SO_2 and ash plume retrievals using MSG-SEVIRI measurements. Test case: 24 November 2006 Mt. Etna eruption.

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Abstract— **In this work the Thermal InfraRed (TIR) measurements of the Spin Enhanced Visible and Infrared Imager (SEVIRI) on board the Meteosat Second Generation (MSG) geosyncronous satellite, have been used to estimate the daily evolution of the SO_2 columnar abundance and ash plume optical thickness, particle effective radius and total mass of Mt. Etna volcanic plume. As test case the 24 November 2006 eruption has been considered. SEVIRI is an optical imaging radiometer characterized by 12 spectral channels, a high temporal resolution (one image every 15 minutes) and a 9 km^2 footprint. The instrument's spectral range includes the 8.7 µm band (channel 7) and the 10.8 and 12.0 µm split window bands (channels 9 and 10) used respectively for SO_2 retrieval and volcanic ash detection and retrievals. The SO_2 columnar abundance is estimated by means of a Look-Up Table (LUT) least squares fit procedure applied to channel 7, while the ash detection and retrievals are carried out by using the Brightness Temperature Difference algorithm applied to channels 9 and 10. All the simulations needed for the retrievals have been realized using MODTRAN 4 radiative transfer model. The SEVIRI volcanic plume SO_2 and ash retrievals have been compared with the results obtained by processing the data collected at 12:20 GMT by the MODIS sensor on board of Aqua satellite. Results show the ability of SEVIRI to recognize and estimate the daily trend of SO_2 and ash in an eruptive plume; for the 24 November 2006 eruption, the SO_2 and ash emissions started at about 4 and 8 GMT respectively and terminated simultaneously at about 14 GMT. The comparison between SEVIRI and MODIS retrievals indicate a general good agreement.**

Keywords; SO_2 retrieval; ash retrieval; MSG-SEVIRI; MODIS

I. INTRODUCTION

Volcanic eruptions inject huge amounts of solid particles [1] and gases into the atmosphere. Volcanic ash is composed of fragments of pyroclast rocks smaller than 2 mm which are released during explosive events, forming the typical volcanic plume and leading to characteristic ash falls [2]. Depending on eruptive intensity the volcanic ash can reach different altitudes in the atmosphere and the residence time depends on particle size [3]. Volcanic ash falls cause respiratory problems [4], damage to agricultural and industrial activities [5] and, in particular, represent a severe threat to aviation security [6]. The particle with dimension of some several millimeters can damage the aircraft structure (windows, wings, ailerons), while particles less than 10 µm may be extremely dangerous for the jet engine beside being undetectable by the pilots during night or in low visibility conditions [7]. Volcanic fine ash clouds can not be detected by aircraft radar and they are often indistinguishable from water clouds even in daytime.

The gases principally present in the volcanic plumes are H_2O, CO_2, SO_2 and HCl. SO_2 is an important volcanic gas because of its effects on the environment (e.g. acid rain, effects on plants and public health) and also because once it is high in the atmosphere (> 6 km) it can be transported over long distances, has a greater residence time and can be oxidised to form sulphates. The sulphates are capable of reflecting solar radiation and causing surface cooling [8].

Because of the sporadic nature of volcanic eruptions, the large geographic distribution of volcanoes and the difficulty of direct sampling, remote sensing provides the most suitable technique to detect and retrieve volcanic emissions on a consistent and comprehensive basis. Several methodologies and algorithms have been developed and tested in order to detect and track drifting volcanic clouds either in the Thermal InfraRed (TIR) and/or the UltraViolet (UV) spectral range. Theoretical calculation demonstrates that in the TIR 10-13 µm spectral range, the radiative effect of volcanic ash clouds is spectrally distinct from that of water droplets [9, 10]. In particular the difference between the brightness temperature of two channels centered around 11 µm and 12 µm, is used to discriminate volcanic and meteorological clouds and for volcanic ash retrievals [11–13]. Moreover in the TIR spectral range the SO_2 presents two wide spectral features around 7.3 and 8.7 µm.

In this work a simultaneous retrievals of volcanic ash properties (aerosol optical thickness (AOT) at 0.55 µm, effective radius (r_e) and total mass) and SO_2 in the TIR spectral range has been performed using MSG-SEVIRI satellite data. As test case the images of Mt. Etna volcano (Sicily-Italy) acquired by SEVIRI on 24 November 2006 have been considered. To take into account the ash influence on SO_2 retrieval, an ash correction procedure has also been applied [14]. The estimations have been compared with the ash and SO_2 retrievals obtained using MODIS images collected at 12:20 GMT.

II. MSG-SEVIRI

The Spinning Enhanced Visible and InfraRed Imager (SEVIRI) is the main sensor aboard of the Meteosat Second Generation (MSG) geosyncronous satellite. SEVIRI is a 50 cm diameter aperture, line-by line scanning radiometer which provides image data in four Visible and Near InfraRed (VNIR) channels and eight infrared (IR) channels (see Table 1). The VNIR channels include the High Resolution Visible (HRV) channel which contains 9 broadband detection elements to scan the Earth with a 1 km of spatial resolution. All the other channels (including the IR channels) are designed with 3 narrow band detection elements per channel, to scan the Earth with a 3 km spatial resolution. Its main peculiarity is the possibility to corresponds to a continuous Earth image using 12 channels with a baseline repeat cycle of 15 minutes, including the on-board calibration, the retrace and the overall satellite stabilisation process. The bands 6 and 7 (centered around 7.3 and 8.7 µm) and the bands 9 and 10 (centered around 10.8 and 12 µm) are used for the SO_2 and ash retrievals respectively. SEVIRI characteristics allow to obtain close time-spaced retrievals very useful in the study of temporal evolution of volcanic plumes.

TABLE 1. SEVIRI spectral channels, spatial resolution and temporal acquisition.

Channel Number	Central Wav. (µm)	Spatial Res. (km)	Temporal Res. (min)
1	0.6	3	15
2	0.8	3	15
3	1.6	3	15
4	3.9	3	15
5	6.2	3	15
6	7.3	3	15
7	8.7	3	15
8	9.7	3	15
9	10.8	3	15
10	12	3	15
11	13.4	3	15
12 (HRV)	0.8	1	15

III. ASH AND SO_2 RETRIEVAL

The ash detection is carried out by using the Brightness Temperature Difference (BTD) procedure (Prata 1989a,b) applied on channels centered around 11 and 12 µm while effective radius and aerosol optical thickness at 0.55 µm have been retrieved computing the inverted arches curves BTD-brightness temperature of channels centered around 11 µm [11,12,13] varying AOT and r_e. To take into account the atmospheric water vapour absorption in the 11-12 µm spectral range, a water vapor correction procedure has also been applied [15]. Using the AOT and r_e retrievals, the pixel-by-pixel ash mass is computed by using the simplified formula suggested by Wen and Rose [11]. The simulated radiances needed for the ash retrievals, have been computed using MODTRAN RTM [16].

As described above in the TIR spectral range, the sulphur dioxide has two wide absorption bands centered around 7.3 and 8.6 µm. Due to the strong presence of atmospheric water vapour the 7.3 µm band is generally used when the volcanic plumes arise over 3-4 km, i.e. above the most of the water vapour. The 8.6 µm channel lies in a relatively transparent region and can be used to retrieve SO_2 in the lower troposphere. The 8.7 µm SO_2 retrieval scheme has been described by Realmuto et al. [17], Watson et al. [18] and Pugnaghi et al. [19] respectively for TOMS, MODIS and ASTER and is based on a pixel-by-pixel least squares fit procedure applied to the satellite sensor measurements and the simulated radiances computed by using MODTRAN 4 Radiative Transfer Model (RTM). To take into account that the simultaneous presence of SO_2 and ash produces a meaningful overestimation of the SO_2 columnar abundance retrieval, an ash correction procedure has also been applied [14].

IV. 24 NOVEBER 2006 MT. ETNA ERUPTION

Mt. Etna is located in the eastern part of Sicily (Italy) and is one the major degassing volcanoes in the world [20]. Its generally quiescent state is periodically interrupted by eruptive crisis during which significant SO_2 and ash are emitted, causing problems to the population of the region [21] and to air traffic (Catania and Reggio Calabria airports are nearby). During 2006 Mt. Etna exhibited episodic explosive activity producing SO_2 and ash plumes that rose up into the atmosphere and drifted several km away from the vent. The 24 November 2006 SO_2 and ash emission started at about 04:00 and 08:00 UTC respectively and ended simultaneously at about 14:00 UTC. The eruption took place both at the summit and the south east crater of Mt. Etna and produced the largest volume of ash in the entire September-December eruptive period. On this day the wind was blowing from the N-NW direction causing the ash plume to move towards the city of Catania. The ash fallout created major problems for the "Fontanarossa" International Airport of Catania which was subsequently closed to air traffic.

V. RESULTS

Figures 1, 2 and 3 show the total mass, effective radius and the aerosol optical thickness at 0.55 μm retrieved from the SEVIRI measurements for different hours respectively.

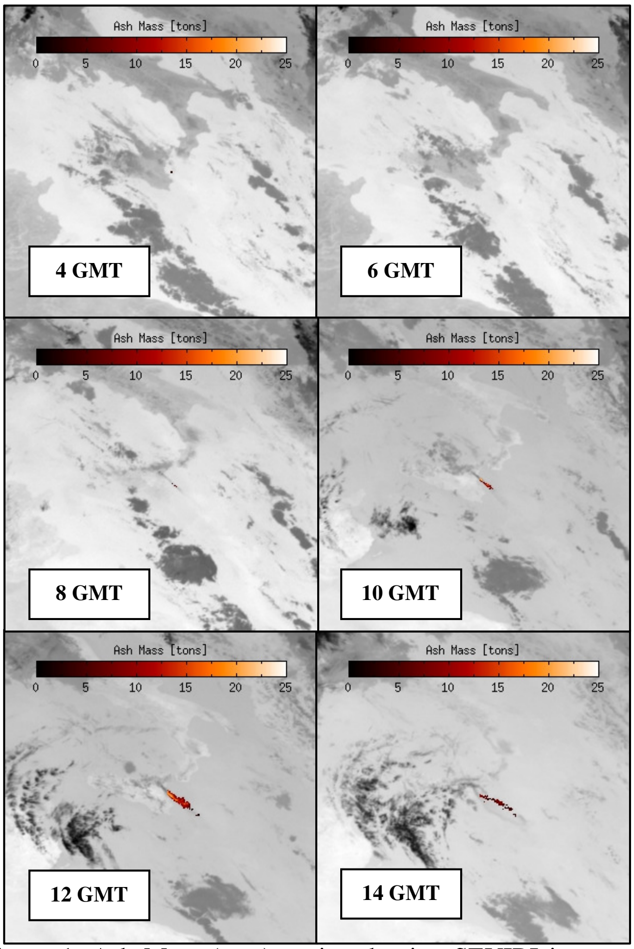

Figure 1. Ash Mass (tons) retrieved using SEVIRI images at different hours.

As figures show the ash eruption start at about 8 GMT and stop at about 14 GMT with a maximum of emission at about 12 GMT. As expected, the largest ash mass and AOT occurs in the area close to the vent and the smallest at the cloud edges. There are also other regions of high ash mass and AOT probably due to volcanic puffs. The particle effective radii are distributed non-uniformly along the plume and the larger particles (up to 4 μm) are found around the western part of the plume itself.

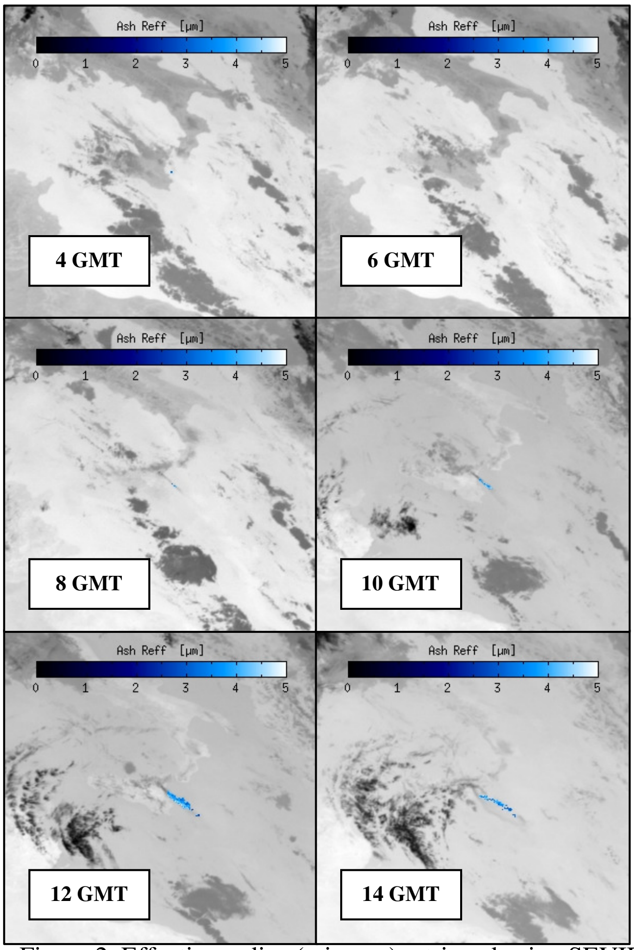

Figure 2. Effective radius (microns) retrieved using SEVIRI images at different hours.

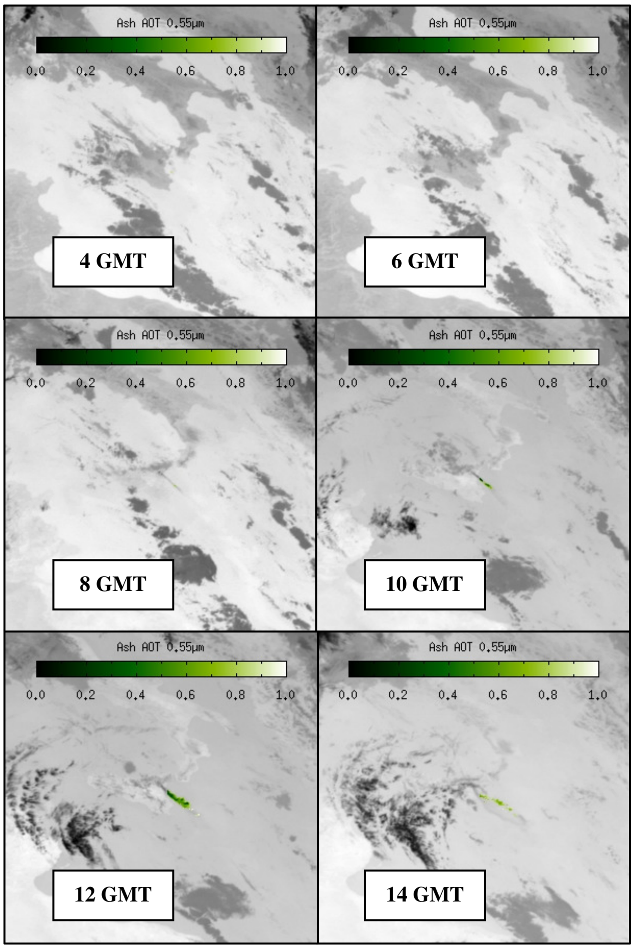

Figure 3. Aersol optical thickness (0.55 µm) retrieved using SEVIRI images at different hours.

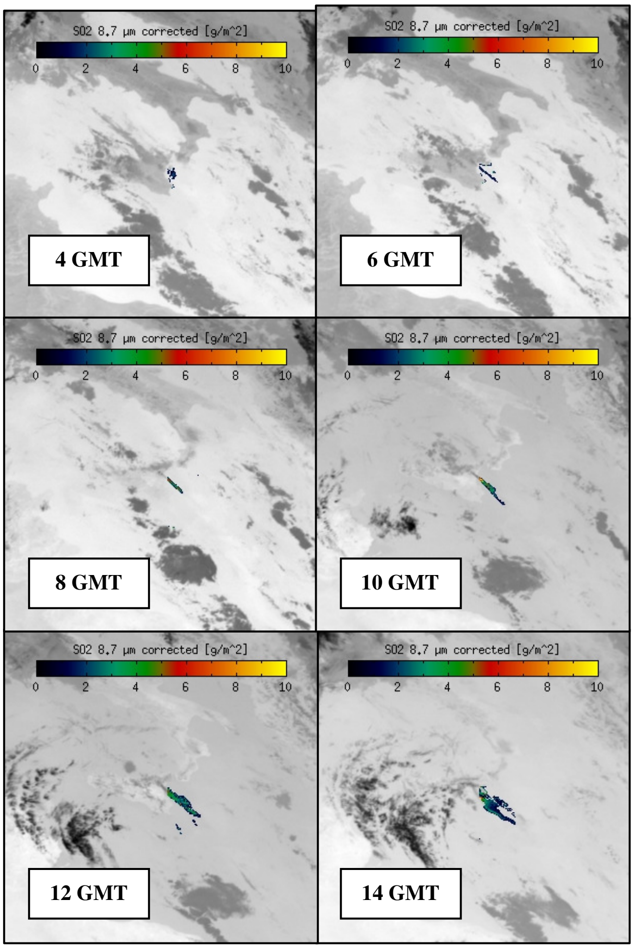

Figure 4. SO_2 columnar abundance (g/m^2) retrieved using SEVIRI images at different hours after the ash correction procedure application.

Figures 4 shows the SO_2 retrieval after the ash correction procedure application. The SO_2 emission start before the ash emission at about 4 GMT and end at about 14 GMT (approximately simultaneously to ash).

In Table 2 have been shown the comparison between the SEVIRI and MODIS ash and SO_2 retrievals for the images collected respectively at 12:25 and 12:20 GMT. Table shows a good agreement between the SEVIRI and MODIS AOT and r_e retrievals while both the SEVIRI ash and SO_2 total mass result underestimated. This can be explained considering that SEVIRI has a higher NEΔT (i.e. lower sensitivity) and smaller ground pixel resolution than the MODIS instrument (1 km^2 for all TIR channels).

TABLE 2. Comparison between SEVIRI and MODIS ash and SO_2 retrievals.

	Mean AOT	**Mean re (µm)**	**Total mass Ash (tons)**	**Total mass SO2 (tons)**
SEVIRI (12:15 GMT)	0.27	3.31	1815	4617
MODIS (12:20 GMT)	0.31	3.06	3145	6167

VI. CONCLUSIONS

In this work the MSG-SEVIRI satellite TIR measurements have been used for a simultaneous retrievals of volcanic ash and SO_2. The SEVIRI channels 9 and 10, centered around 11 and 12 µm, and the channel 7, centered around 8.7 µm, have been used for ash and SO_2 retrievals respectively. To take into account that the simultaneous presence of SO_2 and ash produce a meaningful overestimation of the SO_2 columnar abundance retrieval, an ash correction procedure has been applied. As test case the images of Mt. Etna volcano (Sicily-Italy) acquired on 24 November 2006 are considered. Results show the ability of SEVIRI to recognize and estimate the daily trend of SO_2 and ash in an eruptive plume: the SO_2 and ash emissions start at about 4 and 8 GMT respectively and terminate simultaneously at about 14 GMT. A comparison between SEVIRI and MODIS retrievals has been also analyzed considering the images collected at 12:15 and 12:20 GMT respectively. The results shows a good agreement between the SEVIRI and MODIS AOT and r_e retrievals while both the SEVIRI ash and SO_2 total mass result underestimated. The reasons of such underestimations can be due to the higher NEΔT (i.e. lower sensitivity) and smaller ground pixel resolution for SEVIRI compared to MODIS.

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