GAS FLARING MONITORING USING ATSR NIGHT-TIME MEASUREMENTS

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ABSTRACT

Gas flaring flames are characterised by high temperatures and ATSR instruments are equipped with the appropriate spectral bands to detect them. In order to monitor gas flaring on a global scale a new active flame detection scheme from satellite night-time Short Wave Infra Red (SWIR) measurements (1.6 \(\mu\)m), called ALGO3, has been developed and tested using the Along Track Scanning Radiometer (ATSR) family radiances. The ALGO3 algorithm is based on the verified assumption that, at SWIR wavelengths, the background contribution to the night-time total radiation measured by ATSR is negligible, while that emitted by active flames is fully detectable. ALGO3 products are suitable for detecting gas flares, due to their peculiar high temperature/small area flames. Flaring sites have been discriminated according to time persistency criteria, i.e. location for which hot spots are found at frequencies higher that 4 times a year are assumed to be industrial settlements. Continuity and consistency between the ATSR missions has been verified, and results relative to 1991-2009 time window are reported. Validation of flaring site individuation has been performed by visual inspection of high resolution Earth surface images. The comparison of ALGO3 retrievals with light count data from the Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS) show very good agreement.

1. INTRODUCTION

Flaring and venting of natural gas in oil wells is a significant source of greenhouse gas emissions. Its contribution to greenhouse gases has declined by three-quarters in absolute terms since a peak in the 1970s of approximately 110 million metric tons/year, and now accounts for 0.5% of all anthropogenic carbon dioxide emissions (Marland et al., 2008). A gas flare is an elevated vertical stack found on oil wells, oil rigs, and in refineries, chemical plants and landfills, used for burning off unwanted gas and liquids released by pressure relief valves during unplanned over-pressuring of plant equipment (Beychok, 2005; Shore, 2006). On oil production rigs, in refineries and chemical plants, its primary purpose is to act as a safety device to protect vessels or pipes from over-pressuring due to unplanned upsets. The released gases and/or liquids are burned as they exit the flare stacks. The size (~100 m\(^2\)) and brightness of the resulting flame depends upon how much flammable material was released. Steam can be injected into the flame to reduce the formation of black smoke. In more advanced flare tip designs, if the steam used is too wet it can freeze just below the tip, disrupting operations and causing the formation of large icicles. In order to keep the flare system functional, a small amount of gas is continuously burned so that the system is always ready for its primary purpose as an over-pressure safety system. Some flares have been used to burn flammable "waste" gases or by-products that are not economical to retain. Although safety considerations are valid, a vast amount of energy resources that could be stocked and reused is wasted, contributing to the global carbon emission budget.

In this context, during his long history, the ATSR World Fire Atlas demonstrated its usefulness, as in many other research areas. This ESA projects aims at the detection of night-time hot spots using middle-infrared (MIR) and thermal infrared (TIR) radiations acquired by the Along Track Scanning Radiometer (ATSR) instruments flying onboard ESA ERS-1, ESR-2 and ENVISAT LEO satellites. The basic WFA ALGO1 and ALGO2 retrieval approaches have been recognised to be efficient and the related results satisfactorily accurate (Arino et al. 2005, 2007; Arino and Casadio, 2008a). ALGO1 and ALGO2 simply consist in the detection of the MIR 3.7 \(\mu\)m night-time brightness temperatures exceeding 312 and 308 K respectively. These two values have been chosen according to instrumental characteristics (312 K is the saturation level of the ATSR 3.7 \(\mu\)m channel). The radiometric stability of the ATSR instrument series, along with the excellent stability of the ERS-1/2 and ENVISAT satellites, ensures the consistency of the detection capability for long time periods. Since 2006 ESA has been maintaining a near-real-time elaboration and distribution service through which the ATSR-WFA products are freely available to the public. Archived products are also freely available after a simple on-line registration on the project’s web page.

The ATSR family time coverage spans from 1991 to present (for more detailed information on ATSR history and current status: http://www.atsr.rl.ac.uk/). In Table 1 the satellite names and related launch dates are reported, along with the start and stop dates (T0 and T1) selected for the present analysis.
The application of the ALGO1 and ALGO2 hot spot detection algorithms was allowed only for data acquired after 1995 (ERS-2 and ENVISAT), due to the unavailability of the 3.7 μm detector for ATSR-1 caused by an instrumental problem occurred in early 1992. In order to complement the actual algorithms and to take benefit from the ATSR-1 mission data (1991-1996) we developed a new retrieval scheme, called ALGO3, based on the analysis of ATSR SWIR 1.6 μm reflectance, which was almost continuously available from 1991 onwards.

The visible/near-infrared/shortwave-infrared ATSR radiance measurements are provided to users as “reflectance”, i.e. the ratio between Earthshine radiance and solar irradiance and hereafter indicated with R. The ATSR products used in this work have been produced by the latest version of the level 0 to 1 processing chain (version 6.0.1) (Procter, 2009). They cover the three ATSR missions and have been available to users since March 2009. The new level 1 products are characterised by several radiometric and geolocation processing improvements and several orbit gaps have been filled in order to provide a consistent dataset spanning from 1991 to present.

The radiometric calibration of the ATSR-1 SWIR reflectance has been performed by comparing the ATSR-1 measurements to those of ATSR-2 in the mission overlap period, assuming that the ATSR-1 SWIR channel is not affected by calibration drifts. In practice the ATSR-1 SWIR measurements have been scaled to corresponding ATSR-2 (A. Birks 2010, personal communication).

This work focuses on the analysis of the ALGO3 products, obtained by processing the ATSR-1, ATSR-2 and AATSR Top Of Atmosphere (TOA) level 1 radiance products relative to the period August 1991 – September 2009, i.e. around 18 full years of data, and in particular on the gas flaring monitoring globally, and for a number of selected areas worldwide.

2. METHODS

Pioneering works on night-time light detection and gas flare monitoring from space demonstrated the capability of satellite sensors to derive useful information on human activities at a global scale (Croft, 1978; Welch, 1980; Cracknell et al., 1983; Muirhead and Cracknell, 1984). In particular, TIR instruments demonstrated the possibility to adequately detect and characterise offshore gas flaring sites. The Advanced Very High Resolution Radiometer, AVHRR, and LANDSAT products relative to the North Sea and Mexico Gulf area were analysed and results demonstrated that, despite large uncertainties due to both instrumental and viewing geometry limitations, the unambiguous individuation of platforms responsible for any given flare was possible. In a more recent paper (Elvidge et al., 2001) the Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS) products were used to produce maps of human settlements, fires, fishing boats, and gas flares for 200 nations representing 99% of world population. Later analyses of DMSP-OLS products provided the first globally consistent survey of gas flaring, and, through an ad-hoc calibration method of satellite data, the first long term series of gas flaring volumes, spanning from 1994 to 2007 (Elvidge et al., 2007; Showstack, 2007). More recently, DMSP-OLS gas flaring and emission estimate products have been extended to 2008 (Elvidge et al., 2009).

The ATSR-WFA products are widely used for wild fire monitoring on global scale. In addition to forest fires, a number of private and public research institutions (from USA, Mexico, Brazil, France, Germany, Argentina, Australia, and UAE, registered in the ATSR-WFA user database) declared to use the ATSR-WFA products for gas flaring monitoring. In addition, the possibility to detect gas flaring for ATSR-WFA products has been demonstrated by Mota et al. (2006), although in that work the gas flaring was only considered as a disturbance to the wild fire data analysis, and in a recent paper by Arino and Casadio (2008), where the North Sea gas flaring activity has been analysed. One of the known drawbacks of fixed threshold algorithms for hot spot detection using MIR and TIR radiances (such as ALGO1 and ALGO2) is the dependence of the measured brightness temperature values on the background temperature, i.e. the contribution of the not burning area around the active fire. In fact, being the total radiance reaching the satellite instrument the combination of the contributions from both burning and non burning fractions of the ground pixel, a fixed threshold for the hot spot detection cannot account for seasonal variations of the contributing background. The latter becomes less important as the satellite ground pixel size reduces, but for the 1 km² pixel of ATSR instruments it is the dominant contribution in almost all cases. This is a strong limiting factor for the hot spot detection in generally (or seasonally) cold areas, such as Canada, Alaska, and Russia in Northern Hemisphere, and Chile, Argentina and Australia in Southern Hemisphere, and results in a substantial under estimation of fire (and gas flaring) activity in that regions.

ALGO3 overcomes this problem considering the 1.6 µm behaviour for night-time observations. The exploitation of the ATSR night time SWIR measurements is not new, as it was successfully attempted for volcanic
activity monitoring (Wooster and Rothery, 1997; Rothery et al., 2001). The main advantage of using SWIR measurements is that at these wavelengths the contribution of the background to night-time radiance is far below the noise level of the ATSR detectors (Casadio and Arino, 2008). Hence, the ALGO3 method also is a fixed threshold algorithm, being based on the detection of 1.6 μm band reflectance values larger than a fixed threshold of 0.1. The R=0.1 value is well above the detector noise level.

Figure 1 ATSR SWIR detection lower limit for R=0.1%. Abscissa: fire fraction (lower x-axis) or fire area for a 1km² ground pixel (upper x-axis); ordinates: effective flame temperature.

A simulation has been carried out to establish ALGO3 fire detection limits, considering flames as black bodies, satellite nadir viewing geometry, and atmospheric transmission equal to 1, i.e. the most favourable conditions. The flame temperature has been varied from 400 to 2000 K, the flame area, normalised to the ATSR typical ground pixel size and expressed in “fire fractions”, varied from $10^{-6}$ to 1 (i.e. from 1 to $10^6$ m²). The lower limit detection curve shown in Figure 1 has been evaluated by imposing R=0.1%. At typical gas flaring sizes (fire fraction $\approx 10^{-4}$) flame temperatures must exceed 850 K to be detectable using the ATSR SWIR channel. This implies that the ALGO3 hot spots will unambiguously individuate active flames only, thus excluding false alarms due to human settlement lights.

The ALGO3 product continuity between the different ATSR instruments has been verified by comparing the number of spots detected during mission overlaps, when valuable data have been acquired. The overlap period for ATSR-1 and ATSR-2 was from July to December 1995, while for ATSR-2 and AATSR it was from July 2002 and June 2003. Hot spots for those periods were extracted for each mission, and the list of spot locations converted into global 2D fields (2°x2° cell) in order to allow a cell-to-cell comparison. Moreover, only months for which the orbit coverage, defined as the ratio between the number of acquired orbits with respect to expected one, for both missions was above 90% were used. This procedure was necessary because the pixel-to-pixel comparison is not useful, due to possible differences in the geo-location of the ground pixel, and to the fact that the time delay between ATSR-1 and ATSR-2 is 1 day, a time lag over which fires may move for several kilometres (or are extinguished) and clouds may differently shadow the two sensors. The mission-to-mission comparisons show that the bias is negligible for both ATSR-1/ATSR-2 and ATSR-2/AATSR cases. This implies that the three missions can be safely merged and related data used for the long term monitoring of fires (not only gas flaring).

Figure 2 ALGO3 hot spot logarithmic number density (2002-2009)

As an example of achievable results, Figure 2 shows the AATSR (2002-2009) ALGO3 spots cumulative distribution worldwide on a 1°x1° cell grid. The colour scale indicates the logarithm of hot spot cell density. The large number of hot spots in the area interested by the South Atlantic Anomaly (hereafter SAA) (Cabrera et al., 2005) seems to impair the detection of gas flares over South America and a portion of South Africa. The ALGO3 spots for non SAA areas are generated by biomass burning (wild fires) and industrial fires (e.g. gas flares). The use of ALGO3 spots for wild fire monitoring is not considered here and will be the subject of further studies.

The nature of the SAA spikes is such that they very rarely occur at the same location if the analysis is performed at a 1-2 km scale. Moreover, the intensity of the SAA SWIR spikes is generally high (R>3%). These characteristics allow the removal of undesired spots from single site monthly time series by subtracting the total number of spots showing reflectance values higher than 3%. This correction scheme is not applicable for large wild fires, as the “real” reflectance in those cases can be much larger than 3%.

The overall processing firstly consists in the analysis of a single ATSR TOA product, from which the hot spot geo-location parameters are extracted and saved into single orbit files. Secondly, single-orbit hot spot files are merged into monthly files by a post-processing algorithm, which rejects possible data duplications due
to TOA products overlaps. In addition to the hot spots monthly file, ancillary information files are also produced during the post-processing, such as monthly 2D field of overpasses and of TIR brightness temperatures. The overlap information is used to assess the quality of monthly statistics, while the TIR data are used to ensure the long term radiometric stability of the ATSR detectors. Finally, the content of each monthly file is converted into equal area grid file (2X2 km² cell) for further analyses. The 2 km size has been chosen considering possible small errors in pixel geo-locations.

Two different approaches have been adopted for the gas flaring monitoring: a) using the 2x2 km² monthly fields, cells showing long time persistency of hot spots were discriminated and analysed; and b) using the monthly hot spot location data, monthly and yearly time series of hot spots falling within selected areas were analysed.

3. INDIVIDUATION OF FLARING SITES BY “TIME PERSISTENCY”

An example of results achievable by adopting the time persistency approach a) is shown in Figure 3, where all locations where hot spots were found more often than four times a year (from 1991 to 2009) are reported as open red circles, with radius proportional to the total number of hot spots detected on the specific site. Grey circles indicate the position of volcanoes known to be active during the last 10 years (Smithsonian Global Volcanism Program, http://www.volcano.si.edu/).

As it can be clearly seen, the effect of SAA has been completely eliminated and about 10 thousands flaring (and a few volcanic) sites have been discriminated. The number of detected volcanic site is small (around 50 out of the listed 151) because not all volcanoes are continuously active for such long time periods and, hence, their time persistency is insufficiently low for our criteria.

The 90 days (4 times a year) period limit was chosen in consideration of the fact that flaring from oil/gas platforms is almost continuous in time, that the active flames could be shaded by clouds, and that the revisit time of the ATSR family is around 5 days. The instantaneous swath width increases with latitude. Most of the flaring sites show average detection periods exceeding 10 days, while only for few it reaches 2 days. Given the overpass frequency at equator of about 5 days, it is obvious that the short period sites are located at latitudes above 50°. The hot spot time series for each site (cell) can be analysed separately, allowing a long term monitoring of gas flaring activity at very small scale.

The validation of these results, intended as the verification that an industrial site is present within the discriminated “flaring” cell, is performed by visual inspection of the areas surrounding the flaring sites, using GoogleEarth™ to display high resolution images of the Earth. The procedure is as follows:

1) Flaring sites are grouped by country and related coordinates are saved into separate ASCII files
2) Each country file is ingested by an MS-Excel script which creates a KML file, compatible with GoogleEarth™
3) GoogleEarth™ software is launched and the KML file is ingested
4) 4x4 km² Earth images (from 4 km altitude) of the area surrounding each site are created and saved along with site parameters
5) Images are analysed by an automatic procedure which discards empty scenes (usually sea scenarios)
6) The screened series of images is visually inspected to verify the presence of industrial settlements

Although this procedure allows for a very detailed characterisation of the flaring sites, its major drawback is that the number of sites to be checked is close to ten thousands worldwide and therefore the validation exercise requires time and patience.

A second problem is that images of off-shore platforms are very rarely available (with few exceptions). An analysis of land types associated to the flaring sites using the GlobCover classification scheme (Arino et al., 2008b) revealed that discriminated flaring sites are classified as follows: 27% bare areas; 20 % water bodies; 15% sparse vegetation; 9% evergreen forests; 5% mosaic cropland. This implies that 20% of the sites (i.e. “water bodies”) are potentially excluded from the visual validation exercise, unless they are very close to coasts.
Figure 4 shows some examples of validation images clearly showing gas flaring sites from Russia (upper left), Australia (upper right), USA (lower left) and Iran (lower right). The Russian and USA sites are located at high latitudes (62N and 70N), thus demonstrating the capability of ALGO3 to detect relatively small sized fires in very cold environments. For a lucky circumstance, the two images of Australia and Iran are showing active flames, providing an undisputable evidence of the validity of the ALGO3 retrievals.

The results of the validation exercise are reported in Table 2, where the number of available images (Na), empty image (Ne), valid images (Nv), images containing an industrial site (Nf), and the percentage of success ($S = 100 \times \frac{Nf}{Nv}$), are given for the global ensemble and for the two cases of Russia and Nigeria.

<table>
<thead>
<tr>
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<th>Na</th>
<th>Ne</th>
<th>Nv</th>
<th>Nf</th>
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<tbody>
<tr>
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<td>534</td>
<td>8821</td>
<td>8380</td>
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<td>2409</td>
<td>2168</td>
<td>90</td>
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<tr>
<td>Nigeria</td>
<td>627</td>
<td>206</td>
<td>421</td>
<td>412</td>
<td>98</td>
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Surprisingly, only 6 % of the validation images could not be used globally. In the case of Russia, the 0.1 % of the images was not used, while 33 % of the Nigerian flaring sites could not be identified because the related images were not usable. However, the quality of the Earth images is not globally uniform. As a matter of fact, the granularity of many images of Russia is such that, unless a flare is visible, it was impossible to clearly individuate industrial settlements. This resulted in a lower success rate with respect to the total ensemble, and to Nigeria in particular, where, on the other hand, high resolution images are generally available.

Unfortunately, the validation of the flaring timing is not possible, because precise information on industrial activity is not accessible to the public. In practice, it is possible to unambiguously individuate flaring sites, but the assessment of the quality of retrieved flaring activities, and of the related emissions, is problematic due to missing reference information.

4. GAS FLARING ANALYSIS FOR SPECIFIC AREAS

The alternative option b) consists in specifying a number of area borders, in selecting the ALGO3 spots contained in the given border polygons, and in analysing the time series of monthly (or yearly) total numbers of detections.

The areas selected for this study are those used by Eldridge et al. (2007), freely available from the NOAA-NGDC DMSP web site, along with the related emission inventories (http://www.ngdc.noaa.gov/dmsp/).

The ALGO3 spot time series are normalised to the ATSR overpass frequency for the specific area, in order to reduce the impact of different time samplings on final results as much as possible.

The ALGO3 yearly time series have been compared to the corresponding DMSP-OLS light counts for each selected area, and yearly “flaring ranks” were produced.
Examples of ALGO3 and DMSP-OLS yearly time series are shown in Figure 5, where DMSP-OLS data for Argentina and Russia (excluding the Khanty-Mansiysk region) are indicated with a thick solid line, while the correspondent ALGO3 data are indicated with a dashed line.

In Figure 5 ALGO3 has been scaled to DMSP-OLS, as the latter is larger than ALGO3 by a factor of about 50. This scaling factor is mainly due to the different space and time resolution of the instruments used for the hot spot retrieval. As a matter of fact, the ATSR pixel is 4 times larger than the OLS (1 km² and 0.25 km² respectively), resulting in a reduced number of spots (different sources are merged in a single number), and the DMSP-OLS overpass frequency is higher than that of ATSR. Finally, the signal-to-noise ratio of the DMSP-OLS detectors is much larger than that of the SWIR channel of ATSR, allowing the detection of very weak signals which are below the ATSR sensitivity. Despite these limitations, the agreement between ALGO3 and DMSP-OLS data is satisfactory for all selected areas.

The advantages of the proposed method are:

- Only active flames with temperatures exceeding 800 K are detected by ALGO3, avoiding confusion with other light sources like fishing boats and human settlements
- The combined use of ATSR SWIR, MIR and TIR radiance allows an estimate of the effective flame temperature and size, thus providing a full characterisation of the active flames (Casadio and Arino, 2008), which is not possible with DMSP-OLS.

In addition, the future ESA earth Observation satellites SENTINEL-3, to be launched in 2012, will host the Sea and Land Surface Temperature radiometer (SLST), whose characteristics are very similar to those of ATSR in terms of revisit time, space resolution and spectral sampling (Aguirre et al., 2007, Mavrocordatos et al., 2007): this will ensure a continuity of gas flare monitoring up to 2020 using the ALGO3 approach.

Having assessed the quality of the ALGO3 time series, a “flaring rank” similar to that reported in Eldvidge et al. (2007) has been produced using the ALGO3 data only, which is shown in Figure 6. The contribution from each area is indicated as the percentage of the total number of detected spots (only contributions from areas accounting for 95% of total spots are shown).

Almost 70% of the total ALGO3 flaring from 1991 to 2009 was produced in the first nine listed areas: Russia (12%+12 %), Nigeria (10%), Iran (10%), Algeria (8%), Iraq (6%), Kazakhstan (5%), Libya (5%) and North Sea (3%). The North Sea area represents the combination of UK, Denmark, Norway, Germany, Netherlands and Belgium contributions. The USA contribution is very small (roughly 1/3 of that from India) and is not shown in the plot. This result is in very good agreement with DMSP-OLS emission estimates.

The overall trends from 1992 to 2008 have been estimated by fitting a linear function to the data, and gain results (%/year) are shown in Figure 7, where the list of areas reflects the flaring rank in Figure 6. The 1991 and 2009 were not considered for the trend analysis due to incomplete data coverage. The statistical significance of the estimated trend has been evaluated by applying the Mann-Kendall (M-K) test to the time series (Hirsch and Slack, 1984; Yue and Pilon, 2004). This test provides the probability that a trend is present...
in the time series with a predefined confidence level (we choose 95%). It should be noted the M-K test is not providing the value of the trend, which is evaluated by least square fitting. Results indicate that all positive trends are statistically significant, while for the negative trends only that related to North Sea is significant. Except for very few cases (e.g. North Sea and Argentina), the general tendency is positive, i.e. the gas flaring activity has been growing drastically during the last 18 years.

5. CONCLUSIONS

A new fire detection scheme using ATSR family instruments, called ALGO3, has been developed and tested. The use of SWIR night-time radiances allows the detailed monitoring of gas flaring activity starting from 1991 to present, making use of the ATSR-1 (1991-1996), ATSR-2 (1995-2003) and AATSR (2002-present) top-of-atmosphere radiances. The continuity and consistency of hot spot retrievals has been verified using data acquired during the mission overlap periods. The influence of the undesired spots due to energetic solar particles in the Southern Atlantic Anomaly region has been analysed and a correction scheme successfully applied.

Flaring site individuation is based on time persistency criteria, i.e. by assuming the flaring activity to be almost continuous, in contrast with wild fires which are mostly driven by seasonal forcing factors. Results have been compared to the recently published DMSP-OLS light counts data showing excellent agreement. The limitations of the proposed approach are related to the limited revisit frequency of the ATSR instruments (5-6 times per month at equator, increasing with latitude), and to cloud shading effects. On the other hand, the strengths of the ALGO3 method are:

- Only active flames (T>850 K) are detectable, ensuring the unambiguous individuation of flaring sites
- Flame detection is equally efficient at all latitudes, independently of the background temperature
- Flaring activity is verifiable from 1991 to present (more that 18 years) at global and local scale, extendable to 2020 using SLST (Sentinel-3, 2012)
- Flames can be characterised (effective temperature and size) making use of SWIR, MIR and TIR radiances relative to the same ATSR pixel

Future work will focus on the development of a fully automatic flare detection and characterisation scheme, and on the related estimates of gas volumes injected into the atmosphere. Finally, the application of ALGO3 for wild fire detection and characterisation will be attempted for area not influenced by the Southern Atlantic Anomaly.

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7. REFERENCES


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