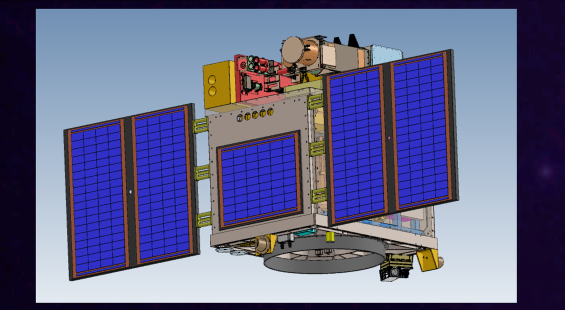
SoSWEET-SOUP Solar Polar Satellite and Ozone & Energy Radiative Balance Constellation Mission



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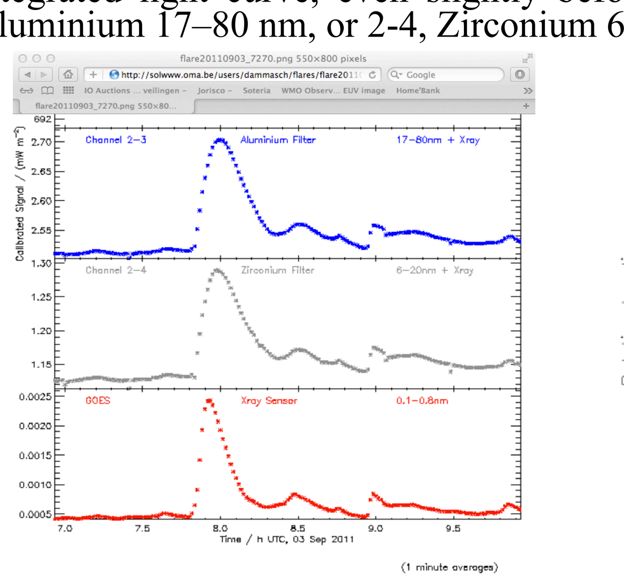
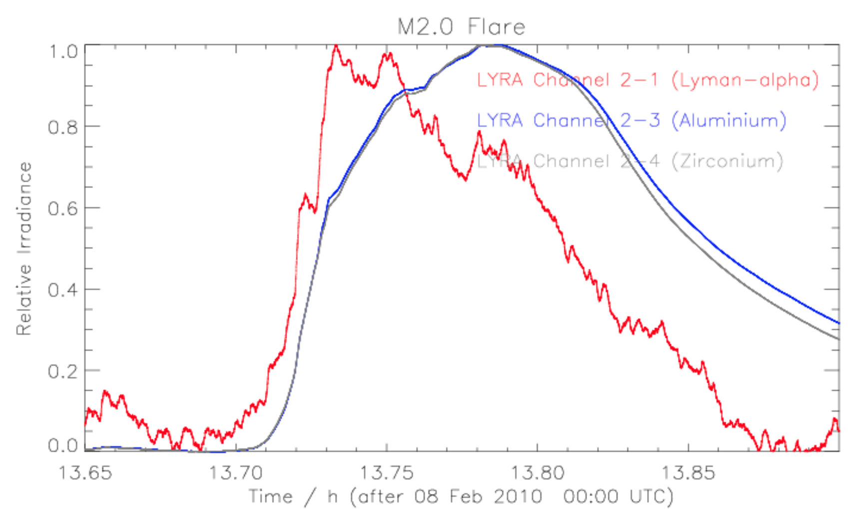
Introduction

SoSWEET-SOUP (Solar, Space Weather Extreme EvenTs and Stratospheric Ozone Ultimate Profiles) is an innovative small satellites constellation which aims to measure on complementary platforms the solar influence on climate, namely, on one part, solar activity and spectral variability and, on the other, the different components of the Earth radiation budget, energy input and energy reemitted at the top of the Earth atmosphere, with a particular focus on the UV part of the spectrum and on the ozone layer, which are most sensitive to solar variability. It includes the prediction and detection of major eruptions and CMEs (Lyman-Alpha and Herzberg continuum imaging 200–220 nm), Extreme Events, the solar forcing on the climate through radiation, and their interactions with the local stratosphere (UV spectral irradiance 170–400 nm and ozone'profiles measurements). The far UV (FUV) is the only wavelength band with energy absorbed in the high atmosphere (stratosphere), in the ozone (Herzberg continuum, 200–220 nm) and oxygen bands, and its high variability is most probably at the origin of a climate influence. A simultaneous observation of the incoming FUV and of the ozone (O_3) production, would bring an invaluable information on this process of solar-climate forcing. SoSWEET Sun-Synchronous polar orbit satellite (OneWeb like platform?) includes several instruments and in particular SUAVE (*Solar Ultraviolet Advanced Variability Experiment*), an optimized telescope for FUV (Lyman-Alpha) and MUV (Herzberg continuum) imaging (sources of variability), SOLSIM (*SOLar Spectral Irradiance Monitor*), a spectrometer with 0.65 nm spectral resolution from 170 to 340 nm, a small coronagraph and ERBO (*Earth Radiative Budget and Ozone*), to measure ozone (6 bands) and 0.1–100 µm radiation. The polar satellite is completed by a constellation of 10 to 12 small satellites of some 20 to 30 kg (large 6 to 12 "U" nanosatellites) on equatorial orbits (+/- 20° in latitude) to acquire simultaneously detailed Energy Balance measurements (miniSCARAB instrument derived from SCARAB/ENVISAT) and ozone profiles (miniGOMOS instrument derived from GOMOS/ENVISAT occultation experiment) to understand the relation between solar UV variability and stratospheric ozone (on arctic and antarctic regions in particular).

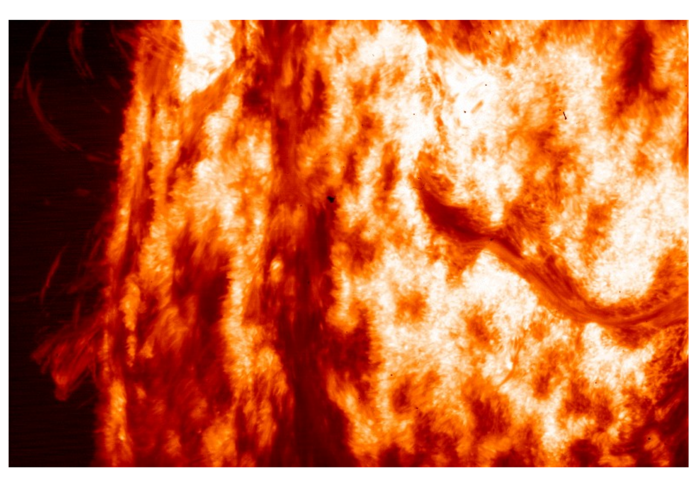
Predicting and Monitoring Large Flares & CMEs: Lyman-Alpha rather than X-ray

One objective is to monitor flares in Lyman-Alpha rather than X-ray or XUV since Lyman-alpha is EXCELLENT at detecting flares as shown by LYRA/PROBA-2. Lyman-Alpha raises, in global integrated light curve, even slightly before GOES X-ray (1–8 Å) or the LYRA channel 2-3, Aluminium 17–80 nm, or 2-4, Zirconium 6–20 nm.





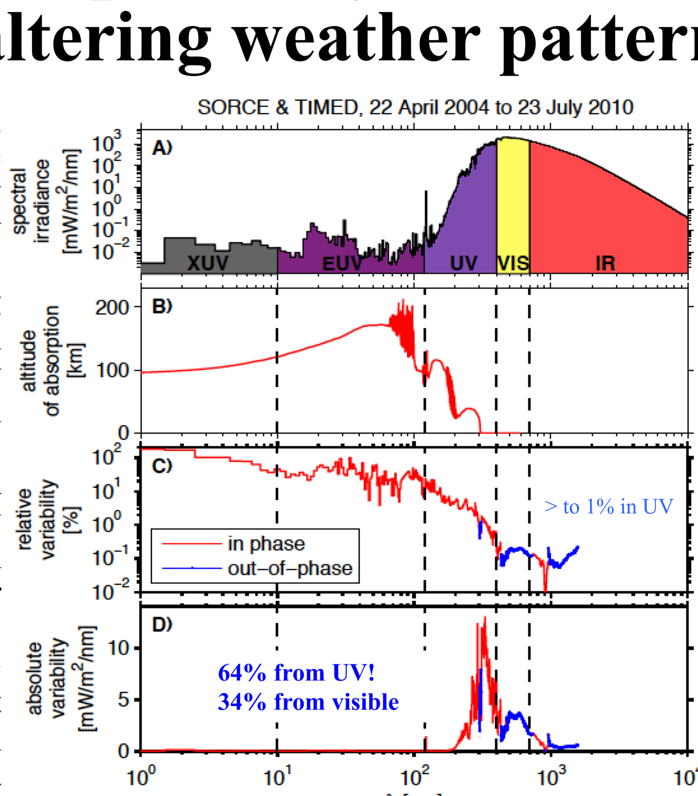
Lyman-Alpha, much like H-Alpha, is also an excellent flares/CMEs PRECURSOR INDICATOR since of filaments and emerging bipolar region (the two major flare's precursors) high visibility in the line (space weather direct application). Furthermore, comparing sensitivity difference with H-Alpha formed slightly below in the chromosphere might lead, hopefully, to even better and robust flare/CME indicators, and possible field lines indications (CME orientation). And since Lyman-Alpha allows easy detection and tracking of filaments and bipolar regions, it allows an easier prediction of large flares happening (the only ones leading to the Space Weather annoying Interplanetary Coronal Mass Ejections, ICMEs, the ones towards the Earth). In comparison, the He II 304 can hardly see filaments and is not suited for the tracking.



High resolution image of the Sun in Lyman-Alpha taken by the VAULT rocket program of NRL and nicely showing prominences and filaments (prominences seen in absorption on the disk). [Vourlidas et al., 2010]

UV affects stratospheric dynamics and temperatures, altering weather patterns

The ultraviolet below 300 nm is still representing 1% of the solar irradiance and the FUV and MUV are the only wavelength bands with energy absorbed in the high atmosphere (stratosphere), in the ozone (Herzberg continuum, 200–220 nm) and oxygen bands, and their high variability (5-10%) is most probably at the origin of a climate influence (UV affects stratospheric dynamics and temperatures, altering interplanetary waves and weather patterns both poleward and downward to the lower stratosphere and tropopause regions). Recent measurements at the time of the last solar minimum suggest that variations in the UV may be larger than previously assumed what implies a very different response in both stratospheric ozone and temperature.



Solar spectrum, its absorption altitude, relative (%) and absolute variability over solar cycle (data from SORCE & TIMED, 2003–2010). [Ermolli et al., 2013]

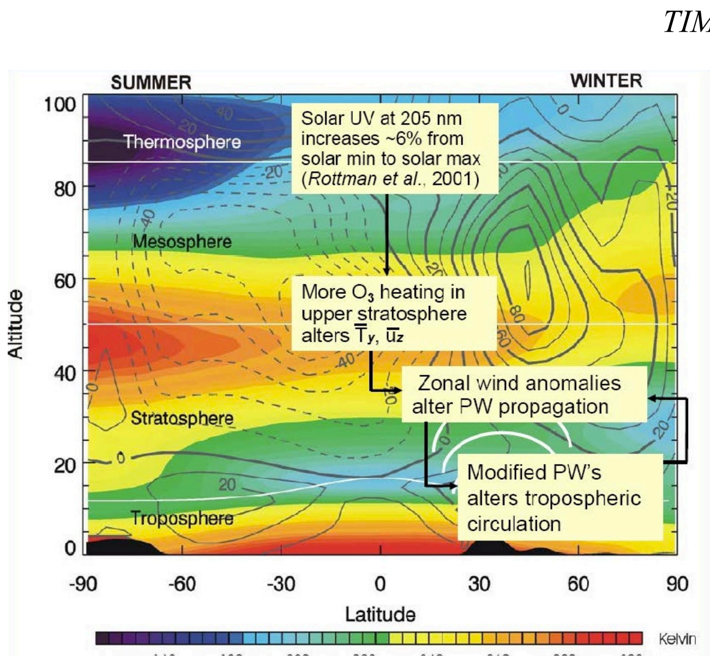
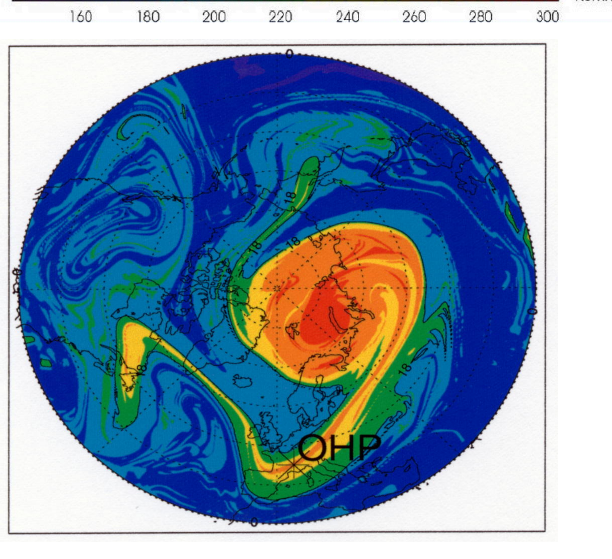


Illustration of the Sun-Climate connection through the variability of solar UV that heats the ozone locally and create defects/anomalies on the propagation of the zonal planetary wave that will, in turn, affects the tropospheric circulation. [Courtesy McCormack 2004]

The effect (known as the **"Top-Down" mechanism**, e.g. Gray *et al.*, 2010) was identified in several studies:
-Ineson *et al.*, 2011, Solar forcing of winter climate variability in the Northern Hemisphere
-Martin-Puertas *et al.*, 2012, Changes in atmospheric circulation amplified by grand solar minimum 2800 years ago
-Reichler *et al.*, 2012, Sudden Stratospheric Warmings correlated circulation evidencing stratosphere-troposphere coupling
-Thiéblemont *et al.*, 2015, Solar forcing synchronizing the decadal North Atlantic climate variability, etc.

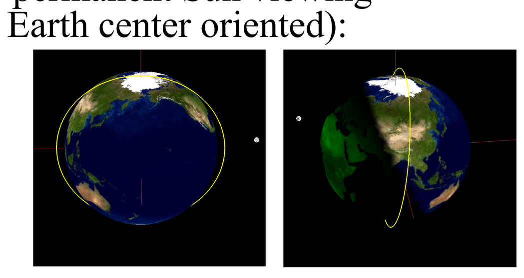


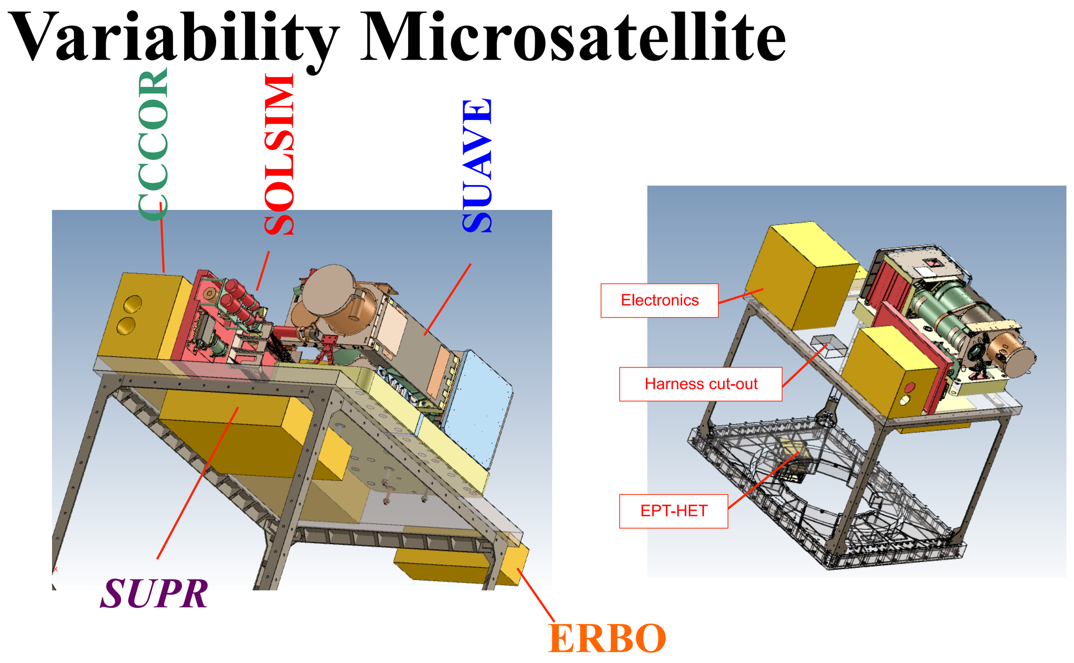
Ozone mapping example (Hauchecorne et al., JGR, 2002, MIMOSA model).

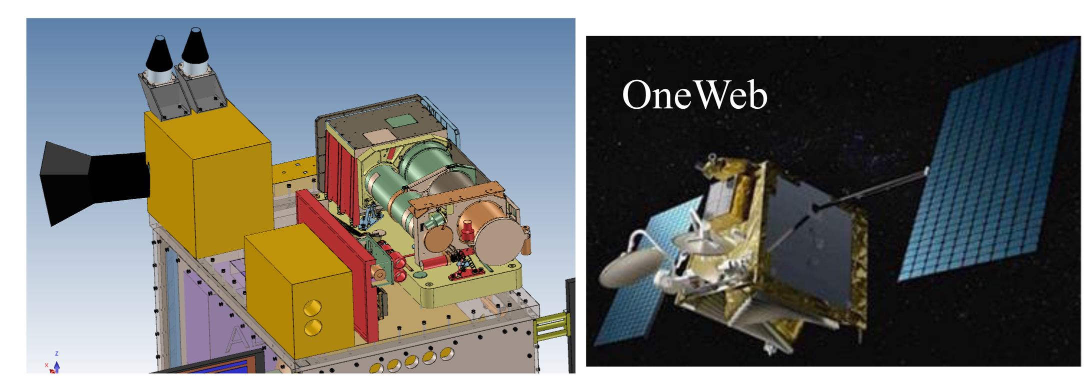
Local ozone and UV flux
Local measurements of the ozone profile and vertical column density are essential. In the stratosphere, this gas forms a layer around 20-40 km absorbing solar UV. Differential measurements between 310 nm (O_3) and 340 nm (no O_3) is carried.
The simultaneous measurement of UV (Lyman-Alpha and Herzberg continuum at 215 nm) will allow to better understand the formation mechanisms of ozone and, by measurements of the local anomalies, modifications and dynamics of the planetary wave, and its repercussions on the troposphere and climate (solar-climate forcing).

SoSWEET polar satellite: a Space Weather & Ultraviolet Solar Variability Microsatellite

- **SUAVE** (*Solar Ultraviolet Advanced Variability Experiment*), Lyman-Alpha and 200-220 nm Herzberg continuum imaging with 3 redundant set of filters to preserve long-term sensitivity (SODISM/PICARD evolution)
- **SOLSIM** (*SOLar Spectral Irradiance Monitor*) 170-340 nm, spectral resolution 0.65 nm (UV double monochromator, evolution of SOLSPEC/SOLAR)
- **SUPR** (*Solar Ultraviolet Passband Radiometers*) based on PREMOS & LYRA with 20 UV filter radiometers for Lyman-Alpha, Herzberg, CN bandhead (385-390 nm) and UV from 180 to 340 nm by 20 nm bandpasses (**replaced by C-SIM**)
- **CCCOR** (*Coronal Context Coronagraph*) small coronagraph (along Goddard/South Korea instrument)
- **ERBO** (*Earth Radiative Budget & Ozone*): 6 wavelengths and a 0.1-100 µm radiometer
- Other instruments (LASP CSIM?) are envisaged depending of platform possibilities
- Orbit with "almost" permanent Sun viewing (alike PICARD but Earth center oriented):
  - Sun synchronous orbit
  - Ascending node: 18h00
  - Altitude: **> 725 km**
  - inclination: 98.29°
  - Eccentricity: 1.04×10^{-3}
  - Argument of periapsis: 90°





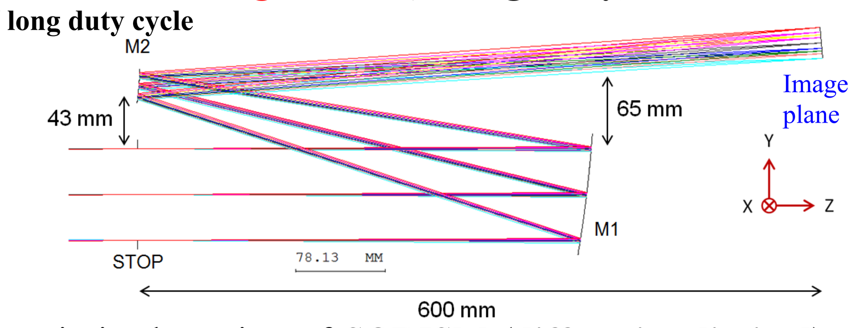


SoSWEET is foreseen to be accommodated on a modified OneWeb platform (< 150 kg); dimensions expected for instruments' plate is less than 700 x 950 mm²

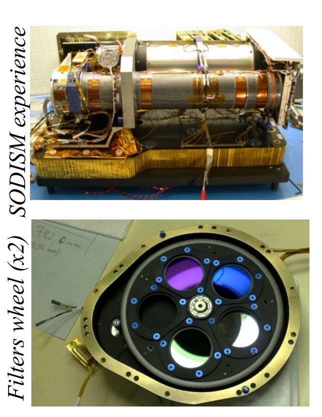
SUAVE: a FUV/MUV Imaging Telescope

Evolution of SODISM/PICARD: no window, SiC mirrors, new "thermal" door and radiators, in a thermally optimized off-axis configuration (homogeneity, no central hole, no back flux on secondary)

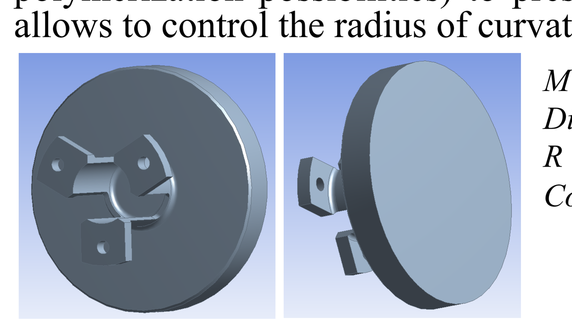
New SiC Mirrors: FUV long duty cycle and advantages:
- conducting
- homogeneous
- heat evacuation
- no coating (no degradation)
- 40% R in UV
- 20% R in visible



SUAVE optical design
Pupil 80 mm
M1 100 mm vertex inclined 0.15°
M2 28 mm vertex inclined 1.26°
Dimensions: 200x300x600 mm³

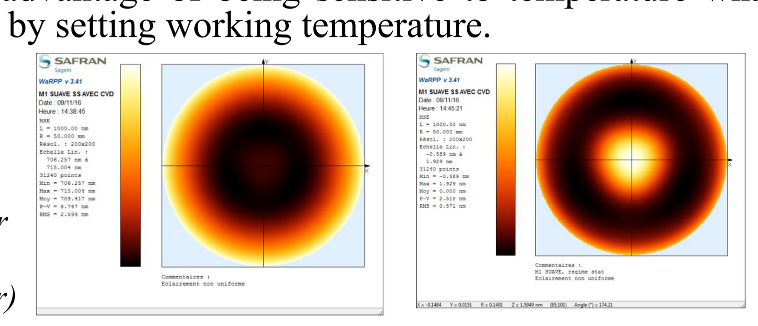


SUAVE is a FUV optimized version of SODISM (**diffraction limited**) with **SiC mirrors in an off-axis configuration** for long observations and ultimate thermal control (heat evacuation, focus control). SUAVE has no entrance window and hosts a main entrance baffle and a new implementation of the door to avoid Earth albedo returns. The radiator of the secondary mirror is increased to improve its cooling. Two radiators areadded: for the CCD and for the primary mirror M1. Using SiC (or CVD SiC) mirrors avoids the degradation of coatings (SiC "naked" reflects 40% in the FUV and 20% in the visible), the thermal load (SiC is homogeneous and conducting) and the flux on the filters (less than 2 solar constants: no or limited polymerization possibilities) to preserve their lifetime. SiC has also the advantage of being sensitive to temperature what allows to control the radius of curvature of the mirror (focal length control) by setting working temperature.



M1 SiC mirror of SUAVE
Diameter 100 mm (84 used)
R 1029.85 mm
Conicity -0.9657 mm

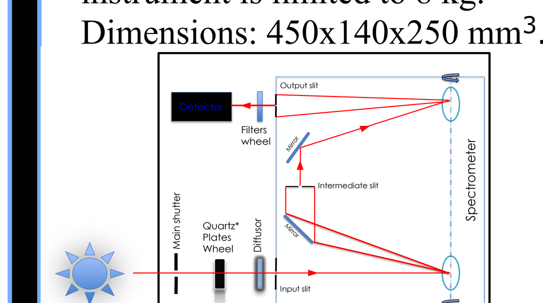
Exemple of SUAVE mirror thermal behavior (0.6 nm peak to peak surface error)



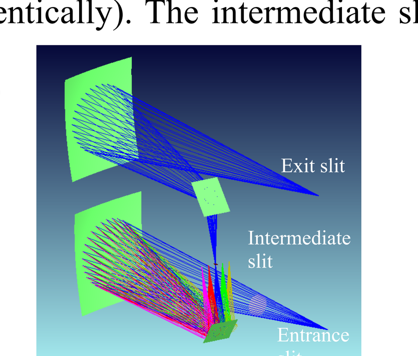
Opto-thermo-mechanical analysis of the SiC primary mirror of SUAVE (M1) in its nominal orbit and solar flux lightning configuration was carried by REOSC and showed that even in extreme conditions peak-to-peak surface error of the mirror stays in within prescriptions. Nominal interface plate (also in SiC) is controlled to 22°C. A representative breadboard of the M1 mirror and support plate is currently under realization for test of the concept in 2019.

SOLSIM: a UV Solar Spectral Irradiance Monitor

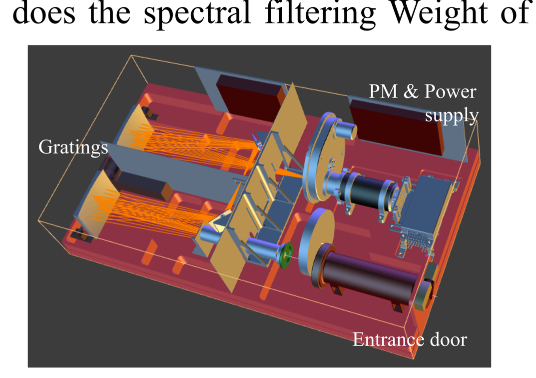
SOLSIM is based on the long experience acquired with the SOLSPEC instrument (SOLAR/ISS) by LATMOS and IASB. SOLSIM has only one subtractive double monochromator of the UV between 170 and 340 nm with an almost constant spectral resolution of 0.65 nm. Gratings have a common rotation axis (rotate identically). The intermediate slit does the spectral filtering Weight of instrument is limited to 8 kg.
Dimensions: 450x140x250 mm³.



SOLSIM concept



Subtractive double-monochromator



Preliminary mechanical implementation

3 Slits
- Entrance Slit : 4 mm × 0.2 mm
- Intermediate Slit : 4.2 mm × 0.21 mm
- Exit Slit : 4.4 mm × 0.3 mm

Etendue Diaphragm
- F/5 beam
- Diameter : 16 mm
- Position : 80 mm form Entrance Slit

2 Gratings G1 & G2
- Strictly identical Gratings
- Toroidal holographic gratings 2000 gr/mm
- Curvatures : 255.676 mm & 245.403 mm
- Position G1 : 250 mm from Entrance Slit
- Position G2 : 200 mm from Deviation Mirror M2
- Dimensions : (X) 62 mm × (Y) 76 mm

Beam Incidence angles vs Wavelength:
- $\lambda = 170$ nm $\Rightarrow \theta = 2.379$ deg
- $\lambda = 340$ nm $\Rightarrow \theta = 12.566$ deg

Deuterium lamps are replaced by UV diodes for calibration avoiding outgassing and thermal issues experienced with SOLAR/SOLSPEC.

Ozone and Earth Energy Radiative Balance Constellation

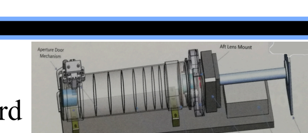
SoSWEET-SOUP is an evolution of the SUITS/SWUSV and SUMO previously proposed missions, acknowledging the scientific advantages of associating a constellation of 10 to 12 small satellites of some 20 to 40 kg (12 to 27 "U" or so nanosatellites) on equatorial orbits (+/- 20° in latitude) to the polar satellite (extreme events and SSI). The constellation includes precise ozone profiles measurements (miniGOMOS experiment with dual Sun and stars occultations derived from GOMOS/ENVISAT) and detailed Earth Energy Radiative Budget (ERB) monitors (miniSCARAB instrument derived from SCARAB/ENVISAT).

A constellation of – ideally – 12 satellites distributed on equatorial orbits (+/- 20°: less than shown on illustration).

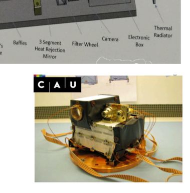
Other Instruments

(may also include another SSI instrument for cross-calibration purposes)

1 – **CCCOR** (*Coronal Context Coronagraph*) based on Goddard and KASI coronagraph program



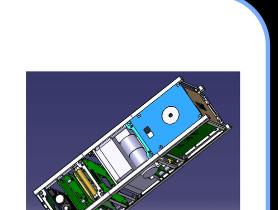
2 – **EPT-HET** (*Electron Proton Telescope & High-Energy Telescope*) for particles:
electrons: 20keV to 30 MeV
protons: 20 keV to 100 MeV
heavy ions: 10 to 200 MeV/nu



3 – Science grade vector **Magnetometer**

4 – Dual spherical **Langmuir Probes** (plasma density and temperature)

5 – **ERBO** *(Earth Radiative Budget & Ozone)* 6 wavelengths to measure ozone and a 0.1-100 µm radiometer (based on SIMBA/ESA nanosat to be launched in 2017; artist view on the right)



Conclusion

The SoSWEET-SOUP microsatellite and constellation program is unique, answering the needs for early detection of Flares and CMEs, and their prediction, and for understanding the ultraviolet variability influence on climate by providing the necessary tools to measure and quantify the FUV/MUV variability and its origins (sources of variability). The program benefits of the in-flight proven performances of SODISM and PREMOS/PICARD, LYRA/PROBA-2, SOLSPEC/SOLAR, GOMOS/ENVISAT and SCARAB ENVISAT, building on them and on our laboratories' expertise in FUV/MUV imaging and measurements. Instruments' design is well advanced and we expect, following further progresses in thermal and mechanical modeling, to rapidly validate concepts on appropriate breadboards (TRL ≥ 6). Program is supported by a CNES R&T and is to be proposed to future small missions calls of CNES, ESA and NASA. SoSWEET-SOUP is an enhanced version of SUITS/SWUSV centered on solar UV spectral variability and its influence on climate, extreme events prediction, ozone global coverage and Earth energy radiative balance (polar satellite using a OneWeb platform type and constellation of ozone/ERB nanosatellites).

Background illustration: Lyman Alpha filtregram obtained in 1979 during the first rocket flight of the Transition Region Camera (TRC) and yet having the best spatial resolution (1 arcsec) for a full disk Lyman Alpha image of the Sun.