# A satellite limb sounder to monitor dynamical and chemical changes in the stratosphere

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SPARC (Stratosphere-troposphere Processes And their Role in Climate) is one of the core projects of the World Climate Research Program (WCRP) focusing on advancing our understanding of variability of the earth's stratosphere and its implications for climate and weather prediction. To address these scientific questions, research activities are developed such as the Data Assimilation Working Group (DAWG). The group establishes a forum for modelers, data providers, assimilators and users around the SPARC scientific community. The DAWG is recommending NASA to accept a limb sounder proposal to provide vertical profiles of atmospheric composition and temperature at high vertical resolution covering the middle atmosphere down into the upper troposphere during day and night.

Prolonged limb observations have been made by the Upper Atmosphere Research Satellites (UARS), launched in 1991, then followed by several limb sounders launched in the early 2000s. Today, some of these instruments are no longer operating, the others are aging and neither NASA nor ESA or other space agencies have plans to replace them. So far, the single planned operational mission that will provide limb profiling in the next decade is JPSS-2 with the Ozone Mapping Profiler Suite Limb Profiler (OMPS-LP) onboard and to be launched in 2022. The single planned research mission is the SAGE-III instrument that will be put on the International Space Station (ISS) in 2016. The OMPS limb sounder will provide day-time ozone profiles and aerosol extinction but will neither measure temperature nor does it provide observations of other important constituents. SAGE-III on ISS will provide accurate solar occultation profiling of $O_3$, $NO_2$, $H_2O$, $NO_3$, OClO, aerosol extinction and high-altitude cloud extinction, albeit with very limited spatial coverage.

The data assimilation (DA) community relies on high vertical resolution profiles with good spatial coverage on a daily basis, including (polar) nighttime observations, to monitor the onset of the stratospheric ozone hole, to assess the chemical ozone loss, and to track the ozone recovery. For numerical weather prediction, high vertical resolution temperature profiling above 5 hPa (40 km) is critical to anchor satellite radiance measurements made from the meteorological nadir instruments and to monitor and improve the modeled stratospheric dynamics, which have an impact on numerical weather prediction and extended-range forecasting. Further, limb sounding observations

are needed to improve tropospheric air quality monitoring by combining nadir (total column) observations with limb profiles in DA systems.

The need for stratospheric limb sounders has been reviewed by the OPEROZ project (van Weele et al., 2015). It reports that the present-day ozone profile observations are essential for climate reanalyses, short-term monitoring services which assimilate and forecast ozone in the troposphere and the stratosphere, and for numerical weather prediction. A series of nadir sounders is planned in order to continue the monitoring of total ozone and other trace gases. However, a similar continuous line of future limb missions is not planned, with the exception of the above-mentioned OMPS-LP instrument on JPSS-2. The situation in the next decade will be in stark contrast with the suite of dedicated limb sounders flown during the last two decades. In contrast to limb observations, nadir profile observations strongly smooth out vertical structure and cannot sufficiently resolve the highly stratified middle atmosphere and upper troposphere. For essential climate variables (ECVs) such as $O_3$, $H_2O$, $CH_4$, aerosols, and the ozone and aerosol precursors, $NO_2$ and $SO_2$, nadir observations cannot provide stratospheric profiles with sufficient vertical resolution. This seriously limits their value for ECV climate reanalyses and the attribution of ozone changes to either chemical or transport processes at different altitudes. OPEROZ also reports the benefit of combining assimilation of limb and nadir types of ozone observations. The limb-nadir combination provides a much more accurate 3-D analysis of ozone in the troposphere and lower stratosphere which will improve upon ozone forecasts for air quality. Assimilation of limb-nadir data will also improve the representation of the upper troposphere and lower stratosphere region in reanalyses. Climate is particularly sensitive to atmospheric composition in this region because this is where much infrared radiation escapes to space and where ozone is most effective as a greenhouse gas.

OPEROZ has defined a minimum mission for ozone monitoring and a number of potential mission extensions. The minimum mission scenario requires a limb sounder providing ozone profiles with daily global coverage (poles, mid-latitudes, tropics) and with day- and night-time measurement capabilities. In the lower stratosphere, the required resolution is 1-2 km vertically and 100-200 km horizontally. In the upper stratosphere, the required resolution is 2-4 km vertically and 200-400 km horizontally. For deducing long-term ozone profile trends, a series of operational satellites with well (inter-)calibrated instrumentation is necessary.

Two mission extensions defined by OPEROZ would help to understand why the ozone is changing in the changing climate. Depending on the adopted technology, delivered limb profiles would be more suited to focus on the dynamical (Brewer-Dobson circulation) or chemical drivers of stratospheric ozone change. Table 1 lists the types of observations required to address these two mission objectives and a first assessment of the ability of three types of observation techniques: shortwave (ultraviolet) scattering, infrared emission and microwave emission.

Although none of the three limb observational techniques could offer all of the user requirements on their own, each of them has a strong heritage and also specific merits. Also, in addition to the observations listed in the above table, the added value of ClO for polar ozone monitoring and $NO_2$ profiling for air quality applications should be noted. In conclusion, the SPARC DAWG recommends NASA to accept a limb sounder mission proposal based on at least one of the three techniques mentioned above, in line with the OPEROZ data requirements on spatial coverage, and horizontal and vertical resolution.

**Table 1 :** Summary of the ability of the various instrument types to meet OPEROZ requirements. Color code: Grey = N/A (no requirement for that altitude range); Green = Meets requirement; Yellow = Requirements are not fully met; Red = Species not available. Atmospheric altitude ranges: UT=upper troposphere; LS=lower stratosphere; MS=middle stratosphere and US=upper stratosphere. (Courtesy: A. Waterfall, RAL)

| Mission Extension | Observable | Shortwave Scattering | | | | Infrared Emission | | | | (Sub-)mm Emission | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | UT | LS | MS | US | UT | LS | MS | US | UT | LS | MS | US |
| 'Brewer-Dobson Circulation' | $SF_6$ | | | | | | | | | | | | |
| | $CH_4$ | | | | | | | | | | | | |
| | $N_2O$ | | | | | | | | | | | | |
| | CFC-11 | | | | | | | | | | | | |
| | CFC-12 | | | | | | | | | | | | |
| | $H_2O$ | | | | | | | | | | | | |
| | HCl | | | | | | | | | | | | |
| 'Stratospheric Chemistry' | Temperature | | | | | | | | | | | | |
| | $HNO_3$ | | | | | | | | | | | | |
| | HCl | | | | | | | | | | | | |
| | $H_2O$ | | | | | | | | | | | | |
| | Ext. coef. | | | | | | | | | | | | |
| | $CH_4$ | | | | | | | | | | | | |
| | $N_2O$ | | | | | | | | | | | | |
| | $ClONO_2$ | | | | | | | | | | | | |
| | BrO | | | | | | | | | | | | |
| 'Tropospheric Ozone' | $O_3$ | | | | | | | | | | | | |

Below, we reply to the specific questions of the survey:

1. What are the key challenges or questions for Earth System Science across the spectrum of basic research, applied research, applications, and/or operations in the coming decade?

    - Monitoring stratospheric changes is a key issue in the coming decade. This includes measuring ozone, temperature and other trace gases related to the dynamics and chemistry of the stratosphere. Providing initial and boundary conditions for air quality forecasts will also be challenging. To tackle these challenges, the DAWG is requesting stratospheric limb profiles of ozone, temperature and other relevant stratospheric trace gases at high vertical resolution.

2. Why are these challenge/questions timely to address now especially with respect to readiness?

    - Because space agencies have not planned future stratospheric limb sounders dedicated to stratospheric change in a changing climate and currently operating instruments are aging.

3. Why are space-based observations fundamental to addressing these challenges/questions?

    - Because space-based limb observations provide high resolution vertical profiles of constituents and temperature with daily global coverage, which is not achievable by other measurement techniques.

a. Whether existing and planned U.S. and international programs will provide the capabilities necessary to make substantial progress on the identified challenge and associated questions. If not, what additional investments are needed?

- OMPS Limb Profiler (LP) onboard S-NPP is currently operating but it only measures daytime ozone profile and aerosol extinction (no temperature or other species, and no measurements in darkness)

- OMPS-LP is planned on JPSS-2 (2022) and SAGE-III is planned on ISS (2016), with the limitations mentioned above.

b. How to link space-based observations with other observations to increase the value of data for addressing key scientific questions and societal needs;

- The DA methodology effectively combines satellite and conventional measurements with model simulations in an integrated statistical framework. For example, the monitoring of the ozone hole is based on ground-based, balloon borne and DA-based analysis of temperature and constituents.

c. The anticipated scientific and societal benefits; and

- A new dedicated stratospheric limb sounder will allow the scientific community to monitor the stratosphere (its composition and dynamics) and its changes in a changing climate, which has societal benefits (e.g. monitoring the Antarctic ozone hole and better constraints on tropospheric ozone relevant for air quality applications).

d. The science communities that would be involved.

- data assimilation, meteorological, climate, air quality, atmospheric chemistry

# Reference

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