Using Satellite Observations to Measure

How accurately can the emissions from a coal-fired power plant be measured from space? Might it one day be possible for a satellite to determine whether a plant is in compliance with emission regulations? This article reviews the current capability of space-borne instruments to detect and quantify power plant emissions and comments on the possibility of enhanced capability in the next five to ten years.

On July 15, 2004, NASA launched the Aura satellite from Vandenberg Air Force Base. It assumed a sun-synchronous orbit at a height of 438 miles with daily global coverage at an equator crossing time of 1:45 p.m. local time. Aura carried a variety of instruments, and one of the most successful of them has been the Ozone Monitoring Instrument (OMI), developed by a Dutch/Finnish team. OMI is an ultraviolet/visible spectrometer that measures the solar radiation backscattered from Earth in the spectral range of 270–500 nm. Trace gases absorb some of this radiation at characteristic wavelengths, and the amount of the absorption can be related to the concentration of the trace gas in the column of air through which the radiation passes. The principal gases that can be detected by OMI are ozone (O₃), nitrogen dioxide (NO₂), sulfur dioxide (SO₂), and formaldehyde (HCHO). We should stress that...
OMI is not the only satellite-borne instrument with these features; three other instruments, GOME-1 on the European ERS-2 satellite (1995–2003), GOME-2 on the European METOP-A satellite (2006–present), and SCIAMACHY on the European ENVISAT (2002–2012), have or have had similar capability; however, what follows in this article focuses on OMI retrievals between 2005 and 2011.

Processing of the raw instrument measurements is a complex procedure involving, among other things, fitting to a reference spectrum, conversion from slant column density to vertical column density, partitioning of stratospheric and tropospheric components, and adjustments for surface reflectivity, surface topography, and the presence of clouds. At the end of this sequence of adjustments, an estimate of the number of molecules in a column of air above Earth’s surface is obtained. OMI has high spatial resolution with a footprint of up to 13 km (along track) × 24 km (across track). It is easy to see, therefore, that if the column of air is centered over an isolated point source of emissions, the OMI signal will be representative of all the molecules within an area of 13 km × 24 km around the source. If there are no other significant emissions in that area, if no molecules enter the area from outside, and if chemical conversion within the area is
Most recently, 55 of the more remote power plants in the United States, located away from large built-up areas, were studied over the period 2005–2011 by Duncan et al., who concluded that it is practical to use OMI NO2 data to assess changes of emissions from power plants that are associated with the implementation of emission control devices (ECDs), though careful interpretation of the data is necessary. They showed that there is a clear response of OMI NO2 data to NOx emission reductions from power plants associated with the implementation of ECDs, though this response varied among facilities. They discussed some of the causes of this variability, which include the magnitude of a facility’s NOx emissions, seasonal variation of the NOx lifetime, proximity to urban areas, changes in regional NOx levels, lack of statistical significance, and retrieval issues.

The main challenge for estimating emissions from power plants using NO2 column data over the last decade is that emissions from mobile sources, the primary source of NOx emissions, have also decreased substantially. Duncan et al. found that OMI data indicated a 30–40% decrease in NO2 levels for much of the eastern United States, which is slightly larger than the decrease indicated by Air Quality Monitoring System (AQS) surface site data. Consequently, one must account for any trend in NO2 associated with changes in mobile emissions when estimating emissions from power plants. Figure 1 shows the change in OMI NO2 columns minimal, then the OMI signal ought to be closely related to the emissions of the point source. Hence, we can see the potential usefulness of satellite observations in estimating emissions.

**NO2 Emissions Data**

By far the strongest absorption by emitted pollutant species is that caused by NO2. For this reason, initial applications of satellite observations to U.S. power plant emissions focused on nitrogen oxides (NOx) emissions and their trends. Three major studies were published, covering all plants in the eastern United States for the period 1999–2005, 13 isolated power plants in the western United States in 2005, and 23 large plants throughout the country for the period 2005–2011. In these studies, various NO2 retrievals were compared with modeled NO2 columns and with NOx emissions from Continuous Emissions Monitoring Systems (CEMS) stack measurements. Agreement between satellite and ground-level measurements was generally good, and it was possible to demonstrate that plant NOx emissions had declined over time as plants complied with the requirements of the 1998 NOx SIP Call and the 2005 Clean Air Interstate Rule (CAIR) by using low-NOx retrofit technologies. Even more dramatic breakthroughs were possible in China and India, where large new power plants with high emission rates had been constructed since the satellite instruments commenced operation—meaning that it was possible to examine the space-based signals with and without the plant operating.
over the eastern United States from 2005 to 2011. While large decreases in NO₂ levels occurred almost everywhere, some of the largest changes occurred in the Ohio River Valley, where many coal-fired power plants are located.

SO₂ Emissions Data

The other major species related to power plant emissions that can be detected by OMI is SO₂. However, absorption by SO₂ mainly occurs at shorter wavelengths where much stronger ozone absorption exists, and therefore only relatively large SO₂ sources can be seen from space. Early work focused on the largest natural and man-made sources, such as volcanoes and metal smelters. Because SO₂ emissions from U.S. power plants are relatively low after compliance with the acid rain provisions of the Clean Air Act Amendments of 1999, attention was initially focused on China, where many new power plants have large SO₂ emissions from uncontrolled coal burning. Li et al. showed that it was not only possible to examine newly constructed SO₂-emitting power plants with OMI, but it was also possible to study the compliance progress of plants scheduled to install flue-gas desulfurization (FGD) equipment under government rules between 2005 and 2008.

Figure 2 shows results for four of the power plants in the Inner Mongolia region of China that were studied by Li et al., but using updated SO₂ and NO₂ retrievals. These plants are relatively far away from other large point sources and urban centers. We show the relative changes in OMI SO₂ and NO₂ retrievals, as well as in SO₂ emissions calculated from coal-use statistics, with and without FGD units, all normalized to the year 2006. The OMI NO₂ trends (green lines) confirm that each plant operated continuously throughout the period and tended to increase its level of operation and NOₓ emissions. The blue lines show OMI SO₂ trends. For two plants, Tuoketuo and Huhehaote, the OMI SO₂ trend is in good agreement with calculated SO₂ emissions, confirming the start of FGD operation in 2006, as was required by government regulations. For the other two plants, Shuozhou complied about one year early (2006 instead of 2007), whereas the Datong plant...
delayed compliance by at least two years (2007 instead of 2005 or earlier). In a country like China, where there are many remote plants only loosely controlled by the Ministry of Environmental Protection, the capability to detect compliance from space is clearly valuable.

**Oversampling Technique**
A powerful technique to improve the OMI detection limit is called "oversampling," in which the original OMI data at 13 km x 24 km resolution are resampled at finer resolution (say, 2 km x 2 km) around the source. This reduces noise and enhances weak signals, enabling smaller sources to be studied. The oversampling technique was originally developed for NO$_2$\textsuperscript{21-24} and later adapted for SO$_2$,\textsuperscript{25,26} resulting in the ability to quantify a reduction in SO$_2$ emissions from power plants in the Ohio River Basin of approximately 40% between 2005/2007 and 2008/2010.\textsuperscript{26} With oversampling enhancements, it has been estimated that OMI can detect SO$_2$ emission sources larger than 70,000 tons/yr,\textsuperscript{26} recently lowered to 50,000 tons/yr in India.\textsuperscript{20}

**Future Work**
Despite the demonstrations of good agreement between OMI measurements and ground-level emission estimates, particularly of NO$_2$, there remain issues to be resolved. The tool is not yet developed to the point where it can be reliably used for regulatory purposes. As discussed above, the many factors influencing the strength of the OMI absorption signal make it difficult to assemble a statistically representative observational dataset indicative of emission strength. More work is needed to develop quantitative relationships and characterize uncertainties.

One of the shortcomings of OMI is that it only yields one observation per day, due to being in sun-synchronous orbit. What would dramatically enhance its utility is if it were in geostationary orbit over North America. After a great deal of support and promotion by the atmospheric science community, there are now considerable prospects for such a capability in the future. Two new NASA satellite missions are on the drawing board that would study tropospheric gases and aerosols from

Figure 2. OMI NO$_2$ and SO$_2$ columns in the vicinity of four power plants in Inner Mongolia, China (center); and normalized OMI columns and SO$_2$ emission trends calculated from coal-use statistics with and without FGD (outer) over the period 2005–2008.
geostationary orbit above North America: the Geostationary Coastal and Air Pollution Events (GEOCAPE) mission27 and the Tropospheric Emissions: Monitoring of Pollution (TEMPO) mission.28 Launch dates are likely to be in the 2017–2020 timeframe or even later, depending on funding availability. The great advantage of these satellites is that they would provide continuous, continental-scale mapping of pollutants at something like hourly, 4 km x 4 km resolution. The potential to better characterize point-source emissions would be enhanced dramatically once these instruments begin to return data. em

References
17. Carr, S.A.; Prata, F.; Satellite-based constraints on the regional scale mapping of pollutants at something like hourly, 4 km x 4 km resolution. The potential to better characterize point-source emissions would be enhanced dramatically once these instruments begin to return data. em

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