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Research highlights

1) Monitoring of gas flaring from off-shore platforms from space
2) Synergy between SAR and ATSR satellite instruments
3) Possible monitoring on global scale
4) Method for gas flaring temperature and size estimation
Title
Use of ATSR and SAR measurements for the monitoring and characterisation of night-time gas flaring from off-shore platforms: the North Sea test case.

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Abstract
A method for the monitoring of night-time gas flaring of off-shore oil/gas extraction platforms using measurements of the Along Track Scanning Radiometer (ATSR) and the Synthetic Aperture Radar (SAR) is presented and discussed in detail. The positions of off-shore extraction sites are accurately estimated by using SAR data, while the flaring activity is estimated from night-time shortwave infrared (SWIR) radiance measured by ATSR. The North Sea area has been selected as test case and related flaring activity from 1991 to 2010 has been analysed at single site and at North Sea area scales. Results indicate a decline in the overall flaring activity during the time period considered in this work, although single sites can show positive flaring trends. The ATSR derived flaring time series has been compared to the crude oil production data provided by the US Energy Information Administration (EIA),
showing very good agreement in terms of trend and seasonal behaviour. We present a simple inversion scheme aimed at the evaluation of the flame parameters (temperature and size) from night-time shortwave, middle and thermal infrared ATSR measurements, and results are discussed in detail. Finally, the possibility to estimate flaring efficiency from satellite measurements and from detailed technical information on flaring devices is envisaged. The proposed approach can be easily extended to other areas in which gas flaring from off-shore oil and gas extraction is an important economic and environmental factor.

[1] Introduction

In general, 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 (1–100 m²) and brightness of the resulting flame depends upon how much flammable material was released. Some flares have been used to burn flammable "waste" gases or by-products that are not economical to retain. Although safety considerations are indeed an issue, a vast amount of energy resources that could be stocked and reused is thus wasted, contributing to the global carbon emission budget.

During the last 150 years off-shore drilling platforms were active in the North Sea, but the attention to the problematic of gas flaring monitoring dates back to the latest years
of the past century (Farina, 2011). In fact, the commercial extraction of oil on the North Sea dates back to 1851 while natural gas was found near Hamburg in 1910. In England, the British Petroleum company (BP) discovered gas in 1938 and in 1939 commercial oil was found in Nottinghamshire. From 1953 to 1961 the Gainsborough field and other smaller fields were discovered. The Netherlands’ first oil extractions took place at De Mient in 1938. The first exploration in the province of Groningen was carried out in 1952 and in 1959 gas was found in the Rotliegendes. The seismic exploration started in 1965 and large gas finds followed in 1966. The discovery of the Forties oilfield occurred in October 1970 and Shell Expro discovered the Brent oilfield in the northern North Sea in 1971. Oil production from the Argyll field started in 1975. The Danish explorations of Cenozoic stratigraphy, undertaken in the 1990s, showed petroleum rich reserves in the northern Danish sector. The largest field discovered in the past 20 years is Buzzard, found in June 2001. UK oil production has seen two main peaks, in the mid 1980s and late 1990s. The monthly oil production peaked in January 1985 although the highest annual production was in 1999 and afterwards declined (http://en.wikipedia.org/wiki/North_Sea_oil).

The monitoring of North Sea flaring activities from space started with the pioneering works of Cracknell et al. (1983) and Muirhead and Cracknell (1984). These papers describe the identification of oil production platforms, responsible for flaring off gas in the North Sea, by using data received from the Advanced Very High Resolution Radiometer (AVHRR) carried onboard the polar-orbiting weather satellites TIROS-N, NOAA-6 and NOAA-7. More recent works on gas flare detection from space are those of Eldvige and co-authors (2001, 2007, and 2009) in which the exploitation of data from the U.S. Air Force Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS) is described. The digital archive of OLS data
extends from 1992 to the present and the observations are expected to continue into
the forthcoming decades from DMSP and from the U.S. National Polar Orbiting
Environmental Satellite System (NPOESS). The analysis of OLS data was carried out
for selected areas where gas flaring is expected to be the major source of night-time
lighting, including the North Sea. Recently ESA decided to exploit the Along Track
Scanning Radiometer (ATSR) night-time radiances for the detection and
characterisation of gas flaring at the global scale (Casadio et al., 2008, 2009, 2011). In
these works the ATSR short wave infrared (SWIR), middle infrared (MIR) and
thermal infrared (TIR) night time radiances were used in synergy providing estimates
of flaring activity for a large number of oil extraction areas worldwide.
A limitation common to the above mentioned methods is related to the unavailability
of a priori independent information on the exact position of the oil/gas extraction sites.
This limitation translates into uncertainties in the attribution of flaring events
specifically to oil and gas extraction platforms. The novelty of the proposed approach
resides in the synergistic use of two types of instrument: the Synthetic Aperture Radar
(SAR) and the ATSR. The SAR is used to unambiguously individuate the position of
off-shore platforms with an accuracy of few hundreds of meters, while the ATSR
provides the night-time radiance values which are used to individuate flaring events at
the SAR retrieved locations.
The advantage of using this approach resides in the high accuracy in the determination
of flaring platform positions independent of external information sources. In addition,
only ATSR data falling within a distance of 2 km from each platform are extracted
and analysed. This implies a drastic reduction in possible false alarms or false
identification of platforms, along with evident computational advantages. It should be
noted that SAR images could be used not only for the identification of platforms but
also for possible oil spill detection in the proximity of the drilling sites, thus providing, along with the detection of flaring events from ATSR, a powerful tool for the monitoring of off-shore extraction activities worldwide.

The results presented in this work are relative to the North Sea area, but the method can be readily extended to other areas of interest, such as Venezuela, Mexico Gulf and Nigeria, where oil and gas extraction from off-shore platform is a dominant economic sector and, in addition, which gives rise to both ecological issues and workplace safety concerns.

[2] Off-shore platform positions from SAR measurements

The Synthetic Aperture Radar (SAR) is a side-looking radar system operating from a flying platform (Ulaby et al., 1982). It emits electromagnetic microwave pulses towards the Earth surface and measures the backscattered energy. A microwave image is formed by means of a focusing processing, built up from time delay, Doppler shift and strength of the returned signals, which depend mainly on the roughness and dielectric properties of the reflecting surface and its distance from the satellite.

Being SAR an active microwave instrument, surface echo images can be acquired in both daytime and night-time, independently of local weather conditions in particular when the C-band frequency (5.3 GHz) is adopted as in the ASAR (Advanced Synthetic Aperture Radar, ENVISAT) case. In this work we used the ASAR Wide Swath Mode (WSM) VV polarisation standard frames to cover the North Sea region as shown in Figure 1. Here VV stands for “Vertical polarisation transmitted / Vertical polarisation received”. The WSM swath is 400 km wide with a spatial resolution of 150 m. The ASAR Image Mode (IM) products, characterised by a spatial resolution of
30 m, were not used due to their reduced swath (100 km) which would have been translated into a much larger number of ASAR products necessary to fully cover the area of interest. In addition, the IM products are specific for land monitoring. In any case, the 150 m spatial resolution of WSM products is sufficient for identifying large reflecting objects on the sea surface. Full details on the ASAR products can be found in the ASAR Product handbook (http://envisat.esa.int/handbooks/asar/).

The ASAR processing described below is fully automatic and has been performed by using the ESA open source Next ESA SAR Toolbox software (NEST, http://earth.esa.int/nest) and ad-hoc developed IDL® routines.

For each ASAR frame three descending mode acquisitions in different days of 2008 have been selected to constitute six independent time series. Details on the specific ASAR acquisitions are reported in Table 1, where the acquisition date is reported along with the track number, referring to the ENVISAT cycle orbit number, and the frame number corresponding to the ASAR product for the given track.

The rationale for using time series is that the criteria to identify a platform is based on the consideration that the same type of signal can be detected in the three different acquisitions over the same location only if the target is not changing its position in time. The time persistency of a highly reflecting target in a fixed position removes any possible ambiguity. In fact, the scattered signal could be also due to ships travelling the area but in this case it would be very unlucky that the same ship (or a different one) would be placed exactly in the same position at different times of the year.
Figure 1 ASAR frames selected to cover the North Sea area. The two frames on the left correspond to track 94, those on the middle to track 237, those on the right to track 108.

Table 1 North Sea ASAR acquisition details

<table>
<thead>
<tr>
<th>Frame number</th>
<th>Track number</th>
<th>Acquisition date</th>
</tr>
</thead>
<tbody>
<tr>
<td>2484</td>
<td>108</td>
<td>15/01/2008</td>
</tr>
<tr>
<td>2484</td>
<td>108</td>
<td>25/03/2008</td>
</tr>
<tr>
<td>2484</td>
<td>108</td>
<td>03/06/2008</td>
</tr>
<tr>
<td>2556</td>
<td>108</td>
<td>15/01/2008</td>
</tr>
<tr>
<td>2556</td>
<td>108</td>
<td>25/03/2008</td>
</tr>
<tr>
<td>2556</td>
<td>108</td>
<td>03/06/2008</td>
</tr>
</tbody>
</table>
In this work we analysed ASAR products acquired in 2008 only. The evaluation of the number and position of off-shore platforms on yearly basis starting from 1991 is under development, as it requires the analysis of a large number of SAR products. Nevertheless, the lifetime of an off-shore platform is between 20 and 30 years (from start to end of production) and most of the exploited fields have been explored before the 90ies of last century (see the Introduction section). Thus, by analysing the 2008 data we assume to have detected and localised almost all platforms active from 1991 onward.

In order to retrieve the position of candidate platforms on the sea surface, each of the six time series listed in Table 1 is analysed as follows:

- Dataset absolute calibration is performed to derive “Sigma0 images”, where Sigma0 is the radar backscattering coefficient (Rosich and Meadows, 2004)
Automatic co-registration of “Sima0 images” is performed through cross correlation analysis (for more details see NEST Help, “SAR Operators / GCP selection” paragraph)

Multi-temporal speckle filtering is applied to the stack of co-registered Sigma0 images. The approach proposed by Quegan et al. (2000) with a 5x5 pixel window is adopted.

Ellipsoid correction of the filtered stack at point 3 is performed by employing a rigours Range-Doppler backward geo-coding method (Small and Schubert, 2008).

An operator to detect objects such as ships on the sea surface from SAR imagery has been applied to each single layer or acquisition of the geo-coded time series to unambiguously identify platforms. The object detection is performed as suggested by Crisp (2004):

a) A land-sea mask is generated to ensure that detection is focused only on the sea portion of the area of interest.

b) Objects are detected with a Constant False Alarm Rate (CFAR) detector (Touzi et al., 1988)

c) False alarms are rejected based on retrieved object size.

The size of the object was required to be between 200 and 500 m and the probability of false alarm (PFA) value was set to $10^{-5}$. These values have been used as input parameters to the object detection procedure, which generates a file containing the positions of detected objects in WGS 84 Geographic coordinates for each input layer.

Finally the time persistency of scattering points is estimated from the object coordinates time series. The scattering objects having the same position ($\pm 500$ m) and
occurring in all the selected dates are labelled as platforms and their coordinates are finally saved into ASCII files for further analysis.

[3] Hot spot detection from ATSR measurements

The ATSR (Along Track Scanning Radiometer) instruments produce images of the Earth at a spatial resolution of 1 km (with an uncertainty of ± 1 km) in the visible to thermal infrared wavelength range, with a ground swath of 512 km. The data from these instruments are useful for scientific studies on land surface, atmosphere, clouds, oceans, and the cryosphere. The first ATSR instrument, ATSR-1, was launched on board the European Space Agency's (ESA) European Remote Sensing Satellite (ERS-1) in July 1991, as part of the ESA Earth Observation Programme. An enhanced version of ATSR-1, the ATSR-2, was successfully launched on board ESA's ERS-2 spacecraft on 21st April 1995. ATSR-2 is equipped with additional visible channels for vegetation monitoring. The AATSR (Advanced Along Track Scanning Radiometer) instrument has been successfully launched on board the ENVISAT spacecraft on 1st March 2002 and it is still in operation (http://www.atsr.rl.ac.uk/).

Although ATSRs were not intended for fire detection, the estimates of sea surface temperature being their primary objective, they demonstrated to provide valuable information on wildfires on global scale for the last 18 years (Arino at al., 2011).

The ATSRs are dual-view instruments, i.e. the Earth’s surface is probed at nadir and at 55° (forward view) line of sight angles, thus providing useful information on both atmospheric and surface status. In this work we used the night-time Top-of-Atmosphere (TOA) radiances measured at nadir. The synergistic use of nadir and
forward view measurements will be exploited in the future, the forward viewing geo-
location accuracy being not yet sufficient for single pixel scale analyses.

The (A)ATSR(-1/2) overpass frequency, defined here as the monthly number of
night-time overpasses at single location in the North Sea region for the 1991-2010
time period is reported in Figure (2). The two vertical dashed lines indicate the
passage from ATSR-1 to ATSR-2 (June 1996) and from ATSR-2 to AATSR (January
2003) missions. As can be seen from Figure (2), the North Sea area (50N to 65N) is
probed from 10 to 16 times per month. The seasonality of the overpass frequency is
due to the definition of “night-time” adopted here to select the TOA radiances. In fact,
we decided to analyse SWIR data for which the solar zenith angle (‘sza’) values are
less than -5°, i.e. when the Sun is well below the horizon, in order to avoid spurious
signals from surface reflection or atmospheric scattering of solar radiance in the
SWIR spectral range. This implies that during boreal summer the highest latitude
considered is around 65N. In addition, the ERS and ENVISAT orbits are Sun-
synchronous resulting in a seasonal variation of the ATSR coverage at high latitudes.
The time series of monthly overpasses also provides indications on the data
availability of the three ATSR missions. Apart from very narrow periods of reduced
operations in 2001 and 2002, and the June 1996 data gap, the ATSR coverage for the
North Sea has remained essentially constant since late 1992.
Figure 2 Time evolution of the (A)ATSR(-1/2) monthly night-time overpass frequency over the North Sea. Vertical dashed lines indicate the passage from ATSR-1 to ATSR-2 (June 1996) and from ATSR-2 to AATSR (January 2003) missions.

Differently from geostationary satellite instruments, for which the revisit time can be as small as 15 minutes (e.g. the METEOSAT Second Generation, MSG), the elapse of time in which a single location is probed by ATSR instruments is a few seconds per month (at roughly 22:00 local time). In practice, a platform is monitored for a very small fraction of the time in which flaring can take place. Thus, the probability of detecting a flare is linked to the frequency (and timing) of the flaring activity, which could be also varying in time. In addition, possible cloud shading drastically reduces the detection probability. Nevertheless, as will be shown in the next paragraph, a large number of flaring events were detected in the North Sea during the considered period, thus demonstrating that the flaring activity for most of the extraction platforms is continuous in time (unless one makes the unrealistic hypothesis that gas flares occur always at 22:00 local time). To exclude possible influence of changes in cloudiness on the estimated flaring trends the monthly precipitation data produced in the context of the Global Precipitation Climatology Project (GPCP) and distributed by National
Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC) ([http://lwf.ncdc.noaa.gov/oa/wmo/wdcamet-ncdc.html](http://lwf.ncdc.noaa.gov/oa/wmo/wdcamet-ncdc.html)) have been analysed for the North Sea area from 1991 to 2010. The precipitation time series does not show any statistically significant trend (-1.5 ± 3.4 %/y). As a consequence we assumed possible changes in the cloudiness over the North Sea to be negligible.

The ATSR instruments are equipped with SWIR, MIR and TIR acquisition channels. All channels, with the exception of the 3.7 μm (MIR) channel of ATSR-1, were active during the eclipsed portion of the satellite’s orbit in order to retrieve the sea surface temperature (SST) during night-time conditions, as reported in Table 2.

<table>
<thead>
<tr>
<th>Mission</th>
<th>Life time</th>
<th>1.6 μm</th>
<th>3.7 μm</th>
<th>10.8 μm</th>
<th>12.0 μm</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATSR-1</td>
<td>1991-1996</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>ATSR-2</td>
<td>1995-2003</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>AATSR</td>
<td>2002-present</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
</tbody>
</table>

The ATSR TOA (level 1) products consist in fully calibrated and geolocated reflectance (VIS, NIR, and SWIR) and brightness temperature (MIR, TIR) values at 1 km space resolution (± 1 km). The SWIR reflectance, defined as the ratio of radiance reflected/emitted from the surface to the solar irradiance (expressed in %), has been converted to radiance by using the set of 1.6 μm calibration parameters ([http://www.atsr.rl.ac.uk/](http://www.atsr.rl.ac.uk/)). The brightness temperature has been transformed into radiance by simply inverting the Planck function at each given wavelength.

In the absence of reflected solar radiance from the surface and cloud free conditions, and assuming the upward thermal radiance emitted from the atmosphere to be negligible, the relation between the nadir TOA radiance at given wavelength λ and the surface parameters can be expressed in the following simplified form:
\[ R_\lambda = \left[ \varepsilon_\lambda^f \cdot f_f \cdot P_\lambda(T_f) + \varepsilon_\lambda^w \cdot f_w \cdot P_\lambda(T_w) + \varepsilon_\lambda^b \cdot \left(1 - f_f - f_w\right) \cdot P_\lambda(T_b) \right] \cdot \Gamma_\lambda \] (1)

Where:

\( \lambda \) = wavelength [\( \mu \text{m} \)]

\( R_\lambda \) = night-time TOA radiance measured by the satellite instrument [W m\(^2\) sr\(^{-1}\)]

\( f \) = ATSR pixel area fraction : flame (f), burnt area (w), background (b)

\( \varepsilon_\lambda^{f,w,b} \) = emissivity of flame (f), burnt area (w), background (b)

\( T_{f,w,b} \) = temperature of flame (f), burnt area (w), background (b) [K]

\( \Gamma_\lambda \) = atmospheric transmissivity from Earth surface to satellite

\( P_\lambda \) = black body Planck function

Equation (1) states that the TOA radiance measured by the nadir-looking satellite instrument at a given wavelength is a linear combination of three separate contributions from the “actively flaming” (I), the “just burnt – still hot” (II), and “background” (III) portions of the ATSR ground pixel. The pixel area fractions are defined as the ratio of the flame (f), burnt (w) and background (b) areas to the total area of the ATSR ground pixel (≈1 km\(^2\)). Such a normalisation makes equation (1) independent of the ground resolution of the instrument.

Assuming \( \varepsilon_\lambda^f = 1 \) for flames (Koseki and Yumoto, 1988) equation (1) becomes:

\[ R_\lambda \approx \left[ f_f \cdot P_\lambda(T_f) + f_w \cdot P_\lambda(T_w) + \varepsilon_\lambda^b \cdot \left(1 - f_f - f_w\right) \cdot P_\lambda(T_b) \right] \cdot \Gamma_\lambda \] (2)

In the special case of gas flaring from off-shore platforms the burnt surface contribution is assumed to be negligible. Thus equation (2) reduces to:

\[ R_\lambda \approx \left[ f_f \cdot P_\lambda(T_f) + \varepsilon_\lambda^b \cdot \left(1 - f_f\right) \cdot P_\lambda(T_b) \right] \cdot \Gamma_\lambda \] (3)

Finally, being the night-time background signal at SWIR wavelengths far below the ATSR detection limits (Casadio et al., 2011), we have:

\[ R_{1,6} \approx f_f \cdot P_{1,6}(T_f) \cdot \Gamma_{1,6} \] (4)
In practice, the ATSR night-time TOA radiance at 1.6 μm is exclusively due to active flame emission. An ATSR ALGO3 hot spot is detected whenever the nocturnal SWIR radiance exceeds a fixed threshold, defined as twice the detector noise level (reflectance = 0.1 %). For each ALGO3 fire count the following parameters are considered: 1) ATSR pixel coordinates; 2) date and time of acquisition; 3) values of SWIR, MIR and TIR radiance values.

The collection of ALGO3 fire count monthly files for the three ATSR missions spans from 1991 to present and it is routinely updated using the near-real time AATSR TOA products (http://due.esrin.esa.int/wfa/).


The ALGO3 fire counts have been attributed to each single platform by prescribing a distance lower than 2 km between the hot spot and the platform. This threshold is twice the spatial accuracy of ATSR instrument and has been chosen in order to account for possible geolocation error of ATSR data. The time series of all ALGO3 fire counts for each platform have been analysed in order to evaluate the flaring activity in terms of both the total number of detected hot spots and the activity trends. The number of platforms for which at least one flaring event was detected during the 1991-2010 time window is 196, out of a total of 345 platforms originally individuated from SAR images. In terms of flaring, the most active area is that corresponding to the “Great Fisher Bank”, while a large number of platforms showing very weak flaring activity have been found in the sector of The Netherlands, as shown in Figure (3), where stations are represented by filled circles whose area is proportional to the number of detected flaring events. Colours indicate the presence of a trend in the
related flaring events (or spots) time series: red is associated to statistically significant positive trend and blue to a statistically significant negative trend, while grey indicates the absence of any statistically significant trend.

Figure 3 Map of flaring platforms in the North Sea (1991-2010). Circle area is proportional to the number of detected flaring events, blue indicates statistically significant negative flaring trend, red indicates statistically significant positive flaring trends, and grey indicates no significant trend.

The statistical significance of trends has been evaluated by applying the Mann-Kendal test to the time series with a rejection value of 5% (Hirsch and Slack 1984). It is interesting to note that all the statistically significant negative trends are found in a very specific region between 57N and 59N, i.e. between the “Little Halibut Bank” and...
the “Old Viking Bank”. This could be due to a progressive exhaustion of the related oil reservoirs in this area causing a reduction of the flaring activity in this sector. The most active platform, located at (1.389E, 57.453N), has been continuously flaring since (at least) 1991 to present, with an average of 8 flaring events per month and no statistically significant trend in the flaring activity. In practice, despite the low detection probability and the possible presence of shading clouds, a flaring event was detected at almost every passage over that station. The maximum monthly number of active flaring platforms is around 70, and no appreciable trend in the number of flaring stations can be found during the considered time period.

The time evolution of the monthly number of detected flaring events (or spots) for the whole North Sea area is shown in Figure (4).

![Figure 4 North Sea monthly ALGO3 spots vs. time (1991 to 2010)](image_url)

The analysis of the North Sea spot time series relative to the 1991-2010 time period indicates that:
1) The total flaring activity shows a statistically significant negative trend ($\approx -1.6 \% / y$)

2) A seasonal signal is evident, with a decrease of flaring during summer

3) The years 1994, 1995, 1999, 2003 and 2008 are characterised by a significant increase in the flaring activity with respect to the average

4) During the years 2001 and 2002 the flaring activity is significantly reduced

The negative trend in ALGO3 time series is in good agreement with the recently reported trends on North Sea oil production. The periods of enhanced flaring activity are well correlated with reported oil production variations (with the exception of the 2008 peak). In particular, the 1994, 1996, 1999 and 2003 peaks are related to increased oil extraction (http://www.oilindustryhistory.com/).

A sort of validation of our results consisted in the comparison between the ALGO3 monthly fire counts and the North Sea crude oil production rate for years 2002÷2010. The most recent monthly data of oil production are freely accessible through the US Energy Information Administration web site. Oil production data are provided in units of million barrels per day (http://www.eia.doe.gov/ipm/supply.html).

The ALGO3 and oil production time series are shown in Figure (5), along with the estimated yearly percentage trends. In Figure (5) the ALGO3 data are reported in black while the oil production data are in red. The estimated linear trends (least square fitting) are essentially equivalent, as the oil production is declining to a $-7.1 \pm 0.3 \% / y$ rate and the flaring activity is decreasing at a $-7.0 \pm 2.8 \% / y$ rate.
Figure 5 North Sea ALGO3 and oil production monthly time series from year 2002 to 2010. Black curves: ALGO3 fire counts and linear fit to the time series; red curves: crude oil production and linear fit to the time series. The yearly percentage trends are also reported for both data sets.

The oil production time series shows a seasonal variation, with a minimum in summer and a maximum in winter, very similar to that registered in ALGO3 data. To quantify the correspondence of the seasonality in the two data sets, ALGO3 and oil production residuals time series have been compared, as shown in Figure (6), in which the oil production time series is represented by the red curve. The residual curves have been obtained by subtracting the linear fit values from the related time series.
From Figure (6) it is evident that the flaring activity and the oil production residual time series are correlated, although characterised by different phases. By performing a cross correlation analysis, and assuming the time lag to vary from -6 to 6 months, a two months time lag in the oil production data with respect the flaring activity was found, as shown in Figure (7). Although we do not have precise information as to the real elapse of time between the extraction and the production of crude oil, it reasonable to expect a significant time lag, as the material has to be extracted, transported to refineries, refined, stored, and, eventually, sold.
Figure 7 North Sea ALGO3 vs. oil production cross correlation as function of the time lag from -6 to 6 months, revealing a time delay of about two months between flaring (i.e. extraction) and production

[5] Retrieval of flame parameters

The knowledge of flame size and temperature is of great importance for the evaluation of the efficiency of the flaring processes. In fact, it has been shown that the combustion efficiency of a flare can be estimated by comparing the radiative losses (i.e. the amount of radiation emitted by the flare) to the sensible heat gains (Beychok, 2005). This method needs not to rely upon a detailed knowledge of chemical reactions involved in the combustion.

In the following we describe a method to evaluate flame size and temperature in order to provide estimates of the flaring radiative losses, to be possibly used in the analysis of combustion efficiencies.
The characterisation of active fires can be achieved by analysing the SWIR, MIR and TIR TOA radiances acquired by the ATSR instruments, provided valid measurements are contemporarily available for all channels. This is not always the case when considering the ATSR instrument series. In fact:

1) The SWIR radiances are not available for some months of 1991 and 1992, when the SWIR band was operated alternatively with the MIR band.

2) The MIR radiances for ATSR-1 are not available after February 1992, due to the failure of the MIR detector.

3) The night-time (A)ATSR(-1/2) MIR radiance values relative to “energetic” fires are so high as to saturate the MIR detector, i.e. the measured brightness temperature at 3.7 μm exceeds the saturation level of 312 K and it is flagged as “-0.05” K. These data, while useful for hot spot detection, cannot be used to characterise fires.

In practice, the analysis of fire parameters proposed here is restricted to non saturated MIR measurements and to the ATSR-2 and AATSR missions only (June 1995 onward).

It should be noted that the limitation due to saturation of the MIR band will be overcome by the next to launch ESA’s SLST instrument (Sea & Land Surface Temperature Radiometer) onboard the SENTINEL-3 satellite series (the launch of the first satellite is planned for 2013). In fact, the SLST radiometer will be equipped with two detection channels explicitly designed for fire detection and characterisation. They are centred at 3.7 and 10.8 μm, with saturation levels exceeding 500 K thus permitting the full characterisation of almost any fire (Mavrocordatos et al., 2007).

However, from the analysis of the ALGO3 spots relative to different areas of the world, we found that the relative number of MIR saturated spots from off-shore
flaring is much smaller than those from wild fires. To quantify this difference, in Table (3) we report the percentage of MIR saturated spots for the North Sea, Borneo, India and Canada areas for the periods in which the MIR measurements were available (i.e. from 1995 onward).

Table (3) Percentage of saturated MIR spots with respect to total SWIR spots

<table>
<thead>
<tr>
<th>Region of Interest</th>
<th>ALGO3 spots</th>
<th>MIR Saturated</th>
<th>MIR Saturated (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>North Sea</td>
<td>29099</td>
<td>396</td>
<td>1.34</td>
</tr>
<tr>
<td>Borneo</td>
<td>79826</td>
<td>27158</td>
<td>34.02</td>
</tr>
<tr>
<td>Canada</td>
<td>238277</td>
<td>38492</td>
<td>16.15</td>
</tr>
<tr>
<td>India</td>
<td>137811</td>
<td>9412</td>
<td>6.83</td>
</tr>
</tbody>
</table>

As a matter of fact, only 1.34% of North Sea SWIR spots are affected by the saturation of the MIR channel, thus allowing a comprehensive analysis of the related flames.

The equations linking the four measured TOA radiances “R” (at 1.6, 3.7, 10.8 and 12 μm) to the “active flame”, the “just burnt still hot” and the “background” temperatures and areas (or pixel fractions) are reported in the following system of equations, where equation 1 has been reformulated for each detection channel and the atmospheric spectral transmissivity contributions are also considered:

\[
\begin{align*}
R_{3.7} &= \left[ f_f \cdot P_{3.7}(T_f) + f_w \cdot P_{3.7}(T_w) + \varepsilon_{3.7}^b \cdot (1 - f_f - f_w) \cdot P_{3.7}(T_b) \right] \Gamma_{3.7} \\
R_{10.8} &= \left[ f_f \cdot P_{10.8}(T_f) + f_w \cdot P_{10.8}(T_w) + \varepsilon_{10.8}^b \cdot (1 - f_f - f_w) \cdot P_{10.8}(T_b) \right] \Gamma_{10.8} \\
R_{12} &= \left[ f_f \cdot P_{12}(T_f) + f_w \cdot P_{12}(T_w) + \varepsilon_{12}^b \cdot (1 - f_f - f_w) \cdot P_{12}(T_b) \right] \Gamma_{12} \\
R_{16} &= \left[ f_f \cdot P_{16}(T_f) + f_w \cdot P_{16}(T_w) + \varepsilon_{16}^b \cdot (1 - f_f - f_w) \cdot P_{16}(T_b) \right] \Gamma_{16}
\end{align*}
\]

In (5) subscript numbers indicate the channel’s wavelength in micrometers.

The nature of gas flaring is such that there is no “just burnt / still hot” area (if we exclude hot smoke plumes) and hence the related contribution in equations (5) is
elided. Moreover, the emissivity of the background (i.e. the sea surface) can be
assumed to be constant ($\varepsilon_b^b \approx 0.98$) (Konda et al, 1994). It should be noted that the
across-track observation angles range being limited to $\pm 17^\circ$ (i.e. very close to nadir)
possible effects due to the angular dependence of the emissivity can be neglected
(Niclos et al., 2005). Thus, the system of equations (5) can be written as follows:

\[
\begin{align*}
R_{3.7} & \approx \left[ f_f \cdot P_{3.7}(T_f) + \left( 1 - f_f \right) \cdot P_{3.7}(T_{b}) \right] \Gamma_{3.7} \quad (6) \\
R_{10.8} & \approx \left[ f_f \cdot P_{10.8}(T_f) + \left( 1 - f_f \right) \cdot P_{10.8}(T_{b}) \right] \Gamma_{10.8} \\
R_{12} & \approx \left[ f_f \cdot P_{12}(T_f) + \left( 1 - f_f \right) \cdot P_{12}(T_{b}) \right] \Gamma_{12} \\
R_{16} & \approx f_f \cdot P_{16}(T_f) \Gamma_{16}
\end{align*}
\]

This is the basic set of equations that will be used to estimate the relevant fire and
background parameters.

The first step of our retrieval consists in the estimate of a set of four values
representing our Initial Guess (hereafter indicated with IG) for the flame temperature,
the flame size, the background temperature, and columnar content of atmospheric
water vapour, which is the main atmospheric absorber in the spectral range of interest
(Barton and Prata, 1999). The contribution of Rayleigh and Mie scattering to the
transmissivity is not considered.

Assuming $f \ll 1$ (i.e. small fires with respect to the ground pixel size), in the first
approximation the equations (6) relative to TIR wavelengths can be written as:

\[
\begin{align*}
R_{10.8} & \approx P_{10.8}(T_{b}) \cdot \Gamma_{10.8} \quad (7) \\
R_{12} & \approx P_{12}(T_{b}) \cdot \Gamma_{12} \quad (8)
\end{align*}
\]

Here it is assumed that the contribution of the active flame to the TIR radiances is
negligibly small. This assumption is acceptable for coarse space resolution
instruments (such as ATSR), for which the area of the ground pixel is almost always
several order of magnitude larger that the flaming area. By taking the ratio of (8) to
(7) we have:
\[
\Psi = \frac{R_{12}}{R_{10.8}} = \frac{P_{12}(T_b)}{P_{10.8}(T_b)} \frac{\Gamma_{12}}{\Gamma_{10.8}} \quad (9)
\]

The natural logarithm of (9) gives:

\[
\ln(\Psi) = \ln \left( \frac{P_{12}(T_b)}{P_{10.8}(T_b)} \right) + \ln \left( \frac{\Gamma_{12}}{\Gamma_{10.8}} \right) \equiv 1 + \Delta \sigma \cdot TCWV \quad (10)
\]

In (10) the Beer-Lambert law for atmospheric extinction is used and “TCWV” is the columnar content of water vapour (Total Column Water Vapour), and \( \Delta \sigma \) is the difference between the effective absorption cross sections of water vapour at 12 and 10.8 \( \mu \)m. The absorption cross sections have been estimated by simulating the contribution to the atmospheric transmissivity, assuming different water vapour column values (mid latitude standard atmosphere) in the Modtran radiative transfer code (MOD5v2r11, Sep 2005). From (10) the approximate IG value of the columnar water vapour can be estimated:

\[
TCWV^{IG} = \frac{\ln(\Psi) - 1}{\Delta \sigma} \quad (11)
\]

and inserted in equation (8). We thus get a rough estimate of the background (sea) temperature (IG):

\[
T_{b}^{IG} \equiv R_{12}^{-1}(R_{12}/\Gamma_{12}^{IG}) \quad (12)
\]

When both estimates (11) and (12) are used in equations (6), relative to 3.7 and 1.6 \( \mu \)m radiances, we get:

\[
R_{3.7} \equiv \left[ f_f \cdot P_{3.7}(T_f) + P_{3.7}(T_{b}^{IG}) \right] \Gamma_{3.7}^{IG} \quad (13)
\]

\[
R_{1.6} \equiv f_f \cdot P_{1.6}(T_f) \Gamma_{1.6}^{IG} \quad (14)
\]

Finally, from equations (13) and (14) the IGs for flame temperature and flame size are estimated.
In equation (15) $h$ is the Planck constant, $k$ is the Boltzmann constant, and $c$ is the speed of light.

The estimate of IG using the same measurements that will be used for the final retrieval is, in principle, not fully correct as we will use the same set of measurements twice. A more rigorous approach should make use of independent information for the estimate of IG. The $T_b$ could be retrieved from SST (Sea Surface Temperature) ATSR Level-2 products, the atmospheric water vapour columns could be extracted from atmospheric analyses (e.g. ECMWF daily or monthly fields), and the $T_f$ and $f_f$ parameters could be estimated from oil/gas extraction technical documentation. The integration of the “more rigorous” approach is under development and will be operational by 2012. In the meanwhile we followed the above described procedure as the most practical way to estimate the IG.

The system of equations (6) can be expressed in matricial form as:

$$\bar{x} = G(\bar{y})$$  \hspace{1cm} (17)

In (17) $\bar{x}$ represent the measurements vector, $\bar{y}$ the vector of unknowns, and $G$ is a non linear operator involving the Planck function and the atmospheric transmissivity.

The Taylor expansion of (17) around the IG vector $\bar{y}_0$ gives:

$$\bar{x} \approx \bar{x}_0 + \frac{\partial G(\bar{y})}{\partial \bar{y}} \bigg|_{\bar{y}=\bar{y}_0} \cdot (\bar{y} - \bar{y}_0)$$ \hspace{1cm} (18)

Where:

$$T_f^{IG} = \frac{\left( \frac{1}{3.7} - \frac{1}{1.6} \right), h \cdot c}{k} \left[ 5 \cdot \ln \left( \frac{1.6}{3.7} \right) + \ln \left( \frac{R_{3.6}}{R_{3.7}} \right) + \ln \left( \frac{\Gamma_{6}^{IG}}{\Gamma_{3.7}^{IG}} \right) \right]$$ \hspace{1cm} (15)

$$f_f^{IG} = \frac{R_{3.6}}{P_{1.6}(T_f^{IG}),\Gamma_{1.6}^{IG}}$$ \hspace{1cm} (16)
\[ \hat{x} = \begin{bmatrix} R_{3.7} \\ R_{10.8} \\ R_{12} \\ R_{1.6} \end{bmatrix} \] is the measurements vector

\[ \hat{y} = \begin{bmatrix} T_f \\ T_b \\ f_f \\ TCWV \end{bmatrix} \] is the unknowns vector

\[ \hat{y}_0 = \begin{bmatrix} T_f^{IG} \\ T_b^{IG} \\ f_f^{IG} \\ TCWV^{IG} \end{bmatrix} \] is the initial guess vector

\[ \hat{x}_o = \begin{bmatrix} R_{3.7} \\ R_{10.8} \\ R_{12} \\ R_{1.6} \end{bmatrix}_{\hat{y}_0} \] is the forward model (6) evaluated at \( \hat{y}_0 \)

From equation (18) we have:

\[ \hat{x} - \hat{x}_o = \hat{A} \cdot (\hat{y} - \hat{y}_0) \] (19)

In (19) \( \hat{A} \) is the Jacobian of the operator G evaluated at \( \hat{y}_0 \).

By inverting the square matrix \( \hat{A} \) (if \( \hat{A}^{-1} \) exists) we finally derive the estimate of the fire and background parameters:

\[ \hat{y} = \hat{y}_0 + \hat{A}^{-1} \cdot (\hat{x} - \hat{x}_o) \] (20)

Thus, the retrieval scheme produces an estimate of the effective flame temperature, of the effective flame size (fraction of ATSR pixel), of the background (sea) temperature, and of the total columnar content of water vapour for all ATSR ALGO3 hot spots for which valid measurements are available.

Rejection values for the retrieved parameters are:

\[ 10^{-7} \leq \text{fire fraction} \leq 1 \]

\[ 500 \leq \text{flame temperature (K)} \leq 2500 \]
0.1 ≤ TCWV (g/m²) ≤ 10

We found that the inverse of the Jacobian matrix actually exists and retrieved parameters are within predefined acceptance ranges for the 83.26% of the analysed spots (around $3 \times 10^4$ events). In the remaining 16.74% we found that the SWIR reflectance values were always below 0.2, i.e., values very close to the noise limit of the SWIR detection channel. The improvement of the efficiency of the inversion scheme, along with a rigorous treatment of the IG and of the uncertainties, is under development and will be the subject for further studies.

[6] North Sea Effective Flame Temperature and Size

The ALGO3 fire parameters for the North Sea off-shore platforms have been estimated and analysed adopting the method described in the previous section.

In order to verify the assumption related to the absence of contribution from “just burnt” pixel fraction, the difference between measured brightness temperatures at 3.7 and 12 μm (‘DTB’) has been plotted vs. the measured 1.6 μm reflectance (we here use direct measurements without conversion into radiance). To a first approximation, the DTB difference is expected to be in one-to-one correspondence with the SWIR reflectance as the only “extra” contributions to the MIR-TIR radiance difference should come from the active flames. In this we assume that the TB at 12 μm is a good estimate of the background temperature. Results of this exercise are shown in Figure (8), where the upper left panel refers to the North Sea, the upper right to the Borneo Region, the lower left to India and the lower right to Canada.
Figure 8 MIR-TIR brightness temperature differences (DTB) vs. SWIR reflectance.

Upper left panel: North Sea; upper right panel: Borneo Region; lower left panel: India; lower right panel: Canada. The analysed data refer to the 1995-2010 period.

As can be easily seen from Figure (8), a clear relationship between SWIR and MIR-TIR radiance difference is verified for the North Sea only, while in the other cases the contribution of the burnt fraction of the pixel is evident, most of the detected spots being relative to large sized biomass fires (forest and/or agricultural). In these cases the MIR-TIR difference can be as high as 40 K, even if the SWIR reflectance values are extremely small. This obviously comes from the contribution of the “just burnt - still hot” surfaces within the ATSR pixel, which is evidently not present for the gas flaring spots relative to off-shore platforms. The presence of the radiative contribution emitted by the ‘just burnt’ fraction of the ATSR pixel (along with the large number of saturated MIR radiances) impairs the adoption of the above described method for the...
evaluation of flame parameters for wild fires over land, as the number of unknowns increases drastically and, hence, the inversion problem is ill-posed. The estimated fire temperatures for the North Sea are displayed vs. the related fire fractions in Figure (9) (red dots) along with the two sensitivity limit curves (thick lines) for the ATSR SWIR (lower curve) and MIR (upper curve) channels. In practice, any combination of $T_f$ and $f_f$ resulting in a point located below the SWIR curve will generate an amount of radiation too low to be detected by the SWIR channel, while for any point placed above the MIR curve the resulting MIR radiance will exceed the saturation value of the MIR channel (312 K).

Figure 9 Fire temperature vs. fire fraction for the North Sea flaring sites. The thick curves represent the SWIR (lower) and MIR (upper) fire detection limits for ATSR

The histogram of retrieved $T_f$ is reported in Figure (10). The modal value is 1300 K with a standard deviation of about 100 K. As a matter of fact, what is estimated here is the “effective” temperature of the flame, a sort of “average” value, thus including,
among others, the effect of local radiation absorption from CO$_2$ and H$_2$O, and the possible shading effect of the smoke plume.

Figure 10 North Sea fire temperature histogram

Figure 11 North Sea fire fraction histogram
The histogram of retrieved $f_f$ is reported in Figure (11). The estimated fire size is found to range between 1 and 40 m$^2$ ($10^{-6} < f_f < 4 \times 10^{-5}$). A small amount of the fire fractions ranges between 0.1 and 1 m$^2$; these values must be considered with caution and ongoing investigations are aimed to assess their reliability. Finally, the retrieved area is the horizontal cross section of the tri-dimensional flame volume. To a rough approximation we can consider flaring flames to be spherical so that the effective flame surface would range between 4 and 160 m$^2$. These values are in full agreement with expected gas flaring parameters.


The estimate of the combustion efficiency is of crucial importance for the determination of the quantities of chemical species produced in the combustion, and one of the key parameters are the flame size and the flame temperature, which could, in their turn, depend on meteorological variables (Beychok, 2005). The parameter which best summarises the flame characteristics is the “radiative heat loss”, i.e. the radiative power of the flame.

Keeping in mind the degree of approximation of our assumptions, the “radiative losses” can be now estimated for the North Sea flaring platforms using the ATSR radiances as inputs. The definition adopted here for the “radiative heat loss” ($R_{HL}$) is the following (Beychok, 2005):

$$ R_{HL} = A_f \cdot \sigma \cdot T_f^4 $$

(21)

In (21) the flame emissivity is set to 1 and:

- $A_f = \text{flame area [m}^2\text{]}$
- $\sigma = \text{Stefan-Boltzmann constant (5.67 \times 10^{-8} \text{ J s}^{-1} \text{m}^{-2} \text{K}^{-4})}$
According to Beychok, the law of energy conservation relating the heat of combustion within the flame to the sensible heat gains and the radiative losses is:

\[ H_f = S + R_{HL} \]  \hspace{1cm} (22)

Where:

a) \( H_f \) = the rate of heat released from combusting gases within the flame

b) \( S \) = rate of sensible heat gain by air

c) \( R_{HL} \) = rate of radiative heat loss by flame

The quantity \( S \) can, in turn, be expressed as follows:

\[ S = \frac{C_p \cdot \rho_f \cdot V_f \cdot (T_f - T_0)}{t_f} \]  \hspace{1cm} (23)

In (23) \( C_p \) is the heat capacity of air at constant pressure. The quantity \( S \) is a function of: a) the air density at flame temperature \( \rho_f \), b) the volume of the flame \( V_f \), c) the fire temperature \( T_f \), d) the ambient temperature \( T_0 \), and e) the time it takes air to pass through the flame \( t_f \) which is, in its turn, dependent on the local wind speed. This implies that the environmental parameters, such as the wind speed and the air temperature, play a fundamental role in the flaring processes.

The combustion efficiency ‘\( E \)’ is defined as follows (Beychok, 2005):

\[ E = 100 \cdot \frac{H_f}{H} = 100 \cdot \frac{S + R_{HL}}{H} \]  \hspace{1cm} (24)

In (24) \( H \) is the heat that would have been released if the combustion of all flare gases went to completion. The following relation holds:

\[ H = \sum H_i \cdot Q \]  \hspace{1cm} (25)

where \( H_i \) is the heat content of the \( i^{th} \) flared gas (20÷80 MJ m\(^{-3}\), depending on the flaring gas) and \( Q \) is the release rate of the gases. The latter can be expressed as:

\[ Q = \frac{\pi \cdot D_0^2 \cdot V}{4} \]  \hspace{1cm} (26)
In equation (26) $D_0$ is the stack diameter ($\approx 0.2$ m) and $V$ is the stack exit velocity $(2 \div 20$ m s$^{-1}$). By definition, complete combustion is achieved if $E = 100\%$.

From equations (22-26) it is evident that most of the parameters involved in the evaluation of the combustion efficiency cannot be estimated from space. Nevertheless, the estimate of the radiative losses is indeed achievable, thus providing valuable information on the combustion processes.

The histogram of $R_{HL}$ values estimated using the $T_f$ and $f_f$ values retrieved from ATSR measurements is shown in Figure (12) (units $10^6$ [J s$^{-1}$]).

If, for instance, we assume $D_0 = 0.2$ m, $V = 2 \div 20$ m s$^{-1}$, and $H_i = 34$ MJ m$^{-3}$ for the combustion of methane (Beychok, 2005), then equation (25) provides estimates of $H$ ranging between 2 and 20 MJ s$^{-1}$. The estimated values of $R_{HL}$ from ATSR measurements range between 0.5 and 10 MJ s$^{-1}$, i.e. they are of the same order of magnitude of theoretical values.
This result indicates that, if the values of the parameters characterising the stack of the platforms are known (e.g. flared gas, stack diameter, exit velocity) it would be possible to provide rough estimates of the combustion efficiency from remotely sensed data.

[8] Conclusions

A method for monitoring the night-time gas flaring activity from off-shore platforms using SAR and ATSR measurements has been presented and results discussed in detail. The ability of SAR to detect highly reflecting targets over the sea surface has been exploited to unambiguously detect drilling platforms in the North Sea, chosen as target testing area. The ATSR night-time SWIR hot spots have been used to detect flaring activity thanks to their peculiarity of being due to active flames only. The characteristics of off-shore flaring, i.e. small size and high temperature flames, allowed for the development of a simple inversion technique aimed at the estimate of flame parameters from space using ATSR SWIR, MIR and TIR measurements. An attempt to evaluate the flaring efficiency from satellite data has been discussed and preliminary results presented. The flaring activity in the North Sea has been analysed for the 1991-2010 time period, and results show a negative trend which is in very good correlation with the oil production data provided by EIA for the same area.

The aim of this study is to demonstrate that: a) the synergy between active (SAR) and passive (ATSR) instruments can be exploited for gas flaring monitoring of off-shore platforms in a relatively simple way; b) the proposed method, in this work applied to the North Sea area, can be extended to any area of the world as the processing steps are fully automatic and do not require the tuning of any free parameter.
[9] Acknowledgments

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[10] References


