A decade of RST applications to seismically active areas monitoring by TIR satellite observations

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Abstract

In order to discriminate *normal* (i.e. related to the change of natural factor and/or observation conditions) fluctuations of Earth's emitted Thermal Infrared (TIR) radiation from *anomalous* transients possibly associated to earthquake occurrence, since 2001 a Robust Satellite Technique (RST; Tramutoli, 1998; 2005; 2007) approach has been applied.
After the first tests performed by using TIR sensors on board polar satellites it was quite evident the advantage offered by the use of geostationary platforms in studies like these, which do not require the higher spatial resolution offered by polar sensors but strongly benefit of the reduced "*observational noise*" (in terms of view angles, ground resolution cells stability and image collection times) guaranteed by geostationary platforms (e.g. Filizzola et al., 2004).
Since then, tens of earthquakes occurred in Europe, Asia, Africa and America have been studied by analyzing long terms (up to 10 years and more) time series of TIR images acquired by geostationary satellites (like MFG, MSG, GOES, MTSAT). In all cases a validation/confutation approach was always applied in order to verify the presence/absence of anomalous space-time TIR transients in presence/absence of significant seismic activity.
Main achievements in more than 10 years using RST approach for seismic area monitoring will be presented and discussed by comparing results obtained on different earthquakes which happened in different geographic areas and using different satellite sensors.

INTRODUCTION

The last 25 years have witnessed the increasing use of remote sensing for understanding the geophysical phenomena underlying natural hazards. The reason of this success is mainly connected to the use of meteorological satellite images that, thanks to their higher temporal resolution (from hours to 15 minutes) and low cost, despite their relatively coarse spatial resolution (at the best 0.5-1.0 km nadir-view), has been not limited to strictly meteorological applications. Many algorithms and data analysis techniques have been proposed up to now, which make use of such data also in the wider field of environmental and natural hazards monitoring and mitigation (forest fires, desertification, volcanic activity, dust storms, hydrological risks and floods, atmospheric aerosol, anthropogenic air and water pollution, (e.g. Tramutoli, 2007 and reference herein). Among the others the seismic area monitoring using long time series of TIR images collected by meteorological satellites represents the topic of this work.
Earth's thermally emitted radiation measured from sensors onboard satellite platforms in the Thermal Infrared (8–14 μm) spectral range is here simply referred as TIR signal and given in units of Brightness Temperature (BT) measured in Kelvin degrees.
Researchers have used different sensors, approaches and satellite products to describe abnormal TIR signal rises preceding earthquakes. In addition several theory have been proposed to justify a possible relation between anomalous variations of Earth's TIR emission and earthquake occurrence (see Freund, 2007, Pulinets and Ouzounov, 2011, Tramutoli et al., 2013 and reference herein).
For several years the claimed connection of TIR emission with seismic activity (e.g. Gorny et al., 1988, Qiang et al., 1992, Tronin, 2000, Ouzounov and Freund, 2004, Choudhury et al., 2006, Ma et al., 2010) has been considered with some caution by the scientific community mainly for the

insufficiency of the validation data-set and the scarce importance attached by those authors to other causes (e.g. meteorological) that, rather than seismic activity, could be responsible for the observed TIR signal fluctuations. Moving from the main elements of criticism (rightly highlighted by scientific community) to the previously quoted papers, Tramutoli et al.(e.g. 2001, 2005) started their work proposing a new approach, RST, as suitable tool for evaluate the effective potential of the anomalous fluctuation of satellite TIR signals in seismically active regions.
TIR signals measured from satellites effectively depends on a number of natural (e.g. atmospheric transmittance, surface temperature, spectral emissivity and topography) and observational (time/season, but also satellite view angles) conditions whose variable contribution to the measured signal can be so high as to completely mask (or simulate) the space–time fluctuations often claimed as anomalous and connected with the seismic event under study. Space–time fluctuations of TIR signal cannot, instead, be assumed as a pre-seismic signal without referring them to a *normal* TIR signal behaviour and without investigating whether or not similar space–time fluctuations can also be observed in the absence of seismic activity (*confutation* phase).
This paper discusses the progress of the use of the RST methodology by comparing results achieved on different earthquakes which happened in different geographic areas and using different satellite sensors.

THERMAL ANOMALIES: A DEFINITION

The Earth's thermal radiation as measured using satellite sensors at the top of the atmosphere is influenced by different factors. As reported in Tramutoli et al., 2005, they can be natural (like atmospheric transmittance, surface emissivity and topography) and/or observational (e.g. time/season, but also solar and satellite zenithal angles). In Table 1 the main natural and observational factors contributing to *normal* TIR signal variability are showed. Individual changing of only one of the mentioned factors could be responsible of a variation of the observed TIR signal, as large as (in some cases larger than) the fluctuations reported in literature as thermal anomaly and related to impending earthquakes.
It is evident, instead, that only those signal variations not related to the *normal* (i.e. independent from any, natural and observational, variation of the investigated signal) space–time variability of the signal itself, could be assumed as anomalous. A preliminary definition of the normal behavior of the TIR signal at specific time and place of the observation becomes then particularly important (e.g. Tramutoli, 1998, and 2005).
Within this context, the proposed RST approach, unlike preceding methods, permits a statistically based definition of TIR anomaly even in the presence of highly variable natural and observational conditions. Initially proposed for monitoring the major environmental risks using AVHRR-NOAA (Advanced Very High Resolution Radiometer onboard NOAA, National Oceanographic and Atmospheric Administration) data, and therefore named «RAT» (Robust AVHRR Techniques, Tramutoli, 1998), its full exportability on different satellite systems suggested a more generic name «RST» (Robust Satellite Technique, Tramutoli, 2005).

Main factors contributing to TIR signal variability	**Description**
a) Surface spectral emissivity	Quite constant (~0.98) on oceans. Over land it is highly variable taking values within 0.90 and 0.98 mainly depending on soil vegetation.
b) Atmospheric spectral transmittance	Depends mainly on atmospheric temperature and humidity vertical profiles
c) Surface temperature (temporal variations)	Related to the regular daily and yearly solar cycles but sensitive also to meteorological (and climatological) factors
d) Surface temperature (spatial variations)	Depend on local geographical (altitude above sea level, solar exposition, geographic latitude) factors
e) Observational conditions (spatial variations)	Variations across the same scene of satellite zenithal angles introduce spatial variations of the registered signal not related to real near-surface thermal fluctuations
f) Observational conditions (temporal variations of satellite view angle)[a]	The same location is observed, at each revisiting time, at a different satellite zenithal angle: this introduces a spurious temporal variation of the measured signal due simply to the change in observational conditions (e.g. air mass)

g) Observational conditions (temporal variations of ground resolution cells)[a]	The change of satellite view angle also determines a sensible change in the size of the ground resolution cell. Spurious temporal variations of the measured signal have to be expected then because of the change in size of the ground resolution cell
h) Observational conditions (variations of the time of the satellite pass)[a]	Satellite pass occurs each day at different times falling in a time-slot up to 3 hours around the nominal time of pass. Spurious variations of the measured signal have to be then expected as a consequence of such (time) variability of observation condition

Table 1: Main natural and observational factors affecting TIR signal (from Tramutoli et al., 2005). [a]Only for instrumental packages on board polar satellites (not applicable to geo-stationary platforms).

Since its first application to seismic area monitoring (Tramutoli et al., 2001), the RST methodology identifies space-time anomalies always respect to a preliminarily defined *normal* (i.e. in unperturbed condition) signal behavior which is achievable by the analysis of long-term series of satellite records.

THE RST ROBUST SATELLITE-BASED TIR INDEXES

A decade of RST applications to seismically active areas monitoring by TIR satellite observations have already been performed in the case of various earthquakes (see a selection in Table 2 updated after Aliano et al., 2008) by using a validation/confutation approach, devoted to verify the presence/absence of anomalous space-time TIR transients in the presence/absence of seismic activity.

EVENT (date and magnitude)	**RST TECHNIQUES**	**REFERENCE DATA-SET (sensor, month, years, hour)**	**S/N ratio**
23 November 1980, Irpinia-Basilicata-Italy Ms=6.9	$\otimes_{\Delta T}$(x,y,m) monthly average (Tramutoli et al., 2001)	NOAA-AVHRR-November (1994-1998) 17:00 19:00	**0,6**
	$\otimes_{\Delta LST}$(x,y,m) monthly average (Di Bello et al., 2004)		**1**
7 September 1999, Athens, Greece Ms=5.9	$\otimes_{\Delta LST}$ (x,y,t) daily analysis (Filizzola et al., 2004)	NOAA-AVHRR-August and September (1995-1998)-01:00 04:00	**1,5**
	$\otimes_{\Delta T}$ (x,y,t) daily analysis (Filizzola et al., 2004)	METEOSAT-August and September (1995-1998) 24:00 GMT	**3**
17 August 999, Kocaeli-Izmit, Turkey Ms=7,8	$\otimes_{\Delta T}$ (x,y,t) daily analysis (Tramutoli et al.,2005)	METEOSAT August (1992-1998, 2000) 24:00 GMT	**3,5**
	$\otimes_{\Delta T}$ (x,y,t) daily analysis (Aliano et al., 2008a)	METEOSAT August (1995-2000) 24:00 GMT	**2**
28 May 1995, Patras, Greece M_b=4,7	$\otimes_{\Delta T}$ (x,y,t) daily analysis (Corrado et al., 2005)	METEOSAT-May and June (1992-1999) 24:00 GMT	**3**
29 May 1995, Cyprus Greece-Turkey M_b=5,3			**3**
3 June 1995, Crete, Greece Greece M_b=4,2			**3**
18 June 1995, Crete, Greece Greece M_b=4,3			**3**
4 May 1996, Erzurum,Turkey M_b=4,3			**3**

13 June 1996, Ionian Sea (Southern Greece) $M_{b=}$ 4.2			**3**
16 June 1996, Patras, Greece M_b= 4.3			**3**
17 June 1996, Crete, Greece M_b= 4.0			**3**
29 June 1996, Isparta, Turkey M_b= 5.1			**3**
21 May 2003 Boumerdes, Algeria Ms=6,9	$\otimes_{\Delta T}$ (x,y,t) daily analysis (Aliano et al., 2007;2009)	METEOSAT-April and May (1992-1999) 24:00 GMT	**3**
26 January 2001, Gujarat, India Ms=7.9	$\otimes_{\Delta T}$ (x,y,t) daily analysis (Genzano et al., 2007)	METEOSAT-January and February (1999-2004)-24:00 GMT	**3**
26 September 1997, Umbria-Marche, Italy Ms=5.9 to 6.4	$\otimes_{\Delta T}$ (x,y,t) daily analysis (Aliano et al., 2008b)	METEOSAT-September (1992-2000) 24:00GMT	**2**
16 October 1999, Hector Mine, California Ms=7,4	$\otimes_{\Delta T}$ (x,y,t)) daily analysis (Aliano et al., 2008a)	GOES (7-9-10)-October (1996-1999) 24:00 LT	**2,5**
23 October 1992, Mestia Tianeti, Georgia M=6.3	$\otimes_{\Delta T}$ (x,y,t) daily analysis (Genzano et al., 2009a)	METEOSAT 7 October (1992-1999) 24:00 GMT	**3**
6 April 2009, Abruzzo, Italy M_w=6,3	$\otimes_{\Delta T}$ (x,y,t) daily analysis (Genzano et al., 2009b)	MSG-SEVIRI March and April (2005-2009) - 24:00 GMT	**4**
	$\otimes_{\Delta T}$ (x,y,t) daily analysis (Pergola et al., 2010)	EOS-MODIS March and April (2000-2009) 24:00 GMT	**3,5**
	$\otimes_{\Delta T}$ (x,y,t) daily analysis (Lisi et al., 2010)	NOAA-AVHRR March and April (1995-2009) 24:00 GMT	**3,5**

Table 2: **Seismic events which have been studied by applying the RST approach. The used variable, the sensor, the length (years) and homogeneity rules (months of the year, time of the day) which have been applied to build the historical data-set (used to compute reference fields) and the minimum Signal to Noise (S/N) ratio of TIR anomalies are indicated, together with the references.**

The above mentioned works used specific indexes, such as the RETIRA (Robust Estimator of TIR Anomalies, after Tramutoli et al., 2005) which belongs to a more general class of ALICE (Absolutely Llocal Index of Change of the Environment) indexes which give a statistically well based definition of *llocal* signal anomalies (since Tramutoli, 1998 the double *l* is used to make reference not only to a specific place *r* but also to a specific time *t*).
Using a general formula, ALICE indexes are computed on the image at hand as follows:

$$\otimes_V (x, y, \tau) = \frac{V(r,t) - \mu_V(r)}{\sigma_V(r)}$$

where $r \equiv (x,y)$ represents location coordinates on a satellite image; t is the time of image acquisition with ($t \in \tau$) where τ defines the homogeneous domain of satellite imagery collected in the same time-slot (hour) of the day and period (month) of the year; $V(r,t)$ is the value of a variable V at location $r \equiv (x,y)$ and at acquisition time t; $\mu_V(r)$ is the time average value of $V(r,t)$ at location $r \equiv (x,y)$ computed on cloud free records belonging to the selected data set ($t \in \tau$); $\sigma_V(r)$ is the standard

deviation of $V(r,t)$ at the location $r\equiv(x,y)$ computed on cloud free records belonging to the selected data set ($t\in\tau$).
For its application to seismic area monitoring, different variables have been used:

$$V(r,t) \equiv \begin{cases} T(r,t) \\ \Delta T(r,t) \equiv T(r,t) - T(t) \\ (\textit{the corrisponding } \otimes_{\Delta T}(r,t) \textit{ also named RETIRA}) \\ \Delta LST(r,t) \equiv LST(r,t) - LST(t) \end{cases}$$

where $T(r,t)$ is simply the TIR radiance at the sensor; LST (Land Surface Temperature) is a specific product of satellite data analysis, which is expected to give, an estimate of the Earth's Surface Temperature corrected by the variable contribute of water vapor in the atmosphere (see Di Bello et al. 2004 and reference herein); $T(t)$ and $LST(t)$ are spatial averages of $T(r,t)$ and $LST(r,t)$ computed in place on the image at hand considering cloud-free pixels only, separately for land and sea: only sea pixels are used to compute $\Delta T(r,t)$ and $\Delta LST(r,t)$ if r is located on the sea; only land pixels are used on the other hand if r is located on land. The use of the excesses $\Delta T(r,t)$ and $\Delta LST(r,t)$, instead of the simple $T(r,t)$ and $LST(r,t)$, is expected to reduce the possible contributions (e.g. occasional warming) to the signal due to the year-to-year climatic changes and/or season time-drifts which usually affect near-surface temperature at a regional scale (Tramutoli et al., 2005).
By construction, all RST indexes turn out to be useful tools for a robust identification of TIR anomalies and allow us to estimate them in terms of Signal-to-Noise (S/N) ratio. In fact, the local excess $V(r,t) - \mu_V(r)$, which represents the Signal (S) to be investigated for its possible relation with seismic activity, is evaluated by comparison with the corresponding observational/natural Noise (N) represented by $\sigma_V(r)$. It is important to note that $\sigma_V(r)$ includes all (natural and observational, known and unknown) sources of the overall (*llocal*) variability of S as historically observed at the same site in similar observational conditions (same platform, time of day, month, etc). This way, the relative importance of the measured TIR signal (or the intensity of anomalous TIR transients) can naturally be evaluated in terms of S/N ratio by the ALICE indexes.

IMPROVING S/N RATIO: MAIN RESULTS DURING A DECADE OF APPLICATIONS

The RST technique has been applied for the first time to the observation of seismically active areas in the case of Irpinia-Basilicata earthquake (23 November, 1980, M~6.9). Using a historical data set of 5 years of NOAA/AVHRR satellite passes (see Table 2), Tramutoli et al. (2001) showed how the use of RETIRA index can reduce the dependence on site properties like, topography, emissivity (strongly depending on vegetation cover), etc.. In that case, the monthly average $<\otimes\Delta T(r)>$ of the $\otimes\Delta T(r,t)$ index was considered to compare the mean signal observed during the month of the earthquake (November 1980) with the one observed during the same month in different years.
Although at a low signal to noise ratio, TIR anomalies (almost absents in non seismic periods) were observed in some spatial correlation with the major faults in the area of study.
These results was reinforced by Di Bello et al. (2004) who demonstrated that a doubling of the S/N ratio can be achieved by using AVHRR based LST products (which take into account the atmospheric water vapour variability) instead of simple TIR radiances as in Tramutoli et al. (2001). The reduction of the natural noise due to the variability of atmospheric transmittance (achieved passing from TIR radiances to LST products) increases from 0.6 to 1 the relative intensity of (monthly averaged) TIR anomalies and strongly reduces "false positives" in the confutation year 1998.
Successively, the study of Filizzola et al.(2004) demonstrated, in the case of Athens's earthquake (7 September, 1999; M_S~5.9), the possibility to reach S/N ratios up to 1.5 by using daily (instead than monthly) RETIRA indexes $\otimes_{\Delta LST}(r,t)$. In this case, the authors, using a sequence of daily AVHRR images report the appearance of (space-time) persistent TIR anomalies in the epicentral area some days before the seismic event (with a peak of intensity 4 days before the earthquake). Moreover, in the same paper, it was for the first time demonstrated the advantages to be expected by the use of TIR sensors onboard geostationary, instead than polar, satellites platforms. In fact, by using TIR data (i.e. even without correction for atmospheric water vapour variation) acquired from MFG (Meteosat First Generation) geostationary satellite (instead than LST products from the polar

NOAA/AVHRR) they quite doubled the S/N ratio ($\otimes_{\Delta T}(r,t)$>3) associated to TIR anomalies observed in correspondence of the same (Athens's) event. Since then, space-time persistence of TIR anomalies has been introduced as a further critical requirement in order to discriminate significant anomalies from residual spurious effects due to simple outliers, to geo-location errors, night-time warm cloud shadows (e.g. Filizzola et al., 2004, Aliano et al., 2008a) or particular distribution of clouds in the scene (first introduced by Aliano et al., 2008a and successively called "*cold spatial average effect*" by Genzano et al., 2009).
The same good RST performances using geostationary data (Meteosat, in this case) were observed by Corrado et al., 2005 in the case of medium-low magnitude events occurred in Greece and Turkey (see Table 2). Also in that case, thermal anomalies were observed in quite evident correlation with known tectonic lineaments.
Spatial correlation between the main tectonic features and the thermal anomalies before strong earthquake appeared also in the work of Tramutoli et al., 2005, in the case test of Izmit earthquake M_S=7.8 (17 August, 1999). In this work, the potential of the geostationary satellite data, was confirmed using RETIRA indexes $\otimes_{\Delta T}(r,t)$ over a long-term series (8 years) of satellite data acquired by Meteosat-7.
One of the most spectacular case of correspondence between thermal anomaly fluctuations and tectonic lineaments remains the case of Gujarat's earthquake (26 January, 2001, Ms=7.9), where the whole India-Eurasia boundary plate seems to be drawn by TIR anomalies (Genzano et al., 2007, Figure 1). The indication for possible large scale effects confirms, also in this case, that high spatial resolution is not a requirement for this kind of studies.

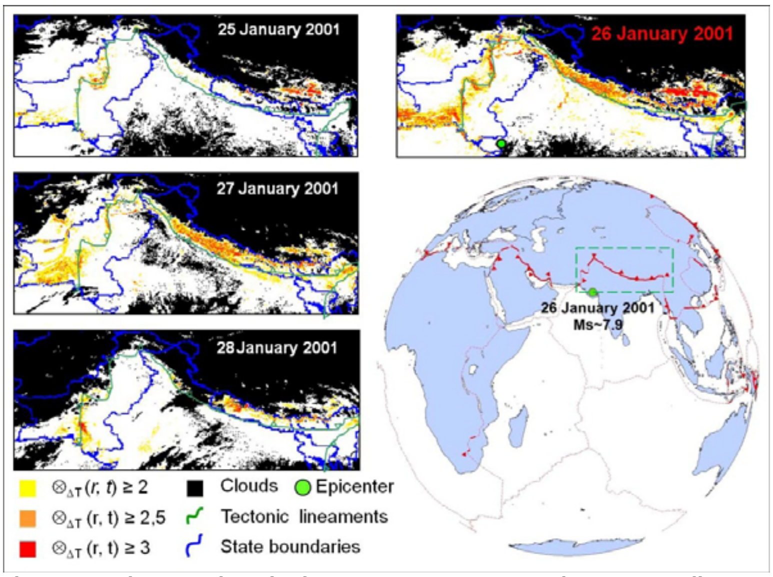

Figure 1: Gujarat earthquake (26 January, 2001, Ms=7.9). TIR anomalies appear one day before the main shock well describing long part of the main tectonic lineaments and continuing reaching their maximum extension the day of the main shock (26 of January) as well as gradually disappear (adapted from Genzano et al., 2007)

In Table 2, are reported all seismic events which have been studied (and published) by applying the RST approach, up to the L'Aquila earthquake (6 April 2009, Mw 6.3) that was analyzed through independent RST analysis on 3 different satellite systems (namely MSG/SEVIRI, NOAA/AVHRR, and EOS/MODIS). In this case the authors (Genzano et al., 2009b; Lisi et al., 2010; Pergola et al., 2010 respectively) found significant and simultaneous TIR anomalies in the epicentral area one week before the main shock and a few hours before its strongest foreshock (30 March 2009 at 13:38 UTC; ML~4.1). For the first time, in the work of Genzano et al., 2009b, a series of nighttime (00:00GMT) passes of MSG/SEVIRI (Meteosat Second Generation/Spinning Enhanced Visible and Infrared Imager) were used in RST analysis for seismic area monitoring (Figure 2).
In addition to the main results previous citied, the RST method proposed by Tramutoli et al., (2001, 2005) has been independently tested by several researchers around the world as well as in the framework of several projects funded by National Space Agencies, like the Italian ASI in 2002 (SEISMASS – Seismically Active Areas Monitoring by Advanced Satellite Techniques) the US NASA (Thermal Properties of Faults In Southern California From Remote Sensing Data, 2005-2007, Eneva et al., 2008) and the German DLR (Early Warning of Earthquakes by Space-Borne

InfraRed Sensors, 2005-2008, Halle et al., 2008), as well as in the most recent EC-FP7 Project named PRE-EARTHQUAKES (Processing Russian and European EARTH observations for earthQUAKE precursors Studies, 2011-12).

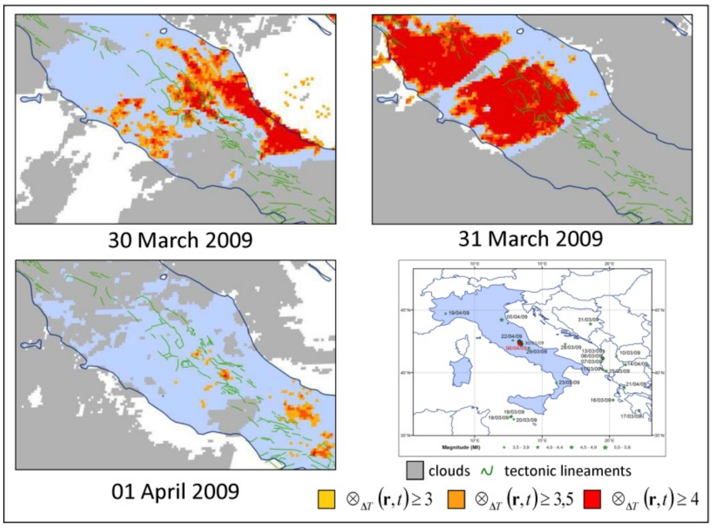

Figure 2: TIR anomalies maps (adapted from Genzano et al., 2009) computing using nighttime (00:00GMT) passes of MSG/SEVIRI satellite sensor. Space time persistent anomalies appear near the epicentral area of Abruzzo earthquake (6 April 2009 Mw 6.3)

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