METOP-SG 3MI (Multi-viewing Multi-channel Multi-polarization Imaging), a powerful observing mission for future operational applications.

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Abstract

The future generation of EUMETSAT polar satellites, METOP-SG, will bring in space a Multi-Viewing Multi-Channel Multi-Polarization Imaging mission (3MI). 3MI task is Earth observation in a multiplicity of conditions, varying spectrally (410 - 2130 nm), polarization (-60°, 0°, +60°) and viewing angles (14 different views of the same target area).
3MI is designed primarily for aerosol observation, supporting the environment monitoring by detection of microphysical properties of the scene. It will also greatly support the observation of Earth radiation budget, clouds microphysics, soil condition, ocean color.
A recently Selex ES industry supported research fellowship was activated at Centro Nazionale di Meteorologia e Climatologia Aeronautica (C.N.M.C.A.), the Italian National Weather Centre, focusing on future operational applications of METOP-SG 3MI data; in particular it is investigated the 3MI capability in operationally detecting, monitoring and measuring volcanic ash presence, by simulation of future instrument behavior, capitalizing the experience done in Europe with other analogous space-based observing missions, e.g. PARASOL. The exploitation of 3MI spectral channels not included in the spectral range of heritage observing missions in the field of aerosol and cloud application it is also investigated.
The paper shows first phase of study results, evidencing the crucial role of METOP-SG 3MI instrument in future operational environment, addressing also potential applications integrated with MTG FCI data.

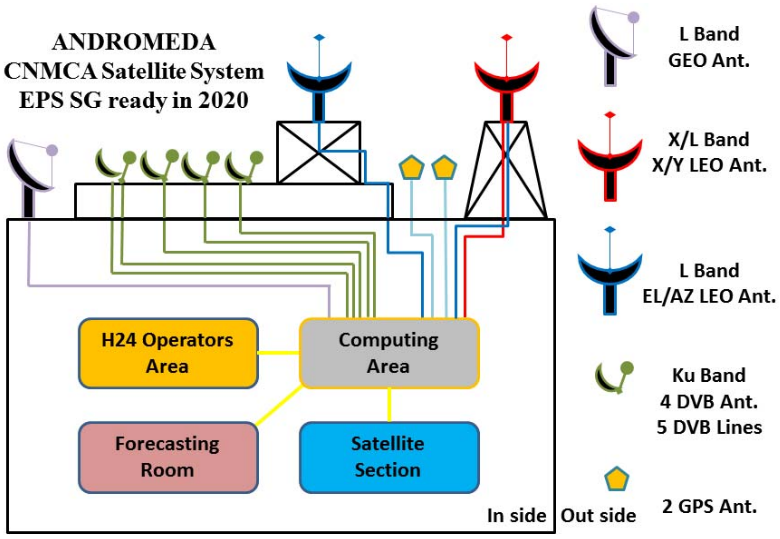
1. Introduction

The European contribution to operational meteorological observations from polar orbit has been provided by the first generation of Meteorological Operational (METOP) satellites, which first satellite has been launched in 2006 and second one in 2012. The METOP Second Generation (METOP-SG) series of satellites will provide continuity and enhancement of these observations in the timeframe of 2020 to 2040.
The METOP-SG program is being implemented in a collaboration between EUMETSAT and ESA. ESA develops the prototype METOP-SG satellites (including associated instruments) and procures, on behalf of EUMETSAT, the recurrent satellites. EUMETSAT is responsible for the overall mission, funds the recurrent satellites, develops the ground segment, procures the launch and LEOP services and performs the satellites operations.
The payload of the METOP-SG satellites consists of the following instruments: the visible and infrared imager (METimage), to provide information on clouds, cloud cover, land surface properties, sea, ice and land surface temperatures; the Infrared Atmospheric Sounding Interferometer–New Generation (IASI-NG), to provide atmospheric temperature and humidity profiles, as well as monitor ozone and various trace gases; the MicroWave Sounder (MWS), to provide atmospheric temperature and humidity profiles; the SCAtterometer (SCA), to provide ocean surface wind vectors and land surface soil moisture; the Radio Occultation sounder (RO), to provide atmospheric temperature and humidity profiles, as well as information about the ionosphere; the Sentinel-5 (S-5) instrument, to monitor various trace gases, air quality and support climate monitoring; the MicroWave Imager (MWI), to provide precipitation monitoring as well as sea ice extent information; the Ice and Cloud Imager (ICI), to measure cloud ice water path, properties and altitude; the Multi-viewing, Multi-channel, Multi-polarization Imager (3MI), to provide information on atmospheric aerosols; and the Data Collection System Argos-4, for the collection and transmission of observations and data from surface, buoy, ship, balloon or airborne data collection platforms.
3MI task is Earth observation in a multiplicity of conditions, varying spectrally (410 - 2130 nm), polarization (-60°, 0°, +60°) and viewing angles (14 different views of the same target area). 3MI is designed primarily for aerosol observation, supporting the environment monitoring by detection of

microphysical properties of the scene. It will also greatly support the observation of Earth radiation budget, clouds microphysics, soil condition, ocean color.
The parallel Phase A/B1 studies have been completed in the first quarter of 2013, with the implementation phases (B2/C/D/E) planned to start in 2014. In parallel, and following an open competitive tender action, the Instruments Prime Contractors for five of the METOP-SG instruments (MWS, MWI, ICI, 3MI, RO) have been selected in March 2013.These five Instruments Prime Contractors will be Subcontractors to the future METOP-SG satellites Prime Contractor, which will be selected following a competitive ITT. Phase B2 activities are planned to start in April 2014. The selected Instrument Prime Contractor for 3MI is Selex ES, a Finmeccanica Company, Campi Bisenzio (Italy).
Being on an operational platform 3MI data will be distributed from METOP-SG satellite in real-time to operational user community, having X-band direct-readout capability, similarly to Suomi-NPP receiving systems. Among the others the Centro Nazionale di Meteorologia e Climatologia Aeronautica (C.N.M.C.A.), the Italian National Weather Centre, will have available this capability.
A recently Selex ES supported research fellowship was activated at C.N.M.C.A, focusing on future operational applications of METOP-SG 3MI data; in particular it is investigated the 3MI capability in detecting, monitoring and measuring volcanic ash presence, by simulation of future instrument behavior, capitalizing the experience done in Europe with other analogous space-based observing missions, e.g. PARASOL. The exploitation of 3MI spectral channels not included in the spectral range of heritage observing missions in the field of aerosol and cloud application it is also investigated.

2. Study description

3MI is designed primarily for aerosol observation, supporting the environment monitoring by detection of microphysical properties of the scene. It will also greatly support the observation of Earth radiation budget, clouds microphysics, soil condition, ocean color. For 3MI multi-viewing is based on the overlapping of 2D images of Earth surface, recorded consecutively at regular interval along the orbit (called along-track, ALT acquisition points) and thus providing the means to sense the Top of Atmosphere (TOA) radiance at different Observation Zenith Angles (OZA) for each target.
The multi-wavelength and multi-polarization measurement capability is facilitated by means of a continuously rotating filter wheel. The 3MI instrument is providing a number of spectral channels spanning over an extended spectral range, from 410 nm to 2130 nm, which are shared between two separate modules; the VNIR and the SWIR module.
All spectral channels within each module are recorded sequentially, while, for the polarized ones, three consecutive polarization measurements are taken with a linear polarizer oriented at +60, 0, and -60 degrees respectively for each channel. A single full rotation of the filter wheel facilitates the measurement of all spectral channels. The two groups of channels (SWIR and VNIR) being arranged on two concentric rings on the same filter wheel can be acquired (each group independently using its corresponding module) in a single filter wheel rotation.
The proximity of the consecutive ALT acquisition points determines the number and the angular spacing of the acquired views for each target on ground, while the rotation speed of the filter wheel determines the temporal and angular co-registration of the various spectral channels of the instrument in each view.
To properly study future 3MI spectral and geometrical imaging capabilities, EUMETSAT has committed in August 2013 the University of Lille and the University of Berlin to produce simulated test data. 3MI benefits of the POLDER / PARASOL heritage, that Centre National d'Etudes Spatiales (CNES) made available through both ftp and web access (http://www.icare.univ-lille1.fr/). POLDER / PARASOL is the only space-based multi-viewing, multi-wavelength and multi-polarization mission that has ever flown on a satellite, the first and still the only "3M" observations available. The POLDER instrument was developed by CNES through a cooperation with NASDA and was launched in August 1996 on ADEOS-I. A second instrument was furbished for ADEOS-II launched in December 2002. A third instrument was then developed to fly on a dedicated CNES microsatellite joining the A-train in March 2005 and still flying without any further orbit control possibility due to complete consumption of fuel reserve.



C.N.M.C.A., actual polar satellites direct-readout L-band and X-band capabilities. EPS SG ready in 2020.

One of the authors, Daniele Biron, being the chief of satellite operational area at C.N.M.C.A., planned a feasibility study, courtesy supported by Selex ES, on the operational exploitation of future 3MI data that will be distributed from METOP-SG satellite in real-time to user community, having X-band direct-readout capability, similarly to Suomi-NPP receiving systems. In particular, the fast delivery towards operational forecaster of level 1 and level 2 products, for immediate recognition of dangerous phenomena, well in advance to the reception of post-processing products possibly assembled at EUMETSAT or Satellite Application Facility (SAF) level. In this context POLDER / PARASOL data are the best proxy to simulate 3MI capabilities.

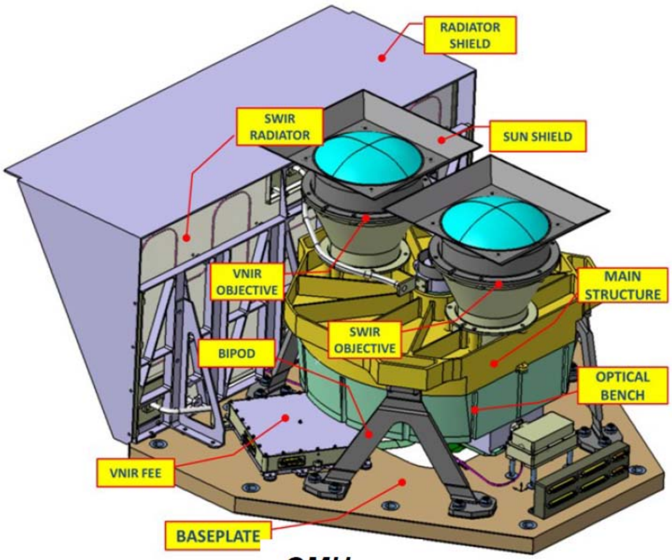
3. 3MI description

The 3MI is composed by the following major elements:

- An Opto-Mechanical Unit (3MI-OMU)
- An Instrument Control Unit Electronics Box (3MI-ICU)
- OMU to ICU interconnection harness (HRN)

The OMU is so designed:

- Two optical modules: a VNIR and a SWIR, each of them including a 100.3° FOV dioptric telescope, an entrance Sun shield and a supporting structure. The objective structure includes some vanes to stop the straylight coming from the first lenses of the objective.
- A filter wheel assembly (FWA), rotating at constant speed including two filter rings: one external ring with 22 positions (21 VNIR filters/polarizers and 1 shutter) and one internal ring with 11 positions (10 SWIR filters/polarizers and 1 shutter).
- A VNIR FPA including 512x512 pixel CCD detector with 26 μm pitch optimized to the broadband VNIR. Baseline semi-custom CCD E2V detector.
- A SWIR FPA covering one half of the optics image plane and offset with respect to the center of the overall FOV to provide asymmetric OZA sampling range. This includes a 1000x256 (only 512x256 used) pixel HgCdTe detector with 30 μm pitch and with a cut-off at 2.5 μm.
- Two FEE modules, one for each detector.
- A cold direct-condensing radiator connected to the SWIR detector package by means of a Loop Heat Pipe, LHP, to ensure the passive cooling of the SWIR detector at 173 K.
- One additional patch radiator to cool the VNIR detector at 0° C by means of a thermal strap and three additional patch radiators to cool, by means of one thermal strap each, the FEEs and the motor within their operational temperature limits

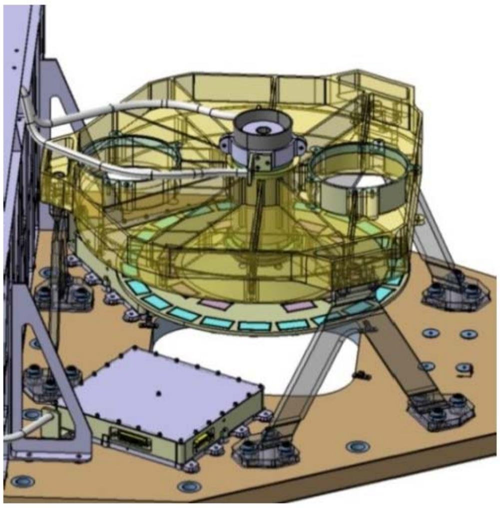


OMU

The FWA is another subsystem that drives the final 3MI performance. The function of the filter wheel is to insert and change band filters in the optical path of both the VNIR and SWIR channels. To this aim the filter wheel is equipped with two series of filters/polarizers disposed on two concentric peripheral regions in the proper number and position. The wheel rotation axis is parallel to the telescopes optical axes to carry the filters in the gap between the telescopes and the FPAs. A precision mechanism operates the filter wheel in a continuous rotation with fixed angular speed, selected on the basis of the corresponding observation sampling frequency of each filter. The continuous rotation of the wheel at a controlled speed allows the insertion of the filters in the optical path of the VNIR and SWIR channel for the time necessary for the image acquisition. Filter and polarizer stack is mounted on a metallic frame. The frames are precisely aligned with the filters.

The instrument optical performances require that all the filters remain thermally stabilized at 20 °C ± 2°C. This requirement has to be fulfilled with thermal control at instrument and the design of the wheel will take into account this requirement when selecting the material and the surface treatments.

Considering the stringent requirement for the rotation speed control and the rotation mechanism lifetime (around 61 million of cycles), a proper selection of the bearings, their preload and lubrication must be carefully considered. Bearing materials and lubrication must be selected with regards to the cleanliness requirements and storage duration.



Filter wheel and its mechanism

4. 3MI Spectral Channels

The primary 3MI mission objective is to provide aerosol characterization for climate monitoring, Numerical Weather Prediction (NWP), atmospheric chemistry and air quality. High quality aerosol imagery delivered by the 3MI mission will facilitate the measurement of all essential aerosol parameters

for climate records, such as aerosol optical depths, particle types and sizes, refractive index, sphericity and height index. When used as constrains to the models, these products will be used to provide improved Air Quality Index and Aerosol Load Masses for different particles sizes.
The measurement of surface albedo as well as improved cloud characterization are 3MI mission's secondary objectives. The first will be facilitated via the observation of the surface BRDF, made possible by the unique multi-angular measurement concept adopted. Similarly, while METimage will provide information on most cloud properties, the multi-viewing and multi-polarization measurements delivered by the 3MI mission will allow for accurate characterization of the extension, optical depth, particle size as well as asphericity factor and crystal orientation of cirrus clouds.
While currently, aerosol and cirrus parameters are mostly used in General Circulation Models for climate simulation and prediction, utilization of these parameters is becoming increasingly important in operational NWP as the representation of radiative processes in the atmosphere is a recognized area of deficiency. Hence, the 3MI mission is expected to be of great benefit to both real-time and non-real-time user communities. Finally the 3MI mission will also contribute to artifact correction on other sensors (e.g. Infrared Atmospheric Sounding Sensor – IASI-NG, the VIS/IR Imager – METimage, and the Ultra-Violet /Visible/Near Infrared/Short Wave Infrared spectrometer – UVNS/S5).
Observation is typically made via different channels of the Electromagnetic spectrum, in particular, the Visible and Infrared portions.

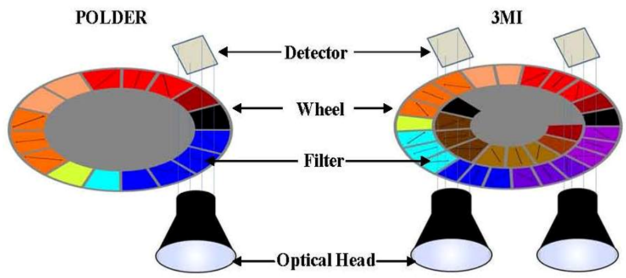
- VIS/NIR is mandatory and sufficient for AOD (aerosol optical depth) basic retrieval over ocean or dark surfaces,
- UV is necessary (but not sufficient) for retrieving absorption information,
- SWIR is mandatory for retrieving AOD over land and suited for the coarser particle mode

Polarization is mostly driven by scattering properties which by themselves are very sensitive to the geometry of observations and to the shape of scatterers. This explains why polarization, when associated with directional capabilities has unique advantages for aerosol and clouds retrievals.
Discrimination between spherical and non spherical particles becomes possible and is a powerful means for differentiating sea salt form dust particles over ocean as well as identifying ice clouds from water clouds in the cloud screening process. Cloud droplet size can also be estimated based on the multi-directional signature of the polarized reflectance.

3MI	Central Wavelength (μm)	Channel Spectral width (μm)	Polariz.	Primary Use
VNIR	0.410	0.02	Y	Aerosol absorption, ash cloud
	0.443	0.02	Y	Aerosol absorption, height indicators
	0.490	0.02	Y	Aer., surf.albedo, cloud refl., cloud opt. depth
	0.555	0.02	Y	Surf.albedo
	0.670	0.02	Y	Aerosol properties
	0.763	0.01	N	Cloud and aerosol heigth
	0.754	0.02	N	Cloud and aerosol heigth
	0.865	0.04	Y	Vegetation, aerosol, clouds, surf. features
	0.910	0.02	N	Water vapour, atmospheric correction
SWIR	0.910	0.02	N	Water vapour, atmospheric correction
	1.370	0.04	Y	Cirrus clouds, water vapour imagery
	1.650	0.04	Y	Ground characterisation for aerosol inversion
	2.130	0.04	Y	Ground characterisation for aerosol inversion, clouds microphysics, vegetation, fire effects

VNIR: Visible and Near Infrared SWIR: Short Wave Infrared.

On the polarized image the geographic contours can hardly be recognized. This is because polarization from molecular scattering in the atmosphere prevails over the polarization contribution from the surface. This explains why the color blue is predominant on polarized images taken in clear sky conditions and why there is little contrast between land and sea. Once molecular scattering and ground polarized contributions have been subtracted, the residual signal provides information on aerosol load in the atmosphere.



	Central Wavelength (nm)	Bandwidth (nm)	Polarisation
VIS-NIR	443	20	N
	490	20	Y
	565	20	N
	670	20	Y
	763	10	N
	765	40	N
	865	40	Y
	910	20	N
	1020	20	N
SWIR			

	Central Wavelength (nm)	Bandwidth (nm)	Polarisation
VNIR	410	20	Y
	443	20	Y
	490	20	Y
	555	20	Y
	670	20	Y
	763	10	N
	754	20	N
	865	40	Y
	910	20	N
SWIR	1370	40	Y
	1650	40	Y
	2130	40	Y

The 3MI spectral bands are shown in table for comparison this table contains also the POLDER / PARASOL spectral bands. Red color is used to indicate the main differences. Channels 354 nm and 388 nm, originally considered for 3MI, have been replaced by the channel at 410 nm, in order to reduce risk and maintain affordability of the instrument.

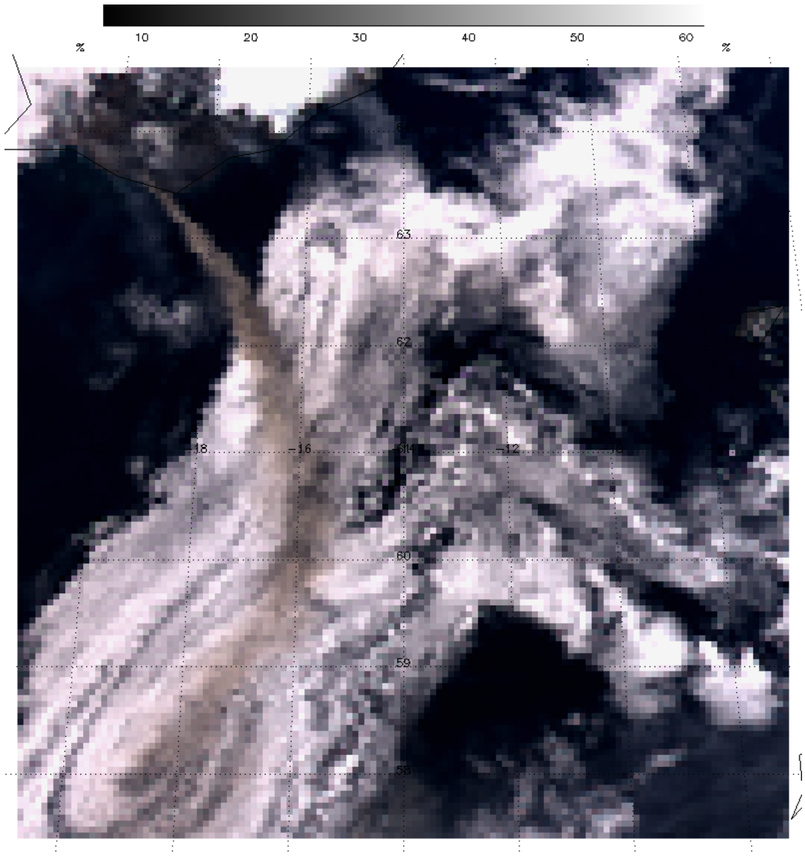
The surface of the ocean acts as a mirror which generates highly polarized light leading to a bright spot on both images corresponding to the glitter pattern whose intensity decreases with the surface roughness (wave slope). Apart from reflection phenomena, the polarized component measured at the top of the atmosphere results primarily from single scattering by the atmosphere molecule and aerosol, which depends strongly on the scattering angle. Polarized images are thus easier to interpret by overlying scattering angles isolines. Last but not least single scattering phase functions are highly sensitive to particle shape and reveals inmost details of micronic scatterers such as sphericity/non sphericity of salt/dust particles, droplets in the rainbow or oriented ice crystals in clouds

5. POLDER / PARASOL as a proof of the 3MI concept

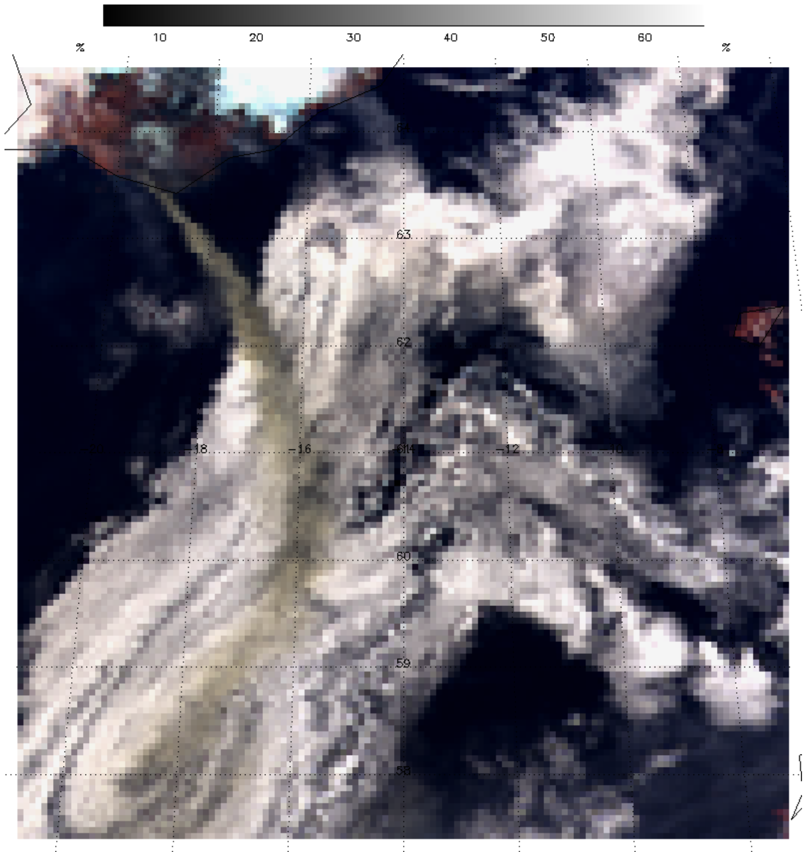
The results obtained from 3 missions of POLDER / PARASOL observations have clearly demonstrated the potential of 3M measurements to derive improved and innovative information on atmospheric constituents for operational monitoring of aerosols. Nevertheless, POLDER suffered from a number of limitations which can be nowadays overcome thanks to technological improvements performed over the past 15 years.

Namely, POLDER capabilities were partially hampered by limited cloud screening performances and lack of information on non-polarizing aerosols over land. Both aspects can now be improved significantly through affordable enhancements of the instrument. Three directions for improvement have been identified for 3MI (3M Imager) which are the total spectral range, the spatial resolution and the swath of the instrument.

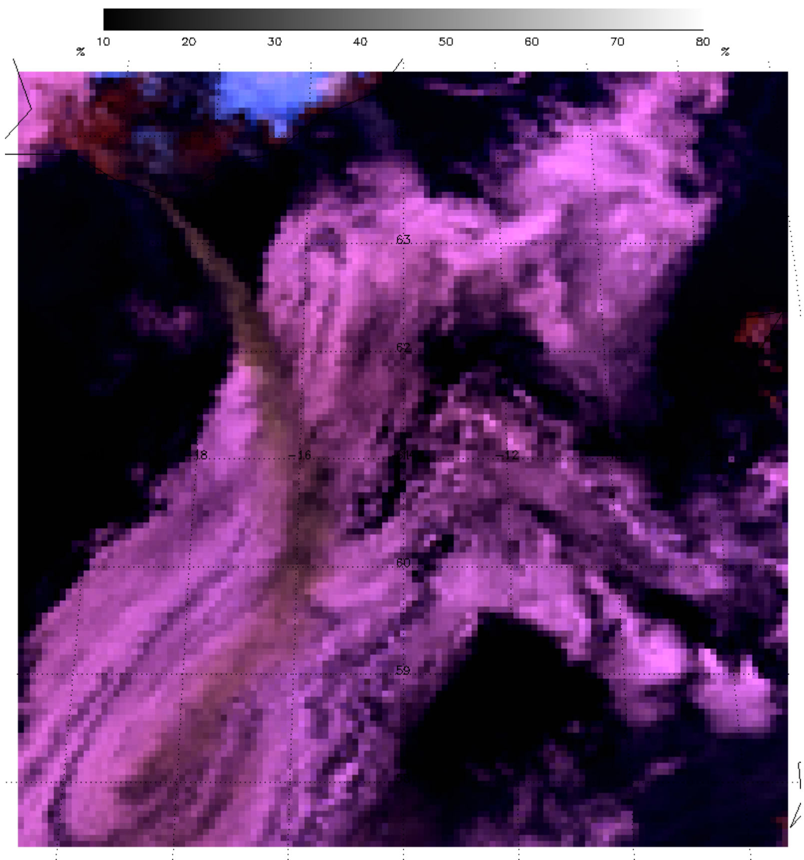
Anyway over the course of three missions, CNES mission has provided a unique dataset to study and better understand aerosol and cloud radiative effects and microphysical properties. In that context



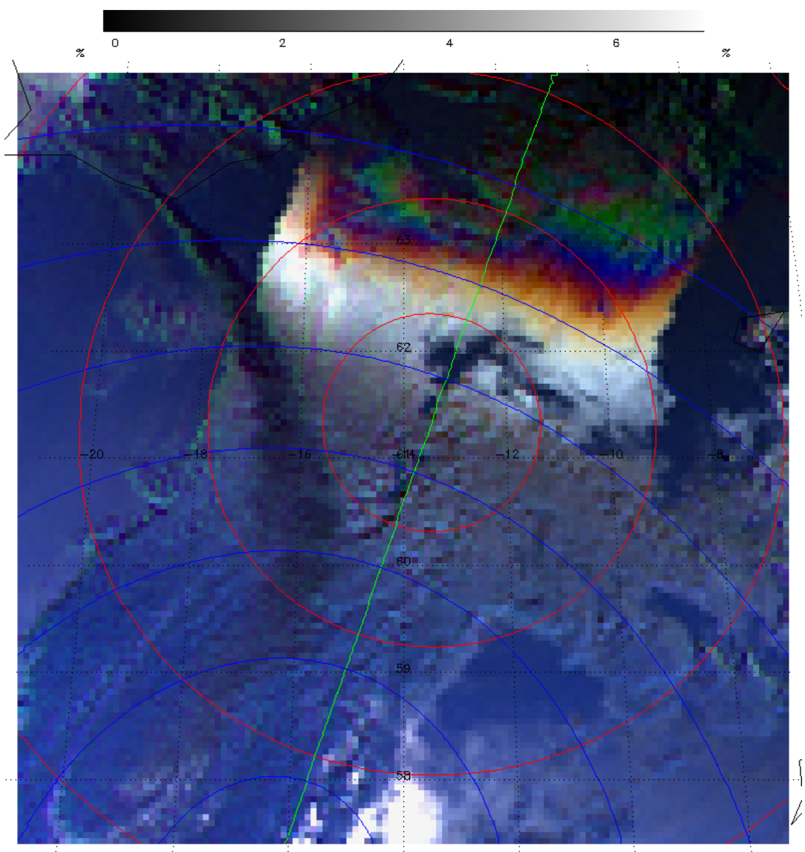
PARASOL spectral bands RGB composition: Red 670 nm, Green 565 nm, Blue 443. In grey, volcanic ash.



PARASOL spectral bands RGB composition: Red 865 nm, Green 670 nm, Blue 443. In dark yellowish color, volcanic ash. In red vegetated areas.



PARASOL spectral bands RGB composition: Red 1020 nm, Green 763 nm, Blue 443. In turquoise ground ice, dark violet color water droplet clouds, grey volcanic ash. In red vegetated areas.



PARASOL polarized reflectance spectral bands RGB composition: Red 865 nm, Green 670 nm, Blue 443. Top with rainbow colors water droplet clouds. Bottom center sunglint.

6. *Conclusions*

The future generation of EUMETSAT polar satellites, METOP-SG, will bring in space a Multi-Viewing Multi-Channel Multi-Polarization Imaging mission (3MI). 3MI task is Earth observation in a multiplicity of conditions, varying spectrally (410 - 2130 nm), polarization (-60°, 0°, +60°) and viewing angles (14 different views of the same target area).

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The paper shows first phase of a recently Selex ES industry supported research fellowship activated at Centro Nazionale di Meteorologia e Climatologia Aeronautica (C.N.M.C.A.), the Italian National Weather Centre, focusing on future operational applications of METOP-SG 3MI data; in particular it is investigated the promising 3MI capability in operationally detecting, monitoring and measuring volcanic ash presence, capitalizing the experience done in Europe with other analogous space-based observing missions, e.g. PARASOL.