ON GROUND TIR CAMERA FOR VOLCANIC PLUME DETECTION: SENSITIVITY STUDY ON SULPHUR DIOXIDE AND VOLCANIC ASH RETRIEVAL

Corradini S.(1), Tirelli C .(2), Gangale G.(2), Pugnaghi S.(2), Carboni E. (3), Buongiorno M.F. (1), Amici S. (1)

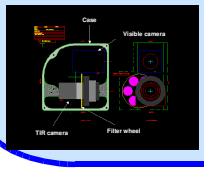
Istituto Nazionale di Geofisica e Vulcanologia

(1) Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Roma; (2) Dipartimento di Ingegneria dei Materiali e dell'Ambiente, Università di Modena e Reggio Emilia; (3) Atmospheric, Oceanic and Planetary Physics, Clarendon Laboratory, University of Oxford, U.K.

In this work a sensitivity study on sulphur dioxide and volcanic ash retrieval using on ground TIR camera (named BIRD) has been carried out. BIRD, a new semiconductor device (SCD) uncooled camera is composed by a matrix (320x240) of microbolometric sensors with pixels pitch of 25 microns. The spectral range is between 8 and 14 microns with Noise Equivalent Delta Temperature (NEΔT) better than 50 mK at 300 K. The camera will be used to mitigate the risk and impact of volcanic eruption on the civil society and transport (Highway and International Airport of Catania are about 20 km from the craters). A minimum number of filters (right bandwidth and effective wavelength) have been selected for SO_2 and ash retrievals. The sensitivity study has been carried out to determine either the SO_2 and ash minimum concentration detectable by the system then the better altitude to locate the camera. The sensitivity analysis has been also used to discriminate from volcanic and meteorological clouds varying the effective radius and optical thickness.

TIR CAMERA (BIRD)

- **Bird is an uncooled camera composed by a matrix (320x240) of microbolometric sensors with a pixel pitch of 25 microns**
- **Spectral interval: 8-14 μm**
- **NEΔT better than 50 mK at 300 K**
- **This camera can be remotely controlled in its pointing angle and can be modified with a filter wheel where it is possible to insert five different interference filters.**



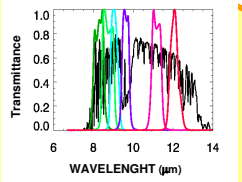
Camera channels has been defined to study the atmospheric species of interest.

- **Theoretical camera sensitivity ΔR = 0.084 $Wm^{-2}sr^{-1}cm$ (considering a camera NEΔT of 0.1 K at 300 K)**

CAMERA CHANNELS SELECTION

- **Central wavelength selection** (analysing the spectral transmittance of the different atmospheric species of interest as SO_2, H_2O, O_3 and volcanic ash);
- **Full Width Half Maximum (FWHM) definition** (to collect a sufficient energy amount and minimize the interference of the nearest species)

Channel	λ (μm)	Species	FWHM (μm)
1	8.27	Water vapour	0.5
2	8.72	SO_2	0.5
3	9.05	Volcanic aerosol	0.5
4	9.61	O_3	0.5
5	11.15	Volcanic aerosol	0.5
6	12.01	Volcanic aerosol	0.5



This study is focused on:

- **SO_2 retrieval;**
- **volcanic ash retrieval;**
- **discrimination between meteorological and volcanic clouds.**

RADIATIVE TRANSFER EQUATION

In the TIR spectral region the radiance (L_λ) measured by a camera sensor on ground looking towards volcanic area is given by:

$$L_\lambda = (1 - \tau_{a,\lambda})\, B_\lambda(T_a) + (1 - \tau_{p,\lambda})\, B_\lambda(T_p)\tau_{a,\lambda}$$

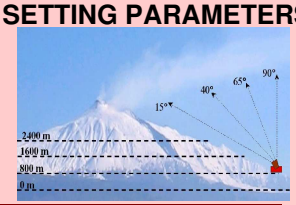
$\tau_{a,\lambda}$ is the atmospheric transmittance

$\tau_{p,\lambda}$ is the plume trasmittance

T_a is a characteristic temperature of the atmospheric column above the instrument

T_p is a characteristics atmospheric temperature at plume altitude

SETTING PARAMETERS FOR RTM SIMULATIONS



Instrument altitude (m) : 0, 800, 1600, 2400 ;
Instrument elevation angle, θ (degree): 15, 40, 65, 90.

Wavelength range (μm): 6-14 ;
Atmospheric profiles :
Midlatitude Summer, Midlatitude Winter.

MODTRAN input for aerosol clouds

Plume geometry: 5000 m h top, 1000 m thickness
Optical thickness, AOT : 0, 0.1, 0.2, 0.3, 0.4, 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 6, 7, 8, 9, 10
Effective radius , Reff (μm) : 0.785, 1.129, 1.624, 2.336, 3.360, 4.833, 6.954, 10.
Aerosol optical properties derive from a Mie Code (Oxford University AOPP)

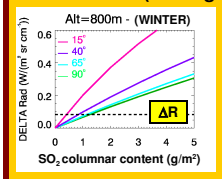
MODTRAN input SO_2

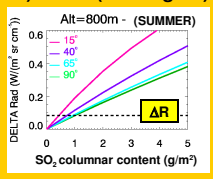
Plume geometry: 3300 m h top, 100 m thickness
SO_2 abundance ,cs (g/m^2): 0 – 15, step 1

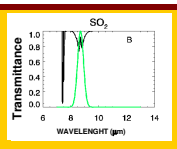
SO_2

Sensitivity study:

ΔRad = Rad (cs =x g/m^2) – Rad (cs = 0 g/m^2)







Results:

- **cs detectable values: from 0.5 to 1 g/m^2 ;**
- **sensitivity: better for smaller θ ;**
- **∀ no significant variation for altitude and atmospheric profile.**

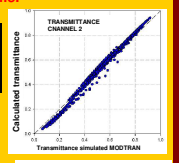
SO_2 retrieval:

Transmittance parameterisation:

$\tau_{a,\lambda} = \exp[(-a_{w,\lambda}(pw)^{b_{w,\lambda}})/\sin\theta]$; $\tau_{p,\lambda} = \exp[(-\beta_\lambda c_s)/\sin\theta]$

Precipitable water — SO_2 abundance

$a_{w,\lambda}$	0.05 mm^{-1}
$b_{w,\lambda}$	0.77
β_λ	0.03 $m^2 g^{-1}$

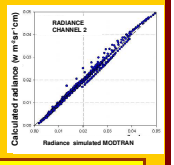


Radiance parameterisation:

$L_{M,\lambda} = [a_{\tau,\lambda}(T_a - T_0) + C_{\tau,\lambda}](1 - \tau_{a,\lambda})\tau_p + [a_{p,\lambda}(T_p - T_0) + C_{p,\lambda}](1 - \tau_{p,\lambda})$

$a_{w,\lambda}$, $b_{w,\lambda}$, β_λ, $a_{\tau,\lambda}$, $C_{\tau,\lambda}$, $a_{p,\lambda}$, $C_{p,\lambda}$: parameters computed, for channel 2 using non linear regression from MODTRAN simulated atmospheric terms.

$C_{\tau,\lambda}$	0.04	$W m^{-2} sr^{-1} cm$
$a_{\tau,\lambda}$	1.3	$W m^{-2} sr^{-1} cm K^{-1}$
$C_{p,\lambda}$	0.05	$W m^{-2} sr^{-1} cm$
$a_{p,\lambda}$	6.3	$W m^{-2} sr^{-1} cm K^{-1}$

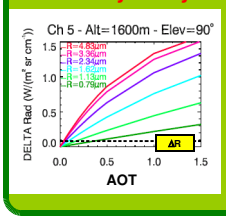


c_s is derived inverting the radiative transfer equation, knowing pw, T_p and T_a:

$$cs = -\left[\frac{\sin(\vartheta)}{\beta}\right] \cdot \ln\left\{1 + \left[\left(\frac{1}{\tau_{a,\lambda}}\right) - 1\right]\left[\frac{C_{a,\lambda} + a_{a,\lambda}(T_a - T_0)}{C_{p,\lambda} + a_{p,\lambda}(T_p - T_0)}\right]\right\} - \left[\frac{L_{M,\lambda}}{C_{p,\lambda} + a_{p,\lambda}(T_p - T_0)}\right]$$

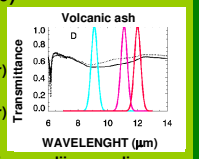
VOLCANIC ASH

Sensitivity study: ΔRad = Rad (AOT=x) – Rad (AOT=0)



Minimum AOT detectable values:

- **channel 5: from 0.15 (2400m - 15°)**
  to 0.5 (0m - 15° - summer)
- **channel 6: from 0.25 (2400m - 15°)**
  to 1.2 (0m - 15° - summer)

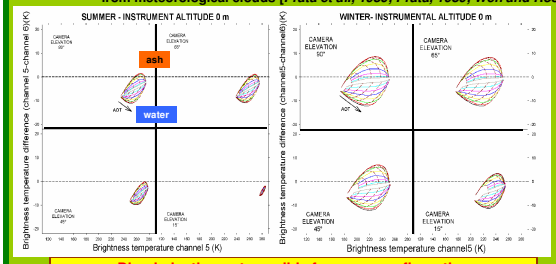


Sensitivity:

- **Increase for increasing R_{eff} to 4.8 μm, for bigger radii curves lie over;**
- **Increase for increasing instrument altitude;**
- **channel 5 is more sensitive than channel 6.**

DISCRIMINATION BETWEEN METEOROLOGICAL AND VOLCANIC CLOUDS

Volcanic clouds show optical properties in TIR spectral range that can be used to discriminate them from meteorological clouds [*Prata et al., 1989; Prata, 1989; Wen and Rose, 1994*].



The discrimination algorithm is based on the difference between channel 5 (11.15 mm) and channel 6 (12.01 mm) brightness temperature: Δ Tb = Tb(5)-Tb(6)

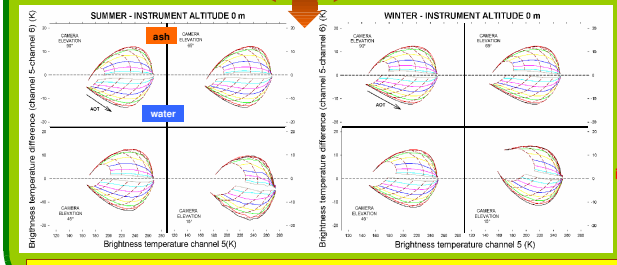
The ΔTb = Tb(5)-Tb(6) values are plotted to the Tb(5) for a given season and instrument altitude varying instrument elevation. **In each graphic are showed ash (red) and water vapour (down) results for all particles radii (coloured lines) and AOT (dashed lines).**

Discrimination not possible for every configuration

WATER VAPOUR CORRECTION

$$|L_{M,\lambda}| = \frac{L_{M,\lambda} - |1 - \tau_{a,\lambda}|\,|C_{a,\lambda} + a_{a,\lambda}|T_a - T_0|}{\tau_{a,\lambda}}$$

The (ΔTb)* = Tb(5)*-Tb(6)* obtained considering ($L_{M,\lambda}$)* values have been plotted with the same criteria.



The results obtained with this correction process, demonstrate a great improvement for all seasons and instrument configuration.

Discrimination is always effective and it's possible to determine AOT and particle radius values.

CONCLUSIONS

- Six channels have been identified in camera range of work (8-14 μm) to study different atmospheric species of interest (H_2O, SO_2,volcanic ash, O_3).
- The sensitivity study on BIRD camera shows the ability to retrieve **from 0.5 to 1 g/m^2** (for different measurement configurations) of **SO_2 columnar abundance**. The best results are for high instrument altitude (1600, 2400 m) and low elevation angle (15°, 40°).
- The same study about volcanic ash retrieval reveals that the **AOT** values that BIRD camera is able to measure vary **from 0.15 to 0.5 for channel 5** and **from 0.25 to 1.2 for channel 6**.
- Discrimination between meteorological and volcanic clouds results strongly seasonal dependent and in many cases impossible. **The water vapour correction procedure** makes **discrimination always effective** and **AOT and particle radii retrieval greatly improved**.

FUTURE DEVELOPMENTS

- The sensitivity and retrieval study must be extended also to the **other atmospheric species and aerosol types.**
- It could be interesting to use **more specific temporal and spatial atmospheric profiles** in order to generalize the results obtained only from midlatitude summer/winter profiles.
- Creation of a **self-sufficient system for atmospheric measurements** that doesn't need other instruments application.

References

- **Prata A.J., Burton I.J.,** *Detection and discrimination of volcanic clouds by infrared radiometry –I:Theory*, Proceeding of the first international symposium on volcanic ash and aviation safety, U.S. Geological Survey Bullettin 2047, pp. 4356-4369, 2003.
- **Prata A. J.,** *Infrared radiative transfer calculations for volcanic ash clouds*, Geophysical research Letters, Vol. 16, No. 11, pp. 1293-1296, 1989.
- **Wen S. and Rose W.,** *Retrieval of sizes and total masses of particles in volcanic aerosol clouds using AVHRR bands 4 and 5*, Journal of Geophysical Research, Vol. 99,no. D3, pp. 5421-5431, march 20, 1994.
- **Tirelli C.,** *Verifica della presenza di ceneri vulcaniche nel plume dell'Etna mediante misure IR da Terra*, Graduation Thesis, 2007.