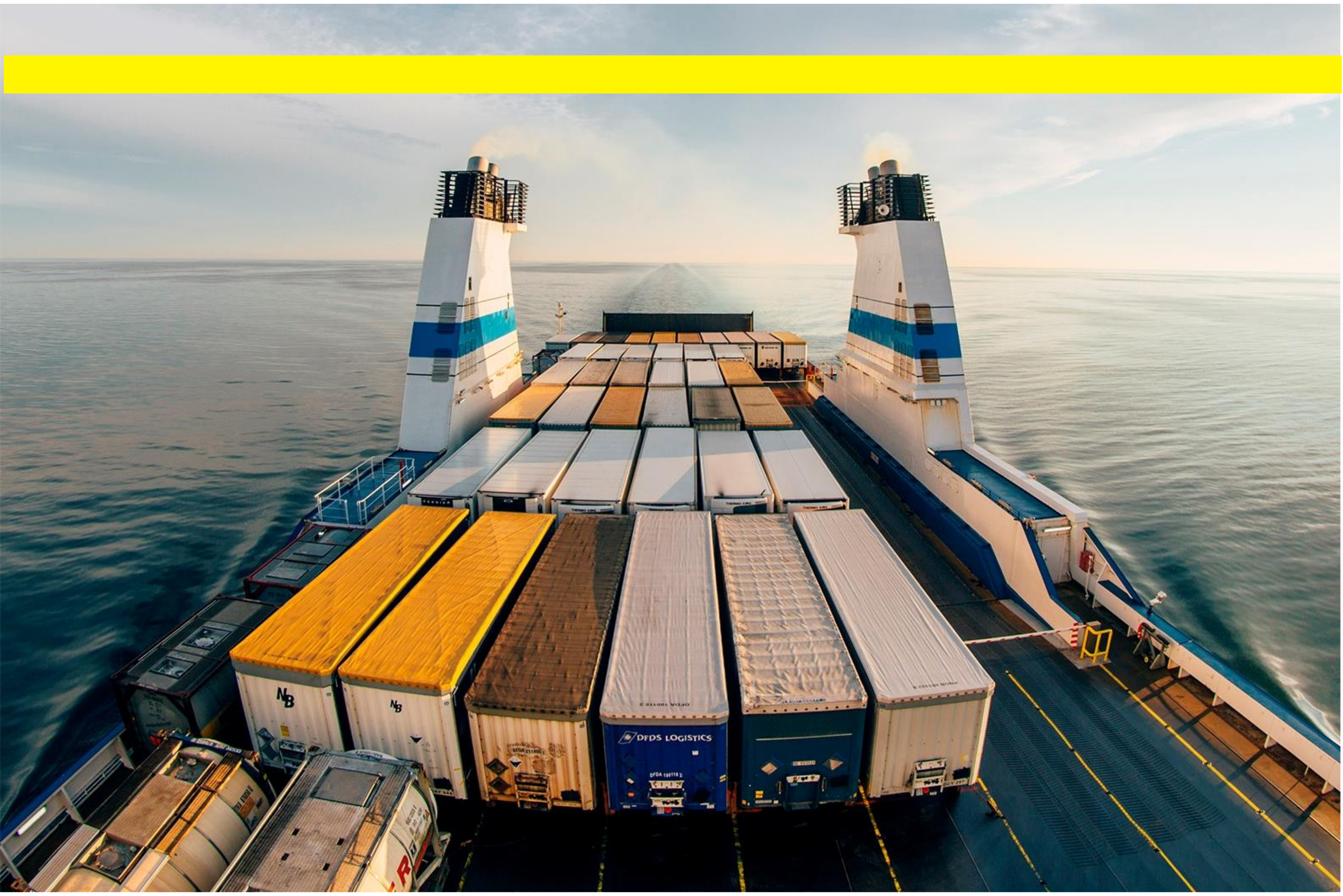
CompMon

Compliance monitoring pilot for Marpol Annex VI



4.5 Report of the newest satellite earth observation capabilities for CompMon purpose

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Abstract
Satellite-based instruments are capable of detecting signals from ship emissions in the trace gases measurements, mostly using nitrogen dioxide (NO_2) atmospheric concentration retrievals. Recent studies based on satellite observations showed a growing share of the shipping contributions to the overall European NOx emissions since 2005, which suggest the need for the shipping sector to implement additional measures to reduce pollutant emissions. Future satellite missions will improve the capability of deriving information on ship emissions from space, by improving the spatial resolution, the signal-to-noise ratio and the amount of available measurements in Europe. New instruments will also improve the capability of detecting signal from other gases such as SO_2, which has been detected only once (in the Red Sea) with the current instrumentation.

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1. State-of-the-art of satellite-based observations for ship emission monitoring

Satellite-based instruments have been capable of detecting signals from ship emissions in the trace gases measurements, mostly using nitrogen dioxide (NO_2) atmospheric concentration retrievals. Satellite-based NO_2 retrievals have been available since 1996 from several instruments (GOME, SCIAMACHY, OMI, GOME-2), measuring the solar light backscattered from the Earth's surface. These instruments provide information on the atmosphere once a day typically, in the morning or in the afternoon, depending on the polar orbit of the satellite. Beirle et al. (2004) first discovered signatures of ship emissions over the Indian Ocean using GOME tropospheric NO_2 columns. Later on, several studies (e.g., Richter et al., 2004, 2011; Marmer et al., 2009) reported signature of ship emissions in NO_2 concentrations from successive satellite instruments, characterized by improved spatial resolution and signal-to-noise ratio. The global economical cycle and satellite-derived NO_2 trends (1996-2010) over the major international shipping lanes have been compared by de Ruyter de Wildt et al. (2012). They found that the NO_2 signal over four major shipping lanes (Mediterranean Sea, Red Sea, Indian Ocean and South Chinese Sea) displays a large increase of 62–109% between 2003 and the summer of 2008 and a sharp decline of 12–36% afterwards, corresponding to the global economic recession of 2008-2009.

Currently, the best NO_2 retrievals are performed by the Ozone Monitoring Instrument (OMI), with 13x24 km2 spatial resolution at nadir and 13x128 km2 at the edges of the field of view. Vinken et al. (2014) used the GEOS-Chem model to produce a ship emission top-down inventory (2005-2006) based on OMI tropospheric NO_2 products in four European seas, including the Baltic Sea. They found increased emissions for the Baltic Sea ship track, with emission totals 131% higher than existing emission databases (EMEP). Furthermore, they stressed the potential of top-down satellite-based emission estimates in providing timely information on ship emission, more quickly than the traditional bottom-up emission estimates (usually only available with several years of delay). Ialongo et al. (2014) showed similar year-to-year variability between modeled ship emission data and OMI NO_2 concentrations in the Baltic Sea, with a drop in the year 2009, confirming the effect of the economic recession. Boersma et al. (2015) pointed out that ships are going slow in reducing their NOx emissions. They analysed the changes in 2005–2012 European ship emissions inferred from satellite OMI measurements. Their results indicate that the practice of 'slow steaming', i.e. the lowering of vessel speed to reduce fuel consumption, has been implemented since 2008 and can be detected from space. In spite of the implementation of slow steaming, the share of the shipping contributions to the overall European NOx emissions increased since 2005. This suggests a need for the shipping sector to implement additional measures to reduce pollutant emissions similarly to what was achieved for the road transport and energy sectors in Europe.

Recently, Theys et al. (2015) presented a new algorithm for sulphate dioxide (SO_2) retrieval from OMI measurements, which shows improved capability in capturing weak SO_2 sources, for example, detecting shipping SO_2 emissions in long-term averaged data over the Red Sea.

2. Assessment of requirements to the satellite observations for compliance monitoring of SO2 emission from ships.

As shown in the state-of-art analysis, the SO_2 and NO_2 concentrations originating from ship emissions can in principle be seen by the existing instruments. However, these require long time averaging and are sufficiently accurate only in remote pristine areas, where impact of other pollution sources is minimal. These features substantially limit the applicability of the satellite remote-sensing to the compliance monitoring, especially of SO_2: the bulk of the regionally-imposed SECA and NECA are in the vicinity of large cities. As seen from the Figure 1 (presenting the SILAM model simulations with the setup outlined below), in such regions even busy ship lanes are not immediately evident from the total-sulphur load map. This is despite the differences between the emissions of the high- and low-sulphur content scenarios can reach a factor of several times.

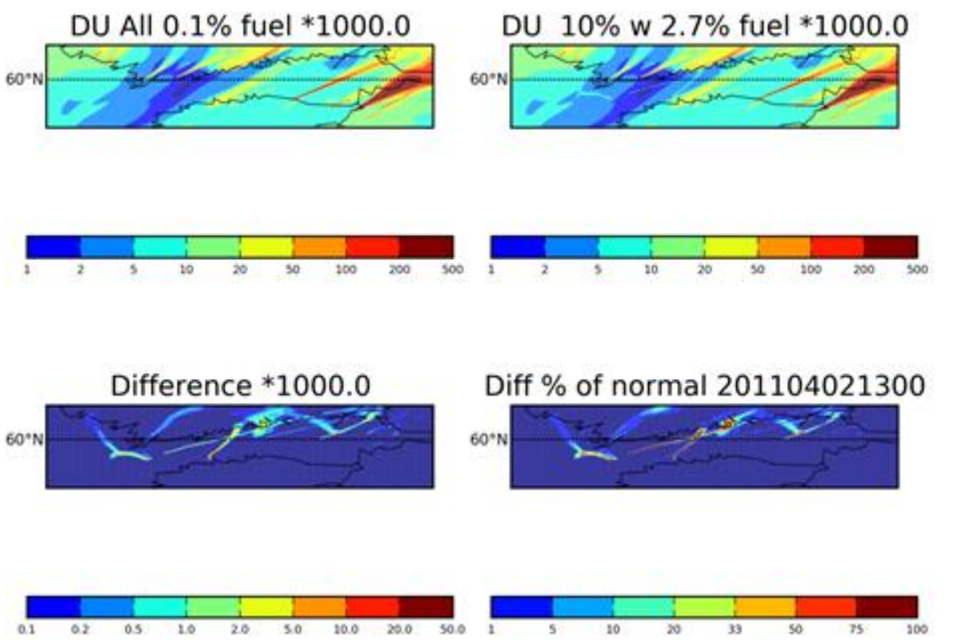

Figure 1. SO_2 total column load, mDU, screenshiot 7:00 2.4.2011. Upper row: scenario of 0.1% of sulphur fuel content (upper left) and 2.7% (upper right). Lower row: absolute (lower left) and relative (lower right) between the scenarios.

The example of the Figure 1 illustrates the key challenge for the ship emission monitoring: to decipher the ship-induced pollution from that of other sources. Since the characteristic total emission contribution from ships is around 10% (differ from region to region), this signal is mostly well within the uncertainty of both observations and models.

One can however address the disturbance of the SO2 background level due to a moving point source, such as a large vessel. Evaluation of such disturbance is a less uncertain task but it requires sufficient contrast of the satellite image. The image should be sharp enough for the model to recognize and follow the individual ship plumes and trace them back to the originating ships (solving the inverse problem). For such task, the key parameters of the instrument are its sensitivity, level of noise, and spatial resolution. The model experiment described below aims at setting the (rough) requirements to these parameters.

The requirements to the satellite observations were derived from the modelling experiment performed with the System for Integrated modeLling of Atmospheric coMposition (SILAM, http://silam.fmi.fi, (Sofiev et al. 2015; Soares et al. 2013; Simpson et al. 2014)).

The model experiment was made as follows. The SILAM model was run with 1km horizontal and 30m vertical spatial resolution and time step of 1 minute. It took into account emission from all European sources and two scenarios of ship emission in Gulf of Finland: full compliance to the 0.1% sulphur content requirement and 90% compliance (10% of ships use 2.7% of the Sulphur content). For both scenarios, the STEAM ship emission from actual ship traffic was employed to generate the realistic temporal and spatial distributions of the ship emission. The STEAM emission had 1km spatial resolution and 6 minutes time step.

The output of the model simulations was averaged over 30 min time interval and over grids with cell size of 1 km (the native resolution of the computations), 2 km, 4 km, 8 km, 16 km and 32 km. The primary output variable was total sulphur column load – the quantity most-closely representing the one observed by the nadir-looking satellites. To maintain generic assessment, we did not imposed any averaging kernel, which is satellite-specific. As a side effect, this resulted in certain over-estimation of the SO2 signal because all current satellites have lower sensitivity towards the boundary layer and the surface.

The Figure 2 shows a screen-shot of the simulations: the difference between the SO2 column load between the scenarios, as seen at different resolutions. As seen from the screen-shot, the strength of the signal expectedly get much lower at lower resolutions, also loosing shape and other fine-scale features that may help identifying the source of pollution. Qualitatively, the resolution better than 4-8 km, would potentially make the observations usable for the compliance monitoring purposes.

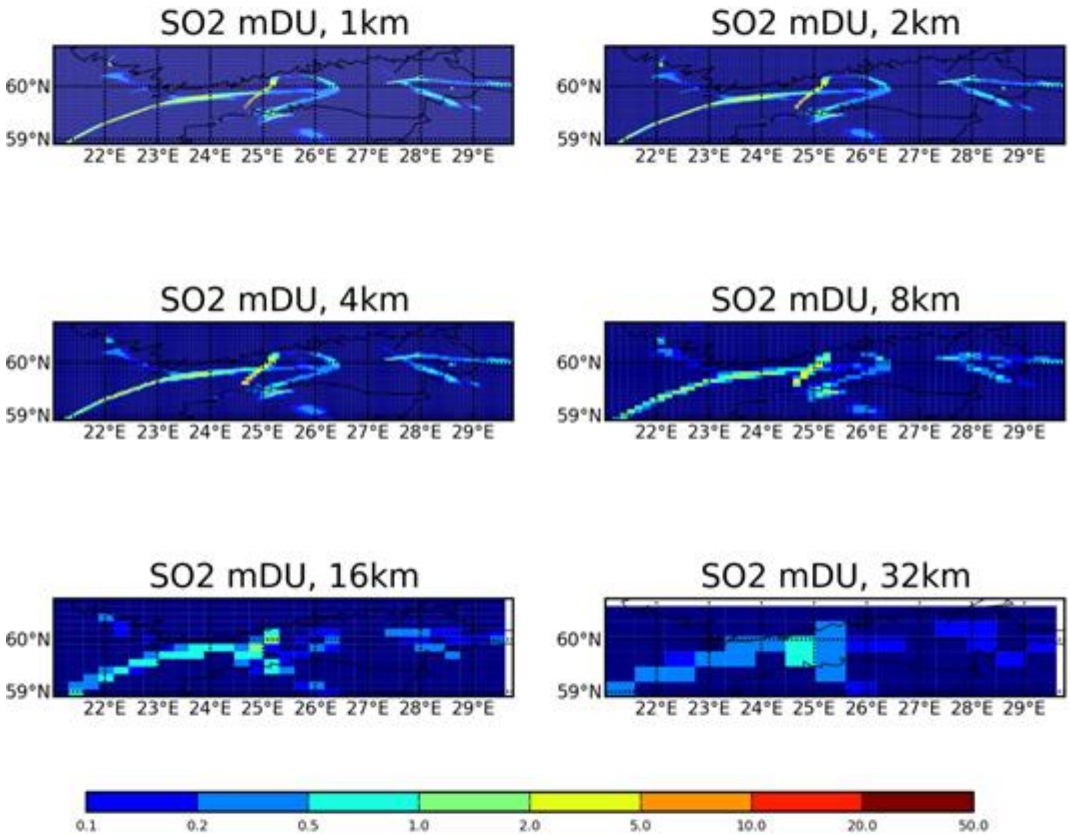

Figure 2. Example of the difference between the full- and 90%- compliance scenario for different spatial resolution, [mDU]

The model results can be analyzed from a different prospective: already detection of presence of an outlier can be a valuable piece of information, which can trigger more in-depth inspection of the ships ceiling in the suspected area. However, the satellite should be sensitive enough to notice the exceedance of the expected pollution level. The above model experiment allows establishing this relation. In Figure 3, the fraction of the grid occupied with the above-threshold SO2 plumes is related to the threshold itself, computed for the above spatial resolutions. From the chart, one can see that, for instance, the 16-km grid does not have any single grid cell with more than 5 mDU difference between the scenarios – and a practically relevant fraction of 0.1% of the map is only above the threshold of 0.5 mDU. These numbers are way below any reachable noise level in the satellite retrievals. The resolution of 1 km, being out of reach for current SO2 observing satellites has noticeable fraction of grid cells with the anomaly as high as 0.01 DU, which is a more feasible goal for future satellite sensors.

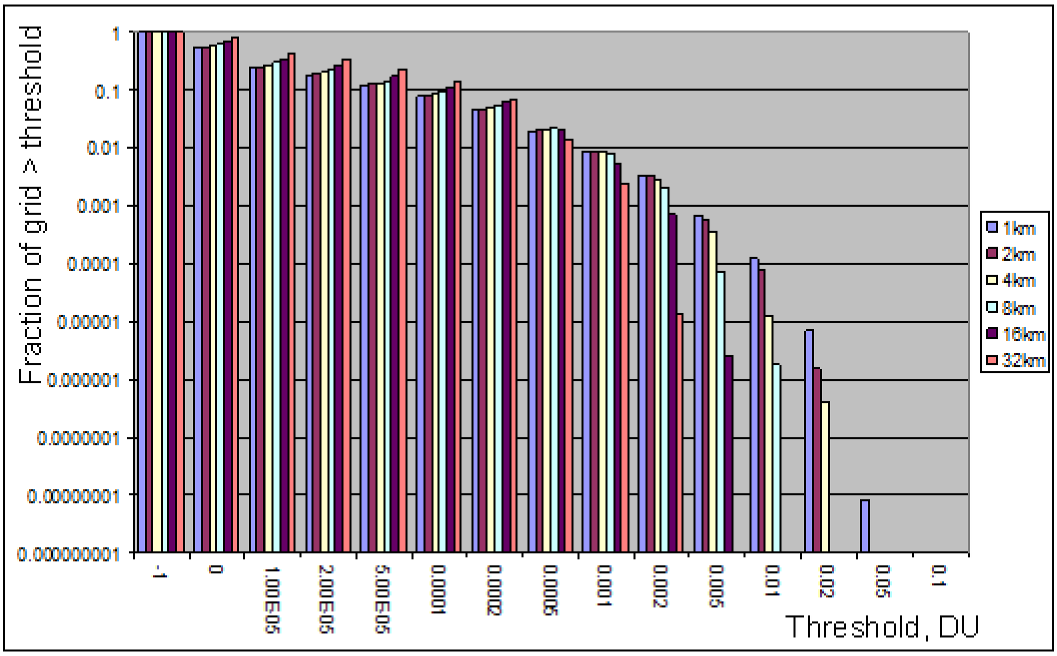

Figure 3. Relation of the fraction of the grid cell with abnormal SO_2 load, the exceedance threshold and the spatial resolution of the observations.

3. Potential of future satellite instruments for ship emission monitoring

3.1 Satellite-based monitoring of SO2 emissions

The SILAM-model based analysis of the hypothetical SECA violations in the area of Gulf of Finland showed that the current nadir-looking satellite SO2 products have way too coarse spatial resolution and too high detection and noise levels to be usable for the compliance monitoring purposes. A rough estimate of the required resolution and sensitivity has been made demonstrating an inverse relation between the spatial resolution and sensitivity/noise requirements. A target for the future sensors may be 1 km resolution of the retrieval grid and 10 mDU of the sensitivity and the noise levels. Boosting the resolution, one can relax the requirements to the sensitivity and noise – and vice versa.

3.2 Satellite-based monitoring of NO2 emissions

The main limitations in the existing shipping NO_2 products are related to the instrument's signal-to-noise ratio, the spatial resolution and the effect of the cloud contamination. Upcoming satellite instruments such as TROPOMI on Sentinel 5 Precursor (on a polar orbit) and the geostationary Sentinel 4 (S4) will provide improvements concerning all three aspects. The Figure 4 below illustrates how the pixel size for TROPOMI (7x7 km2) and S4 (8x8 km2) will improve compared to previous instruments.

Instrument	GOME-2	OMI	TROPOMI	Sentinel-4
Pixel Size (km²)	40×80	13×24 at nadir 24×128 at edge	7×7	8×8

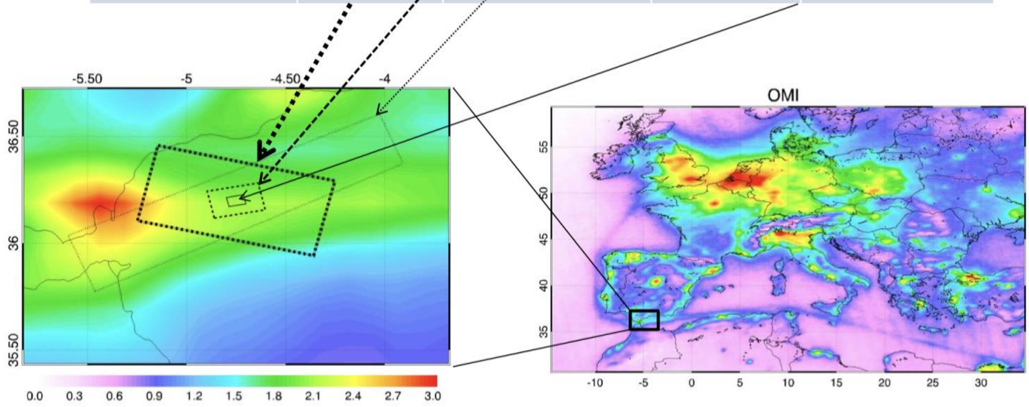

Figure 4: OMI NO2 tropospheric column mean field and zoom on the Mediterranean Sea shipping lane south of Spain.

The improved spatial resolution will reduce the error level of NO_2 columns by a factor of 2 for TROPOMI (compared to OMI). Furthermore, because S4 will operate on a geostationary orbit, it will provide about 10 measurements a day (compare to TROPOMI daily measurements) over Europe. This will further reduce the noise for example in the monthly mean fields by a factor of 3 for S4, in comparison with TROPOMI. In addition, the reduced spatial resolution will also increase the amount of cloud-free scenes and available NO_2 retrievals from TROPOMI especially over Northern Europe and during autumn-winter seasons. For S4, the number of cloud-free pixel will be even larger (5-10 times more than TROPOMI) but it will not cover the most northern areas in Europe, e.g. the northern Baltic Sea, due to fact that the geostationary orbit does not cover the polar region. More information on the added value of upcoming satellite mission in ship emission monitoring are available for example here: http://uv-vis.aeronomie.be/meetings/documents/20150424_hyu.pdf

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