Solar Occultation Constellation for Retrieving Aerosols and Trace Element Species (SOCRATES) Mission Concept

R.M. Bevilacqua and M.D. Fromm
Naval Research Laboratory
Washington, DC  20375; 202-767-3391
rich.bevilacqua@nrl.navy.mil

S.M. Bailey
Virginia Polytechnic Institute and State University
Blacksburg, VA 24061-0002; 540-231-0459
baileys@exchange.vt.edu

C.S. Fish
Atmospheric & Space Technology Research Associates, LLC
5777 Central Ave. Suite 221, Boulder, Colorado 80301;(303) 993-8039
cfish@astraspace.net

L.L. Gordley
GATS, Inc
11864 Canon Blvd, Newport News, VA 23606; 757-952-1042
l.l.gordley@gats-inc.com

ABSTRACT

The goal of SOCRATES is to quantify the critical role of the upper troposphere/lower stratosphere (UTLS) in the climate system. The mission would provide, for the first time, the suite of measurements required to quantify stratosphere/troposphere exchange (STE) pathways and their contribution to UTLS composition, and to evaluate the radiative forcing implications of potential changes in STE pathways with climate change. The discrimination and quantification of STE pathways requires simultaneous measurement of several key trace gases and aerosols with high precision, accuracy, and vertical resolution. Furthermore, aerosol and clouds, often present in the UTLS, complicate the measurement of trace gases. The SOCRATES sensor is a 23-channel Gas Filter Correlation Radiometer (GFCR), referred to as GLO (GFCR Limb solar Occultation), with heritage from HALOE on UARS, and SOFIE on AIM. GLO measures aerosol extinction from 0.45 to 3.88 µm, important radiatively active gases in the UTLS (H2O, O3, CH4, N2O), key tracers of STE (HCN, CO, HDO), gases important in stratospheric O3 chemistry (HCl and HF), and temperature from cloud top to 50 km at a vertical resolution of 1 km. Improved pointing knowledge will provide dramatically better retrieval precision in the UTLS, even in the presence of aerosols, than possible with HALOE. In addition, the GLO form factor is only a few percent of that of HALOE, and costs for a constellation of GLO sensors is within the cost cap of a NASA Venture mission. The SOCRATES mission concept is an 8-element constellation of autonomous nano-satellites, each mated with a GLO sensor, deployed from a single launch vehicle. The SOCRATES/GLO approach reaps the advantages of solar occultation: high precision and accuracy; robust calibration; and high vertical resolution, while mitigating the sparse coverage of a single solar occultation sensor. We present the SOCRATES science case, and key elements of the SOCRATES mission and GLO instrument concepts.

MOTIVATION

The goal of SOCRATES is to quantify the critical role of the upper troposphere/lower stratosphere (UTLS) in the climate system. The mission would provide, for the first time, the suite of measurements required to quantify stratosphere/troposphere exchange (STE) pathways and their contribution to UTLS composition, and to evaluate the radiative forcing implications of potential changes in STE pathways with climate change. The discrimination and quantification of STE pathways requires simultaneous measurement of several key trace gases and aerosols with high precision, accuracy, and vertical resolution. Furthermore, aerosol and clouds, often present in the UTLS, complicate the measurement of trace gases. The SOCRATES sensor is a 23-channel Gas Filter Correlation Radiometer (GFCR), referred to as GLO (GFCR Limb solar Occultation), with heritage from HALOE on UARS, and SOFIE on AIM. GLO measures aerosol extinction from 0.45 to 3.88 µm, important radiatively active gases in the UTLS (H2O, O3, CH4, N2O), key tracers of STE (HCN, CO, HDO), gases important in stratospheric O3 chemistry (HCl and HF), and temperature from cloud top to 50 km at a vertical resolution of 1 km. Improved pointing knowledge will provide dramatically better retrieval precision in the UTLS, even in the presence of aerosols, than possible with HALOE. In addition, the GLO form factor is only a few percent of that of HALOE, and costs for a constellation of GLO sensors is within the cost cap of a NASA Venture mission. The SOCRATES mission concept is an 8-element constellation of autonomous nano-satellites, each mated with a GLO sensor, deployed from a single launch vehicle. The SOCRATES/GLO approach reaps the advantages of solar occultation: high precision and accuracy; robust calibration; and high vertical resolution, while mitigating the sparse coverage of a single solar occultation sensor. We present the SOCRATES science case, and key elements of the SOCRATES mission and GLO instrument concepts.

The most pressing need in lower and middle atmospheric science is to understand and predict global climate change resulting from anthropogenic increases in greenhouse gases. A key but poorly documented component of the climate system is the upper troposphere and lower stratosphere (UTLS), a region where radiative, dynamical, and chemical forces drive climate feedbacks. Transport of radiatively active gases and aerosols into the UTLS strongly influences these feedbacks, yet the
transport pathways remain poorly quantified. The critical role that the UTLS plays in the near-term predictability of the climate system is highlighted in the NRC Decadal Survey and in two of NASA’s Earth Science Focus Areas, identified in the Science Mission Directorate 2010 Science Plan: Climate Variability and Change; and Atmospheric Composition.

The UTLS (see schematic in Figure 1) plays a key role in controlling the Earth's outgoing long-wave radiation and surface climate [1]. Understanding changes in the composition of the UTLS requires quantifying the complex STE mechanisms. STE is primarily driven by the Brewer-Dobson circulation (BDC), quasi-isentropic mixing, tropopause folding, and large volcanic eruptions [2]. However, extreme overshooting cumulonimbus [3] and forest fire-induced cumulonimbus (pyroCb) thunderstorms [4], the Asian monsoon [5], and mid-latitude cyclones [6] have also been shown to transport significant amounts of material into the UTLS. Such episodic events alter the distribution of aerosols and trace species in the UTLS, significantly impacting climate forcing. These impacts are predicted to change as climate changes (e.g., increases in biomass burning [7], strengthening of tropical upwelling [8], and poleward shifting of the subtropical front which results in widening of the tropical UTLS [9; 10]. These important feedbacks are currently unquantified.

The importance of the UTLS was underscored by recent suggestions [11; 12] that H2O and aerosol changes in the UTLS from 2000-2009 produced a negative radiative forcing (cooling) large enough to offset about 2/3 of the positive forcing over that period from increased CO2, the most important well-mixed greenhouse gas. The processes responsible for these UTLS H2O and aerosol changes are not well understood, highlighting the need to quantify the role of sources, sinks, and stratosphere-troposphere exchange (STE) pathways.

Probing the UTLS is challenging because of its narrow vertical scale (~8 km total, with a ~1 km scale for radiative processes and composition gradients) and large spatiotemporal variability of constituents. The discrimination and quantification of STE pathways requires simultaneous measurements of several key trace gases and aerosols with high precision, accuracy, and vertical resolution. Furthermore, aerosol and clouds, often present in the UTLS, complicate the measurement of trace gases. Because of these challenges, the role of the UTLS in the climate system not been adequately investigated by any space-based mission.

MISSION OBJECTIVES

The proposed Solar Occultation Constellation for Retrieving Aerosols and Trace Element Species (SOCRATES) mission seeks to provide the first measurements that fully characterize the distribution of key radiatively active gases and aerosols in the UTLS, to quantify STE pathways and their contribution to UTLS composition, and to evaluate the radiative forcing of changes in STE pathways, thereby closing an important gap in our ability to predict surface climate change. In addition, there is a continuing need to observe the entire
stratosphere and to extend the global trace gas record (WMO, 2010).

SOCRATES will answer the following science questions, which form the major objectives of the mission:

1. What are the global distribution and variability of key radiatively active gases, aerosols, and transport tracers in the UTLS?
2. What are the amount and composition of material transported into the UTLS via different exchange pathways?
3. What is the impact of these transport pathways on global climate forcing?
4. What are the abundances of stratospheric ozone and related constituents and how are they changing?

MISSION IMPLEMENTATION OVERVIEW

SOCRATES objectives require simultaneous measurement of gases and aerosols in and near the UTLS. Utilizing Gas Filter Correlation Radiometry (GFCR), SOCRATES will operate in the solar occultation (SO) measurement mode from low earth orbit (LEO) to make these measurements. SO sensors are the only space-based instruments that have demonstrated the vertical resolution needed to adequately measure in the UTLS. SO sensors have a long, successful heritage of atmospheric measurements, with long-term calibration stability and good precision. Important examples include the Halogen Occultation Experiment (HALOE) on the Upper Atmosphere Research Satellite (UARS), the Stratospheric Aerosol and Gas Experiment (SAGE) I-III, the Polar Ozone and Aerosol Measurement (POAM) II-III, the Canadian Space Agency’s Atmospheric Chemistry Experiment (ACE) on SciSat, and the Solar Occultation For Ice Instrument (SOFIE) on the Aeronomy of Ice in the Mesosphere (AIM) mission.

The proposed SOCRATES sensor, referred to as GLO (GFCR Limb solar Occultation), is a 23-channel SO sensor which measures multi-wavelength aerosol extinction, 7 trace gases important in STE, and temperature (see Figure 2). The SOCRATES’ GLO heritage dates back to HALOE and incorporates advances from the more recent SOFIE instrument, combined into a simple, static, inexpensive, compact package (reference Figure 3 and Figure 4). Despite its simplicity and small size, the GLO sensor surpasses the performance specifications of any previous occultation sensor.

![Figure 2. SOCRATES provides a very comprehensive set of observations. Aerosols measurements are also key components of the observation set.](image)

However, a single SO instrument provides unacceptably sparse sampling (two occultations per orbit: orbital sunrise and sunset in opposite hemispheres). To achieve sufficient sampling of the UTLS region with SO sensors, a constellation of sensors is required. Our analysis indicates that a constellation of 6-8 SOCRATES sensors, on 6U-Cubesats, would have the necessary precision, accuracy, and measurement sampling to fully achieve the SOCRATES mission objectives (i.e., understanding the role of the UTLS in the climate system). The constellation could be deployed from a single launch vehicle into orbits, with slightly different altitudes that precess at varying rates which then produce global coverage within a year.
The SOCRATES constellation could be implemented using an innovative launch approach that inserts eight 6U observatories from a single Pegasus launch vehicle into slightly varying inclinations, and at mildly eccentric LEOs, to create different precessing rates between the observatories. The diverse inclinations and altitudes induce different observatory procession rates in the form of a time-varying distribution of right ascension due to gravitational harmonics [13; 14]. This process effectuates the timely global distribution of the constellation such that the eight observatories achieve a global pattern of > 90° latitudinal coverage after one year.

The SOCRATES constellation envelops in two distinct mission science phases. Phase 1 represents the one-year period following launch and deployment. During this period, the entire constellation will begin orbiting as “a dense cluster of observatories” before gradually dispersing, providing for high resolution temporal/spatial measurements as well remarkable cross-calibration of the observatory measurement sets.

During the first few months of these early operations, each of the observatories will have been commissioned and transitioned into autonomous operation in which the SOCRATES sensor will determine orbit period and predict occultation times based on its solar occultation measurements, enabling automated switching in and out of science mode in concert with the bus, thus eliminating the need for regular ground commanding to the bus. This method has been functioning continuously for many years on the AIM observatory, and is centered on the SOFIE sensor solar occultation measurements. The observatory will still maintain complete command and control capability from the ground that can override or update the autonomy operations at any time.

Phase 2 commences one year after launch and is characterized by a globally distributed constellation. At this point in time, the constellation will have matured such that distinct and globally distributed nodal crossings are occurring at a minimum of 180° across the nodal spread.

During on-orbit calibration activities, the spacecraft will execute scans across the Sun (in both azimuth and elevation) to determine co-registration offsets, relative response, non-linearity effects, and stray light/off-axis response. Data during eclipse (just before sunrise and after sunset) determine dark current and detector offsets. Snapshots above the atmosphere of the 23 images provide bad pixel maps, sunspot status, dark-current trends, and pixel flat-fielding coefficients.
Figure 4. Overview of the compact but very capable SOCRATES atmospheric GLO sensor and its integration with a 6U Cubesat bus.
Immediately after launch, all eight satellites (blue lines) are in the same orbit plane. Due to slightly different precession rates, the satellite orbits spread over time such that within a year they are spread equally over the globe.

**Figure 5.** Proposed SOCRATES constellation implementation (top panel) and resultant coverage (bottom panel).
SUMMARY AND CONCLUSIONS

Over the next decades CubeSat-sized science and operational observatories with sensor performance rivalling that of traditional systems will enable financially feasible implementations of global observations networks in space. These CubeSat based constellations will facilitate and allow the closing of key system science questions and provide operational platforms for both government and commercial ventures.

The SOCRATES mission constellation, launched from a single launch vehicle into low Earth orbit (LEO), will consist of 6-8 identical CubeSat sized observatories, each instrumented with an identical single SO UTLS GLO sensor. Autonomous operation of each of the observatories, patterned after the AIM mission, will greatly simplify the mission operations planning and command effort. The global earth observations acquired from this constellation, together with the ground data system, mission operations, and data analysis efforts, will achieve the SOCRATES science goals. The SOCRATES mission is planned for 3 years of on-orbit operations, including one year of orbit spread.

REFERENCES