An Overview Of The Ozone Mapping And Profiler Suite (OMPS) And Its Science Products

Laura Dunlap

A scholarly paper in partial fulfillment of the requirements for the degree of

Master of Science

December 2015

Department of Atmospheric and Oceanic Science, University of Maryland
College Park, Maryland

Advisor: Dr. Russell Dickerson

Table of Contents

Abstract

The Joint Polar Satellite System (JPSS) is NOAA’s answer to a need for continuous Earth monitoring from a polar-orbiting satellite. Such satellites provide data used in weather forecasts, climate models, and environmental monitoring, among many other applications. One such application is ozone monitoring. The Ozone Mapping and Profiler Suite (OMPS) on JPSS is used for this task. OMPS has two nadir detectors and one limb detector that can measure total column ozone content and vertical ozone profiles. In addition to ozone, OMPS has the capability of detecting other trace gases such as sulfur dioxide, formaldehyde, and nitrogen dioxide. This paper reviews the current state of the OMPS instrument and products as well as potential improvements for the future.

Acknowledgements

I would like to thank my advisors Dr. Russell Dickerson and Dr. Can Li for leading me through my master’s degree. I would also like to thank the NOAA JPSS Program for supplementing my knowledge of atmospheric science satellites and NASA for funding my work. Finally, I would like to thank my friends and family who have supported me throughout this adventure.

List of Tables

List of Figures

Comment [RD1]: Subs everywhere

Chapter 1. Introduction

The National Oceanic and Atmospheric Administration (NOAA) revolves around the ideas of Science, Service, and Stewardship. These tenants make up the NOAA mission: to understand the changes in weather, climate, and oceans, and to be able to share this information with others [Goldberg et al., 2013]. One way that NOAA can support their mission is through the use of polar-orbiting satellites. Such satellites pass over the same area on the globe at the same time every day, giving uniform data collection. Polar-orbiting satellites are invaluable to Numerical Weather Prediction (NWP) as they provide the majority of the data for models and data assimilation. For example, 85% of the input to the National Centers for Environmental Prediction (NCEP) models comes from polar-orbiting satellites [Goldberg et al., 2013]. In addition, such satellites are used in environmental, climate, and hazard monitoring.

The Joint Polar Satellite System (JPSS) is NOAA's answer to the need for a continuous data stream from polar-orbiting satellites. The first satellite in the JPSS program, the Suomi-National Polar-Orbiting Partnership (SNPP), was launched on October 28, 2011 [Wu et al., 2014]. JPPS-1 is scheduled to follow in FY2017, and JPSS-2 in FY2022 [Goldberg et al., 2013]. SNPP and the JPSS satellites are planned to have four common instrument suites: the Advanced Technology Microwave Sounder (ATMS), Cross-track Infrared Sounder (CrIS), Visible Infrared Imaging Radiometer Suite (VIIRS), and Ozone Mapping and Profiler Suite (OMPS). See Figure 1 for an illustration of the SNPP satellite.

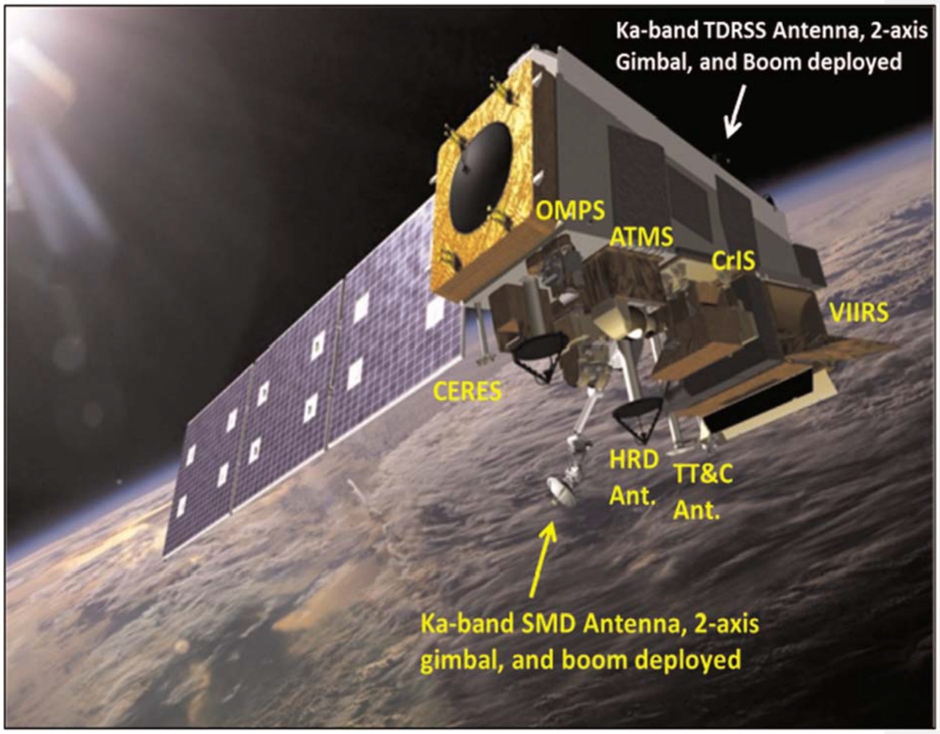


Figure 1. Illustration of SNPP satellite.

Together these instruments make up a complete satellite suite able to produce data for weather forecasting, climate prediction, air quality monitoring, and much more.

This review will focus on the OMPS instrument and the scientific advances made possible by the availability of OMPS data. OMPS has a primary role of measuring ozone. Stratospheric ozone is important in preventing harmful ultraviolet (UV) radiation from reaching the Earth's surface. Therefore, it is important that the integrity of the ozone layer be monitored in order to fully understand UV exposure. On the other hand, ozone in the troposphere is a harmful greenhouse gas pollutant that is hazardous to human health and plays a part in global warming. Comprehensive ozone monitoring is paramount in creating plans to reduce ozone pollution and improve human health. OMPS has the complicated job of measuring both the helpful stratospheric ozone and the harmful tropospheric ozone. In addition, OMPS has the ability to detect other trace gases, as well. This paper will summarize the state of the science on such issues. Section 2 will provide an overview of the instrument and product specifications. Section 3 contains examples of OMPS data applications. Section 4 reviews the future of the OMPS instrument and data products followed by a summary and conclusion in section 5.

Chapter 2. OMPS Instrument & Product Specifications

2.1 Nadir Detectors

The SNPP OMPS instrument was built by Ball Aerospace & Technologies Corporation [Dittman et al., 2002]. It consists of three detectors with their own Charge-Coupled Device (CCD) focal plane arrays (FPA) [Flynn et al., 2004]. Two of the detectors make nadir measurements and share a telescope. The first of these is called the Nadir Mapper (NM) whose purpose is to collect total column (TC) ozone concentration. The NM has a 50 km x 50 km horizontal spatial resolution at nadir with a spectral resolution of 1 nm full-width half maximum (FWHM) between 300 nm and 380 nm. The second nadir detector is referred to as the Nadir Profiler (NP). The NP collects data to create a vertical ozone profile from 0 to 60 km through the atmosphere. On SNPP, NP has a horizontal spatial resolution of 250 km x 250 km at nadir and a spectral resolution of 1 nm FWHM from 250 nm to 310 nm [Flynn et al., 2004].

2.2 Limb Detector

The third detector is called the Limb Profiler (LP). This sensor will not be flown on JPSS-1 [Goldberg et al., 2014]. The purpose of the LP is to measure ozone vertical profiles in the upper troposphere, stratosphere, and lower mesosphere (approximately 30-50 km in altitude) at a vertical resolution of 1-3 km [Kramarova et al., 2014]. Measurements at these levels can be very hard to make due to the large range of the UV, visible, and NIR limb spectra. Signals may vary by up to five orders of magnitude in this range, so limb sensors must have a large dynamic range and high signal to noise ratio

(SNR) [Dittman et al., 2002]. OMPS LP achieves this by using multiple gain ranges from different aperture areas.

2.3 Product Overview

The OMPS instrument on SNPP opened its door to begin collecting data in January 2012 [Wu et al., 2014]. This data is processed by the Interface Data Processing Segment (IDPS) run by Raytheon. The products produced are grouped into three categories: (1) Raw Data Records (RDR), raw data from the spacecraft, (2) Sensor Data Record (SDR), data products such as radiance and reflectance that explain what the sensor is receiving; and (3) Environmental Data Records (EDR), fully processed data that represents an environmental variable. This review will focus mainly on the EDRs as they are the products primarily used for science and research applications.

Ozone total column amount can range from 100 Dobson Units (DU) to 600 DU. Ozone retrieval algorithms take advantage of the knowledge of the details of the ozone absorption spectrum in order to choose which wavelengths should be detected. The major range of absorption is in the ultraviolet part of the spectrum, starting around 360 nm (Huggins bands) and ending around 255 nm (Hartley Band) [Rodriguez et al., 2003]. Figure 2 below from Rodriguez et al. [2003] shows an example spectrum of the gases measured by the Global Ozone Monitoring Experiment (GOME).

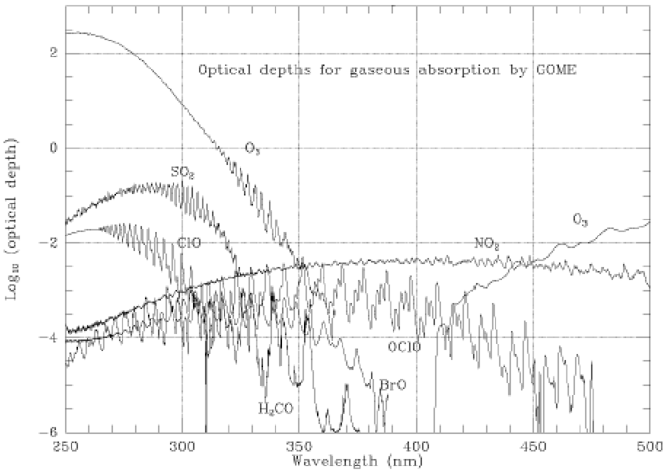


Figure 2. Example absorption spectra for trace gases.

OMPS NP and NM together cover the 250 nm to 380 nm range. From Figure 2, the amount of ozone absorption greatly varies in this range. This is a feature that algorithm developers are able to take advantage of for ozone retrievals.

The TC algorithm begins with a 'first guess' which calculates ozone sensitivity as a linear interpolation of radiative transfer table values of a pair of wavelengths at 318 nm and 336 nm [Rodriguez et al., 2003]. From there, the algorithm is referred to as a multiple triplet method. The three wavelengths in the 'triplet' are: (1) wavelength from an ozone-sensitive channel; (2) and (3) a pair of shorter wavelengths that contain one strongly absorbing channel and one weakly absorbing channel. The algorithm then computes the total column ozone content as an average of multiple triplets. Multiple triplets are used in order to decrease uncertainty due to changes in ozone sensitivity [Flynn et al., 2004].

The NP algorithm is based on the heritage Version 6 SBUV/2 algorithm that is used with other satellites such as NOAA-18 and NOAA-19 [Flynn et al., 2004]. The LP algorithm is based on a scattering retrieval technique from the Shuttle Ozone Limb Scattering Experiment/Limb Ozone Retrieval Experiment (SOLSE/LORE). Details about the NP and LP algorithms can be read in Bartia et al. [1996] and McPeters et al. [2000], respectively.

2.4 Validation

The main method of validation for the OMPS instrument and its products is through comparison to other satellite and in situ data. It is assumed that existing operational products have high enough measurement accuracy and precision to consider them as truth. Comparison with radiosondes and other in situ measurements helps verify this truth. GOME-2 is a common instrument used for validation of OMPS. GOME-2 has a spectral range of 240 nm to 790 nm which includes the spectral range of both OMPS NP and NM [Wu et al., 2014]. Additionally, METOP-A/B, the satellite that carries GOME-2, and SNPP cross paths approximately every 50 days. This is referred to as a Simultaneous Nadir Overpass (SNO) [Wu et al., 2014]. SNOs are often used in validation studies because the conditions sensed by both instruments are near identical due to the close observation times. Wu et al. [2014] comparisons between GOME-2 and OMPS are shown in Figure 3 below.

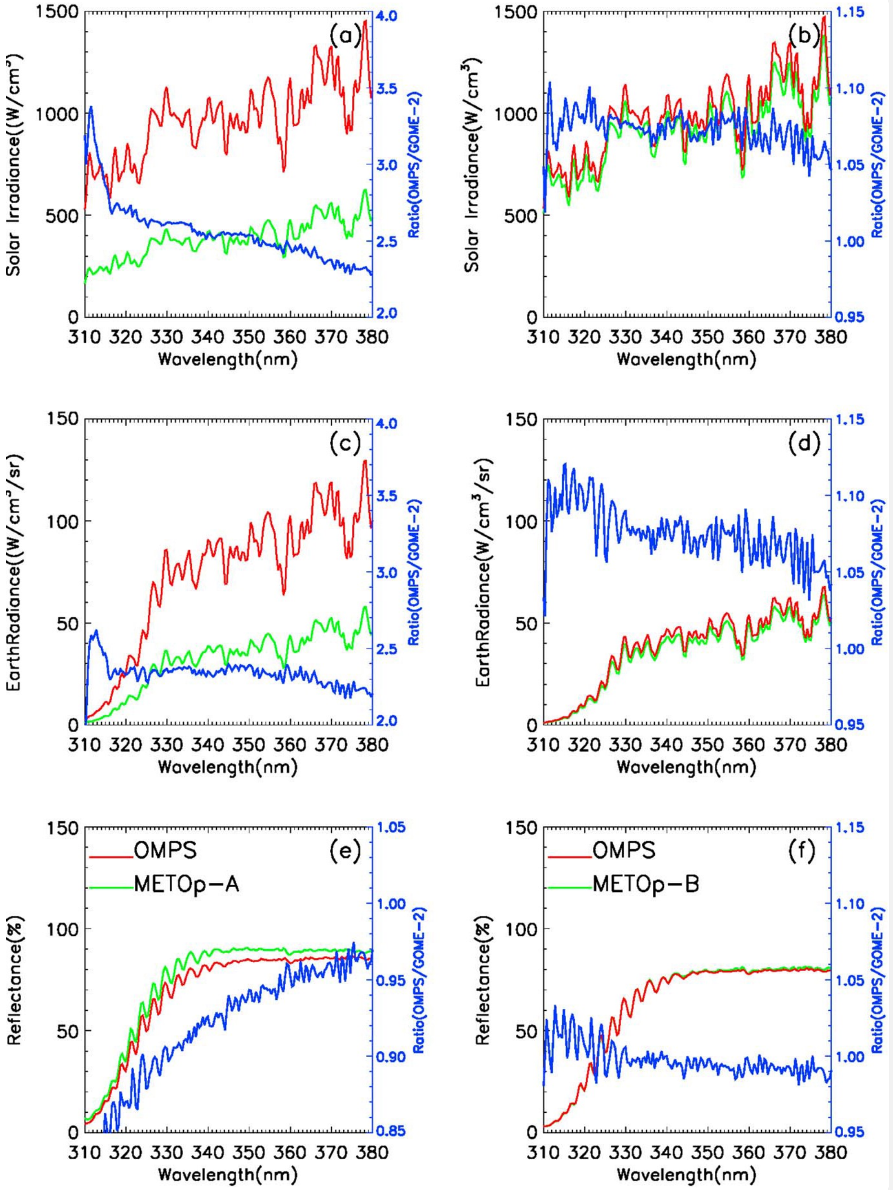


Figure 3. Comparisons of OMPS NM and GOME-2 total column ozone measurements.

These SNO validations compare SDR variables such as solar irradiance, earth radiance, and reflectance. These variables are chosen because they have not gone through EDR processing, thus minimizing differences due to retrieval algorithms. The figures showing OMPS and Metop-B GOME-2 comparisons show that the OMPS SDR is consistent with GOME-2, and thus working properly. A reliable SDR is essential in order to produce a reliable EDR. EDR validation will be discussed in more detail on a case by case basis in Section 3.

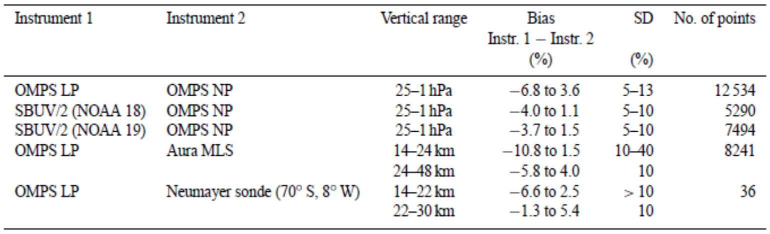
Chapter 3. Product Application Results

3.1 Ozone

One application of the OMPS ozone products is the study and monitoring of the Antarctic ozone hole. Kramarova et al. [2014] discuss how OMPS ozone hole measurements compare to previous observations from other satellites.

This study also helped to compare the data retrieved from the different OMPS detectors. They found that, when compared, OMPS LP and OMPS NP measurements have an average bias that ranges from -6.3% to 3.6% depending on the atmospheric level. The measurements have a standard deviation of less than 5% between 1 hPa and 10 hPa where NP has vertical resolution comparable to the LP measurements. Kramarova et al. state that this demonstrates 'high consistency' between measurements.

Table 1 below shows a summary of Kramarova, et al.'s ozone profile comparisons.



Instrument 1	Instrument 2	Vertical range	Bias Instr. 1 – Instr. 2 (%)	SD (%)	No. of points
OMPS LP	OMPS NP	25–1 hPa	−6.8 to 3.6	5–13	12 534
SBUV/2 (NOAA 18)	OMPS NP	25–1 hPa	−4.0 to 1.1	5–10	5290
SBUV/2 (NOAA 19)	OMPS NP	25–1 hPa	−3.7 to 1.5	5–10	7494
OMPS LP	Aura MLS	14–24 km	−10.8 to 1.5	10–40	8241
		24–48 km	−5.8 to 4.0	10	
OMPS LP	Neumayer sonde (70° S, 8° W)	14–22 km	−6.6 to 2.5	> 10	36
		22–30 km	−1.3 to 5.4	10	

Table 1. Summary of ozone profile comparisons over 55S-82S in September-November 2012. SD = Standard Deviation

OMPS NP shows good consistency with NOAA 18 and NOAA 19 Solar Backscatter Ultraviolet Instument-2 (SBUV/2) profile measurements. OMPS LP shows poorer agreement with the Aura Microwave Limb Sounder (MLS) from 14-24 km, but both OMPS LP and Aura MLS show good agreement with Neumayer sondes in the lower stratosphere. Details of these measurements are shown in Figures 4 and 5.

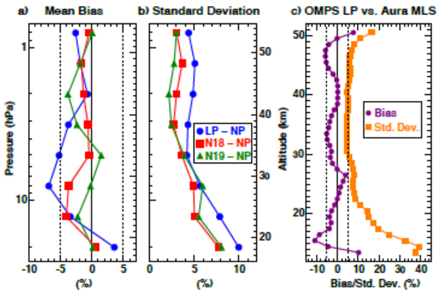


Figure 4. Vertical profiles of a) mean bias and b) standard deviation of OMPS LP (blue), NOAA-18 (red), and NOAA-19 (green) as compared to OMPS NM. c) Vertical profiles of bias (purple) and standard deviation (orange) between OMPS LP and Aura MLS.

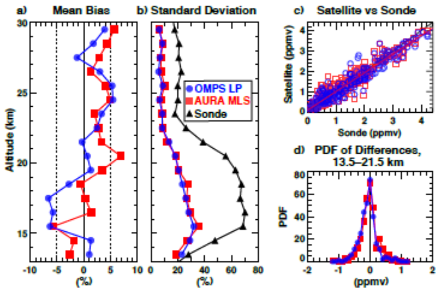


Figure 5. Vertical Profiles of a) mean bias and b) standard deviation of OMPS LP (blue), Aura MLS (red) as compared to a Neumayer sonde. c) OMPS LP and Aura MLS versus the sonde measurements. d) Probability density function of differences between OMPS LP/Aura MLS with the sonde for layers between 13.5 km and 21.5 km.

Kramarova et al. also show total column comparisons between OMPS and Aura's Ozone Monitoring Instrument (OMI). The period of 7 September to 13 October was chosen for this comparison because this period is often used as a standard for measuring the extent of the ozone hole. In particular, the area of the 220 DU contour during this time period is considered the area of the hole. They found OMPS to have a mean ozone hole area of 17.6 x 10^6 km^2 with a standard deviation of 2.6 x 10^6 km^2. This shows a standard error of 0.4 x 10^6 km^2 when compared to OMI measurements. OMPS measures a smaller hole than OMI, and this is consistent with the positive OMPS biases outside of the Antarctic when comparing with OMI. This bias is due to different ozone cross sections used in the different algorithms. Examples of OMPS and OMI ozone hole measurements can be seen in Figure 6 below.

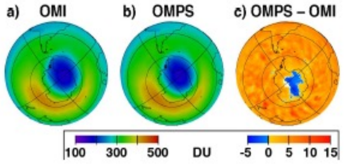
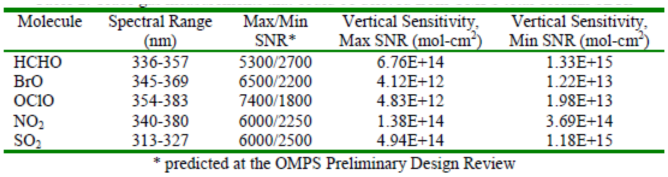


Figure 6. Total column ozone for October 2012 for a) OMI, b) OMPS, and c) the difference between the two.

The Kramarova et al. study proved that the OMPS instrument is as good as the OMI instrument in total column ozone detection. In addition, the OMPS NP and LP are able to produce ozone profiles at the same level or better than existing instruments. Having a reliable ozone product is the first step in OMPS atmospheric monitoring. In fact, OMPS is capable of measuring other trace gases, as well. A summary of other trace gas measurements that could be produced from OMPS is shown in Table 2 below [Rodriguez et al., 2003].



Molecule	Spectral Range (nm)	Max/Min SNR*	Vertical Sensitivity, Max SNR (mol-cm^2)	Vertical Sensitivity, Min SNR (mol-cm^2)
HCHO	336-357	5300/2700	6.76E+14	1.33E+15
BrO	345-369	6500/2200	4.12E+12	1.22E+13
OClO	354-383	7400/1800	4.83E+12	1.98E+13
NO_2	340-380	6000/2250	1.38E+14	3.69E+14
SO_2	313-327	6000/2500	4.94E+14	1.18E+15

* predicted at the OMPS Preliminary Design Review

Table 2. Trace gas measurements that could be derived from OMPS total column SDRs.

The remainder of Section 3 gives examples of some of the work that is being done using these other trace gas measurements.

3.2 Sulfur Dioxide

Yang et al. [2013] show the first sulfur dioxide (SO_2) observations from OMPS through a study of air pollution over China. The authors state that ‘anthropogenic SO_2 is the key signature of air pollution in China,’ meaning that measurements of SO_2 can be used a proxy for fossil fuel combustion emissions. Thus, satellite sensed SO_2 is great indicator of the spatial distribution of pollution sources and transport.

Yang et al. use an iterative spectral fitting (ISF) algorithm [Yang et al. 2009] on OMPS NM radiance between 308 nm and 345 nm in order to retrieve the SO_2 data. This retrieval method has a measurement precision of about 0.2 DU and is most accurate when used in high SO_2 concentration areas. When compared to OMI SO_2 measurements (Figure 7), OMPS measurements show about 7 times better precision due to the lower SNR of the OMI retrievals.

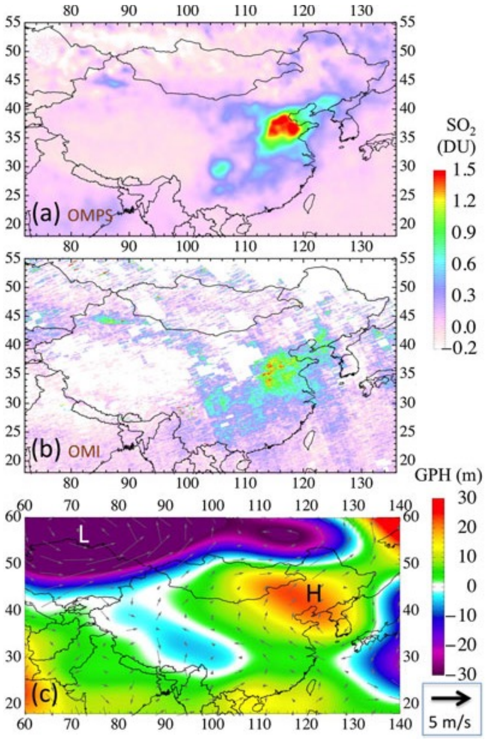


Figure 7. (a) Average SO$_2$ measured by OMPS NM for January 2013. (b) The corresponding OMI SO$_2$ map. (c) The corresponding 500 hPa geopotential height anomaly and 700 hPa wind vector anomaly.

Yang et al. conclude that the OMPS NM is ‘uniquely suitable’ for SO$_2$ measurements due to the improved SNR which allows for the detection of small emissions sources. In addition, OMPS NM is the instrument of choice for SO$_2$ detection because it is the only UV satellite that provides daily global coverage of low-to-midlatitude data because it has significantly less data gaps than OMI and GOME-2. This ability to see small sources while providing contiguous daily global coverage makes

OMPS NM great for detecting air pollution events. Moreover, Yang et al. state that OMPS NM has the ability to perform with higher spatial resolution when samplings are averaged. This further improves the ability to observe sparse source events such as a volcanic eruption.

3.3 Formaldehyde

Li et al. [2015] show the possibility of detecting formaldehyde (HCHO) with OMPS NM. HCHO forms as an intermediate product of the oxidation of volatile organic compounds (VOCs). It has a lifetime on the order of a few hours, so it is a good indicator of the spatial distribution of its originating VOCs. Satellite retrieval of HCHO is difficult due to weak signals and high interference that give the need for sensors with high SNR. HCHO can be retrieved from radiances between 328.5 nm and 356.5 nm. The SNR of OMPS NM in this range, about 2000:1 or better [Seftor et al., 2014], is well suited for HCHO observations.

Global HCHO retrievals made by Li et al. shown in Figure 8 demonstrate the ability for OMPS NM to indeed see small sources of HCHO.

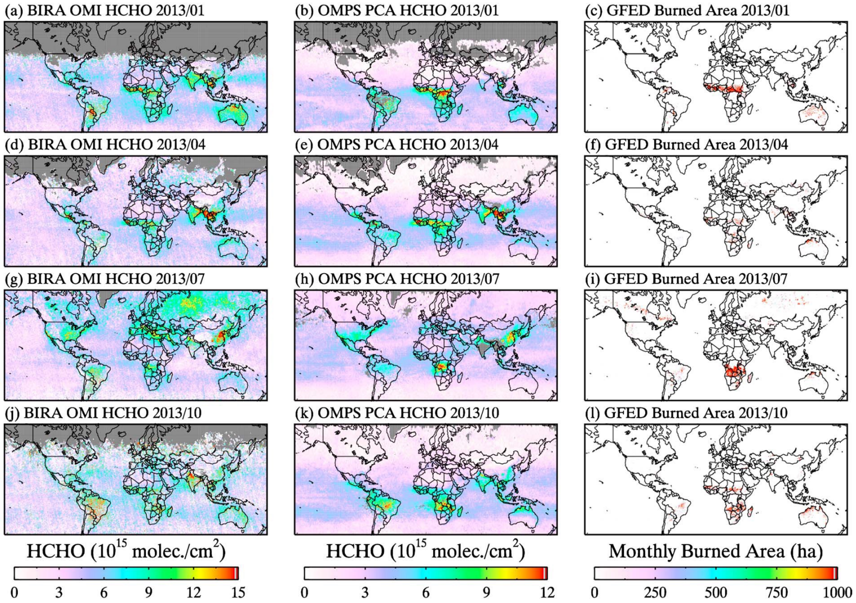


Figure 8. (a) Monthly mean OMI HCHO for January 2013. (b) The corresponding monthly mean OMPS HCHO. (c) GFED burnt area for January 2013. The same as (a–c) but for April (d-f), July (g-i), and October 2013 (j-l)

These retrievals are compared to OMI retrievals from the same time period, and show consistency between the two instruments. Retrievals from both instruments also compare well with GFED fire products, further demonstrating their validity. This ability for OMPS NM to make HCHO measurements consistent with other satellite instruments is important for maintaining the time record of HCHO as data from older satellites begins to degrade.

3.4 Nitrogen Dioxide

Similar to the study of SO_2, Yang et al. [2014] proved it's also possible to retrieve Nitrogen Dioxide (NO_2) concentration from OMPS data. NO_2 is an important atmospheric trace gas because it is a precursor to tropospheric ozone and nitric acid, both of which degrade tropospheric air quality.

Example daily maps of NO_2 are presented in Figure 9.

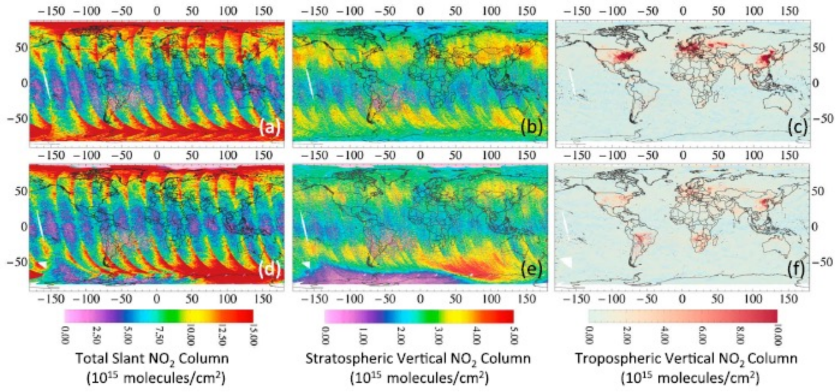


Figure 9. (a, d) Total slant, (b, e) stratospheric vertical, and (c, f) tropospheric vertical NO_2 columns from OMPS NM for 2 days: 21 March 2013 (a–c) and 22 September 2013 (d–f).

These images produced by Yang et al. are proof that OMPS is currently capable of making a NO_2 product. However, the OMPS product is not as sensitive to NO_2 as the OMI product. Comparisons of the two retrievals are shown in Figure 10.

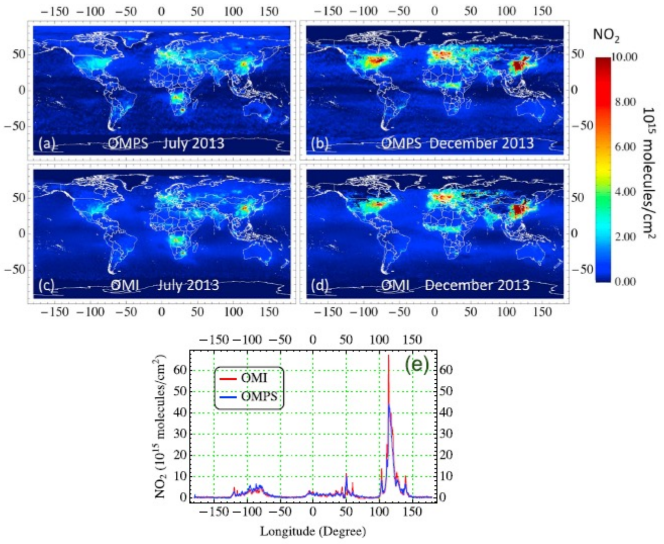


Figure 10. Monthly averages of tropospheric NO_2 vertical columns measured (a, b) by OMPS NM and (c, d) by OMI for July and December (e) Comparison between OMPS and OMI monthly (December 2013) averages of tropospheric NO_2 vertical columns at 36◦N, from 180◦W to 180◦E.

The two retrievals show agreement in spatial distribution. The OMPS retrievals have a slant column precision of about 0.9 x 10^{15} mol/cm^2, which is only slightly worse than the OMI precision of 0.75 x 10^{15} mol/cm^2. However, it is clear from the figure that OMPS is less sensitive to NO_2 than OMI. This is due to the fact that the 410 nm to 460 nm violet blue spectral range commonly used in NO_2 retrievals is not available on SNPP OMPS. Despite this shortcoming, Yang et al. feel confident that OMPS will be able to continue the NO_2 data record should OMI fail. In the meantime, retrieval algorithms can be improved.

Chapter 4. Future Plans*

While SNPP OMPS is currently working well, there is always room for future improvement. As previously stated, the JPSS program has at least two more satellites in preparation. JPSS-1 is being actively worked on and is set to launch in FY2017. The satellite will house both OMPS NM and OMPS NP, but no LP detector will be onboard. The launch of JPSS-1 will also bring about changes to the OMPS products.

One major change to the products is increasing the horizontal spatial resolution of NP to from 250 km x 250 km to 50 km x 50 km at nadir. This will allow for more dense profile detection and will put NP at the same spatial resolution as NM. Moreover, there are studies ongoing to determine if NM spatial resolution can be increased to 17 km x 17 km at nadir. This will put it near the resolution of OMI and further improve trace gas detection. Additionally, the spectral range on NM will be extended to 420 nm. This will provide more channels for better detecting gases such as nitrogen dioxide. It is pertinent that OMPS be able to continue data records if existing ozone and trace gas instruments should fail. The science teams involved will continue to investigate to improve existing algorithms and create new and better products.

*Information on this page came from personal correspondence with Dr. Lawrence Flynn of NOAA STAR.

Chapter 5. Summary and conclusions

The Ozone Mapping and Profiler Suite is currently operating on the Joint Polar Satellite System's SNPP satellite. OMPS is slated to fly on the remainder of the JPSS satellites, as well. OMPS provides data on total ozone content and vertical ozone profile distribution. OMPS data can also be used to retrieve other trace gases such as sulfur dioxide, formaldehyde, and nitrogen dioxide.

The primary purpose of OMPS is to measure ozone. Part of this purpose is to monitor the extent of the Antarctic ozone hole. Kramarova et al. showed that OMPS Nadir Mapper, Nadir Profiler, and Limb Profiler sensors all have the capability to measure stratospheric ozone. Kramarova et al. also showed that OMPS ozone is consistent with ozone measurements from other instruments such as Aura MLS and OMI.

Yang et al. [2013] showed that SO_2 measurements from OMPS have a higher SNR than that from OMI. This allows better detection of emissions sources. In addition, OMPS has more complete global coverage than other trace gas measuring instruments. OMPS can also detect formaldehyde and nitrogen dioxide. Both of these retrievals are consistent with other instruments and can be considered reliable.

Reliability of OMPS retrievals and the OMPS instrument itself is very important in maintaining data records into the future. Satellites such as Aura will eventually fail, so it is important for the continuity of weather forecasting, climate modeling, and hazard detection that another satellite be able to produce comparable data. The OMPS instrument and products are able to continue the data record at a high level of accuracy and precision and will continue to improve through the extent of the JPSS program. OMPS, together with the rest of the sensor suites on JPSS, is a major component to

NOAA’s mission of Science, Service, and Stewardship, and plays a prominent role in the next-generation of polar-orbiting satellites for the United States and the world.

References

Bhartia, P.K., R.D. McPeters, C.L. Mateer, L.E. Flynn, and C. Wellemeyer, “Algorithm for the estimation of vertical ozone profiles from the backscattered ultraviolet technique,” J. Geophys. Res., 101(D13), 18793-18806, 1996.

Dittman, M. G., Leitch, J. W., Chrisp, M., Rodriguez, J. V., Sparks, A. L., McComas, B. K., ... & Wasinger, D. (2002, September). Limb broad-band imaging spectrometer for the NPOESS Ozone Mapping and Profiler Suite (OMPS). In International Symposium on Optical Science and Technology (pp. 120-130). International Society for Optics and Photonics.

Flynn, L. E., Homstein, J., & Hilsenrath, E. (2004, September). The ozone mapping and profiler suite (OMPS). The next generation of US ozone monitoring instruments. In Geoscience and Remote Sensing Symposium, 2004. IGARSS'04. Proceedings. 2004 IEEE International (Vol. 1). IEEE.

Goldberg, M. D., Kilcoyne, H., Cikanek, H., & Mehta, A. (2013). Joint Polar Satellite System: The United States next generation civilian polar-orbiting environmental satellite system. Journal of Geophysical Research: Atmospheres, 118(24), 13-463.

Kramarova, N. A., Nash, E. R., Newman, P. A., Bhartia, P. K., McPeters, R. D., Rault, D. F., ... & Labow, G. J. (2014). Measuring the Antarctic ozone hole with the new Ozone Mapping and Profiler Suite (OMPS). Atmospheric Chemistry and Physics, 14(5), 2353-2361.

Li, C., Joiner, J., Krotkov, N. A., & Dunlap, L. (2015). A new method for global retrievals of HCHO total columns from the Suomi National Polar-orbiting

Partnership Ozone Mapping and Profiler Suite. Geophysical Research Letters,42(7), 2515-2522.

McPeters, R.D., S. Janz, E. Hilsenrath, T. Brown, D. Flittner, and D. Heath, “The retrieval of ozone profiles from limb scatter measurements: Results from the Shuttle Ozone Limb Sounding Experiment,” Geophys. Res. Lett., 27, 2597-2600, 2000.

Rodriguez, J. V., Seftor, C. J., Wellemeyer, C. G., & Chance, K. (2003, April). An overview of the nadir sensor and algorithms for the NPOESS ozone mapping and profiler suite (OMPS). In Third International Asia-Pacific Environmental Remote Sensing Remote Sensing of the Atmosphere, Ocean, Environment, and Space (pp. 65-75). International Society for Optics and Photonics.

Seftor, C. J., Jaross, G., Kowitt, M., Haken, M., Li, J., & Flynn, L. E. (2014). Postlaunch performance of the Suomi National Polar-orbiting Partnership Ozone Mapping and Profiler Suite (OMPS) nadir sensors. Journal of Geophysical Research: Atmospheres, 119(7), 4413-4428.

Wu, X., Liu, Q., Zeng, J., Grotenhuis, M., Qian, H., Caponi, M., ... & Li, W. H. (2014). Evaluation of the Sensor Data Record from the nadir instruments of the Ozone Mapping Profiler Suite (OMPS). Journal of Geophysical Research: Atmospheres, 119(10), 6170-6180.

Yang, K., Krotkov, N. A., Krueger, A. J., Carn, S. A., Bhartia, P. K., & Levelt, P. F. (2009). Improving retrieval of volcanic sulfur dioxide from backscattered UV satellite observations. *Geophysical Research Letters*, *36*(3).

Yang, K., Dickerson, R. R., Carn, S. A., Ge, C., & Wang, J. (2013). First observations of SO_2 from the satellite Suomi NPP OMPS: Widespread air pollution events over China. Geophysical Research Letters, 40(18), 4957-4962.

Yang, K., Carn, S. A., Ge, C., Wang, J., & Dickerson, R. R. (2014). Advancing measurements of tropospheric NO_2 from space: New algorithm and first global results from OMPS. Geophysical Research Letters, 41(13), 4777-4786.