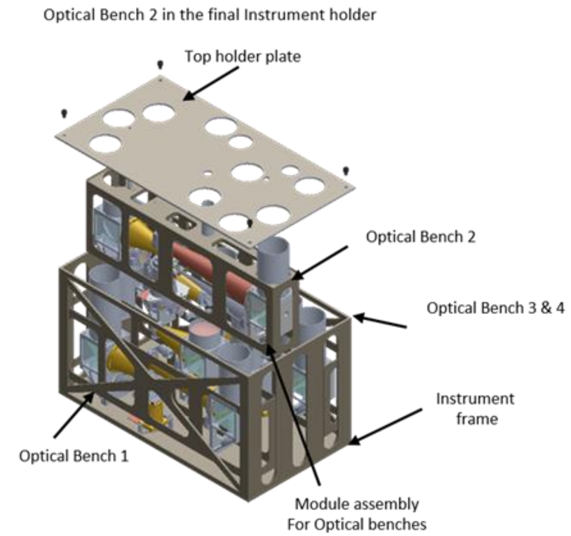
The GLO (GFCR Limb Occultation) Sensor: *A New Sensor Concept for Upper Troposphere and Lower Stratosphere (UTLS) Composition and Transport Studies.*



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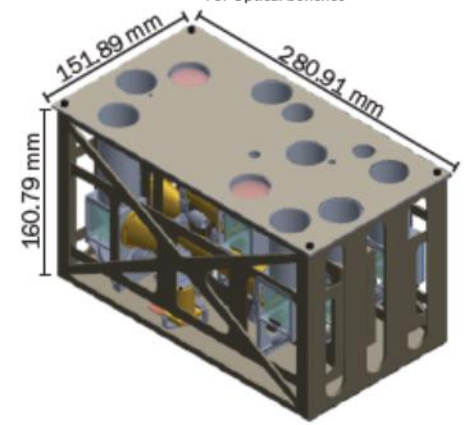

Earth Science Technology Forum 2018

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Introduction

- **GLO is a VNIR/MWIR (0.45-4.0μm) solar occultation sensor for measuring trace constituents, aerosol and temperature in the upper troposphere and stratosphere at < 1 km vertical resolution.**
- **GLO was designed for a mission concept we refer to as SOCRATES (Solar Occultation Constellation for Retrieving Aerosol and Trace Element Species).**

SOCRATES Primary Goal:

Quantify the role of the upper troposphere/lower stratosphere (UTLS) in climate change

SOCRATES Primary Objectives:

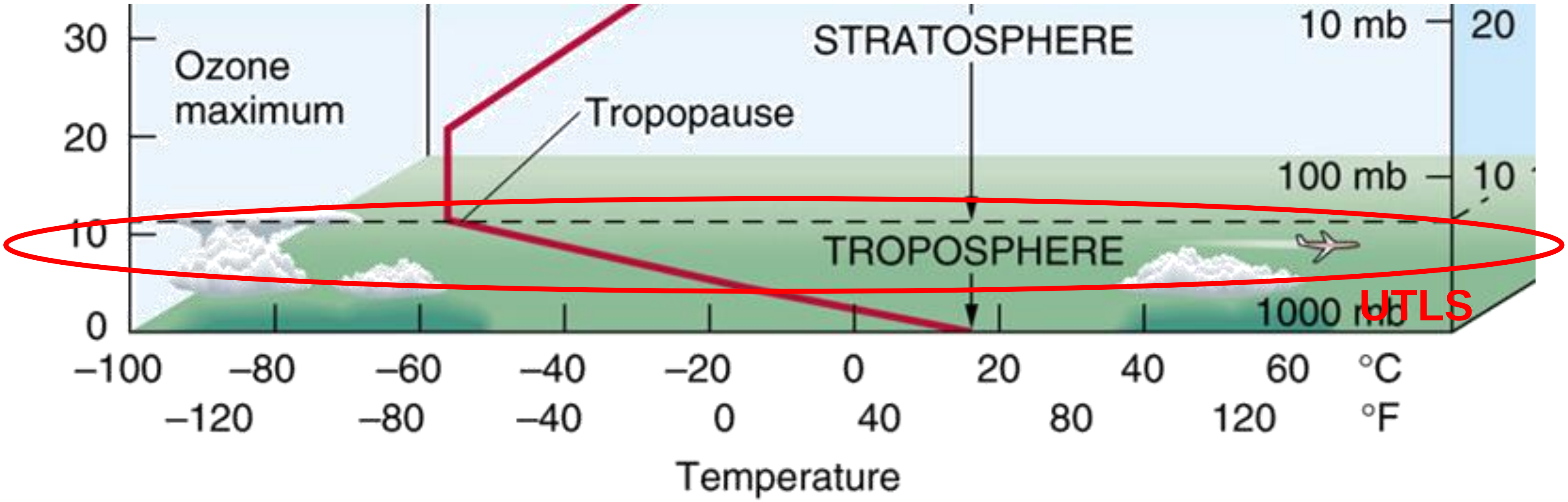
- Measure temperature, key radiatively species, and aerosol with sufficient precision, vertical resolution, and geographic coverage to quantify radiative forcing.
- Quantify UTLS transport pathways and their role in climate and climate change, providing critical data for model predictions.

Mission Implementation

- Fly a constellation of 6 GLO/MicroSats launched from a single launch vehicle

- **Under the NASA ESTO Incubator Program we have been funded to build and test a prototype GLO sensor to support the SOCRATES mission.**

The Upper Troposphere / Lower Stratosphere (UTLS)



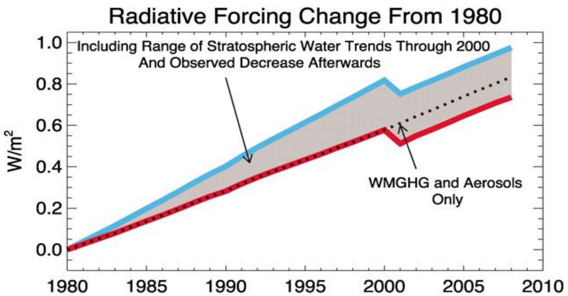
- The UTLS is the interface between the troposphere (temperature decreasing with height) and stratosphere (temperature increasing with height):
  - Both dynamically and radiatively complex
  - Difficult to monitor globally at sufficiently high vertical resolution
- The UTLS plays a key role in controlling the Earth's outgoing long-wave radiation flux and surface climate.
- Transport of constituents into and out of the UTLS is not well understood, with potentially important relevance to radiative forcing and climate modeling.

Recent composition changes in the UTLS have significant implications for climate change but are not understood.

H_2O trends:

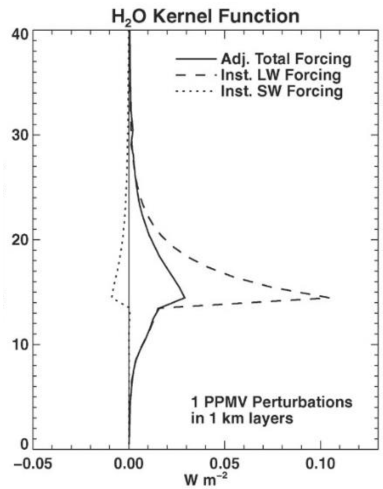
1980-2000: up to 0.5 ppmv/decade increase
2000-2001: ~0.5 ppmv decrease

Solomon et al., 2010



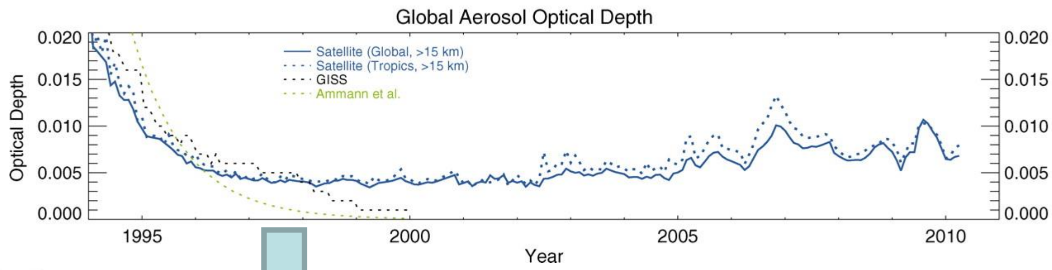
H_2O radiative forcing:
1980-1998: +0.24 Wm^{-2}
(CO2 forcing: ~+0.36 Wm^{-2})

1996-2005: -0.098 Wm^{-2}
CO_2 forcing: ~+0.26 Wm^{-2}



LS aerosol trends:

2000-2010: 4-7% per year from increase (Hoffman et al., 2009)



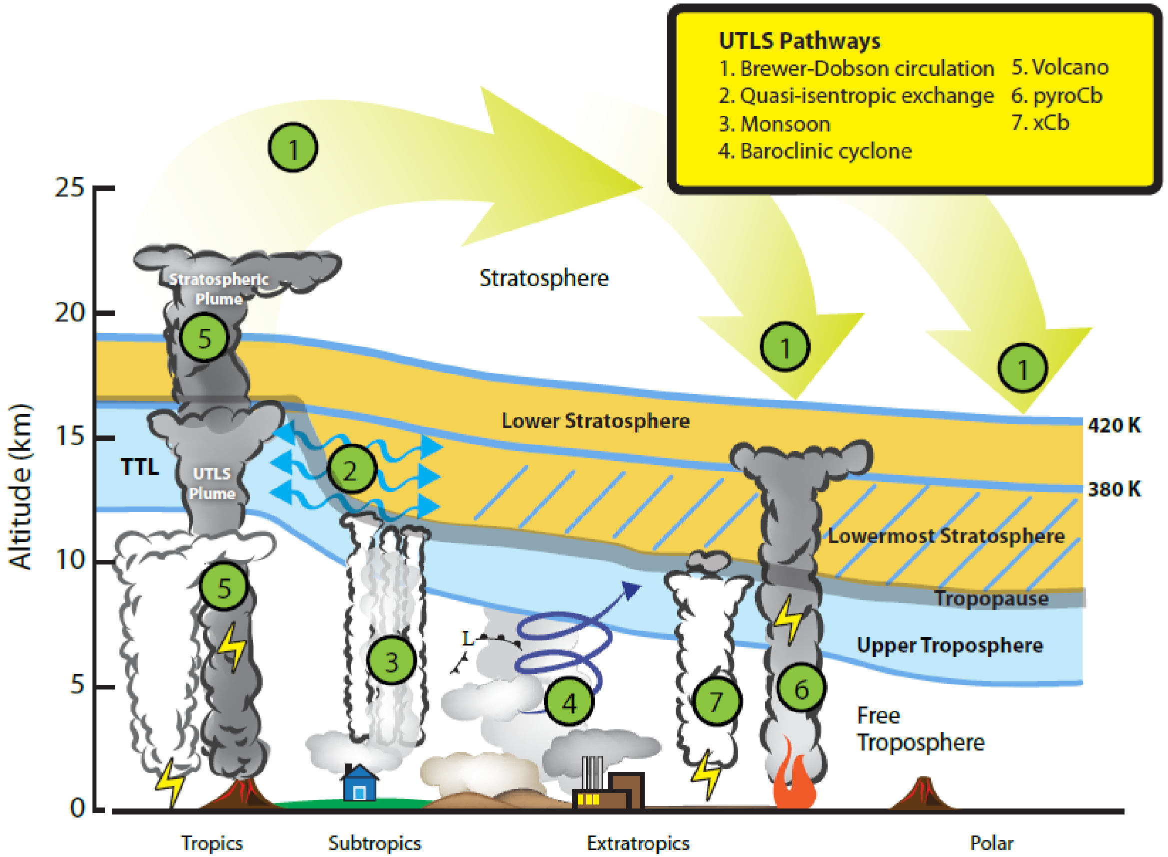
Solomon et al. 2011

Aerosol radiative forcing:
2000-2010: ~-0.19Wm^{-2}
45% of forcing between trop and 15 km
Ridley et al., 2014

Combined effects resulted in a negative (cooling) radiative forcing of ~80% of the positive CO_2 forcing (warming) during the 2000-2009 period

The cause of these changes is not well understood: indicative of importance of UTLS transport

GLO designed to study the role of the UTLS in the climate system by quantifying transport pathways which establish the composition of the UTLS



- These processes are expected to change as the climate changes
- The way in which these predicted changes will alter the composition of the UTLS, and resultant radiative forcing impacts, represent potentially important climate feedbacks that are currently unquantified.

GLO Relevance: 2017 Decadal Survey (Excerpts from the Climate Variability and Change Panel)

- *Question C9: "How are the abundance of ozone and other trace gases in the troposphere and stratosphere changing and what are the implications for the earth's climate.*
- *Question C5: How do changes in aerosols affect the earth's radiation budget and offset global greenhouse gas increase warming….?*
- **Question C2: *"How can we reduce the uncertainty in the amount of future warming…."***
  - ***C-2g (Very Imp't): "Quantify the contribution of the UTS to climate feedbacks and change…."***
    - ***Measurements: Vertical profiles in the UTS of: temperature, radiatively active gases, aerosol radiative properties, volcanic and biomass burning emissions, deep convective clouds, small-scale transport and the Brewer-Dobson transport, dynamical features such as the polar vortex, planetary and gravity waves, stratospheric ozone and related constituents. Measurement vertical resolution < 1 km.***
- **Decadal Survey also points out that the present Program of Record (POR) going forward does not include vertical profiling for species other than ozone, and aerosol**

The GLO sensor and SOCRATES mission concept, which could contribute in a substantial way to UTLS composition and transport studies, are responsive to the Decadal Survey

GLO Measurement Requirements

A measurement system designed to study UTLS composition, transport and radiative impacts needs the following attributes:

- **Constituent Measurements:**
  - **Key non-well mixed radiatively active gases important in the UTLS.**
  - **Atmospheric aerosol (extinction plus composition identification)**
  - **Suite of long-lived tracers for quantifying transport pathways that control the distribution of radiatively active constituents**
  - **Gases important in stratospheric ozone photochemistry**
- **Altitude Range: 3 km below the tropopause to 50 km.**
- **Vertical Resolution: ≤1 km (driven by the vertical scale of radiative processes).**
- **High precision and accuracy: to delineate and distinguish transport pathways (established by field measurements).**
- **Capability to make measurements in the presence of aerosols.**

Proposed Sensor Solution:

- **VNIR/MWIR GFCR.**
- **Solar occultation.**
- **Suitable for orbital constellation:**
  - **SmallSat compatibile**
    - **Inexpensive**
    - **Small SWAP**
    - **Modest s/c requirements**

GLO Measurements

- **Constituent Measurements:**
  - **Key radiatively active gases: H_2O, O_3, CH_4, N_2O**
    - **CO_2 not required because of its long lifetime and small vertical gradients**
    - **CFCs not required because of their long lifetimes.**
  - **Aerosol extinction from the visible to MWIR (for integrated properties of the aerosol size distribution, and particle composition identification)**
  - **Transport tracers: HCN, CO, HDO, HF, HCl**
  - **Temperature**
- **Altitude Range: 3 km below the tropopause to 50 km.**
- **Vertical Resolution: 0.5 km (from 600 om orbit)**
- **High precision and accuracy (including in the presence of heavy aerosol loading).**

Pathway	Diagnostic
Volcanic eruptions	ash,sulfates,HCl, SO_2
PyroCbs	Smoke,CO,CO_2,HCN
Baroclinc cyclones	Mineral dust
Deep convection (xCbs)	H_2O,HDO
Monsoon transport	O_3,H_2O,HCl,HDO,HCN
Brewer-Dobson and Quasi Isentropic Exchange	H_2O,O_3,CH_4,N_2O,HF, HCl

NASA Instrument Incubator Program has provided the opportunity to build a prototype GLO sensor and fly it on a high altitude (35 km float altitude) NASA balloon in September 2019

GLO Instrument Overview

Top system-level requirements (subset)

- **0.5 km vertical resolution from 600 km orbit**
- **SNR: 300,000:1 above the atmosphere**
- **MicroSat compatible SWAP**

Top level derived requirements (subset)

- **Image full sun for pointing knowledge - automated edge detection**
- **Solar diameter of 211 pixels for signal aggregation (supports SNR and vertical resolution requirements)**

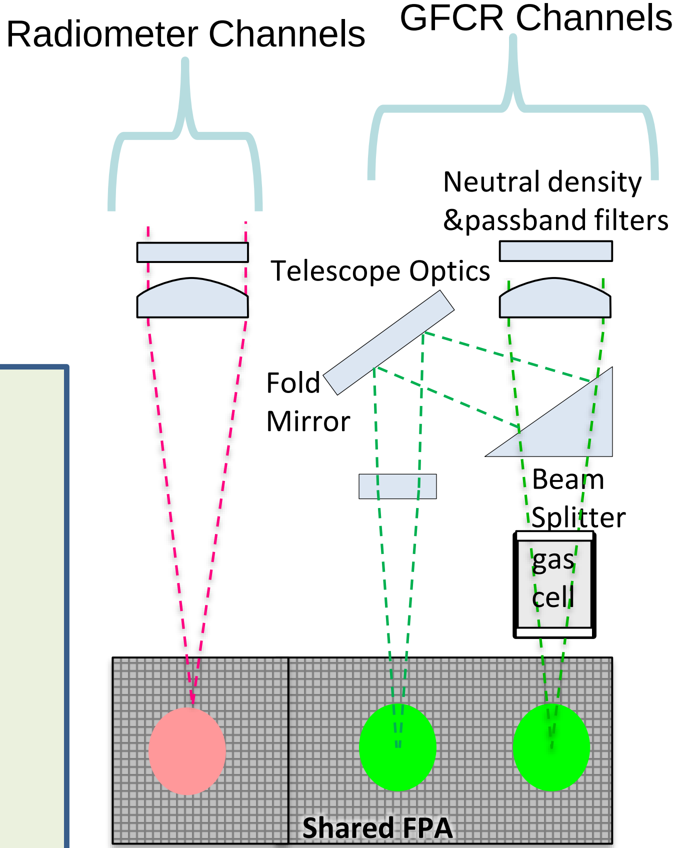
9 GFCR Channels

Channel	λ_0 (μm)	$\Delta\lambda$
CH_4	2.305	0.0461
CO	2.335	0.0537
HF	2.455	0.0491
O_3	2.475	0.0371
H_2O	2.503	0.0626
HCN	3.005	0.0601
HCl	3.380	0.1014
HDO	3.710	0.1113
N_2O	3.905	0.0976

5 Single (broadband) Radiometer Channels

Channel	λ_0 (μm)	$\Delta\lambda$
aerosol	0.45	0.0045
aerosol	1.02	0.0102
aerosol	1.556	0.0156
H_2O	2.60	0.052
CO_2	2.80	0.056

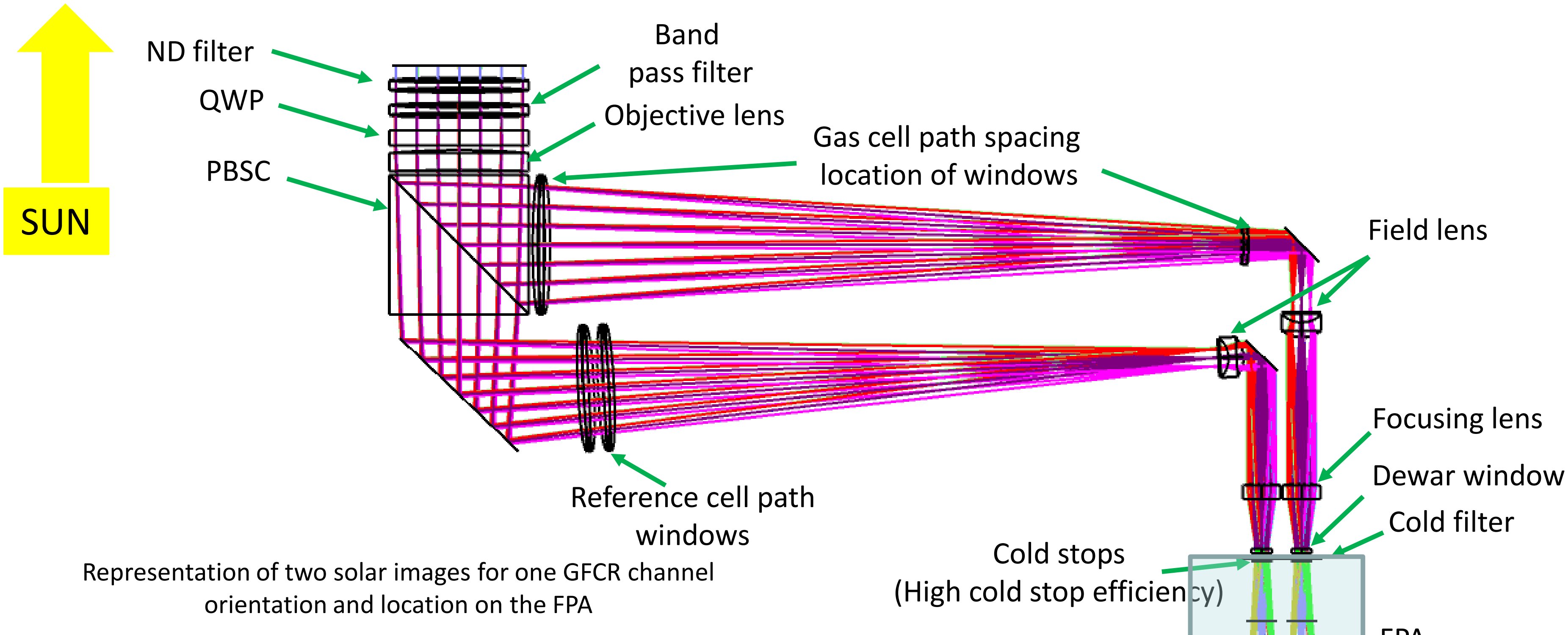
Basics of instrument approach

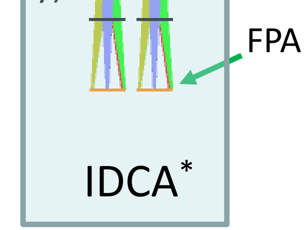


6 images of the sun on each detector

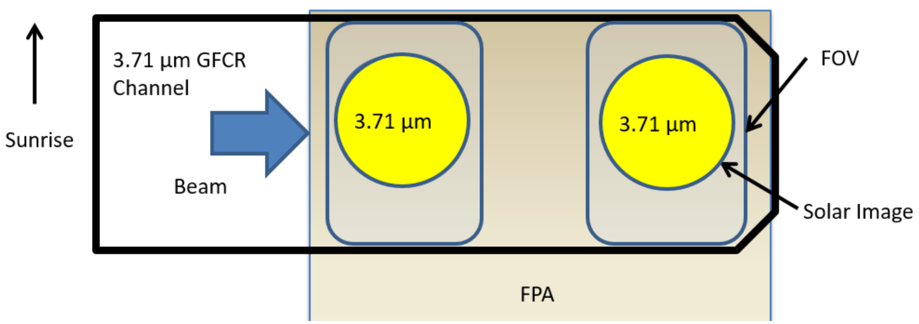
Optical telescope configuration

Telescope for the 3.71µm (HDO) channel



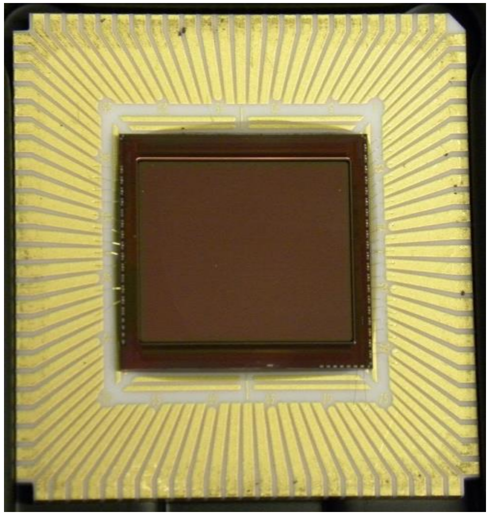


Representation of two solar images for one GFCR channel orientation and location on the FPA



*Integrated Detector & Cooler Assembly

GLO Enabling Technology



Lockheed Martin nbn SBF207 Focal Plane Array

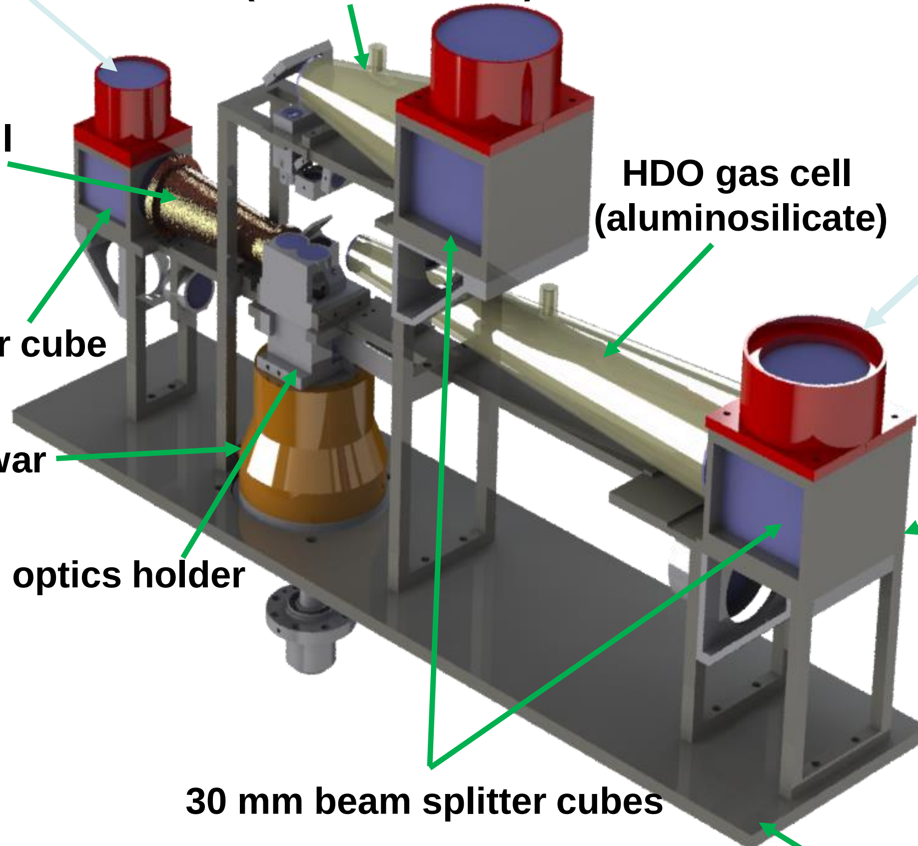
Size	1280 x 1024 pixels
Pixel pitch	12 microns
A/D	13 or 14 bit
Frame Rate	99 Hz full frame and 14 bit
Well Depth	2.05 million electrons
ROIC noise	300 electrons (max)
Responsivity	125 electrons/bit
Power	160 mWatts
Integration modes	Snapshot- integrate while or then read
Windowing	608 x 8 in 1 x 4 increments
QE	>80%
Operability	>99.5%
Readout	Direct injection

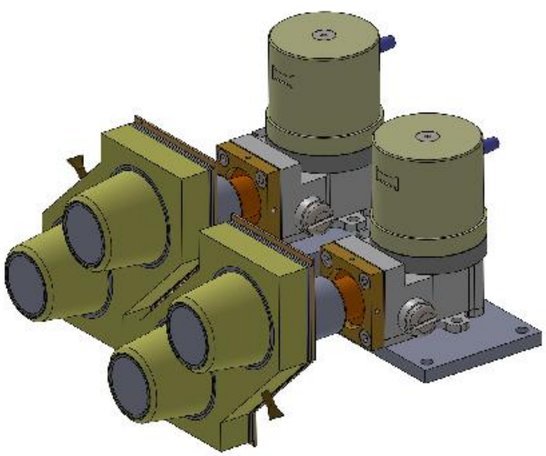
GLO uses 4 FPAs: 3 with 1.7-4.2 µm, 1 with 0.4-3.3 µm sensitivity

- **Ricor K508N is straight-forward update of model with significant space heritage.**
- **GLO uses 2 coolers (each unit cools 2 FPAs): operating temperature ~ 150K.**

Ricor K508N sterling cycle micro cryocooler

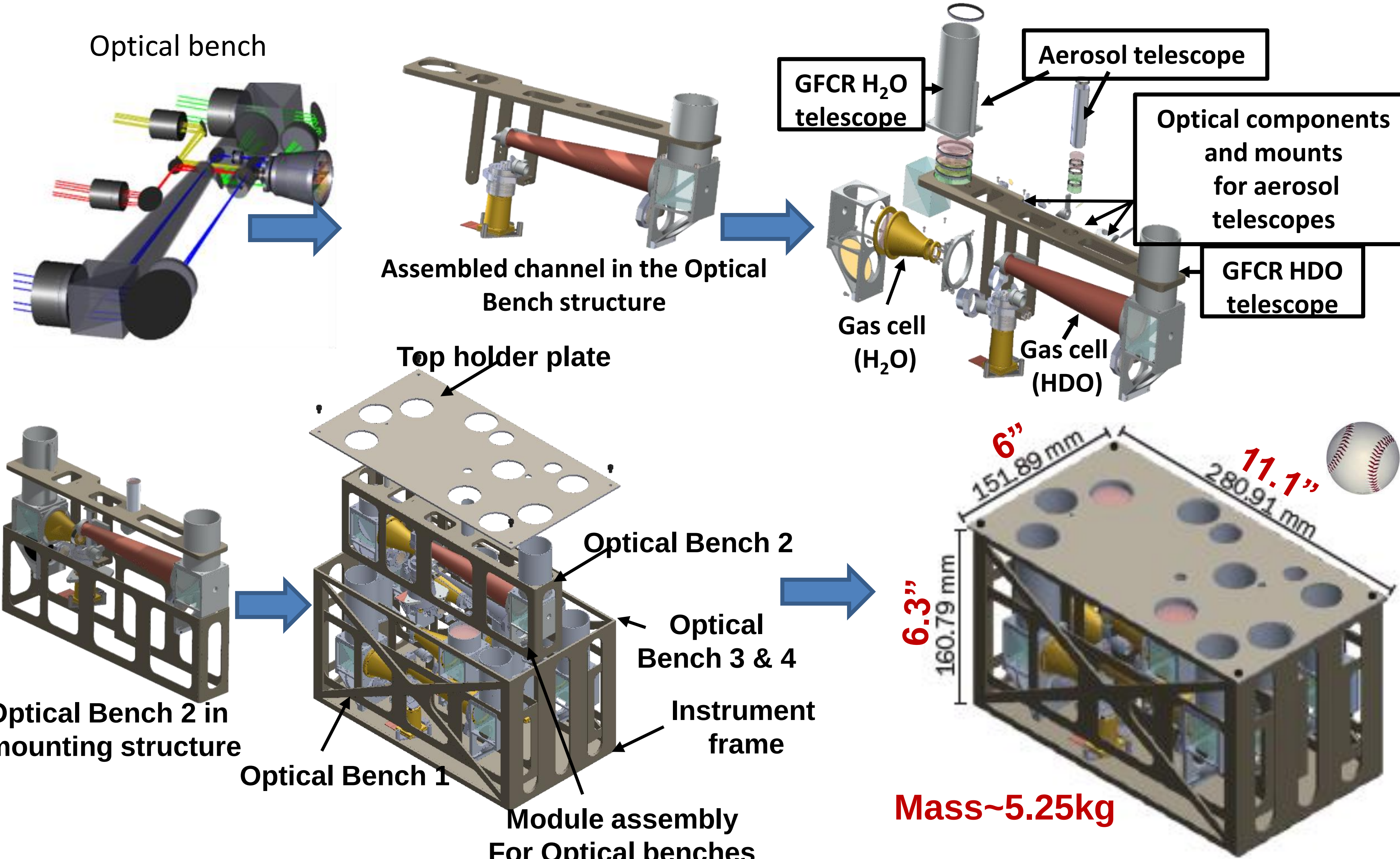
GLO Optomechanical Design (Optical Bench #4)



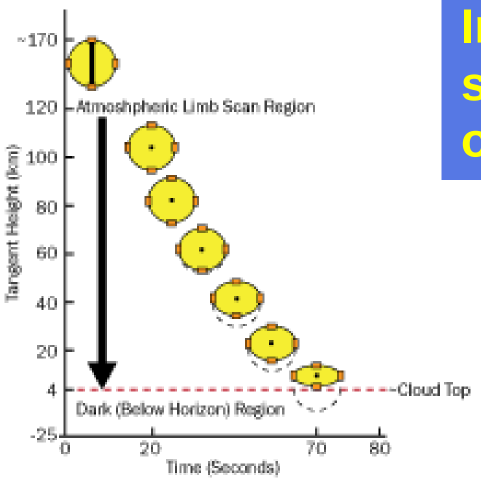


Teledyne Judson Integrated Detector Cooler Assembly (IDCA) Design

GLO Optomechanical Design



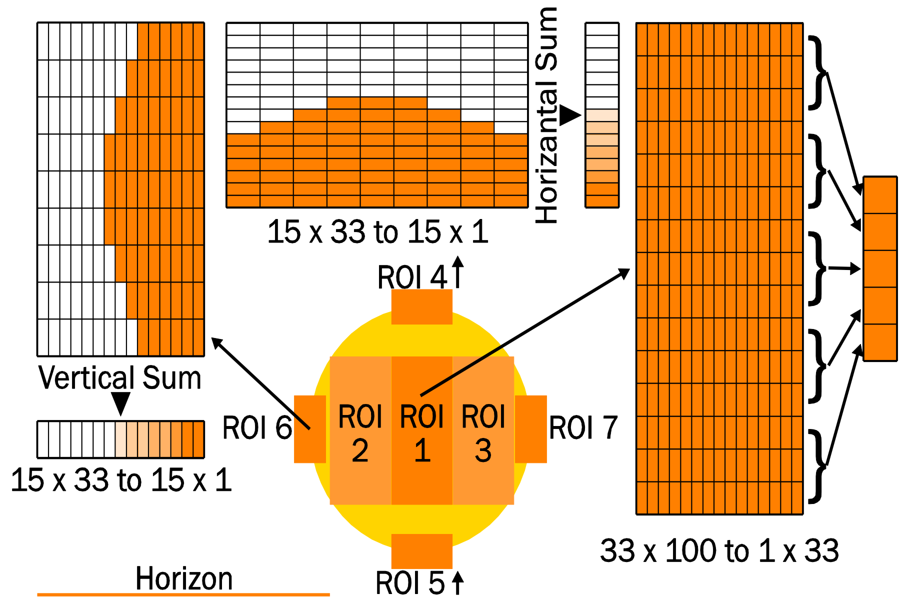
GLO Data Acquisition



In the GLO orbital configuration the sensor does not scan, rather the MicroSat inertially points the sensor optics toward the sun (~0.1° pointing accuracy required).

GLO uses the solar edge detection algorithm developed and used operationally on SOFIE for 10 years

- **1024x1280 FPA.**
- **6 images of the sun on each FPA.**
- **Solar diameter subtends 211 pixels:**
  - **From orbit ~125m/pixel**
  - **From balloon ~21m/pixel**
- **SOFIE demonstrated solar edge detection to ~1 m from orbit.**



GLO is Well Suited to Constellation Applications

The GLO instrument is designed to study UTLS composition, transport and radiative impacts. Its approach allows the following benefits for space flight applications:

- **SWAP allows for implementation on small (≤ ESPA class) spacecraft, allowing for constellation applications with flight from a single launch vehicle.**

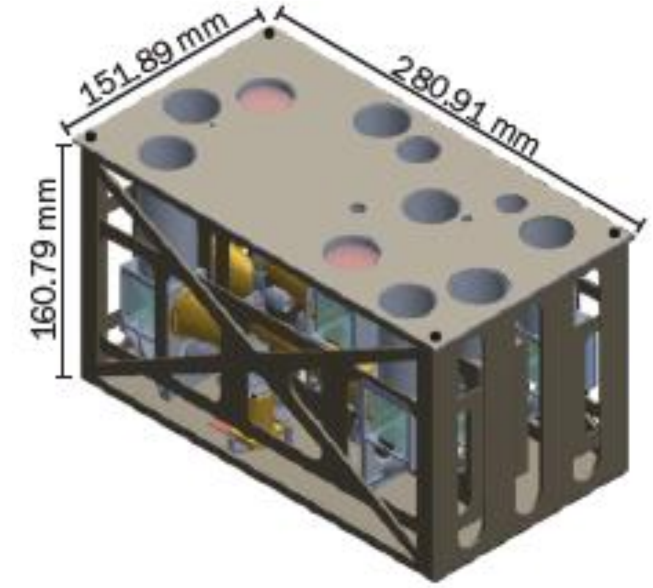
- **Solar imaging allows for very accurate pointing knowledge, while placing only modest requirements on the spacecraft pointing system.**

- **Very low impact from any decreases in sensitivity.**

- **Modest calibration requirements.**

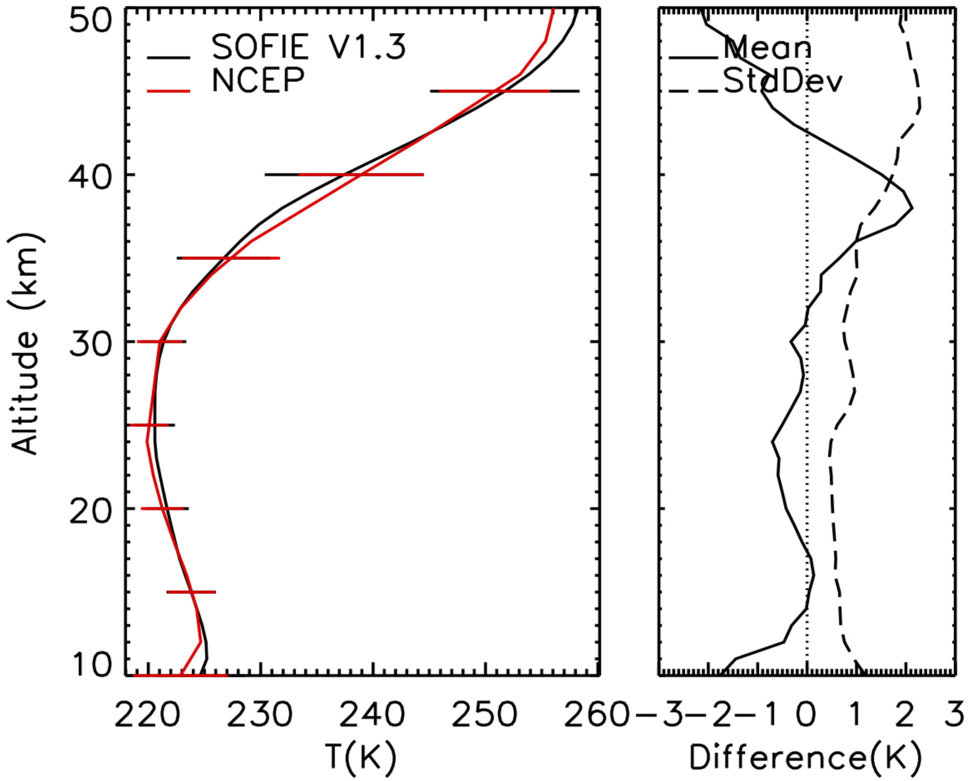
- **Modest alignment requirements.**

- **Full images are not required for data analysis, allowing for reasonable data downlink requirements.**



GLO Temperature Measurement

GLO will measure temperature using refraction and CO_2 absorption measurements (above 50 km) as done operationally on AIM/SOFIE for 10 years (Gordley et al., 2009, Marshall et al., 2011)

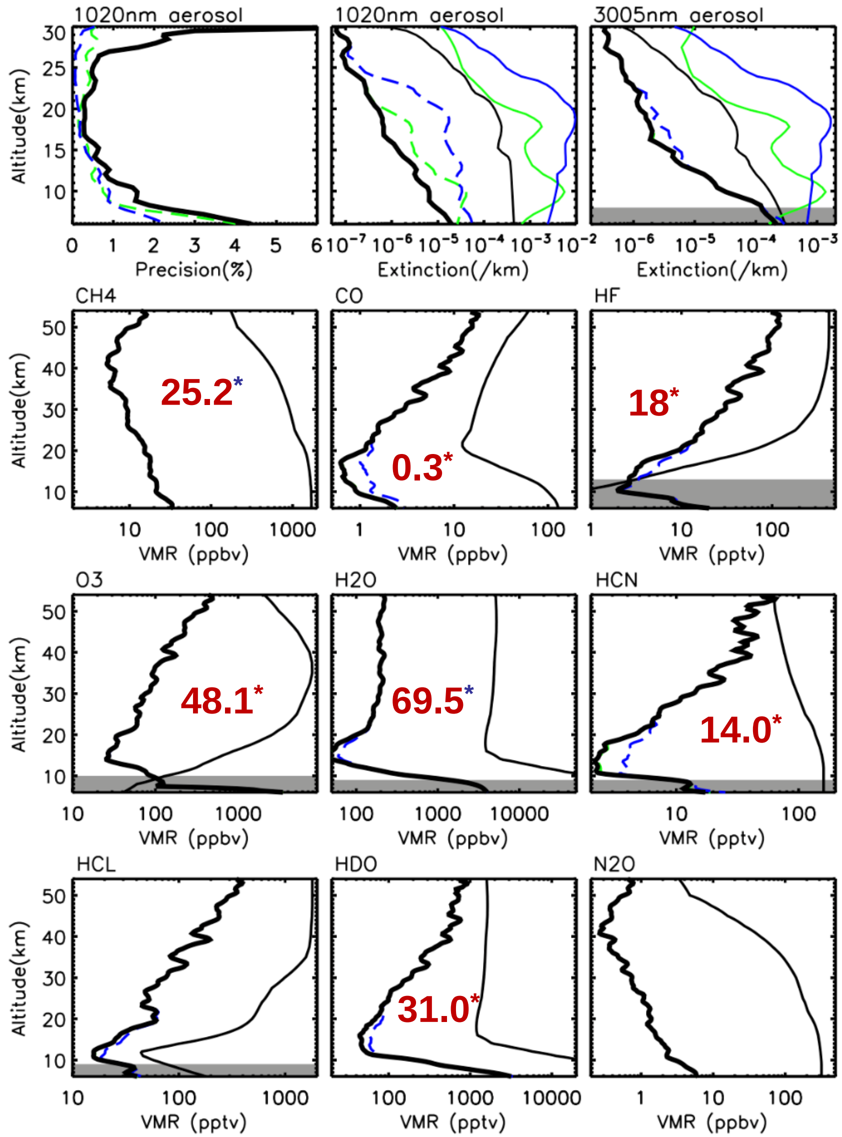


SOFIE/NCEP temperature retrievals: April, 2008, 75-80ºN

SOFIE has demonstrated T profiling with 0.5 km resolution, and precision of <1K

GLO Retrieval Simulation Analysis (Orbital Case)

- Retrieval performance for cloudless sky (1-σ precision including expected SNR, and interfering gas, Rayleigh scattering, and temperature uncertainties)
- 0.5 km grid
- Thick black line: background aerosol
- Green dashed line: moderate aerosol (Kasatochi + 1 month)
- Blue dashed line: heavy aerosol (Pinatubo+1yr)
- Thin lines: VMR or extinction profiles used in the analysis:
  - same color code as above
- Lower limit altitude (cloudless sky):
  - Gas retrievals: τ ≈ 3
  - Aerosol retrievals: τ ≈ 7 (≤ 5 km)
- Cloud top generally determines lower limit:
  - HALOE measurements showed 50% probability of measuring to >3 km below the tropopause.



*ACE (Atmospheric Chemistry Experiment) estimated error @20.5 km (in individual plot units)

GLO Aerosol Measurements
(GLO includes 3 VNIR spectrally pure bands)

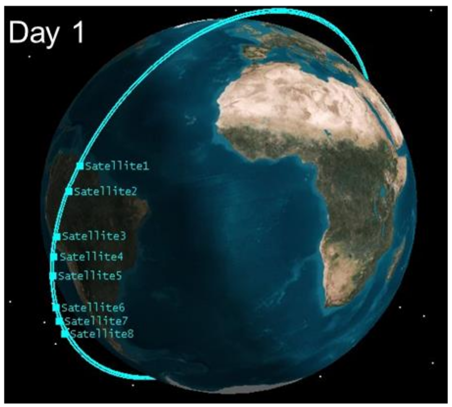
Channel/Type[1]	λ (μm), υ (cm^{-1}), Δυ (%)	Target Primary / Secondary	Interference (aerosol as target)	Aerosol Signal Fraction (%)[2], Bkg (Pinatubo 93-95)	Aerosol Error (%)[2,3,4], Bkg (Pinatubo 93-95)
1 / B	0.450, 22222, 1.0	aerosol	Rayleigh	40 (87)	7 (<1)
2 / B	1.020, 9804, 1.0	aerosol	Rayleigh	65 (91)	3 (<1)
3 / B	1.556, 6247, 1.0	aerosol	Rayleigh	80 (97)	1 (<1)
4 / G	2.305, 4338, 2.0	CH_4	CH_4, H_2O, N_2O, CO	6 (48)	75 (5)
5 / G	2.335, 4283, 2.3	CO	CO, CH_4, H_2O	6 (47)	78 (6)
6 / G	2.455, 4075.0, 2.0	HF / aerosol	HF, H_2O, N_2O, CH_4	17 (69)	24 (2)
7 / G	2.475, 4040, 1.5	O_3 / aerosol	O_3, H_2O, CH_4, HF	11 (63)	40 (3)
8 / G	2.503, 3995, 2.5	H_2O / aerosol	H_2O, O_3, CH_4, HF	9 (56)	51 (4)
9 / B	2.600, 3820, 2.0	H_2O	CH_4, H_2O	1 (20)	>100 (21)
10/ B	2.80, 3590, 2.0	CO_2	CO_2, H_2O	2 (22)	>100 (18)
11 / G	3.005, 3328.0, 2.0	HCN / aerosol	HCN, H_2O, CO_2, N_2O	25 (68)	14 (2)
12 / G	3.380, 2959, 3.0	HCl / aerosol	HCl, H_2O, O_3, N_2O, CH_4	7 (38)	53 (8)
13 / G	3.710, 2695, 3.0	HDO / aerosol	HDO, CH_4, CO_2	26 (68)	14 (2)
14 / G	3.905, 2561.0, 2.5	N_2O / aerosol	N_2O, H_2O, CO_2, CH_4	11 (48)	34 (6)

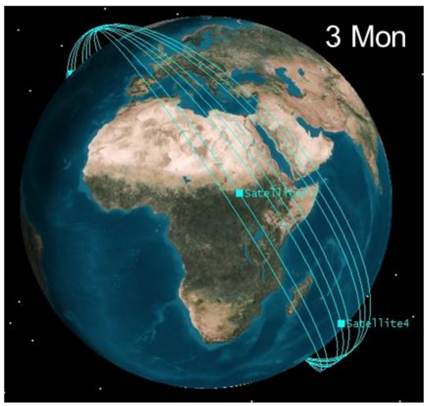
[1]G = gas correlation; B = broadband. [2]Based on in-situ SSA observations over Laramie (41°N). [3]Assuming 5% errors on all interference. [4]Best aerosol measurements (both high and low loading) encircled.

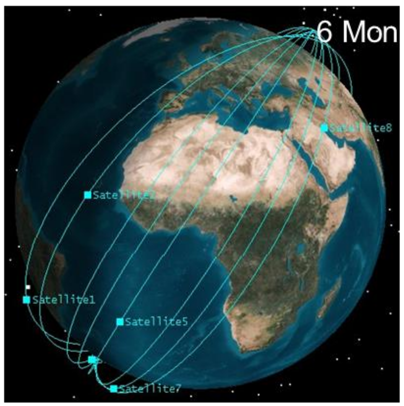
SOCRATES Mission Implementation I

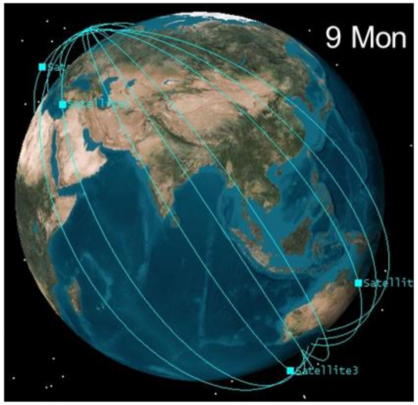
Analysis suggests that GLO has the measurement complement, vertical resolution, and precision for UTLS transport studies. The sparse solar occulation measurement coverage can be somewhat mitigated by a constellation approach. SOCRATES plans 6 satellites

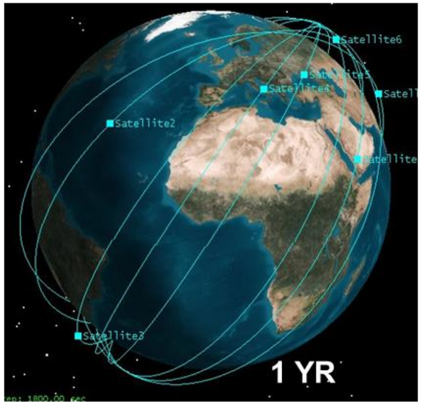
SOCRATES Approach: The Satellites are Launched From a Single Launch Vehicle and the Orbits Evolve over <~ 1 Year to Achieve Near-Global Coverage





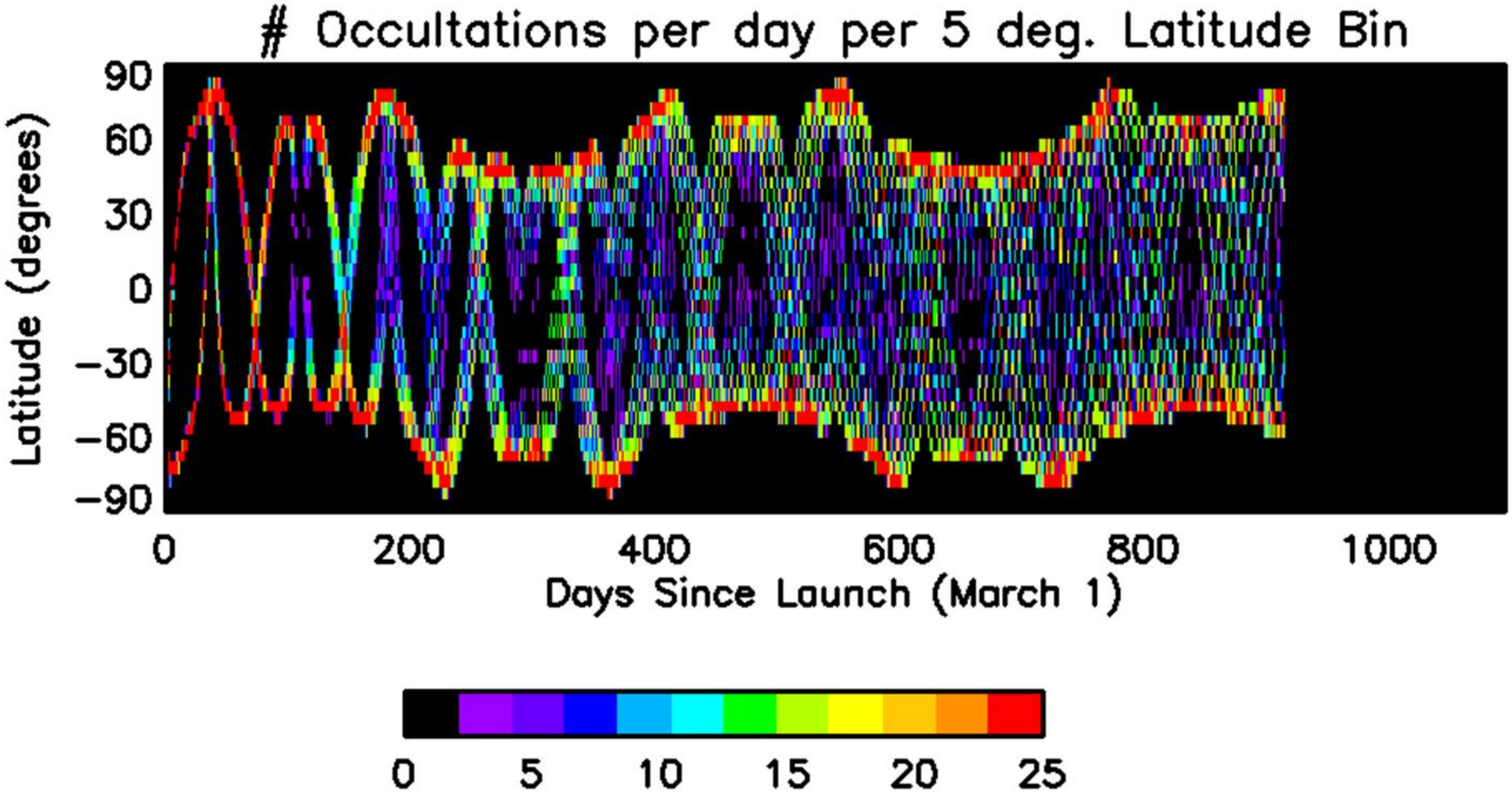




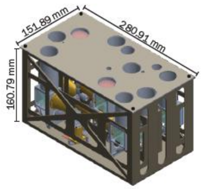


Immediately after launch, all satellites (blue lines) are in the same orbit plane. Due to slightly different precession rates, the satellite orbits spread over time such that within a year they are spread equally over the globe.

SOCRATES Approach: The satellites orbits evolve to achieve near-global coverage measurement coverage



GLO Schedule and Status



Current Schedule

April 2017	Project Initiation Meeting and SRR
Sep 2018	Sun tracker test balloon flight
April 2019	GLO Fabrication complete
April-June 2019	GLO checkout and ground-based testing
July 2019	GLO Environmental Testing
Sep 2019	First GLO Balloon flight test*
Sep-March 2020	Analysis of Balloon flight test data
Sep 2020	Second GLO Balloon Flight ?

*High altitude balloon flight from Fort Sumner with JPL MKIV instrument should provide complete instrument check out in relative environment

Current Project Status

- Optomechanical design complete.
- MWIR FPAs (Lockheed-Martin SBF207 NBN device) have been tested at AFRL. SWIR FPAs at AFRL for testing).
- Contract in place (Teledyne Judson) for Integrated Detector Cooler Assembly (IDCA).
  - Design review complete.
  - Few mods being incorporated.
- Most optical components ordered.
- Broad-band filters in house.
- Gas cell filters on order (HDO cell in-house).
  - HF cell handled separately.
    - Considering notch filter replacement for HF proxy cells.
- Electronics for prototype are mix of COTS and custom – COTS in place and tested, custom board design being finalized.

We are grateful to NASA ESTO for giving us the opportunity to demonstrate the GLO sensor concept