common characteristics of the numerical simulations are described. Given the relatively short time available we try to examine possible shortcuts to reduce the number of simulations or alternatively the time required for each single simulation.

Temperature profile

The expected dependency from the temperature profile of the results of the simulations are the following:
• changes of the gas extinction profile due to broadening of the absorption lines. This should be negligible for filtered radiometric measurements because:
  - most of the absorption lines should be broadened within the filter response function and being the solar spectrum relatively slow varying in the spectral regions the overall effect is expected to be negligible;
  - the expected range of variability of temperature within an atmospheric level is not so large;
  - some possible ideas on the entity of such an effect could be obtained by looking at the extinction profiles. In fact, if somehow, by increasing the geometrical thickness we can keep the absorber relatively constant, the differences in the extinction spectra should be due to pressure and temperature broadening;
• limiting the range of physically possible water vapour amount, in fact the load of water vapour is limited by the condition that should not condensate;
• the most important contribution, in our case, is on the 3.7 $\mu$m channel whose signal is partly due to radiation emitted.
Once verified that in the visible the temperature profile sensitivity is negligible (let’s say < 1 %) there are two possibilities to handle the 3.7 µm channel problem:

- assuming all the thermal emission contribution being removed with the help of the other TIR window (10 and 12 µm) channels;
- performing a set of simulations with varying temperature profile only for the 3.7 µm.

**Pressure**

For all experiments, three values of surface pressure have been considered:
- the reference value of 1013 hPa
- and two disturbed values of 1013 ± 15 hPa.

Being the reference variable, for the vertical profile, the altitude, rather than the pressure, the perturbed pressure profile $p^*(z)$, for a given altitude value, has been computed as

$$p^*(z) = p(z) + \Delta p \, e^{-z}$$

where $p(z)$ is the reference pressure profile and $\Delta p$ is the surface pressure perturbation. For a change in pressure, MODTRAN re-computes the concentration for uniformly mixed gases to adjust for the density given the temperature and volume; in addition, a more evident consequence is in the Rayleigh scattering contribution.

**Water vapour profile**

Tropospheric water vapour has been perturbed in the various experiments either by changing by ± 30 % or by fixing the relative humidity value (see experiment description).

**Ozone profile**

In all experiments the ozone density profile has been perturbed of ± 15% as shown in Fig. 14.

![Fig. 14 – O₃ density profiles used in the numerical experiments.](image)
Surface

For the retrieval of products like the aerosols characteristics, as well as the cloud microphysical properties, the value of the surface bidirectional reflectance should be known in order to take into account the contribution, to the total measured radiance, due to photons being reflected by the surface.

Such contribution is, for the aerosols, larger than any other geophysical disturbances considered in this study. Unless a realistic multi-spectral retrieval scheme is introduced, it is difficult to evaluate the contribution of the surface reflectance in the process of optimisation of the channel spectral characteristics. In fact, the spectral variability of the surface reflectance, within the typical range of the investigated spectral intervals, is relatively low, compared to gas absorption. Except in particular parts of the spectrum (for example between 700 and 750 nm for vegetated surfaces) the larger variability due to the surface is in the average value of the spectral reflectance within the investigated range, therefore the contribution in the process of selection of the channel spectral characteristics is expected to be low. As a consequence, for all numerical experiments a spectrally neutral lambertian surface with 0.05 albedo has been used because assumed as representative of surface reflectance for vegetated land and ocean at visible wavelengths (< 700 nm), and such types of surfaces covers most of the case where MTG is expected to retrieve geophysical products.

Particle shapes

Given the objective of this study and the timeframe within which it should have been obtained, all scattering particles have been considered as spherical and their single scattering optical properties have been computed with a well documented and widely used programme applying the Mie theory (MIEV0, Wiscombe 1980).

Horizontal homogeneity

All simulations assumes a plane parallel, horizontally homogeneous scene both for atmospheric as well as surface variables. No attempt has been done to evaluate the effect of sub-pixel variability.

Bands and spectral resolution

To optimise the computational time for each geophysical scene the radiation spectra at the top of the atmosphere have been divided in bands that are expected to largely contain at least one channel. The spectral resolution at which the simulations have been run is the best allowed by MODTRAN: 1 cm\(^{-1}\). Table 21 reports for each band the channel(s) included within the band boundaries and minimum and maximum spectral resolution in nm within each band.

<table>
<thead>
<tr>
<th>Band</th>
<th>Channel / Imager</th>
<th>(\lambda_{\text{min}}) [cm(^{-1}) (nm)]</th>
<th>(\lambda_{\text{max}}) [cm(^{-1}) (nm)]</th>
<th>(\Delta\lambda_{\text{min}}) [nm]</th>
<th>(\Delta\lambda_{\text{max}}) [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>VIS 0.4, VIS 0.6</td>
<td>26315 (380.011)</td>
<td>14285 (700.035)</td>
<td>0.014</td>
<td>0.049</td>
</tr>
<tr>
<td>1b</td>
<td>VIS 0.6 VIS 0.6</td>
<td>18182 (550.000)</td>
<td>14285 (700.035)</td>
<td>0.030</td>
<td>0.049</td>
</tr>
<tr>
<td>2</td>
<td>VIS 0.8</td>
<td>11904 (840.053)</td>
<td>11236 (889.996)</td>
<td>0.071</td>
<td>0.079</td>
</tr>
<tr>
<td>3</td>
<td>NIR 1.3</td>
<td>7463 (1339.94)</td>
<td>7042 (1420.05)</td>
<td>0.18</td>
<td>0.20</td>
</tr>
<tr>
<td>4</td>
<td>NIR 1.6</td>
<td>6667 (1499.93)</td>
<td>5882 (1700.10)</td>
<td>0.22</td>
<td>0.29</td>
</tr>
<tr>
<td>5</td>
<td>NIR 2.1 NIR 2.1</td>
<td>5000 (2000.00)</td>
<td>4167 (2399.81)</td>
<td>0.40</td>
<td>0.58</td>
</tr>
<tr>
<td>6</td>
<td>IR 3.8 IR 3.8</td>
<td>2941 (3400.2)</td>
<td>2500 (4000.0)</td>
<td>1.2</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Observation/illumination geometry

For the observation/illumination geometry we assumed, practically for all numerical experiments, the following values:

\[
\theta_0 = 0^\circ \quad \theta_v = 0^\circ \quad \Phi = 0^\circ
\]

where \(\theta_0\) and \(\theta_v\) are the solar and viewing zenith angle respectively, and \(\Phi\) is the relative azimuth between the two paths.
A limited set of experiments were performed also with low illumination geometry i.e.:
\[ \theta_0 = 69.5^\circ \quad \theta_v = 0^\circ \quad \Phi = 0^\circ \]
where the value of \( \theta_0 = 69.5^\circ \) is considered as maximum solar zenith angle for which the plane parallel approach could still apply.

**Sun spectra**

All computations have been performed using the MODTRAN solar irradiance file, Version 4V1R1 (newkur.dat).

**The 3.7 \( \mu \)m thermal component**

Within this study we consider applications that make use of the analysis of the contribution, to the radiation measured in the 3.7 \( \mu \)m window, of the solar scattered radiation. Since at this wavelengths range the radiation measured by a satellite sensor contains, at daytime, both the contributions from solar reflected as well as from thermal emission, we need to evaluate the latter in order to subtract it from the total radiation to obtain the former.

Practically (see for example, Kaufmann and Nakajima 1993, or Rosenfeld and Lensky 1998) this is done by applying a correction that evaluates the brightness temperature of the scene from measurements at longer wavelengths (i.e. in the 11 \( \mu \)m window).

For all simulations within this spectral range we performed, according with the options offered by MODTRAN that does not allow to simulate only the solar radiance, two separate simulations:
- a total (solar + thermal) radiation
- a thermal radiation only.

The spectrum of solar contribution was evaluated by simply subtracting from the spectrum of total radiation the spectrum of the thermal component. From a retrieval viewpoint this corresponds to the assumption of no errors in the procedure used to remove the thermal component.

A second issue regarding the 3.7 \( \mu \)m range is that the channel within this window will be mostly used in association to thermal IR channels; as a consequence its spectral and radiometric characteristics should be driven by its use as thermal channel. We took partially into account this fact by forcing the channel to be in the longer wavelength portion of this window. In fact, even if we considered for the simulation and for the sensitivity study the whole 3400-4000 nm range, the final selection of the channels for both mission was forced to be within the sub-window 3700-4000 nm. From the viewpoint of sensitivity to the variables considered in this study (i.e. cloud effective radius and even cloud top phase) the sensitivity, function of the imaginary part of the refractive index of condensed water, is higher at shorter wavelengths, in addition the extraterrestrial solar flux is larger at shorter wavelengths.

However, taking into account the primary use of such channel as a thermal emission channel, the thermal component decrease for shorter wavelengths. **Table 22** reports, for both sub-windows that can easily be identified considering the water vapour absorption feature around 3700 nm, the integrated solar and blackbody radiation. It appears that while from the solar viewpoint, considering longer wavelengths reduces of about 25% the incoming solar energy, from the thermal viewpoint more than 50% of energy is lost when moving from longer to shorter wavelengths.

**Table 22** – Values of solar spectrum (\( F_\lambda \)) and Blackbody (BB) emission at 270 K for two 300 nm spectrally integrated intervals within the 3400-4000 nm range.

<table>
<thead>
<tr>
<th>Range [nm]</th>
<th>( F_\lambda ) [W cm(^{-2}) sr(^{-1})]</th>
<th>BB [W cm(^{-2}) sr(^{-1})]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3400÷3700</td>
<td>1.33 E-4</td>
<td>1.97 E-6</td>
</tr>
<tr>
<td>3700÷4000</td>
<td>0.97 E-4</td>
<td>4.19 E-6</td>
</tr>
</tbody>
</table>
Vertical resolution

The MODTRAN standard internal profiles are given at 36 levels: from 0 to 25 km at 1-km vertical resolution (26 levels), from 25 to 60 km at 5-km vertical resolution (7 levels), then 3 levels: 70, 80 and 100 km. It may be of interest to reduce the number of levels to reduce mostly the computation time and partly the size of the output database. Although, internally an optimisation of the number of levels is already done by MODTRAN before entering in the multiple scattering computation, we reduced the number of levels from 36 to 22 decreasing the vertical resolution above the tropopause. A preliminary analysis has demonstrated that in terms of radiances in the spectral range of interest such reduction in vertical resolution introduces negligible variations (< 0.5 %), where the maximum sensitivity is, as expected, in regions of the spectrum where absorption from O$_3$ occurs (for example in the Chappius band). In fact, because the majority of O$_3$ is found above the tropopause, decreasing the vertical resolution introduce slight variations in the computation of the total O$_3$ amount.

In order to save computer time, a 22-level (or 26-level, see below) profile has been adopted.

The numerical solution of the radiative transfer equation in presence of multiple scattering includes in most of the numerical schemes computation involving matrices of quantity function of the optical properties. MODTRAN before to call DISORT, the multiple scattering solver, optimises for the number of layers by merging relatively optically thin, from a gas extinction viewpoint, layers. This give, from a gas extinction viewpoint, relatively homogeneous layers.

From the scattering viewpoint it seems that such operation is not performed. **Fig. 15** shows for a relatively narrow part of the 2100 nm window (4648-4656 cm$^{-1}$) the total integrated radiance at the TOA for a scene including a 1-km thick liquid cloud between 2 and 3 km. The two different curves refer to the simulated integrated radiance, as a function of a cloud optical thickness, for two cases:

- the cloud is specified as a single layer of optical thickness $\tau$;
- the cloud is specified as a 5-layer cloud, included within the same boundaries, each layer of optical thickness $0.2 \cdot \tau$.

**Fig. 15** – Spectral radiance in the interval 4648-4656 cm$^{-1}$ as a function of the cloud optical thickness. Red curve: the cloud is in a single 1-km thick layer. Black curve: the cloud is in 5 contiguous layers of 0.2-km thickness with equal optical thickness. Upper and lower boundaries of the cloud are unchanged.
Note that for relatively thin optical thickness values (< 10) the single layer radiance is larger than the one obtained from the cloud distributed over the 5 vertical levels. For larger optical cloud optical depth values the single layer tend to decrease.

By comparing the reflectance values in the two cases with the expected values for relatively thick clouds, from literature or observations, the results obtained with a single layer cloud appear as very low. For such reason for all experiments clouds were distributed over 5, optically equal and contiguous layers.

For the aerosol experiments, given the relatively low value of the total optical thickness and the fact that a vertical distribution is already adopted to distribute the total optical thickness, standard 1-km layers were adopted.

**Multiple scattering issues**

MODTRAN adopts DISORT 1.3 to solve the multiple scattering equation. It is possible to specify several options of DISORT.

An important parameter is the number of streams. **Fig. 16** shows simulated TOA radiance (left panel) for the multilayered cloud of Fig. 15 computed with 2, 4 and 8 streams as a function of the cloud optical depth. For cloud optical thickness greater than 20 the relative difference exceeds 10 %.

![Fig. 16 – Sensitivity to number of streams. Simulated TOA radiance (left panel) for the scenes described in Fig. 15 (with the multilayered cloud) for 2 (black), 4 (cyan) and 8 (red) streams as a function of the cloud optical depth. Percent difference between 2 and 8 streams computations (right panel).](image-url)
While it is suggested to use at least 8 streams to have realistic results, all simulation databases, except for some sensitivity test as the one showed, was produced with the 2 streams options for the following reasons:

- computer time is reduced when using low number of streams;
- the simulations dataset created for this study is aimed at sensitivity studies, with a simplified geometry, and not to the development of a realistic database for inversion purposes; therefore
- the ‘g’ approximation for the coefficient of the Legendre polynomial, that somehow invalidates the gain in precision expected by increasing the number of streams.

4.4 Comments on performances

After having reached the objective of this study, we started to re-analyse the whole procedure, including the design of the numerical experiments and we took time to investigate with little more detail the behaviour of the model depending from the slicing of the cloud layer.

Ou et al. 2002, in their study for the retrieval of cloud effective particle size and cloud optical thickness for the VIIRS mission, compared their radiative transfer model, based on a line-by-line for gas extinction and an adding and doubling scheme for the multiple scattering, against MODTRAN (version 3) outputs for different combinations of cloud optical thickness and effective radius. They observed large differences between the spectra simulated with the two models. They discussed the origin of the discrepancy in terms of reduced capability of MODTRAN to reproduce azimuth-dependent scattering. MODTRAN 4 introduced an option (DISAZM) to include azimuth dependencies in the calculation of DISORT solar scattering contribution. It is also suggested (Berk et al. 2000):

> “Since this option increases computation time, DISAZM should be set FALSE:
- if only vertical fluxes are needed
- if solar or viewing zenith angle is near vertical
- or if solar multiple scattering is a small radiance component (e.g. for LWIR calculations).”

Since:

- we were searching solutions to save time,
- we were using MODTRAN 4 (compared with the MODTRAN 3 used by Ou et al. 2002) where some sort of correction for the azimuth-dependence is announced, and therefore we assume also the description of the DISAZM option should reflect such effort,
- we were performing simulations in the simplified geometry where both solar and viewing zenith angle are near the vertical,

we switched OFF the option for azimuth dependence.

Apparently the third option should be an AND rather than an OR. In fact, we performed a set of simulations switching the azimuth-dependence option ON and we obtained results that differs largely from the same scenario with the option OFF.

**Fig. 17** shows for the same cases of Fig. 15 the integrated radiance as a function of the cloud optical thickness for the combination of the following parameters:

- number of streams (2: line, 8: + symbols)
- slicing of the cloud layer (RED: sliced layer, BLACK: single layer)
- azimuth-dependence option [DISAZM] (thick: TRUE, thin: FALSE).

Note that very different behaviour of the 8 curves derived from the different combinations of computational parameters for a same geophysical scene. Surprisingly, the number of streams produces the smallest difference (differences between line and symbol).
Fig. 17 – Integrated radiance, for the same cases in Fig. 15, as a function of the cloud optical thickness for the combination of the following parameters: 1) number of streams (2: line, 8: + symbols); 2) slicing of the cloud layer (red: sliced layer, black: single layer); 3) azimuthal dependence option [DISAZM] (thick: TRUE, thin: FALSE).

Finally, Ou et al. 2002 concluded their comparison between the radiance for a cloudy scene derived from MODTRAN against the ones derived with their own model (section 3.3.1.7 of Ou et al. 2002) with the following sentence:

“In fact, having recognized that retrievals of the cloud parameters must be properly coupled with a reliable forward radiative transfer program, established cloud retrieval algorithm teams (e.g. King et al. at NASA-GSFC, Minnis et al. at NASA-LRC and Rossow et al. at NASA-GISS) all have developed their own radiative transfer programs based on sound physical principles for the purpose of algorithm development and sensitivity studies.”

The results shown in the rest of this study are obtained, unless otherwise specified, with:

- 2 streams;
- sliced clouds. No slicing was done for the aerosols because of the relatively low value of the optical thickness in a single layer (< 0.2);
- DISAZM option set as FALSE according with the MODTRAN Users’ Manual.

---

2 Please note that the MSG study by Watts et al. 1998 also is based on a radiative transfer programme, that uses DISORT for the multiple scattering, developed by the authors of the study.
It is difficult to evaluate the absolute impact of the uncertainty shown in Fig. 17 in the results obtained from this study. However, the procedure of definition of the channel spectral characteristics is based on differences (to define the signal and the disturbances) and ratios: therefore, assuming the an incorrect use of the model introduces a bias, the effects should be minimised. In addition, the main process that drives the definition of channel spectral characteristics is the atmospheric gas absorption that, for MODTRAN, has been extensively validated, while the discrepancies between simulated radiance are due to variables and parameters related to the scattering, that among the others has also a slower spectral variability compared to gas absorption.

Similarly the SNR estimation is based on ratios of radiances or differences and therefore any bias introduced by the model should be minimised too.

The only use of absolute values of radiance is when specifying the reference scenario at which the SNR are given. Having set the DISAZM option as FALSE produces, according to Fig. 17 (thin lines against thick lines), an underestimation of the radiance value compared with the results obtained with the option set as TRUE. Assuming that the TRUE option gives the correct value, having required the SNR (that being a result of ratios we assume as less dependent from the DISAZM option) at a lower radiance value generate more strict requirements.

A possible solution to have an absolute estimate of the uncertainties would require practically to simulate all cases with a different and more reliable (therefore validated in a scattering regime) radiative transfer model. For example, the solution of multiple scattering with an adding and doubling method, should in principle be less dependent from the slicing of the scattering layer. However, being such solution unfeasible with the given time constraints, the MODTRAN team was contacted to ask for their opinion on the results obtained.

The model inputs for the whole set of cases shown in Fig. 17 have been submitted to the MODTRAN team to be analysed.

A first suggestion from the MODTRAN team was that we were using a relatively old version (MODTRAN 4 Version 1 Rev. 0) against the currently available MODTRAN 4 Version 3 Rev. 1 (see http://www.vs.afrl.af.mil/Division/VSBYB/modtran4.html) (NB: Version number is incremented when new features are added, and revision number is incremented when corrections are made). However, because no mention in the web page was done to possible improvements related to the observed problems, before to purchase the more recent version we asked the MODTRAN team to perform the same set of simulations that produce the radiance shown in Fig. 17.

Currently (Dec. 2004) we have received only the output relative to one case (i.e. one single point over the set of curves) with a relatively low optical thickness that, as far as it can be seen by the output description, is generated with MODTRAN 5 Version 2.4 (released at August 2004) that is not even the version advertised in the web site. The only comparison possible with our results gave differences in the radiances of less than 1 %. As a consequence, we conclude that the absolute accuracy of MODTRAN derived results for user defined scattering atmosphere is still an open issue.
5. EXPERIMENT DESCRIPTION

5.1 Cloud optical thickness and effective radius [CLM]

5.1.1 Background

Cloud is a poly-dispersion composed by drops (or ice elements). In other words, cloud is composed of different particles with different dimensions suspended in a media with different characteristics.

To facilitate inversion of radiation measurements the size distribution must be described with the minimum number of parameters (Hansen and Travis 1974). Clearly the first parameter should be some measure of the mean particle size. The arithmetic mean is:

\[ r_{\text{mean}} = \frac{\int_{r_1}^{r_2} r N(r) dr}{\int_{r_1}^{r_2} N(r) dr} = \frac{1}{N_{\text{tot}}} \int_{r_1}^{r_2} r N(r) dr \quad [\mu m] \]  

(5)

where \( N_{\text{tot}} \) is the total number of particles per unit volume.

The effective radius of a spherical particle polydispersion, is defined as the ratio:

\[ r_{\text{eff}} = \frac{\int_{r_1}^{r_2} r^2 N(r) dr}{\int_{r_1}^{r_2} r^2 N(r) dr} \quad [\mu m] \]  

(6)

where \( N(r)dr \) is the number of particle in the interval \([r, r+dr]\) (size distribution), and \( r_1 \) and \( r_2 \) are the lower and upper limit of the particles radius.

The effective radius is the parameter that represent the typical dimension of liquid water drop particles that compose the upward part of cloud. It is the ‘best size distribution’ single parameter to describe the scattered light by a monodispersion (Hansen and Travis 1974).

As for cloud microphysics, in the last few decades it has been demonstrated that from satellite passive radiometry it is possible to retrieve the following quantities:

- the water phase at cloud top
- the cloud optical thickness and the cloud particle effective radius for liquid clouds
- and, if some assumption or retrieval technique can give the information on ice particles habit, the same parameters for ice clouds.

A generalised cloud microphysical retrieval scheme would consist at least of the following steps:

- cloud detection where pixels are classified as cloudy or clear. Note that the definition of cloudy for a cloud microphysical retrieval scheme may not be the same as for other parameter as for example surface or aerosol properties retrieval. In fact, while for the latter any cloud contaminated pixel should be considered as cloudy, for cloud microphysical retrieval the pixel should be completely cloudy;
- cloud phase determination;
- cloud optical thickness and droplet effective radius retrieval in case of liquid cloud or ice cloud with assumption on the cloud particle habit;
- or cloud particle habit retrieval in case of ice cloud; and successively
- cloud optical thickness and droplet effective radius retrieval.

5.1.2 Experiment description

In order to test the sensitivity of different channel spectral characteristics to the cloud optical thickness and effective radius, the spectral radiance was computed for a reference cloud perturbing its values of optical thickness and effective radius as shown in Table 23.
### Table 23 – Reference cloud characteristics and applied perturbations.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Values</th>
<th>Number of values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective Radius [µm]</td>
<td>8.7 ± 10 %</td>
<td>3</td>
</tr>
<tr>
<td>Optical Thickness</td>
<td>5, 26.8 ± 10 %, 36</td>
<td>5</td>
</tr>
<tr>
<td>Cloud Top Height</td>
<td>3, 6</td>
<td>2</td>
</tr>
<tr>
<td>H2O [kg/m²]</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>O3 [DU]</td>
<td>292</td>
<td>3</td>
</tr>
<tr>
<td>Pressure</td>
<td>1013 ± 15</td>
<td>3</td>
</tr>
<tr>
<td>Number of simulations</td>
<td>3 x 5 x 2 x 3 x 3 x 3 = 810</td>
<td></td>
</tr>
</tbody>
</table>

However, since the retrieval of the cloud optical thickness is based mostly on the information in the visible channel and the derived requirements would be similar (but even less severe) of what derived from the aerosols, the channel defined with this set of numerical experiments are only the channels that should contribute to the estimation of the effective radius (FD-NIR 2.1 and FD-IR 3.7).

**Reference stratus cloud**

In the absence, at our knowledge, of a climatology of micro-macro-physical characteristics of stratiform clouds, we used the results from a ground based remote sensing technique to retrieve cloud microphysical properties (Dong et al. 1997). The retrieval assumes a log-normal with a logarithmic width \( \sigma = 0.38 \) (Miles et al. 2000):

\[
    n(r) = \frac{N}{(2\pi\sigma)^{0.5}} \left\{ -\frac{1}{2} \left[ \frac{\ln(r) - \ln(r_m)}{\sigma} \right]^2 \right\}
\]

We remind that for a log-normal distribution the modal radius is related to the effective radius by the following relationship:

\[
    r_m = r_e \exp \left( -5 \sigma^2 / 2 \right)
\]

Fixing \( \sigma \) in the cloud retrieval scheme does not lead to significant errors in the retrieved value of \( r_e \), while \( N \) changes by 15 to 30% as \( \sigma \) varies from 0.2 to 0.5. The reference stratus cloud characteristics are as follows:

- geometrical thickness \( \Delta Z = 0.85 \text{ km} \)
- Liquid Water Path \( LWP = 151 \text{ g/m}^2 \)
- Liquid Water Column \( LWC = 0.245 \text{ g/m}^3 \)
- effective radius \( r_e = 8.7 \text{ µm} \)
- particle density \( N = 213 \text{ cm}^{-3} \)
- optical thickness (at 550 nm) \( \tau = 26.8 \)
- effective solar transmission \( \gamma = 0.331 \)
- cloud albedo \( \rho = 0.672 \)
- albedo at Top Of Atmosphere \( \rho_{TOA} = 0.563 \)

**Fig. 18, Fig. 19** and **Fig. 20** show the single scattering optical properties for such reference stratus cloud.

**Disturbances**

The most important disturbance is the absorption from water vapour, mostly above the cloud, that could be erroneously interpreted as cloud droplets being larger than in reality. However, the presence of a relatively strong CO₂ absorption band at shorter wavelength should be considered as geophysical disturbances too. Since CO₂ is not considered as an explicit variable, two values of cloud top height (3 and 6 km) have been used in the simulation so that two different CO₂ amounts above the cloud are considered.
Fig. 18 - Extinction coefficient, normalised to its value at 550 nm, of the simulated clouds as a function of wavelength. Spectral range 0.4-4.0 \( \mu \text{m} \) (upper panel) and zoomed over the two spectral intervals of the channels optimised with this experiment (lower panels). Different lines refer to the three different effective radii [\( \mu \text{m} \)].
Fig. 19 - Single scattering albedo of the simulated clouds as a function of wavelength. Spectral range 0.4–4.0 \( \mu \text{m} \) (upper panel) and zoomed over the two spectral intervals of the channels optimised with this experiment (lower panels). Different lines refer to the three different effective radii [\( \mu \text{m} \)].
Fig. 20 - Asymmetry factor of the simulated clouds as a function of wavelength. Spectral range 0.4-4.0 \( \mu m \) (upper panel) and zoomed over the two spectral intervals of the channels optimised with this experiment (lower panels). Different lines refer to the three different effective radii \([\mu m]\).

5.1.3 Experiment analysis

Spectral characteristics

Fig. 21 shows the best RATIO value (as defined in eq. 4) as a function of the channel width (upper left panel). It is evident that the ratio decreases monotonically with the bandwidth and the absolute maximum occurs for unrealistic, especially from geostationary orbit, narrow channel width (< 5 nm). As a consequence we analysed in detail a range of realistic channel width (i.e. 20-65 nm). In this range the ratio is almost constant between the channels width values of 42 and 47 nm. The lower left panel of Fig. 21 shows the portion of the curve highlighted in the upper left panel. In order to maximise the channel width for similar ratio value, the 47 nm width was selected. The right panels of Fig. 21 show the best central wavelength as a function of the channel width (again the lower panel is a zoomed portion of the upper one). Note that the optimum channel has always the shorter wavelength limit corresponding to the shorter wavelength boundary over which the optimisation is performed. This is because the signal (i.e. the sensitivity to the cloud droplet radius) depends on the absorption properties.
of the water that have a maximum at shorter wavelengths (see for example Fig. 19 for the single scattering albedo or Fig. 23, to follow, showing the complex part of the refractive index).

Fig. 21 - Selection of the 2100 nm channel characteristics. Left panels: Best RATIO (eq. 4) as a function of the channel width. Right panels: central wavelength corresponding to the best ratio as a function of the channel width. The lower panels detail the bandwidth range highlighted with a thicker line in the upper panels.

Fig. 22 shows the RATIO (eq. 4) as a function of the central wavelength and bandwidth. It is evident that the absolute maxima are located at very narrow bandwidths. Another interesting feature is the relative minimum generated by the water vapour absorption around 3.66 µm. This feature, in particular, splits the domain considered in two regions that are approximately the same analysed in Section 4.3 concerning the 3.7 µm channel. Because of the balance between thermal and solar energy considered in Section 4.3 and for consistency with the ABI selection, a relative maximum of the RATIO was searched in the longer wavelength part of the domain. However an alternatively possibility that avoids to give priority to the thermal or the solar use of such channel is to consider a broad channel that covers large part of the considered window. In fact, apart for the mentioned H₂O absorption feature at about 3.66 µm, the whole window has no evident clear range as for the other windows; therefore, except considering an extremely narrow channel, the lost in performance is relatively low when passing from a relatively narrow channel to a channel covering practically the whole window. In addition, more realistic representation of sensor responses and noises may demonstrate that the overall performances are better for a broad than for a narrow channel. Fig. 22 also reports the selected position (+) as well as a possible position of a broader channels (x). Taking into account that the RATIO in the figure ranges from 0.0121 to 0.0255, we report in the following table the spectral characteristics as well as the RATIO value for both the selected channel and a possible broader one. Note that, at least in term of the used RATIO, the performances for a broader channel are not dramatically decreased.

<table>
<thead>
<tr>
<th></th>
<th>λ₀ [nm]</th>
<th>∆λ [nm]</th>
<th>RATIO</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ Selected</td>
<td>3910</td>
<td>174</td>
<td>0.0231</td>
</tr>
<tr>
<td>x Broad</td>
<td>3682</td>
<td>589</td>
<td>0.0216</td>
</tr>
</tbody>
</table>
Fig. 22 - Selection of the 3.7 μm channel characteristics. Best RATIO (eq. 4) as a function of the bandwidth and central wavelength. Also shown the position of the selected channels (+) and a possible broad one (x).

Fig. 23 and Fig. 24 show the position of the selected channels (light orange rectangles) together with the total (gas + molecular scattering) one-way transmittance for the US76 Standard atmospheric model. As a reference the channel spectral response of the instruments analysed in Chapter 2 are reported too as well as the imaginary part of the refractive index of water and ice and their difference.

Fig. 23 - Position of the selected 2100 nm channel (light orange rectangle). Total (gas + molecular scattering) one-way transmittance for the US76 Standard atmospheric model (black line). Reference channel spectral responses (dash-dotted lines). Imaginary part of the refractive index of water, ice and their difference (dashed lines).
SNR experiments

The SNR estimation was performed with the approach outlined in Section 3.2.2 in case of quantitative retrieval. The practical implementation is described, for each channel, by the following steps.

a. For each experiment, the integrated radiance $R_{\text{BAND}}(\text{exp})$ is computed according to the definition of channel central wavelength and bandwidth.

b. For a given cloud optical depth value (whose variation is used to obtain different reflectance values) we have a subset of experiments corresponding to the combination of the values assumed by the parameters others than the cloud optical thickness (i.e. O$_3$, H$_2$O, pressure, cloud height and droplet effective radius).

c. Within this subset defined from the cloud optical thickness value, we select all possible sets of three radiances corresponding to the experiments that differ only for effective radius ($X$). We consider then the two radiance differences between the radiance that corresponds to the reference radius ($r_1 = 8.7 \mu m$), and the radiances corresponding to the perturbed radii ($r_2 = 7.8 \mu m$, $r_3 = 9.6 \mu m$):

$$\Delta R_{\text{BAND}}^a = \text{abs}(R_{\text{BAND}}^{r_1} - R_{\text{BAND}}^{r_2})$$
$$\Delta R_{\text{BAND}}^b = \text{abs}(R_{\text{BAND}}^{r_1} - R_{\text{BAND}}^{r_3})$$

The minimum of radiance change would correspond to the expected sensitivity to the variable of interest.

d. Assuming that the expected sensitivity should be larger than the noise we compute the maximum allowable noise as a portion of the sensitivity. We assume a low demanding scenario were the noise can be as much as half of the sensitivity:

$$\text{Noise} = 0.5 \cdot \min(\Delta R_{\text{BAND}}^a, \Delta R_{\text{BAND}}^b)$$

By using the corresponding radiance value of $\Delta R_{\text{BAND}}^a$ as signal we obtain:

$$\text{SNR} = \frac{R_{\text{BAND}}^a}{\text{Noise}}$$

e. Steps b. to d. are repeated for a different cloud optical thickness value in order to have a dynamics in the signal.

The following tables report the SNR estimations computed with the above procedure. As a reference also the cloud optical thickness value as well as the scene reflectance are reported.
5.2 Cloud Phase [CLP]

5.2.1 Background

Cloud phase from passive satellite radiometry can be retrieved using the following physical principles:

a. The spectral position of relative maxima of absorption for liquid and solid water is different and in some cases occurs outside of water vapour absorption bands. As a consequence, clouds will have different reflectance (VIS/SWIR based techniques, Pilewskie and Twomey 1987a,b) or emittance (IR based techniques).

b. Liquid cloud particles are generally spherical while ice particles are more likely to be non-spherical. As a consequence, it is possible to discriminate between water and ice particles by analysing the angular signature of scattered radiance (Goloub et al. 2000).

c. Below (above) a given temperature the water phase is very likely to be ice (water). This reduces the problem of cloud top phase to the measure of cloud top physical temperature or, more indirectly, cloud top height/pressure. For example, the commonly adopted assumptions for a temperature-based cloud discrimination are:
   - \( T < -23 \, ^{\circ}\text{C} \) \( \rightarrow \) ice
   - \( T > 0 \, ^{\circ}\text{C} \) \( \rightarrow \) liquid
   - \(-23 \, ^{\circ}\text{C} < T < 0 \, ^{\circ}\text{C} \) \( \rightarrow \) mixed

The first approach would be the basis for the MTG imagers, with some expected contribution from the third. The second technique requires polarization and multi-angular capability.

5.2.2 Experiment description

Cloud Phase [CLP] numerical experiments have been designed to optimise the FD-NIR 1.6 channel characteristics. In order to optimise a channel position in the 1600 nm atmospheric window as a function of the cloud phase product, a simulation data set is produced by simulating the radiance spectra for an atmosphere with a cloud of fixed size distribution and varying particle phase.

Cloud top pressure is varied within the levels with temperature included between 273 and 253 K where both phases are expected. In addition, water vapour is varied too. The combination of the water vapour changes and cloud top pressure constitutes the main disturbance at 1610 nm. In fact, the signature of an ice cloud compared to a water cloud is a stronger absorption by the cloud particles; as a consequence, for all other variables fixed, the radiance emerging from the scene with the ice cloud is lower than the one with the water cloud. However, water vapour absorbs too within the wavelength range considered for the FD-NIR 1.6 channel, therefore depending on the amount of water vapour included in the channel response, there may be ambiguity between the radiance from a relatively moist atmosphere with a low water cloud and a dry atmosphere with a high ice cloud. The optimisation process is performed to minimise such ambiguity using the skill scores approach introduced in Chapter 3.

As a reference cloud, the same stratus cloud used in the CLM experiments has been selected (see section 5.1.2). The following assumptions have been adopted:

- no change in the size distribution as a function of the water phases,
- no change in the size distribution as a function of the cloud top altitude,
- ice particles have been assumed as spherical.

Figures 25, 26 and 27 show the single scattering optical properties for both the ice and water clouds used in the simulations. The two lower panels report the same variable zoomed over the range of the FD-VIS 0.6 channel and the FD-NIR 1.6. Three values of cloud optical thickness have been considered: 5, 26.8 (as average climatological value) and 36. The upper value represents somehow a saturation value; in fact, for larger values of the optical thickness the upwelling radiance has relatively low changes. The lower limit (5) does not really represent the lowest optical thickness limit at which the retrieval of the cloud phase detection is performed.
Independently on the cloud optical thickness value, the cloud has been set as 1 km thick and the slicing in five equally optically thick portion has been adopted.

Fig. 25 - Spectral behaviour of extinction coefficient, normalised to its value at 550 nm, for ice and water clouds used in the simulations. All spectral range of interest (upper panel) and zoomed over the two channel ranges (FD-VIS 0.6 and FD-NIR 1.6) specifically used in the experiments (lower panels). Different lines represent the two phases, water and ice.
Fig. 26 - Spectral behaviour of the single scattering albedo for ice and water clouds used in the simulations. All spectral range of interest (upper panel) and zoomed over the two channel ranges (FD-VIS 0.6 and FD-NIR 1.6) specifically used in the experiments (lower panels). Different lines represent the two phases, water and ice.
5.2.3 Experiment analysis

In both phases of the experiment analysis, the spectral definition and the estimation of the SNR, the characteristics of the FD-VIS 0.6 channel have been considered as already determined from the Aerosol retrieval mission. This reduces the search for the channel position to a single channel search.

*Spectral definition experiments*

The channel position is selected on the basis of the capability of the FD-NIR 1.6, used with the FD-VIS 0.6, to discriminate between water and ice clouds. Reflectance for ice clouds is expected to be lower than for water clouds, nevertheless gas absorption over the cloud, mostly water vapour, can produce a decrease in the reflectance that could be erroneously interpreted. The search for the optimised position
is based on a compromise between channel width (the larger the channel the higher the possibility of gas absorption) and the capability to discriminate between the two possible cloud phases.

In order to select the FD-NIR 1.6 optimised channel position having fixed the FD-VIS 0.6, for each combination of $\lambda_0$ and $\Delta \lambda$ in the 1610 band the following test is performed. For each couple of experiments, that differs only for the cloud particle phase, the ratio:

$$K = \frac{R_{1610}}{R_{670}}$$

is computed, where $R_{1610}$ and $R_{670}$ are the reflectances respectively for the NIR and VIS channel. Within the whole set of ratios the following variables are computed:

$$K^W_{\min} = \min (K^W(\lambda_0)) \quad \text{and} \quad K^I_{\max} = \max (K^I(\lambda_0))$$

Where $K^W_{\min}$ and $K^I_{\max}$ represent the minimum and maximum values of the ratio of reflectances for Water and Ice clouds respectively. A classification threshold is computed as average between the two quantities above. Using such threshold all experiments have been re-analysed and the FAR and HR have been computed for each combination of $\lambda_0$ and $\Delta \lambda$.

**Fig. 28** reports as a function of the channels width the value of the central wavelength at which the best skill values (lowest FAR and largest HR) occur (lower panel) as well as the skill values (upper panel). As a reference, the 50 % threshold for the skills is plotted. Note that, as expected, enlarging the channel width decreases the skill as an effect of including water vapour absorption features. However, a local maximum is observed around 1575 nm and for a channel width of about 50 nm. Based on this test we selected the following spectral characteristics for the FD-NIR 1.6 channel:

$$\lambda_0 = 1576 \text{ nm} \quad ; \quad \Delta \lambda = 52 \text{ nm}.$$
Fig. 29 shows the position of the selected channel (light orange rectangle) together with the total (gas + molecular scattering) one-way transmittance for the US76 Standard atmospheric model. As a reference the channel spectral response of the instruments analysed in Chapter 2 are reported too, as well as the imaginary part of the refractive index of water and ice and their difference.

**SNR experiments**

Once defined channel position and width, spectral radiances have been integrated within the selected band limits in order to obtain the radiance \( R_{\text{BAND}}(\text{exp}) \) for each experiments. We introduced the Noise in both channels that would produce the largest uncertainties. Since we expect \( K_W > K_I \) the following combinations have been considered:

\[
K_W^{\text{noise}} = \frac{R_{670}^{1610} - N_{670}^{1610}}{R_{670} - N_{670}} \\
K_I^{\text{noise}} = \frac{R_{670}^{1610} + N_{670}^{1610}}{R_{670} - N_{670}}
\]

where \( N_{\text{exp}} \) is the noise contribution. The noise value for the visible channel (\( N_{670} \)) has been estimated using the SNR vs reflectance regression found with the AEROSOL experiments for the FD-VIS 0.6:

\[
\text{SNR}_{670} = 49 + 2 \cdot R_{670}
\]

With the above \( K_W^{\text{noise}} \) and \( K_I^{\text{noise}} \) the skill scores values (FAR and HR) have been computed increasing progressively the Noise in the FD-NIR 1.6 channel. The minimum SNR allowable is defined as the higher Noise level that still satisfies the condition on the skill scores:

\[
\text{FAR} < 50 \% \quad \text{HR} > 50 \%
\]

The following values are obtained for the three cloud optical thickness values (and therefore reflectance values) considered in the experiments:

<table>
<thead>
<tr>
<th>Channel</th>
<th>( \tau = 5 )</th>
<th>( \tau = 26.8 )</th>
<th>( \tau = 36 )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SNR</td>
<td>( \rho (%) )</td>
<td>SNR</td>
</tr>
<tr>
<td>FD-VIS 0.6</td>
<td>115</td>
<td>33</td>
<td>192</td>
</tr>
<tr>
<td>FD-NIR 1.6</td>
<td>59</td>
<td>31</td>
<td>8</td>
</tr>
</tbody>
</table>

Note that increasing the signal, i.e. the cloud optical thickness, the SNR requirements decrease. This behaviour, that does not correspond to the expected tendency for a realistic sensor, derives from the nature of the procedure. In fact, for large cloud optical thickness values, the effect of water absorption below the cloud decreases, being such portion of the atmosphere partly masked by the cloud. As a consequence, the major source of uncertainties decreases and therefore the minimum acceptable skill values are reached by adding larger amount of noise, compared to low optical thickness values.
Practically the specification is to reach the SNR obtained for the lower optical thickness value. This condition is expected to satisfy also the requirements, in terms of skill scores, for larger cloud optical thicknesses.

5.3 Cirrus [CIR]

5.3.1 Background

Cirrus clouds have been identified as one of the most uncertain components in atmospheric research. Recently, the importance of relatively thin cirrus ($\tau \ll 1$ in the VIS e NIR) has emerged for the following reasons:
- they are potentially radiatively important
- they potentially play an important role in the de-hydration of air entering the stratosphere.

In addition, it appears that relatively thin cirrus have a high occurrence in large areas. A less indirect impact derives from the fact that geophysical variables, derived from satellite passive remote sensing in the VIS and NIR (e.g. NDVI, Aerosols properties, Chlorophyll), may be erroneously estimated in the presence of undetected cirrus.

The main problem in evaluating the effective importance of optically thin cirrus arises from the difficulty in measuring them, which, of course, is due primarily to their low optical depth.

Before the MODIS mission two main techniques where somehow able to sense relatively thin cirrus:
- IR-based techniques
- limb extinction techniques.

However, the capability of detecting thin cirrus is limited to IR-based technique, especially over relatively warm background, while limb techniques, even if they are sensitive to extremely thin cirrus clouds, lack in both spatial and temporal coverage.

Aircraft observations in strong water vapour absorption band in the NIR (1.3 and 1.9 $\mu$m) revealed high capability in detecting thin cirrus. Based on such experience a specifically dedicated cirrus detection channel at 1.375 micron was designed for MODIS and the currently available observations seems to confirm the capability of such technique although limited to daytime observations only.

In addition, in principle, another region of the e.m. spectrum for day/night thin cirrus cloud detection would be in the FIR (e.g., 18.2 and/or 24.4 $\mu$m), where the lower troposphere is totally screened out by the water vapour continuum; but this is precluded by the low level of signal, not consistent with a scanning imager.

5.3.2 Experiment description

Two sets of simulation experiments have been designed.

The first set consists in simulations to test thin cirrus detection feasibility. We define “thin” a cirrus of optical thickness 0.02 at 550 nm. This corresponds to the accuracy required for the aerosols optical thickness in case the cirrus detection is only performed with the purpose of screening out aerosol products with uncertainties greater than the expected detection.

This is also the minimum detectable cirrus optical thickness according to the data analysis study of Dessler and Yang 2003. In this set of experiments the thin cirrus, of fixed 1 km geometrical thickness, is moved between the pressure level with temperature $> 253$ K and the tropopause: 8 and 13 km respectively for the mid-latitude profile. At the same time, the average aerosol layer with optical thickness 0.2 used in the aerosol retrieval experiments (Section 5.4) occupies the lowest 4 km of the troposphere.

The second set of experiments is designed to test the ability to retrieved cirrus optical thickness. This is done simply by testing the sensitivity without any attempt to introduce some sort of correction for the
Two reference values, and tentative expected accuracy, are tested:

- 0.2 ± 100 % and 20 ± 10 %

In both sets of experiments, we assume that the main difficult in detecting a relatively thin cirrus or optical thickness changes would be the absorption from water vapour above the cirrus therefore we compute TOA radiances for different cirrus top height (all levels from 253 K to the tropopause) and three water vapour scenarios:

- standard water vapour profile
- dry profile
- moist profile.

As regards the reflectance contribution from the earth surface (or, more in general, from below-the-cirrus) we considered the scenario that the cirrus is above a cloud-free no glint surface with reflectance varying from 0.05 to 0.3. The expected effect to simulate varying reflectances should be to limit the channel selection toward too transparent part of the wavelength range considered; in fact, this is the expected tendency when the water vapour is increased.

Given the fact that thin cirrus are expected to consist of relatively small particles, and an average value of effective size around 8 µm was observed (Dessler and Yang 2003) as characteristic for such cirrus, we adopted the same size distribution as in the CLM experiments with, of course, ice spherical particles.

### 5.3.3 Experiment analysis

The experiments have been analysed firstly with the objective of detecting thin cirrus and therefore the approach of the skill scores described in Section 3.2 has been applied. We considered the baseline spectral characteristics i.e.:

\[ \lambda_o = 1375 \text{ nm and } \Delta \lambda = 30 \text{ nm}. \]

Such a position has already been optimised by Gao and Kaufman 1995 by positioning the MODIS channel in the shorter wavelength part of the high absorption water vapour band at 1.3 µm. Here, the maximum absorption is searched to mask the surface and the lower troposphere clouds, while the shorter wavelength is selected for maximising the solar input radiance as well as to have possibility, in case of a shift in the channel response (that generally increase the central wavelength), to still be in a region of strong absorption.

**Fig. 30** shows the position of the selected channel (light orange rectangle) together with the total (gas + molecular scattering) one-way transmittance for the US76 Standard atmospheric model. As a reference the channel spectral response of the instruments analysed in Chapter 2 are reported too.

The estimation of the SNR, for cirrus detection, gave as a result a required SNR of 25 for \( \rho = 0.5 \% \). This is consistent with the requirements in Gao and Kaufman 1995.

A channel defined with the above characteristics would fail, according to our experiment results, in detecting 0.02 optical thin cirrus with the cloud top at the lower level considered (8 km) in case of a moist atmosphere. However, to improve the cirrus detection in such case, it is necessary to enlarge the band width toward lower, and more transparent, wavelengths. This however increases the possibility of detecting as a cirrus either highly reflecting water clouds or aerosols, like dust, that can be located in the mid-troposphere and have large optical thickness (\( > 1 \)). Of course, a multi-spectral analysis coupled with the analyses from the other retrieval algorithm could help in discriminating between cirrus and non-cirrus. On the other hand, the interest in detecting thin cirrus, apart from correction for aerosols and NDVI retrieval that would be already critical for the above cases, the radiative effect of thin cirrus is of interest because of their capability in trapping emitted radiation. In the case where the selected channel fail the cirrus is relatively low and above there is still water vapour: therefore the contribution of the cirrus to greenhouse effect is limited.
Finally, the above performance still allows the detection of cirrus optical thickness for medium cirrus optical thickness. For large optical thickness the sensitivity decreases and therefore the SNR computed as a portion of the sensitivity increases.

Fig. 30 - Position of the selected 1370 nm channel (light orange rectangle). Total (gas + molecular scattering) one-way transmittance for the US76 Standard atmospheric model (black line). Reference channel spectral responses (dash-dotted lines).

5.4 Aerosols [AER]

5.4.1 Background

The concept of atmospheric aerosols is used to describe a complex mixture of micron-sized \((10^{-2}\) to \(10^2 \) µm) liquid or solid particles (except water) suspended in the air. Ideally, atmospheric aerosols are defined when, in a given air volume, the total number of aerosol particles is determined and when size, shape and chemical composition of each single particle are known. With a similar approach the knowledge of atmospheric aerosols is clearly a problem with a huge number of unknowns. A first step in the solution of the aerosol problem is to reduce the number of unknowns by introducing the concept of aerosol components and their mixture (aerosol models) (e.g., D’Almeida et al. 1991).

A single aerosol component is defined as the ensemble of particles in a given air volume originated:

- by a source (e.g. soil dust, sea salt particles etc.), mostly responsible for the particles’ chemical composition and shape;
- through a physical process (e.g., condensation, coagulation etc.) responsible for their size distribution.

From the radiative viewpoint an aerosol component is generally defined by assuming:

- a single shape for all particles: mostly spherical;
- a complex refractive index: a variable containing the information on the chemical composition of the particles;
- a size distribution \(N(r)\): in general an analytical function (1 to 4 parameters) that gives the number density of particles as a function of their radius \(r\).

An aerosol model is a mixture (external or internal) of aerosol components and represents the influence in a given air volume of different sources and processes responsible for the emission of the particles in the atmosphere.

Given the above definitions, remote sensing of atmospheric aerosols is generally reduced to the determination of fewer variables:

- the amount, through the concepts of Aerosols Optical Thickness (AOT) or Aerosol Optical Depth (AOD);
and the type, through the selection of an aerosol component or model or a parameter, usually the Angstrom coefficient ($\alpha$) (Angstrom 1964) from which information on the aerosols model can be inferred (see for example: King et al. 1978 or Shifrin 1995).

A comprehensive overview of satellite aerosols retrieval methods and missions at wavelength from UV to TIR can be found in Liberti and Cheruy 2002 and in King et al. 1999.

For the characteristics of the geostationary observation and the number of channels that can be dedicated to aerosol observations it seems reasonable to adopt the most common approach, in the solar range, of a multi-spectral analysis of the aerosol scattered radian ce to retrieve aerosol properties. The main issue for this approach is that the aerosol contribution to the measured radiance represents a small portion of the overall signal. Other contributions include atmospheric gas absorption, molecular scattering, cloud contamination (in particular thin cirrus) and surface reflectance.

Over land, the major problem is the surface reflectance contribution that, other than being larger than the aerosol one, is generally known with an uncertainty level close to the aerosol signal level for most of the land surface type and aerosol amount scenarios. The usefulness of the 2130 nm channel to estimate the land surface contribution has been shown by Kaufmann et al. 2002 for the MODIS mission. Given the presence of such channel in the MTG imager, we assume the MODIS aerosol retrieval over land as a possible approach to be used for MTG.

5.4.2 Experiment description

The sensitivity of a set of channel radiances to detect changes in the aerosol properties from a reference scenario has been used for the definition of the characteristics of the channels FD-VIS 0.4, FD-VIS 06 and FD-VIS 0.8. The channel optimisation has been performed only on the basis of aerosols optical thickness retrieval.

Reference AOD and Angstrom coefficient ($\alpha$) value

For the definition of a reference scenario we used an approach that:

- takes advantage of the large amount of data available from AERONET (Holben et al. 1998) for the definition of a reference optical thickness value;
- but makes use of standard aerosol models, the so called LOWTRAN MODELS (Shettle and Fenn 1979), for the computation of spectrally detailed optical properties.

In fact, in the last few years there has been an increasing availability of reliable data on aerosol characteristics as a result of the growth of the AERONET network. It would be unreasonable to base the definition of a reference scenario without taking full advantage of such an effort. In principle, from the AERONET dataset, it is possible to obtain a statistical distribution of aerosol optical thickness as well as of the variables, such as size distribution and refractive indices, that allow the computation of spectrally detailed optical properties needed for the simulation experiments.

Practically, it is not easy to define from the AERONET available products a most common aerosol model. In fact, this would require the computation of histogram of distribution with several dimensions including the size distribution class limits as well as the spectral real and imaginary part of the retrieved complex refractive index. In addition, using a so defined model:

- would not have the spectral detail that could be obtained from the LOWTRAN aerosol models. In fact, the AERONET model variables are obtained from the inversion of diffused radiances at a limited number of wavelengths (4) and as a consequence the complex refractive index is given at such wavelengths. LOWTRAN aerosol models are based on measures of the refractive index that are available for at least 8 wavelengths in the same spectral interval. In addition, the AERONET derived refractive index does not cover the hole spectral interval at which the simulation have been performed;
- the results of the simulations would not be easily comparable with studies that make use of the LOWTRAN models that constitutes anyhow still a reference.
In order to select the reference AOT value, 4 years of AERONET AOD were analysed over the Venice site. We choose to analyse the AOT daily average of level 2 AERONET assured quality data. Aerosol optical depth were binned on 0.02 width classes in order to find the interval in which the major number of events are present. Fig. 31 shows the occurrence number of AOT as function of AOT. It was selected the value of AOT = 0.2 as reference value with a perturbation of 0.02. The qualitative analysis of monthly/annual SeaWiFS AOT’s confirm the high occurrence of such AOT value at least over the Mediterranean Sea.

⇒ AOT = 0.2 ± 0.02

![Fig. 31 - Frequency distribution of AOT at 500 nm for 0.02 AOT width classes. The data used are level 2 daily mean from the AERONET site of Venice for the years 1999-2003.](image)

A similar analysis of occurrence of Angstrom coefficients would give relatively high values that correspond to the LOWTRAN tropospheric model that is representative of the background aerosol in the free troposphere. The occurrence of such relatively high values of Angstrom coefficients in the Venice site seems to be due to the influence of the highly industrialised area close to the site.

In order to use a more general model, the reference aerosol optical properties model considered was assumed as a combination of 50 % maritime and 50 % rural (LOWTRAN MODEL). Here the percent refers to the optical thickness value at 550 nm.

This model have an Angstrom coefficient, $\alpha$, of 0.83. A perturbation of 0.25, that corresponds to the expected accuracy of the AERONET derived Angstrom coefficient, was considered:

⇒ $\alpha = 0.83 \pm 0.25$

Using an aerosol model, that combines the spectral optical properties of maritime and rural model, these different value of $\alpha$ correspond to:

- 88 % maritime and 12 % rural $\rightarrow \alpha = 0.58$
- 50 % maritime and 50 % rural $\rightarrow \alpha = 0.83$
- 14 % maritime and 86 % rural $\rightarrow \alpha = 1.08$. 
Fig. 32 shows the spectral behaviours of the aerosol optical properties used. Stratospheric aerosol was not included in the simulations and the total AOT, assumed to be due mostly to boundary layer aerosols, was distributed vertically over the first 4 layers as follows:

- \(0.50 \cdot \text{AOT } 0 \div 1 \text{ km}\)
- \(0.25 \cdot \text{AOT } 1 \div 2 \text{ km}\)
- \(0.15 \cdot \text{AOT } 2 \div 3 \text{ km}\)
- \(0.10 \cdot \text{AOT } 3 \div 4 \text{ km}\).

Fig. 32 - Spectral behaviour of extinction coefficient normalised to the extinction coefficient at 550 nm, single scattering albedo and asymmetry factor. Different lines represent the two aerosol models used.
**Water vapour**

Water vapour has been varied by changing the whole density profile of ± 30 % as shown in Fig. 33. This would change the relative humidity and in principle, for hygroscopic aerosols, this would have as a consequence a change in the single scattering optical properties (see for example Hanel 1984). In order to separate the effect of water vapour absorption from the effect due to the change of aerosol optical properties as a function of the relative humidity, aerosol optical properties have been kept constant despite the change in relative humidity.

*Fig. 33 - H₂O density profiles used in the numerical experiments.*

**Surface**

Surface has not been considered as a disturbance (similarly to cloud contamination) and an albedo value of 5 % has been used for all channels.

**Pressure**

The core wavelengths for the aerosol retrieval (670 and 870 nm) have a relatively low molecular scattering optical thickness. Nevertheless, the observation geometry (solar angle: from dusk to dawn and geostationary satellite viewing geometry) are such that large double-path air masses can occur and in particular this will depend on the geographical position of the pixel. In order to avoid biases due to such large air mass effect, the sensitivity to the uncertainties on the surface pressure, that we assume available as an auxiliary data, are investigated varying the value between 998 and 1028 hPa.

**5.4.3 Experiment analysis**

For the channel spectral characteristic selection for the FD-VIS 0.6 and FD-VIS 0.8 the procedure described in section 3.2.1 has been adopted. Fig. 11 represents an example referring to such optimisation process for the FD-VIS.
Differently, for the three shorter wavelength options investigated (443, 470 and 550 nm) the optimisation has been done only in term of bandwidth. Fig. 34 shows the RATIO (eq. 4) as a function of the bandwidth for fixed central wavelength. For the 443 and 470 nm options the first relative maximum, that also corresponds to an absolute maximum, has been selected as bandwidth. For the 550 nm option the first maximum occurs for relatively narrow wavelength and also is quite instable. Therefore the bandwidth corresponding to such option was selected as that one at which the second maximum occurs. Note that the RATIO range is different and the maximum value reached decreases with the central wavelength value: this could be used as an possible argument to select among the three options.

![Fig. 34 - RATIO (eq. 4) as a function of the bandwidth for fixed central wavelength (in panel title).](image)

The SNR has been estimated by considering, in addition to the data set used for the selection of channel spectral characteristics, two additional scenarios:
- a dark scenario with low surface reflectance (0.05) and extremely low aerosol optical depth (0.04);
- a bright scenario with high surface reflectance (0.3) and a relatively high aerosol optical depth (0.3).

The sensitivity to changes of 0.02 (for AOD 0.04 and 0.2) and 10 % (for AOD of 0.3) was used to define the maximum allowable noise following the approach described in Section 3.2.2 for quantitative retrieval. Fig. 35 shows the estimated minimum allowable SNR (assuming the maximum allowable noise as 0.5 the sensitivity) for three different scenarios (the reference, the dark and the bright one) for the FD-0.8 VIS as a function of the scene reflectance. A similar procedure has been applied to the other channels analysed.

The overall results are summarized in Table 25 while Figures 36, 37 and 38 show the position of the selected channels (light orange rectangles) together with:
- the total (atmospheric gases + molecular scattering) one-way transmittance for the US76 Standard Atmosphere;
- the channel response for the instrument analysed in Chapter 2.
Fig. 35 - Estimated SNR (assuming the maximum allowable noise as 0.5 the sensitivity) as a function of the scene reflectance.

Table 25 - Summary results from the aerosol optimisation numerical experiment.

<table>
<thead>
<tr>
<th>FDHSI VNIR channels</th>
<th>$\lambda_r$ recommended [nm]</th>
<th>$\Delta\lambda_r$ recommended [nm]</th>
<th>High signal SNR</th>
<th>$\rho$ [%]</th>
<th>Low signal SNR</th>
<th>$\rho$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>FD-VIS 0.4</td>
<td>444</td>
<td>30</td>
<td>120</td>
<td>23</td>
<td>54</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>470</td>
<td>19</td>
<td>112</td>
<td>20</td>
<td>51</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>551</td>
<td>34</td>
<td>108</td>
<td>17</td>
<td>50</td>
<td>2</td>
</tr>
<tr>
<td>FD-VIS 0.6</td>
<td>680</td>
<td>21</td>
<td>106</td>
<td>14</td>
<td>49</td>
<td>2</td>
</tr>
<tr>
<td>FD-VIS 0.8</td>
<td>870</td>
<td>21</td>
<td>154</td>
<td>14</td>
<td>52</td>
<td>2</td>
</tr>
</tbody>
</table>

Note that the position of the FD-VIS 0.6, as obtained from the described procedure, is at wavelengths larger than the reference channels and is contaminated by a weak $O_2$ absorption band (around 0.690 $\mu$m). This is because the disturbances considered in the channel spectral characteristics selection are for this channel mostly the molecular scattering and the $O_3$ Chappius band that both occur at shorter wavelengths. The procedure applied does not consider explicitly the $O_2$ as a disturbance: for example, changing the aerosol vertical distribution however the $O_2$ absorption effect is included in the disturbance because it varies with the pressure but as magnitude is less important than molecular scattering.

In addition, in such region of the spectrum there is the transition, for vegetated surfaces, from low to high reflectances (see Fig. 39). It is important, both for the computation of the vegetation index (that among the other can be used in the cloud detection algorithm) as well as for the aerosol retrieval to locate the red channel in such a way that the reflectance from the vegetation is minimum.

Because neither the $O_2$ absorption nor the consideration of surface reflectance have been included in the optimisation procedure, the values selected with the above procedure should be moved to shorter wavelengths in such a way that the longer wavelength end of the channel response is located still in a spectral region of low reflectance for the vegetation.
Fig. 36 - Position of the selected blue-green channel options (light orange rectangle). Total (gas + molecular scattering) one-way transmittance for the US76 Standard atmospheric model (black line). Reference channel spectral responses (dash-dotted lines).

Fig. 37 - Position of the selected 870 nm channel (light orange rectangle). Total (gas + molecular scattering) one-way transmittance for the US76 Standard atmospheric model (black line). Reference channel spectral responses (dash-dotted lines).

Fig. 38 - Position of the selected 670 nm channel (light orange rectangle). Total (gas + molecular scattering) one-way transmittance for the US76 Standard atmospheric model (black line). Reference channel spectral responses (dash-dotted lines).
5.5 Cloud top drop size (HRFI) [CLMF]

5.5.1 Background

In the HRFI mission from the MTG Mission Requirements Document (table 2 page 17) four products are identified. Only the cloud top drop size is derived from the ‘solar channels’ (plus the 3.7 µm channel) and therefore should be tested within this study.

The background that applies to this set of numerical experiments is the same that for the CLM experiments described in Section 5.1. However, because of the nowcasting nature of the HRFI mission, the interest in cloud top drop size arises from the possibility to use such parameter, and in case its time derivative, as an additional information for the estimate (or nowcasting) of precipitation (see for example Rosenfeld and Gutman 1994). There is no primary interest in the cloud optical thickness expressed for such mission.

5.5.2 Experiment description

As mentioned above, the interest of a nowcasting mission in cloud top drop size is because it can be used as an indicator of precipitation when its value is larger than a given threshold. As a consequence, for this mission we expect to be able to detect a positive growth of the effective radius of top of particle size in particular when it passes the threshold value of 14 µm as indicated by Rosenfeld and Gutman 1994. We test the ability of the 0.6, 2.1 and 3.7 µm channels to retrieve such gradient with a FAR < 0.5 and HR > 0.5 against a possible false signal due to increasing moisture above the cloud up to a completely saturated profile above the cloud. Taking into account the nowcasting nature of the HRFI mission the derived products are expected to be more like flags than quantitative products. Therefore, while the retrieval of the cloud droplet effective radius for the FDHSI mission would be probably based, as for the current satellite retrievals, on multidimensional look-up-tables, such procedure is likely to be too time demanding for the relatively short time at which the product should be generated and analysed to be useful for nowcasters. In addition, we assume that processing of data for nowcasting purposes will be performed as much as possible locally by the users in order to reduce the time due to transmission. Therefore it is expected that the facilities of a local users cannot support processing highly demanding in terms of computer facilities. As a consequence, we assume a scenario of very simple data processing based on the analysis of a simple parameter for example comparison against a threshold. The requirements for a more quantitative products are, of course, similar to what computed for the FDHSI mission (Section 5.1).
Top of atmosphere (TOA) radiances are sensitive to cloud droplet radius in the NIR atmospheric windows, such as the 2.1 and the 3.7 $\mu$m ones, where condensed liquid water absorbs. In order to take into account the dependence from the cloud optical thickness, we introduce as key parameter the ratio:

$$K_{NIR}^i = R_{NIR}^i / R_{VIS}^i$$

We simulated, with the MODTRAN code, the atmospheric spectral radiance at TOA at the best available computational resolution ($1 \text{ cm}^{-1}$) for a number of scenes derived from the combination of the following variables.

The reference cloud is defined according to Rosenfeld and Gutman 1994. The optical thickness of the clouds is assumed:

$$\tau_{cloud} = 40 \pm 5$$

The cloud top pressure is assumed corresponding to a level with 263 K. The cloud is assumed 1 km thick and is divided into 5 optically equivalent 200-m layers. For a cloud of such an optical thickness the assumption of a 1 km total thickness is likely to be unphysical, however computationally convenient, having 'sliced’ the cloud and being sufficiently optically thick to reduce the dependence of the TOA radiance from the variables below the cloud.

In order to compute the single scattering optical properties, cloud particles are assumed:

- spherical
- liquid phase
- distributed with a log-normal size distribution with the dispersion ($\sigma$) dependent on the mean geometrical radius ($r_0$) as:

$$\sigma = \frac{-0.084 + 0.43 \cdot \ln(r_0)}{\ln(10)}$$

The effective radius is varied around the threshold value of 14 $\mu$m with the same step as Rosenfeld and Gutman 1994: 4 $\mu$m. **Fig. 40** shows the single scattering optical properties (extinction coefficient normalised to its value at 550 nm, single scattering albedo and asymmetry factor) for three clouds characterised by effective radius $r_e = 14 \pm 4 \mu$m.

The main disturbance consists in changing the above cloud total precipitable water vapour. In fact, an increase (decrease) in the above cloud total integrated water vapour amount, and consequently of its absorption, can produce a signal that can be interpreted as a growth (reduction) of the cloud particles. Therefore 3 cases were considered: the reference one and a completely dry (RH = 0 % for $z > z_{cloud}$) and moist (RH = 80 % for $z > z_{cloud}$). Summarising, the following different atmospheric conditions ($\Delta Y$) were used:

- $O_3$: 85 %, 100 %, 115 %
- $H_2O$: RH = 0 %, standard profile, 80 %
- $p_0$: 998, 1013, 1028 hPa.
Fig. 40 - Extinction coefficient (normalised to its value at 550 nm), single scattering albedo and asimmetry factor, as a function of the wavelength, for the 3 adopted water clouds (see text) with effective radius: 10, 14 and 18 µm.
5.5.3 Experiment analysis

Spectral definition experiments

Similarly to the approach adopted for the FDHSI mission, we started by setting up a set of experiments for the definition of channel spectral characteristics ($\lambda_0$ and $\Delta\lambda$). Being the sensitivity to the effective radius almost constant over the whole VIS range, we assumed the VIS channel with the maximum $\Delta\lambda$, that is integrating over all the simulated spectra at visible wavelength. For each of the other two bands (NIR and IR) we searched for the values of $\lambda_c$ and $\Delta\lambda$ that optimise the detection of drops effective radius changes, around the reference value of $r = 14 \mu\text{m}$.

In order to do that, we defined the skill of each set of possible combinations of $\lambda_0$ and $\Delta\lambda$ values as follows:

$$C(\lambda_0,\Delta\lambda) = \frac{\min K_{10} - \max K_{14}}{\max K_{14} - \min K_{14}}$$  \hspace{1cm} (9)

where:

- $\min K_{10} - \max K_{14}$ is related to the distance (when the two $K$ sets are separated) between the minimum value of $K_{10}$ and the maximum value of $K_{14}$ (the higher the sensitivity to effective radius changes, the higher such distance is expected to be);
- $\max K_{14} - \min K_{14}$ represents the spread in $K$ values for all other geophysical variables changed for a fixed effective radius $r = 14 \mu\text{m}$. This normalisation term is introduced because it should decrease the skill value for combinations of channel characteristics where the distance term is due also to absorption from water vapour.

For each $\Delta\lambda$ value, all the possible central wavelengths $\lambda_0$ are tested and the $\lambda_0$ that maximises the $C$ value is selected as best value.

*Fig. 41* shows the best central wavelength, selected with the $C$ criteria, as a function of $\Delta\lambda$ (blue symbols) for a $\Delta\lambda$ step of 1 cm$^{-1}$. The extremes of the selected band are also reported (yellow and light blue symbols).

The previous set of experiments produced values that were judged not very likely for the HRFI mission for the following reasons:

- the selected bands where relatively too narrow for a similar mission, with consequent required high values of SNR;
- the position of the bands, in particular the 2100 one, was in spectral intervals with the presence of important band absorption from gas (CO$_2$) other than water vapour. This is somehow expected from the design of the experiment that searches for high sensitivity to liquid water absorption (that has a relative maximum around 2000 nm) using as a disturbance mostly water vapour, that at such wavelengths has a relatively weak absorption. The consequence of a similar choice would be a lower overall signal, due to loss of radiant energy absorbed by the CO$_2$ as well as a sensitivity to the cloud top height.

However, the results of such experiments, even if the optimisation is performed in terms of a skill rather than the sensitivity to the quantitative value of the variable of interest, would give relatively narrow channels that would not differ from the ones defined for the FDHSI mission. Considering the different nature of the mission and the fact that the spatial resolution is half the one for the FDHSI we did not perform any optimisation of the channel position but we defined channels as large as possible with the following criteria:

- relatively large transmittance
- channel position possibly including the FDHSI channel
- and, for the 3.7 $\mu\text{m}$ channel, the criteria of considering the longer wavelength half of the window to account for its use as emission channel as discussed in Section 4.3.
Fig. 41 - Best central wavelength, selected with the C criteria (see text), as a function of $\Delta \lambda$ (blue symbols) for a $\Delta \lambda$ step of 1 cm$^{-1}$. The extremes of the selected band are also reported (yellow and light blue symbols).
**Fig. 42** shows the spectra of total transmittance for the NIR and IR spectral regions. Such spectra are obtained with: the reference atmospheric parameters ($p_0 = 1013$ hPa and standard mid-latitude summer profiles of $O_3$, $H_2O$ and remaining gases) and no aerosols or clouds. We repeated therefore the optimisation of the $C$ skill parameter reducing the range of $\Delta\lambda$ to the interval between 500 and 600 cm$^{-1}$ (see Fig 41) and the range of variability of $\lambda_0$ to relatively transparent regions of the spectrum according to the transmittance spectra discussed above.

By applying a similar forcing, the resulting bands are:

- **VIS**: 0.500-0.700 $\mu$m
- **NIR**: 2.102-2.315 $\mu$m
- **IR**: 3.700-4.000 $\mu$m.

**Integrating the TOA radiances between the above channel limits we obtained the radiance values corresponding to each numerical experiments. **Fig. 43** shows the integrated radiances for the VIS, 2100 and 3700 nm channels, defined with the channel limits given above, as a function of experiment number, where different values of effective radius are highlighted using different colours and symbols.
Fig. 43 - Spectrally integrated Visible, Near Infrared and Infrared radiance [W cm⁻² sr⁻¹] as a function of experiment number. Different colours and symbols refer to different effective radius values (i.e. 10, 14 and 18 µm). Signal to Noise Ratio estimation.
The SNR was computed with the same approach used for the Cloud Phase. Since the skills are based on the ratio between two reflectances, we assumed for the VIS channel the SNR specified by the preliminary table i.e. SNR = 10 at $\rho = 1 \%$ and it was computed at the effective reflectance values assuming a square root dependence of the Noise from the signal.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Introduction of results

It is not simple to draw conclusions from this study on MTG Imagers channel specifications because there is the bias that the driving objectives of this study were cloud microphysics and aerosol, that are not the highest priority for the MTG Imagers. It is reminded from the Mission Requirements Document that product priorities are ranked as follows:

- **FDHSI**: 1) Cloud mask/imagery, Cloud top temperature, Cloud motion vector; 2) Cloud type, Clear-sky AMVs, Tracer height assignment; 3) Land and sea surface temperature; 4) **Cloud top phase, Cloud optical thickness, Drop size distribution**; 5) Temperature/humidity gradients; 6) Total column humidity; 7) **Aerosol optical thickness, Aerosol size distribution**, Low visibility at surface; 8) Snow cover, Sea ice temperature; 9) Fire detection, Smoke detection, Volcanic ash detection; 10) Volcanic ash total optical depth, Dust detection, Vegetation stress.
- **HRFI**: 1) Cloud mask/imagery/pattern, 2) Cloud motion vector, 3) Cloud top temperature/pressure, 4) **Cloud top drop size**.

With this in mind, Tables 26, 27 and 28 collect the main results of the study. It is noted that, in case of trade-offs of strongly different impact on the resulting specifications, the quoted figures refer to the less demanding one. Examples of heavy trade-offs are:

- the noise level is set to one half of the sensitivity, that is the minimum requirement, whereas one tenth would be an optimum requirement (i.e., the optimum SNR values would be 5 times higher than those recorded in the Tables);
- when the SNR values necessary for quantitative evaluations turned to be extremely demanding, the values quoted in the Tables refer to the descoped application of detection only (in the body of this Report, however, the full information, including the most demanding figures, is available).

In the Tables 26, 27 and 28 that follow, that summarise the results of the study, the following assumptions have been made.

**Digitisation**

A linear relationship between Digit Number (DN) and radiance at the sensor has been assumed, with no offset. A 16-bit digitisation has been assumed. For a dynamic range up to 120 % this means that 1 DN corresponds to an albedo variation of 0.0018 %. This number of bits has been assumed to start the simulation process. Now that the radiometric accuracy requirements have been established, the most appropriate number of bits can be computed and the process iterated. Very little changes, if any, are expected from the iteration.

**Filter function shape**

The bandwidths have been defined for a rectangular filter response function with maximum transmittance = 1. For width it is meant:

$$\text{width} = (\lambda_{\text{max}} - \lambda_{\text{min}})$$

The main reasons for having simplified the channel response in respect of the template approach followed in Chapter 2 are:

- the radiative transfer simulations have been performed with a regular grid in wavelength unit (cm$^{-1}$). The used RTM allows the definition of the output in different wavelength units such as [nm] but in doing this within the simulated band the spectral resolution, and as a consequence the relative sensitivity, is not kept constant;
• using the template, that are defined symmetric in a nm regular grid, would have increased drastically the computer time needed for the search of the best channel definition. In order to test the methodology and obtain some preliminary results we decided to adopt rectangular ‘ideal response’ filters that would be symmetric in both wavelength and wavenumber units.

**Input radiance**

The following definition of albedo ($\rho$) has been used

$$\rho = \frac{100 \cdot L \cdot \pi}{E_0}$$

In Tables 26 and 27 the required SNR values are quoted for “high $\rho$ value” and “low $\rho$ value” typical of scenes appropriate to the range in which the addressed product can be measured. The indicated $\rho$ values can be converted in input radiance $L$ by scaling from the $L$ value quoted for the maximum of the dynamic range.

In order to provide simplified results, Tables 26, 27 and 28 also include a “Recommended SNR value at the reference 1 % albedo”. The extrapolation from the SNR values computed at the appropriate $\rho$ value to that one at the reference 1 % is performed by applying criteria that are explained in the comments to the Tables.

Further assumptions or explanations specific to individual channels or group of channels are included in the comments to the Tables.

### 6.2 FDHSI VNIR channels

*Table* 26 collects the results relative to the group of VNIR channels of FDHSI.

**Table 26 - Summary table of results for FDHSI VNIR channels.**

<table>
<thead>
<tr>
<th>FDHSI VNIR channels</th>
<th>Central $\lambda$ (nm)</th>
<th>Bandwidth (nm)</th>
<th>High signal SNR</th>
<th>High signal $\rho$ (%)</th>
<th>Low signal SNR</th>
<th>Low signal $\rho$ (%)</th>
<th>Scaled to reference signal SNR</th>
<th>Scaled to reference signal $\rho$ (%)</th>
<th>Max of dynamic range $L$ (W m$^{-2}$ μm$^{-1}$ sr$^{-1}$)</th>
<th>$\rho$ (%)</th>
<th>Max of dynamic range $L$ (W m$^{-2}$ μm$^{-1}$ sr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FD-VIS 0.4</td>
<td>443 444 30</td>
<td></td>
<td>120 23</td>
<td>54 4</td>
<td>25 1</td>
<td>5.79 1</td>
<td></td>
<td></td>
<td></td>
<td>120 695</td>
<td></td>
</tr>
<tr>
<td></td>
<td>470 470 21</td>
<td></td>
<td>112 20</td>
<td>51 3</td>
<td>25 1</td>
<td>6.60 1</td>
<td></td>
<td></td>
<td></td>
<td>120 792</td>
<td></td>
</tr>
<tr>
<td></td>
<td>555 551 34</td>
<td></td>
<td>108 17</td>
<td>50 2</td>
<td>26 1</td>
<td>5.97 1</td>
<td></td>
<td></td>
<td></td>
<td>120 716</td>
<td></td>
</tr>
<tr>
<td>FD-VIS 0.6</td>
<td>645 680 19</td>
<td></td>
<td>106 14</td>
<td>49 2</td>
<td>28 1</td>
<td>4.78 1</td>
<td></td>
<td></td>
<td></td>
<td>120 574</td>
<td></td>
</tr>
<tr>
<td>FD-VIS 0.8</td>
<td>865 870 14</td>
<td></td>
<td>154 14</td>
<td>52 2</td>
<td>41 1</td>
<td>3.02 1</td>
<td></td>
<td></td>
<td></td>
<td>120 363</td>
<td></td>
</tr>
</tbody>
</table>

The following is noted.

**FD-440 VIS** - Two scenarios have been investigated:

• a baseline configuration with a channel at 470 nm;
• an alternative scenario with a blue (443 nm) and a green (555 nm) channel.

**FD-VIS 0.6** - The optimisation procedure, used to define the channel spectral characteristics, gives as a result a channel that includes part of an O$2$ absorption band. This is mainly due to the facts that:

• the vertical distribution of aerosols was not changed, therefore a well-mixed gas as the oxygen would not result as a disturbance;
• even if the change in pressure should induce a sensitivity to the absorption from such band, the other important disturbances in this window (i.e. molecular scattering and ozone absorption) have large effects at shorter wavelengths and, as a consequence, a position at longer wavelength is automatically selected.
FD-VIS 0.8 - The optimisation of channel characteristics for the FD-VIS 0.8 gives a relatively narrow channels that could in principle be larger given the absence, within such an atmospheric window, of strong gas absorption features.

The extrapolation of SNR to the reference 1 % value has been made by square-root, starting from the high-input values.

6.3 FDHSI SWIR/MWIR channels

Table 27 collects the results relative to the group of SWIR/MWIR channels of FDHSI.

<table>
<thead>
<tr>
<th>FDHSI SWIR/MWIR channels</th>
<th>Central $\lambda$</th>
<th>Bandwidth</th>
<th>High signal</th>
<th>Low signal</th>
<th>Scaled to reference signal</th>
<th>Max of dynamic range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nom. [nm]</td>
<td>Rec. [nm]</td>
<td>SNR $\rho$ [%]</td>
<td>SNR $\rho$ [%]</td>
<td>SNR $\rho$ [%]</td>
<td>$L$ [W m$^{-2}$ µm$^{-1}$ sr$^{-1}$]</td>
</tr>
<tr>
<td>FD-NIR 1.3</td>
<td>1375 1371</td>
<td>30 30</td>
<td>N/A N/A</td>
<td>25 0.5</td>
<td>35 1</td>
<td>1.152 80</td>
</tr>
<tr>
<td>FD-NIR 1.6</td>
<td>1610 1576</td>
<td>60 52</td>
<td>8 50 59 31 11 1</td>
<td>0.712 100</td>
<td>71.2</td>
<td></td>
</tr>
<tr>
<td>FD-NIR 2.1</td>
<td>2130 2126</td>
<td>50 47</td>
<td>45 40 173 13 48 1</td>
<td>0.293 100</td>
<td>29.3</td>
<td></td>
</tr>
<tr>
<td>FD-IR 3.7</td>
<td>3800 3910</td>
<td>600 175 31 19 28 16 7 1</td>
<td>0.305 100</td>
<td>3.05</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The following is noted.

FD-NIR 1.3 - We suggest a scenario with a maximum value of the dynamic range of 80 % albedo rather than 100 %. Taking into account the specific role of this channel in the inversion algorithm, we suggest that the possibility to reduce the maximum signal (that basically would correspond to sun-glint over ocean that would still be absorbed by atmospheric water vapour) should be considered. This would increase, for the same number of bits for the signal, the sensitivity to lower changes in radiance. Finally, since the application of measurements from this channel (e.g. cirrus detection) is based on the analysis of the difference between very small amounts of radiation, it may be important to define other channel characteristics, apart from the one defined in this study, that may be very relevant for a successful use. The characteristics to be defined are the ones that can be generate low, in an absolute sense, but high from the application viewpoint, signals, as for example: the out of band response, the spectral stability and the channel cross talking. Because of the peculiarity of such channel a separate study, with an optimised approach, should be dedicated.

FD-NIR 1.6 - The obtained results derive from a trade-off between the relative priority assigned to cloud phase and effective radius. Priority to effective radius pushes the channel towards the 1630 nm region, priority to phase pushes towards the 1580 nm region. If we force towards the 1630 nm region, the sensitivity to phase dramatically drops except for very thick clouds, which implies that extremely demanding SNR values are required. On the other hand, the primary channel for effective radius is FD-NIR 2.1, and also FD-IR 3.7 has been finally optimised for effective radius (see next). Therefore, the FD-NIR 1.6 channel has been optimised for cloud phase, that implied an unusual specification (central wavelength at 1576 nm). Of course, this result might be upset if other applications of the channel are considered (e.g., cloud discrimination over snow fields).

FD-NIR 2.1 - The automatic procedure for the optimisation, based on the use of such channel in the effective radius retrieval, selects the channel in a relatively opaque part of the considered window. The reason is that absorption at the selected wavelengths is due to CO$_2$ that has not been considered explicitly as a disturbance, while in that spectral region the water vapour absorption is not particularly strong while the imaginary part of the complex refractive index of liquid water has a maximum that is the origin of the high sensitivity to effective radius changes. Changing the height of the cloud top introduces implicitly the CO$_2$ change as a disturbance. Including such change slightly shifts the selected FD-NIR 2.1 channel position towards longer wavelengths, but the selected band is still contaminated by the CO$_2$ absorption.
FD-IR 3.7 - Similarly to the FD-NIR 2.1 case, the result of the automatic procedure to select channel position would be at the boundaries (i.e. 3.5 µm or alternatively 4.0 µm) of the spectral interval considered because of higher absorption of condensed water. Again, this would result in a channel either contaminated by CH₄ (at shorter wavelengths) or N₂ and N₂O at longer wavelengths that for the current procedure are not disturbances. We forced the channel position towards longer wavelength (i.e. 3.9 µm). The main reason is that the FD-IR 3.7 is mostly used as an emission channel and moving it toward shorter wavelengths would reduce the thermal energy component of the measured radiance. On the other hand, the information content in terms of cloud top dominant phase for such position compared to a shorter wavelength one should be tested. The specifications for the FD-IR 3.7 channel refer to the cloud top reflectance properties (the thermal component has been subtracted). It is noted that it is recommended to greatly reduce the channel bandwidth (now 175 nm) in respect to the originally envisaged 600 nm.

The representative albedo value for cirrus cloud detection in channel FD-NIR 1.3 turned to be 0.5 %. No value is provided for high input signal, that is meaningless in this strong-absorption channel. For the other three channels the representative albedo values are high, since the application focuses on thick clouds, candidate to produce precipitation. Their SNR values also exhibit an apparently anomalous trend versus the albedo value (decreasing instead of increasing, or insensitive): this is due to the fact that an albedo increase is associated to a thicker cloud with less interference from cross-cloud earth-surface radiation, thus the cloud characterisation is easier and requires lower SNR. In this case, the extrapolation of SNR to the reference 1 % albedo has been made by square-root starting from the low-input values.

### 6.4 HRFI VIS/SWIR/MWIR channels

*Table 28* collects the results relative to the HRFI VIS/SWIR/MWIR channels.

<table>
<thead>
<tr>
<th>HRFI VIS/SWIR/MWIR channels</th>
<th>Central λ</th>
<th>Bandwidth</th>
<th>Appropriate signal</th>
<th>Scaled to reference signal</th>
<th>Max of dynamic range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nom. [nm]</td>
<td>Rec. [nm]</td>
<td>SNR</td>
<td>ρ [%]</td>
<td>L [W m⁻² µm⁻¹ sr⁻¹]</td>
</tr>
<tr>
<td>FD-VIS 06</td>
<td>600</td>
<td>600</td>
<td>&lt; 200 200</td>
<td>86 75</td>
<td>5.49 120</td>
</tr>
<tr>
<td>FD-NIR 2.1</td>
<td>2200</td>
<td>2209</td>
<td>&lt; 200 213</td>
<td>33 30 6 1</td>
<td>0.261 100</td>
</tr>
<tr>
<td>FD-IR 3.7</td>
<td>3800</td>
<td>3850</td>
<td>&lt; 600 300</td>
<td>33 13 9 1</td>
<td>0.322 100</td>
</tr>
</tbody>
</table>

The application here has been descoped from the quantitative measurement of effective radius (which is extremely demanding) to detection of whether the drop size exceeds or not the “magic” 14 µm effective radius, that triggers precipitation. The extrapolation of SNR to the reference 1 % albedo has been made by square-root.

### 6.5 Final recommendations

Although oversimplified in respect of the articulation of the results provided in Chapter 5 and already summarised in the previous sections of this Chapter 6, *Table 29* provides a useful compressed view of what is recommended for revised specifications of the MTG imagers. The information is based on the appropriate columns of Tables 26 to 28, with some round-off applied on bandwidths and SNR values.

It is noted that the accuracy is referred, for comfort, to 1 % albedo, but the essential information is the input radiance L. This can be interpreted not only in terms of albedo, but also in terms of different illumination conditions leading to the same input radiance. In Table 29 we have recommended to move the “blue” channels to 470 nm. However, if at all affordable, it would be very desirable to keep the 443 nm channel and add a “green” 555 nm channel. Apart from benefit for aerosol and cloud microphysics, the triplet 443 + 555 + 680 (B + G + R) would be of use for:
• full colour pictures for TV and aviation (slant visibility);
• better coverage of the short-wave spectrum relevant for PAR (Photosynthetically Active Radiation) measurement and other surface radiative parameters including vegetation indexes.

Table 29 - Recommended revised configuration of the MTG imagers channels.

<table>
<thead>
<tr>
<th>Imaging channels</th>
<th>Central wavelength [nm]</th>
<th>Bandwidth [nm]</th>
<th>Recommended accuracy</th>
<th>Max of dinamic range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>SNR</td>
<td>(\rho) [%]</td>
</tr>
<tr>
<td>FD-VIS 0.4</td>
<td>470</td>
<td>20</td>
<td>25</td>
<td>1</td>
</tr>
<tr>
<td>FD-VIS 0.6</td>
<td>680</td>
<td>20</td>
<td>30</td>
<td>1</td>
</tr>
<tr>
<td>FD-VIS 0.8</td>
<td>870</td>
<td>20</td>
<td>40</td>
<td>1</td>
</tr>
<tr>
<td>FD-NIR 1.3</td>
<td>1371</td>
<td>30</td>
<td>40</td>
<td>1</td>
</tr>
<tr>
<td>FD-NIR 1.6</td>
<td>1576</td>
<td>50</td>
<td>15</td>
<td>1</td>
</tr>
<tr>
<td>FD-NIR 2.1</td>
<td>2126</td>
<td>50</td>
<td>50</td>
<td>1</td>
</tr>
<tr>
<td>FD-IR 3.7</td>
<td>3910</td>
<td>180</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>HR-VIS 0.6</td>
<td>600</td>
<td>200</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>HR-NIR 2.1</td>
<td>2209</td>
<td>220</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>HR-IR 3.7</td>
<td>3850</td>
<td>300</td>
<td>10</td>
<td>1</td>
</tr>
</tbody>
</table>

We remind that the recommended definition of FD-NIR 1.6, in the 1580 nm region, descends from:
• the existence of the FD-NIR 2.1 channel and the selection of the FD-IR 3.7 central wavelength in the 3.9 \(\mu\)m region to optimise sensitivity to effective radius, thus reserving the priority of cloud phase for FD-NIR 1.6;
• the lack of consideration for the use of the channel in other applications such as cloud/snow discrimination.

Final remarks
In order to obtain the required channel characteristics, given:
• the number of channels
• the different missions
• the different geophysical products that are expected to be retrieved
• the relatively short time available for the study,

a simplified approach was adopted, that would optimise each single channel basically maximising the sensitivity to a single geophysical variable and, in most cases, in a stand-alone configuration.

This approach showed its limits and capabilities.

About the definition of the SNR, further studies are needed. The largest difficulty is in the lack of information of the relationship between the Signal and the Noise to transfer any ‘geophysically based’ estimation to the reference scene.

A larger simulation dataset should be analysed to obtain larger statistics and range of validity for the obtained channel characteristics, but more important:
• channels should be optimised also taking into account their contribution to the retrieval of variables where they are not fundamental: for example the 670 nm channel for cloud phase or the 2100 nm channel for its contribution in determining the surface reflectance in the aerosol retrieval over land;
• some sort of retrieval technique should be introduced;
• a more realistic model for the radiometer should be included in such an exercise.

The experience acquired and the tools developed for this study constitute a basis for further studies of options that could be needed in successive phases of the MTG imager definition and development process.
REFERENCES


ACRONYMS AND E.M. BANDS DEFINITION

Definition of bands of the e.m. spectrum (adopted in this text: not necessarily standard)

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
<th>Wavelength Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>UV</td>
<td>Ultra-Violet</td>
<td>0.01 - 0.38 $\mu$m</td>
</tr>
<tr>
<td>VIS</td>
<td>Visible</td>
<td>0.38 - 0.78 $\mu$m</td>
</tr>
<tr>
<td>B</td>
<td>Blue</td>
<td>0.436 $\mu$m</td>
</tr>
<tr>
<td>G</td>
<td>Green</td>
<td>0.546 $\mu$m</td>
</tr>
<tr>
<td>R</td>
<td>Red</td>
<td>0.700 $\mu$m</td>
</tr>
<tr>
<td>NIR</td>
<td>Near Infra-Red</td>
<td>0.78 - 1.30 $\mu$m</td>
</tr>
<tr>
<td>VNIR</td>
<td>Visible and Near Infra-Red (VIS + NIR)</td>
<td>0.38 - 1.3 $\mu$m</td>
</tr>
<tr>
<td>SWIR</td>
<td>Short-Wave Infra-Red</td>
<td>1.30 - 3.00 $\mu$m</td>
</tr>
<tr>
<td>MWIR</td>
<td>Medium-Wave Infra-Red</td>
<td>3.00 - 6.00 $\mu$m</td>
</tr>
<tr>
<td>TIR</td>
<td>Thermal Infra-Red</td>
<td>6.00 - 15.0 $\mu$m</td>
</tr>
<tr>
<td>IR</td>
<td>Infra-Red (MWIR + TIR)</td>
<td>3 - 15 $\mu$m</td>
</tr>
<tr>
<td>FIR</td>
<td>Far Infra-Red</td>
<td>15 $\mu$m - 1 mm (= 300 GHz)</td>
</tr>
<tr>
<td>Sub-mm</td>
<td>Submillimetre wave (part of FIR)</td>
<td>3000 - 300 GHz (or 100 $\mu$m - 1 mm)</td>
</tr>
<tr>
<td>MW</td>
<td>Microwave</td>
<td>300 - 1 GHz (or 1 mm - 30 cm)</td>
</tr>
<tr>
<td>SW</td>
<td>Short Wave</td>
<td>0.2 - 4.0 $\mu$m</td>
</tr>
<tr>
<td>LW</td>
<td>Long Wave</td>
<td>4 - 100 $\mu$m</td>
</tr>
</tbody>
</table>

Acronyms

AATSR Advanced Along-Track Scanning Radiometer (on ENVISAT)
ABI Advanced Baseline Imager (on GOES-R)
AOD Aerosol Optical Depth
AOT Aerosol Optical Thickness
AVHRR Advanced Very High Resolution Radiometer (on NOAA and MetOp)
CNR Consiglio Nazionale delle Ricerche
DISORT Discrete Ordinate Radiative Transfer
DN Digit Number
ENVISAT Environmental Satellite
EOS Earth Observing System (Terra, Aqua, Aura)
FAR False Alarm Rate
FDHSI Full Disk High Spectral-resolution Imager (on MTG)
FWHM Full Width at Half Maximum
GEO Geostationary Earth Orbit
GOES Geostationary Operational Environmental Satellite
GOS Global Observing System
HR Hit Rate
HRFI High Resolution Fast Imager (on MTG)
ISAC Istituto di Scienze dell’Atmosfera e del Clima (of CNR)
MERIS Medium Resolution Imaging Spectrometer (on ENVISAT)
MetOp Meteorological Operational satellite
MODIS Moderate-resolution Imaging Spectroradiometer (on EOS Terra and Aqua)
MRD Mission Requirements Document
MSG Meteosat Second Generation
MTG Meteosat Third Generation
MVIRI Meteosat Visible Infra-Red Imager (on Meteosat 1 to 7)
NDVI Normalised Difference Vegetation Index
NEAT Noise-Equivalent Difference Temperature
NOAA National Oceanic and Atmospheric Administration (satellite and agency)
NPOESS National Polar-orbiting Operational Environmental Satellite System
NPP NPOESS Preparatory Program
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
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<tbody>
<tr>
<td>NWP</td>
<td>Numerical Weather Prediction</td>
</tr>
<tr>
<td>PAR</td>
<td>Photosynthetically Active Radiation</td>
</tr>
<tr>
<td>RTE</td>
<td>Radiative Transfer Equation</td>
</tr>
<tr>
<td>RTM</td>
<td>Radiative Transfer Model</td>
</tr>
<tr>
<td>SeaWiFS</td>
<td>Sea-viewing Wide Field-of-view Sensor (on OrbView-2, former SeaStar)</td>
</tr>
<tr>
<td>SEVIRI</td>
<td>Spinning Enhanced Visible and Infra Red Imager (on MSG)</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
</tr>
<tr>
<td>TOA</td>
<td>Top Of Atmosphere</td>
</tr>
<tr>
<td>VIIRS</td>
<td>Visible/Infrared Imager Radiometer Suite (on NPP and NPOESS)</td>
</tr>
<tr>
<td>VIRI-M</td>
<td>Visible Infra Red Imager (studied for MetOp-3)</td>
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