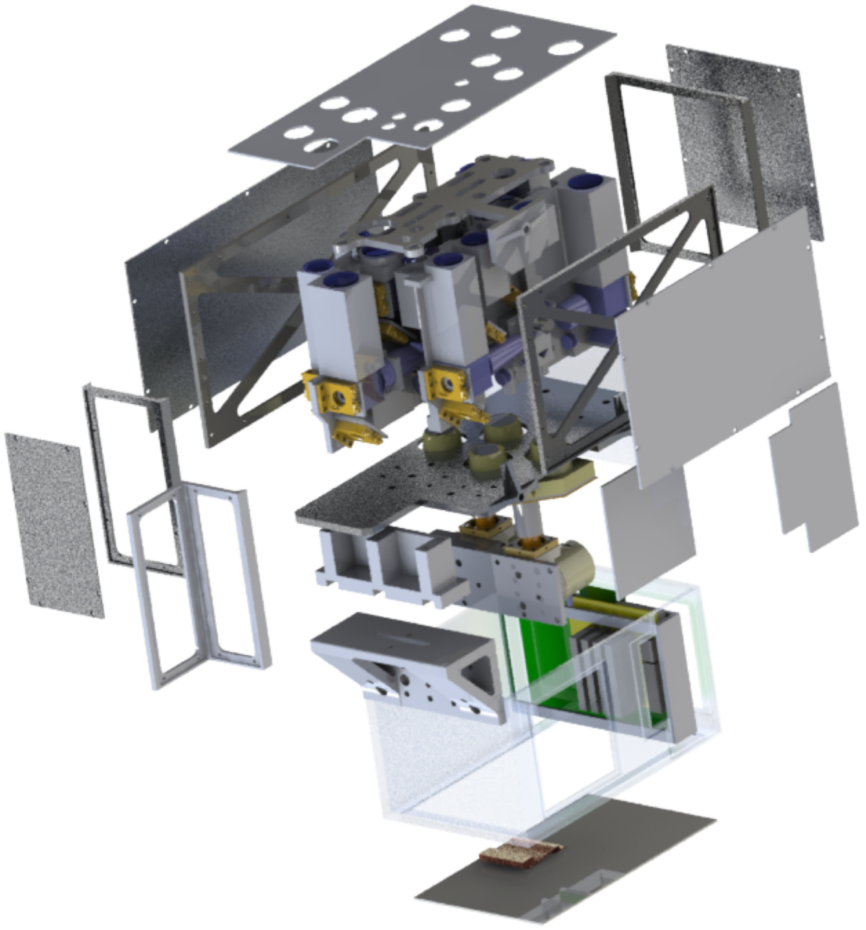
The GLO (GFCR Limb Occultation) Sensor: A New Sensor Concept for Upper Troposphere and Stratosphere (UTS) Composition and Transport Studies.

PI: Scott Bailey (Virginia Tech), DPI: Richard Bevilacqua (Naval Research Laboratory - NRL), Instrument Concept: Larry Gordley

Instrument: S. Restaino, D. Korwan, J. Bobak, F. Santiago (NRL)
Analysis: T. Marshall, and M. Hervig (GATS), K. Hoppel (NRL)

We are grateful for support from NASA / ESTO's IIP Program!



GLO was designed for a mission concept called SOCRATES
Solar Occultation Constellation for Retrieving Aerosol and Trace Element Species

SOCRATES Primary Goal:

To understand the processes that determine the variability and long term changes in composition (trace gases, aerosols, and clouds) in the upper troposphere and lower stratosphere (UTS) in order to reduce the uncertainty in our prediction of climate change.

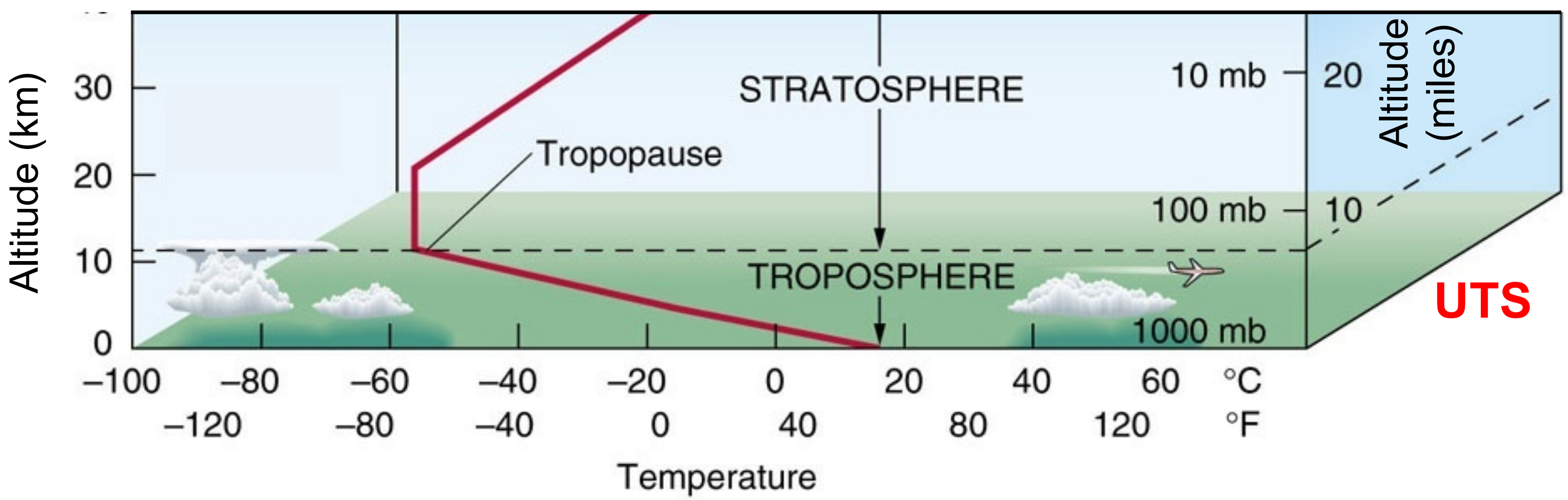
SOCRATES Primary Objectives:

1. Determine how radiatively important trace gases and aerosols in the UTLS vary in time and space, and quantify the key transport processes that control the distribution.

2. Determine the dominant UTS aerosol composition types and space-time distribution.

Mission Implementation

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



- The UTS 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 UTS 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 UTS is not well understood, with potentially important relevance to radiative forcing and climate modeling.

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

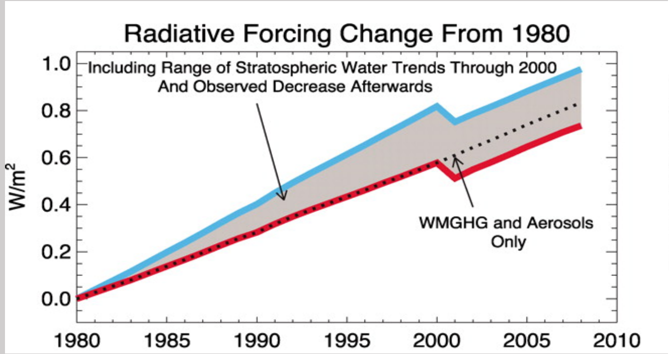
U.S. NAVAL RESEARCH LABORATORY GATS Global Atmospheric Technologies and Sciences VIRGINIA TECH

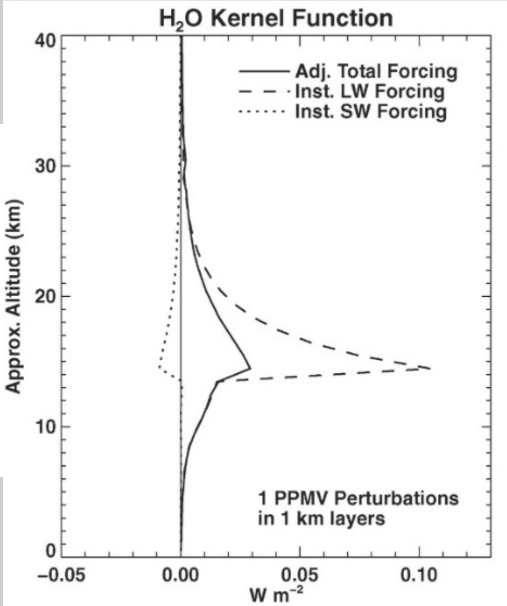
H_2O trends:

1980-2000: up to 0.5 ppmv/decade increase

2000-2001: ~0.5 ppmv decrease

Solomon et al., 2010

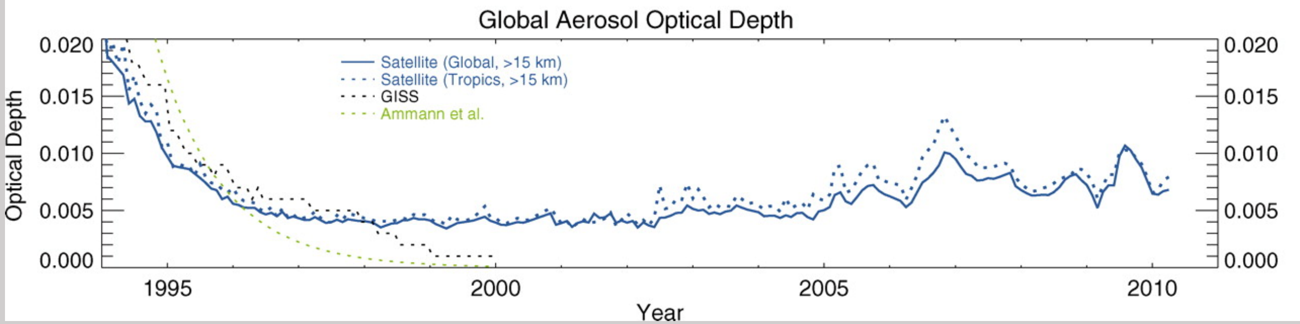




H_2O radiative forcing:
1980-1998: +0.24 Wm^{-2}
CO2 forcing: ~+0.36 Wm^{-2}

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

Lower Stratosphere Aerosol Trends:
2000-2010: 4-7% per year increase (Hoffman et al., 2009)



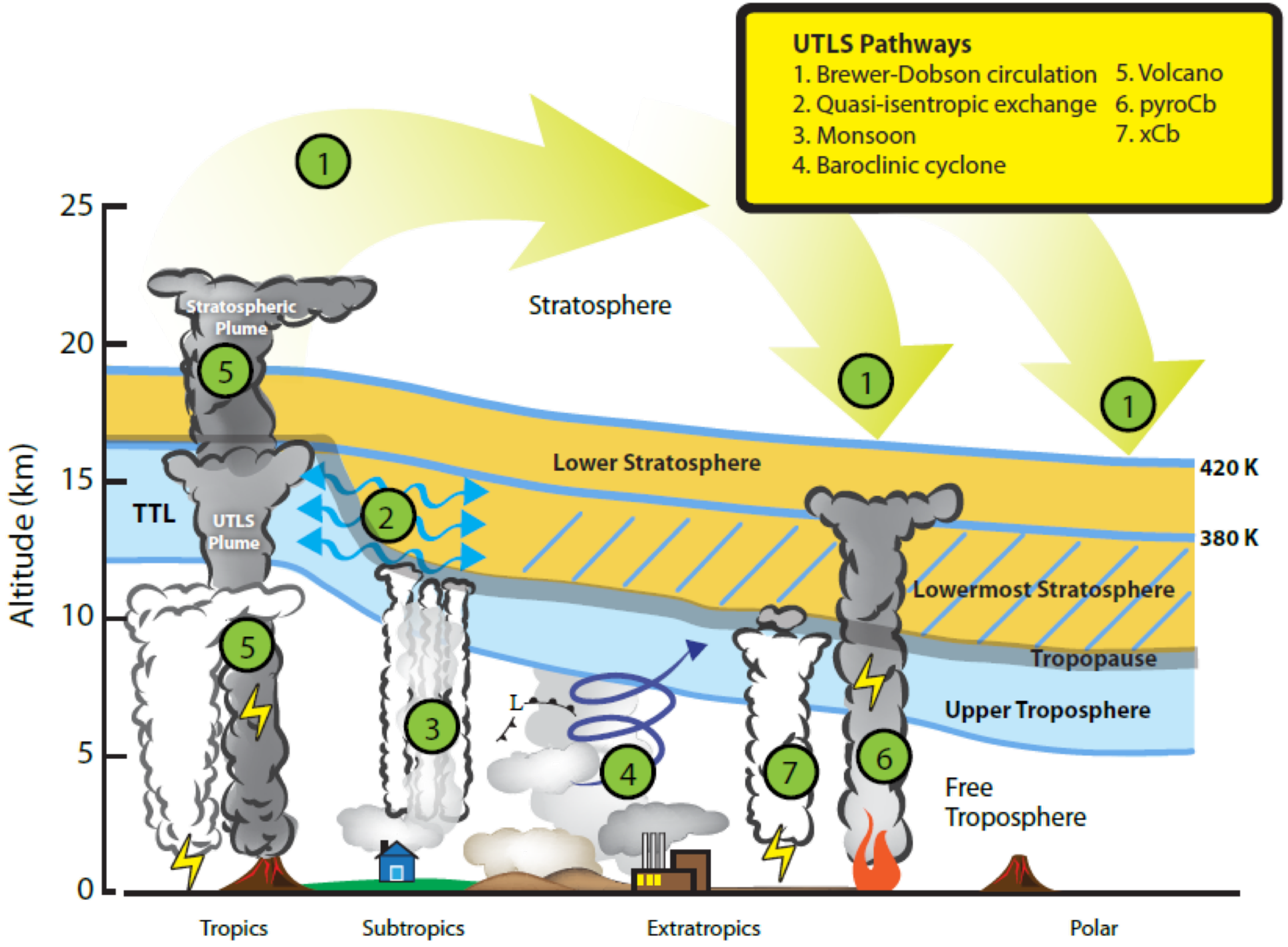
Solomon et al. 2011

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 UTS transport

GLO studies the role of the UTS in the climate system by quantifying transport pathways which establish the composition there.



- 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)

U.S. NAVAL RESEARCH LABORATORY

GATS Global Atmospheric Technologies and Sciences

VIRGINIA TECH

- *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 Important): "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.*

- The 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 UTS 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.**

Sensor Solution:

- **VNIR/SWIR 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 SWIR (for integrated properties of the aerosol size distribution, and particle composition identification)
- Transport tracers: HCN, CO, HDO, HF, HCl
- Temperature

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

- Altitude Range: 3 km below the tropopause to 50 km.
- Vertical Resolution: 0.5 km (from 600 km orbit)
- High precision and accuracy (including in the presence of heavy aerosol loading).

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

Top system-level requirements (subset):
- 0.5 km vertical resolution from 600 km orbit
- SNR: 300,000:1 above the atmosphere
- SWaP: 29x16x16cm (O), 5.25 kg (O), 28.2 W (O)

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)

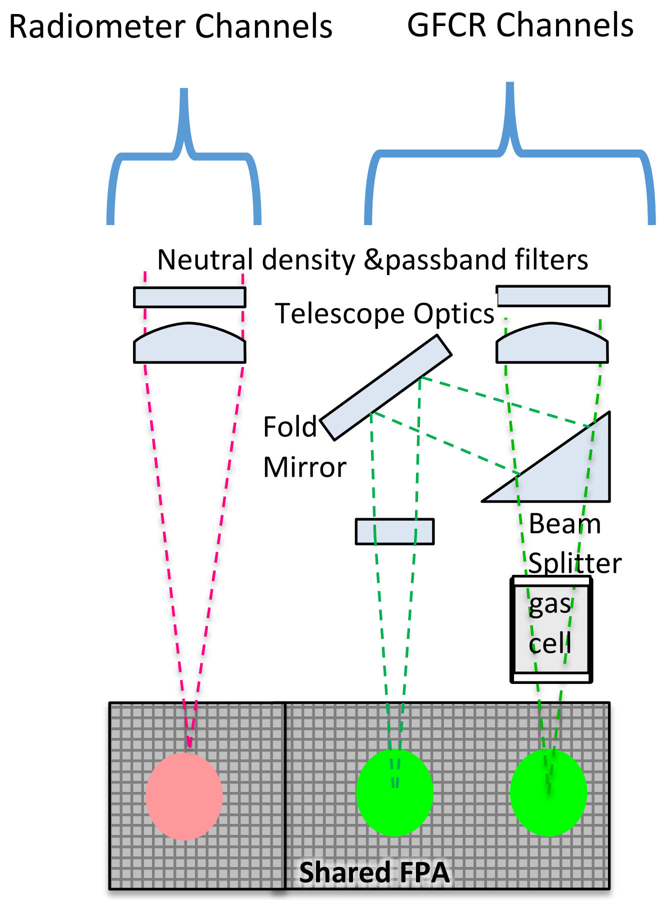
9 GFCR Channels

Channel	λ_0 (μm)	Δλ
CH_4	2.305	0.0461
CO	2.335	0.0537
HF	2.455	0.0491
0_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

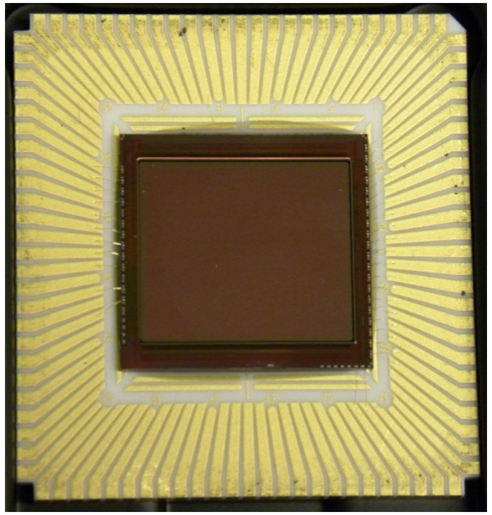
Channel	λ_0 (μm)	Δλ
aerosol	0.45	0.0045
aerosol	1.02	0.0102
aerosol	1.556	0.0156
H_2O	2.60	0.052
CO_2	2.80	0.056

Instrument Approach



6 images of the sun on each detector.

GLO Enabling Technology



Lockheed Martin nbn SBF207
Focal Plane Array

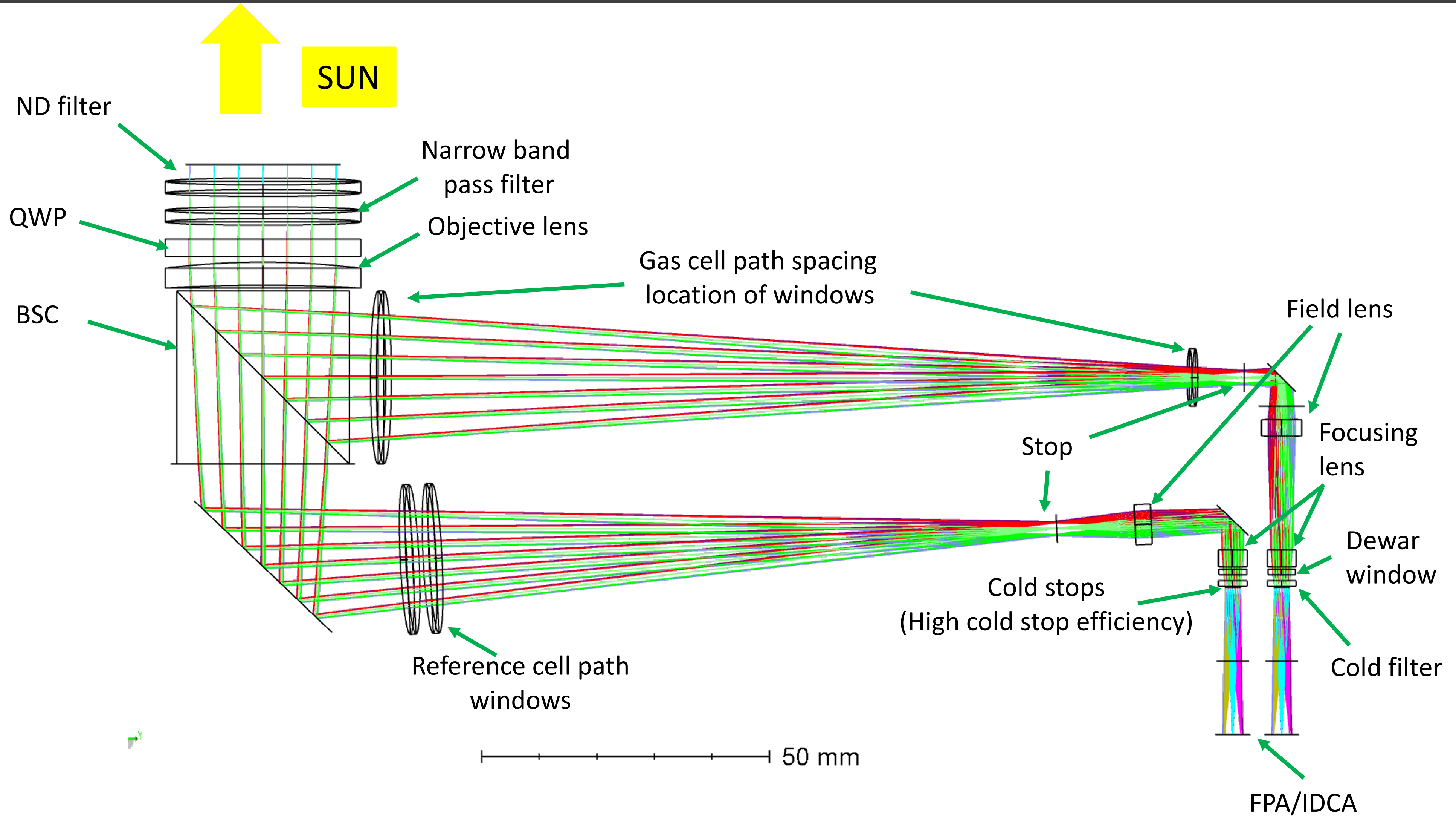
Size	1280 x 1024 pixels
Pixel pitch	12 microns
A/D	13 or 14 bit
Frame Rate	99 Hz full frame and 14 bit
Well Depth	2.05 million electrons
ROIC noise	300 electrons (max)
Responsivity	125 electrons/bit
Power	160 mWatts
Integration modes	Snapshot- integrate while or then read
Windowing	608 x 8 in 1 x 4 increments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

GLO uses 4 FPAs: 3 with 1.7-4.2 µm, 1 with 0.5-4.2 µm sensitivity (substrate removed)

Ricor K508N sterling cycle micro cryocooler

- **Ricor K508N has space heritage**
  - **Prototype uses the (mechanically identical) non-space qualified version of this cooler**
- **GLO uses 2 coolers (each unit cools 2 FPAs) as components of the Integrated Detector and Cooling Assembly (IDCA): operating temperature ~ 150K**

The GLO 3.71µm (HDO) channel



Key Instrument Elements:

Optics:
- 23 optical paths; ~ f\10;
- Beam splitters; Filters

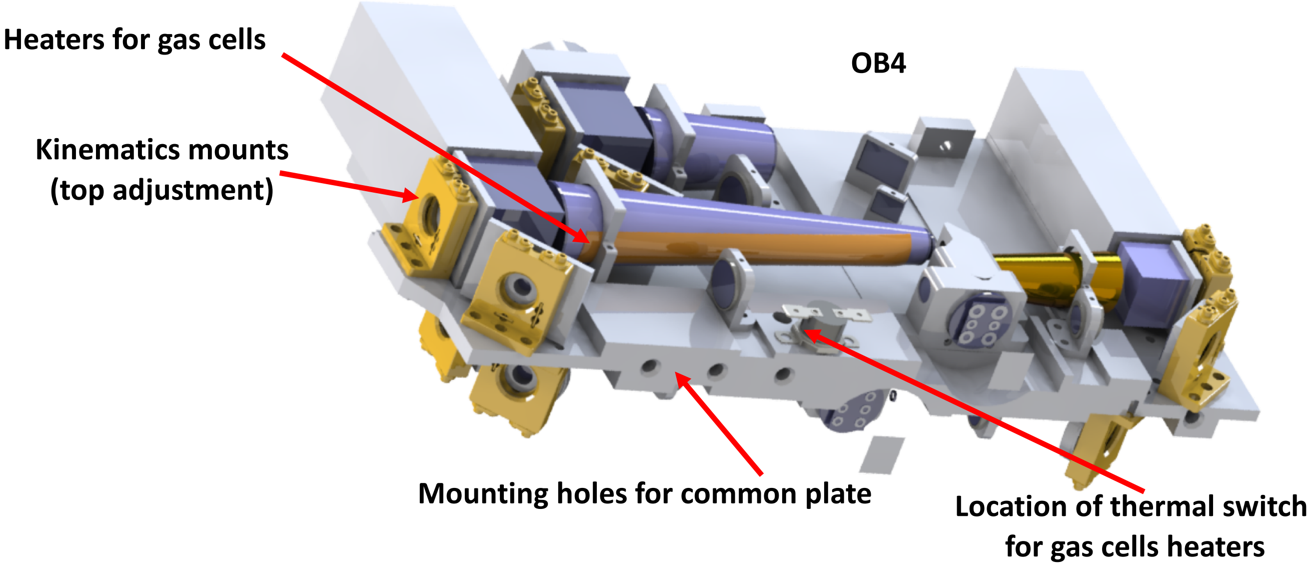
Gas Cells

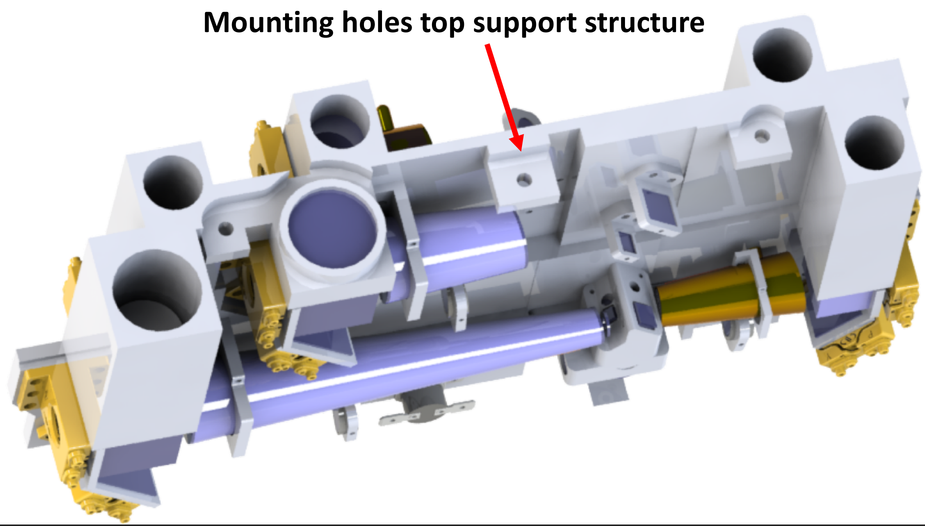
FPAs

Integrated Detector and Cooler Assembly (IDCA)

Modular Optical Bench (OB) design

- Each OB has 5-6 channels and is associated with single FPA
- OBs are mounted on opposite sides of a single structure, which is associated with a separable half of the IDCA
- Increased dimensions to accommodate kinematic mounts and COTS components:
  - Kinematic mounts for mirrors
  - Kinematic mounts for beam splitter cubes
- Open design for alignment
- OB support structures machined from a single piece

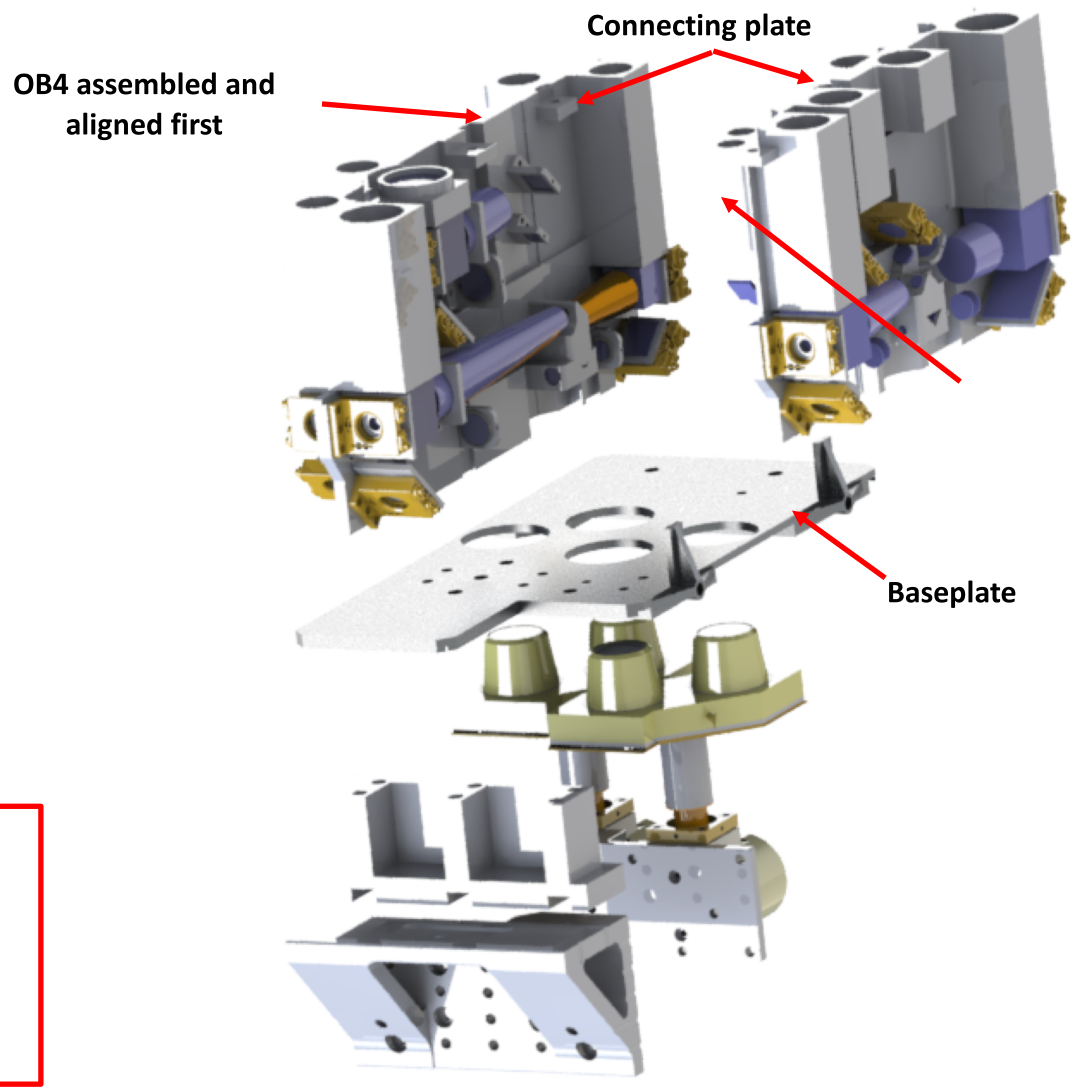




GLO Optomechanical Design II

Assembly and alignment

- Step 1: Mount IDCA to baseplate
- Step 2: OB4 is the first unit assembled and aligned (Interior OB)
- Step 3: Connecting plate is added
- Step 4: OB1 assembled and aligned (second interior OB).
- Step 5: Continue with OB3
- Step 6: Follow by OB2
- Step 7: Add frames and enclosures
- Step 8: Add ND filter plate
- Step 9: Mount to pan/tilt unit (IIP Instrument)



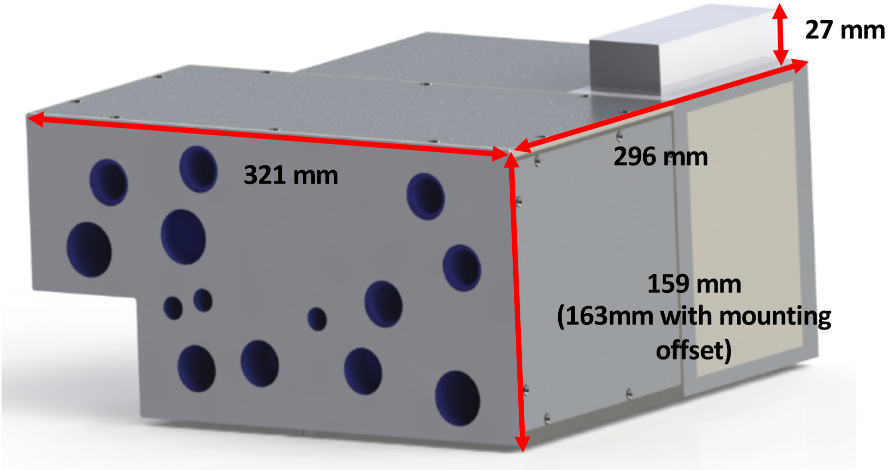
- ➢ The design allows for the OBs to be aligned horizontally with alignment adjustments from top
- ➢ Once all parts are assembled, there is access to kinematic components (including through OBs) for fine tuning prior to locking components

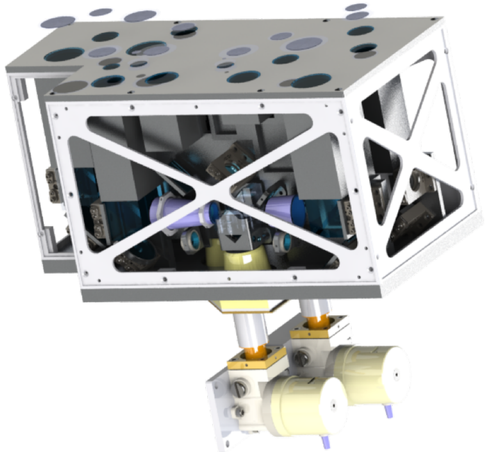
GLO is Well Suited to Constellation Applications

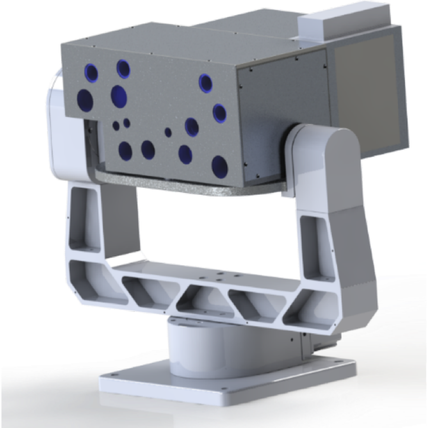
U.S. NAVAL RESEARCH LABORATORY | GATS Global Atmospheric Technologies and Sciences | VIRGINIA TECH

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

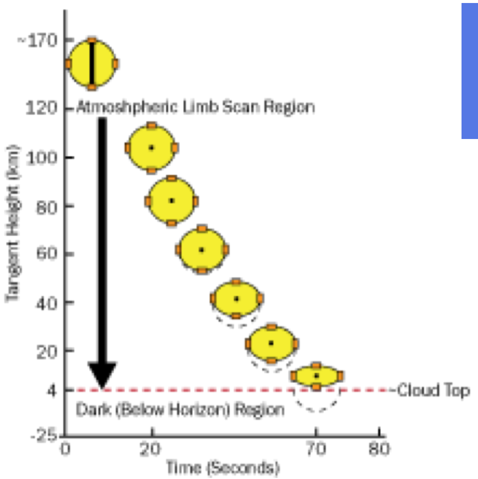
- SWAP allows for implementation on small (≤ ESPA class) spacecraft, allowing for constellation applications with flight from a single launch vehicle.
- Solar imaging allows for very accurate determination of the spacecraft pointing, while placing only modest requirements on the spacecraft pointing system.
- 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.







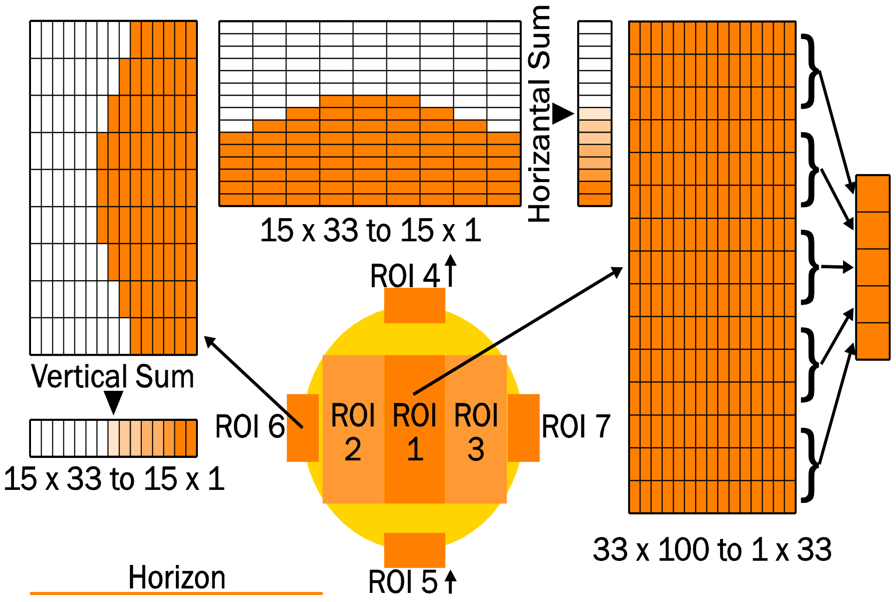
GLO Data Acquisition



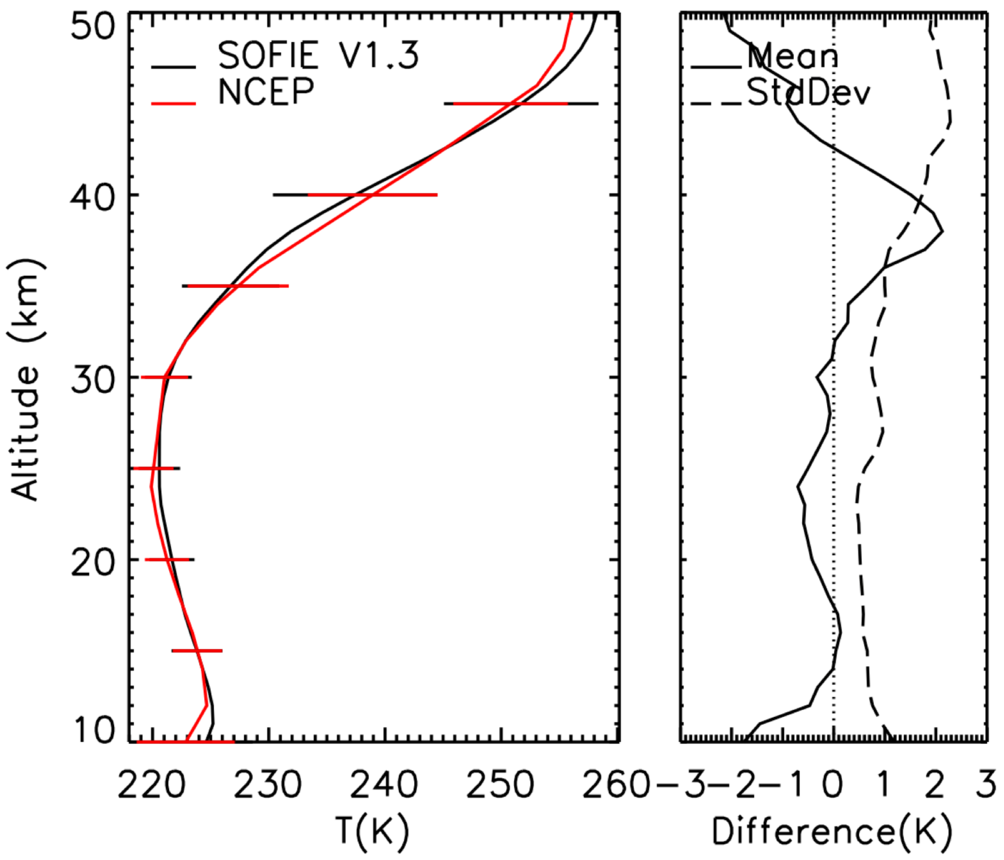
In the GLO orbital configuration the sensor does not scan, rather the MicroSat inertially points the sensor optics toward the sun (~0.1^o pointing accuracy required).

- **GLO uses the solar edge detection algorithm developed and used operationally on SOFIE for 10 years.**
- **This allows for downlinking only a small subset of the image data and placing only modest communications requirements on the spacecraft.**

- **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 (on the limb) from orbit.**



GLO Temperature Measurement



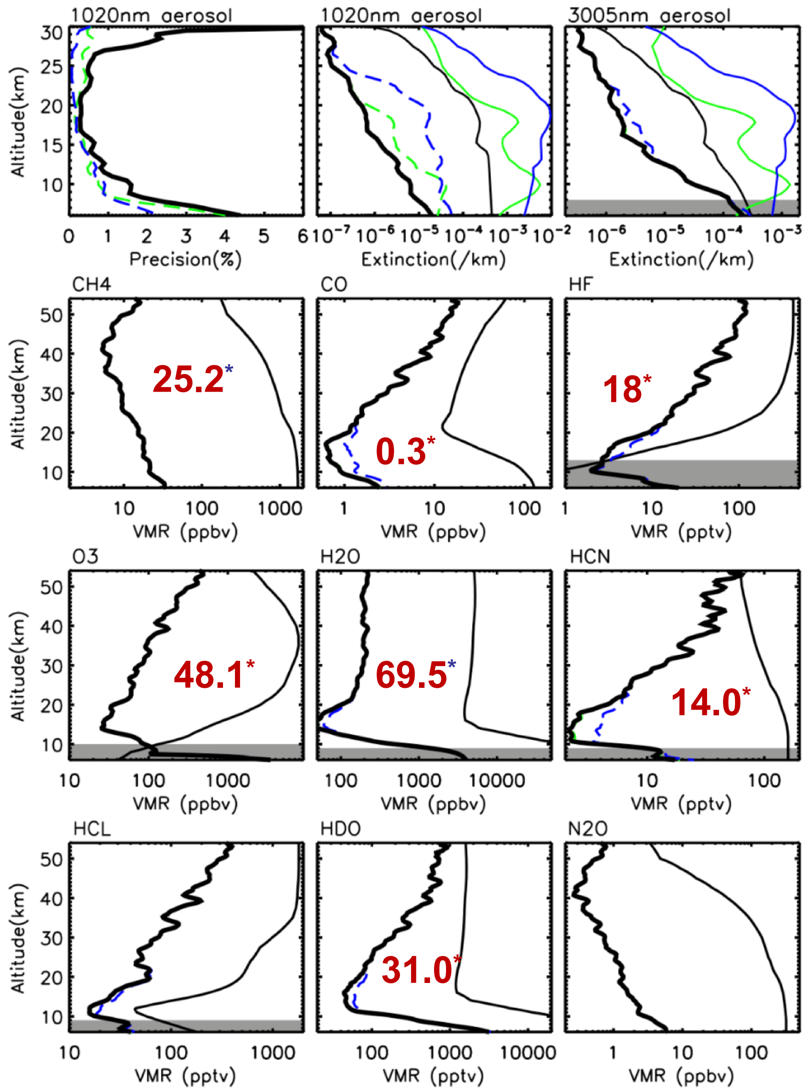
SOFIE/NCEP temperature retrievals: April, 2008, 75-80ºN

- GLO will measure temperature using refraction and CO_2 absorption measurements (above 50 km) .
- The same technique has been done operationally on AIM/SOFIE for 12 years (Gordley et al., 2009, Marshall et al., 2011).

SOFIE has demonstrated Temperature profiling with <1km vertical resolution, and precision of <1K

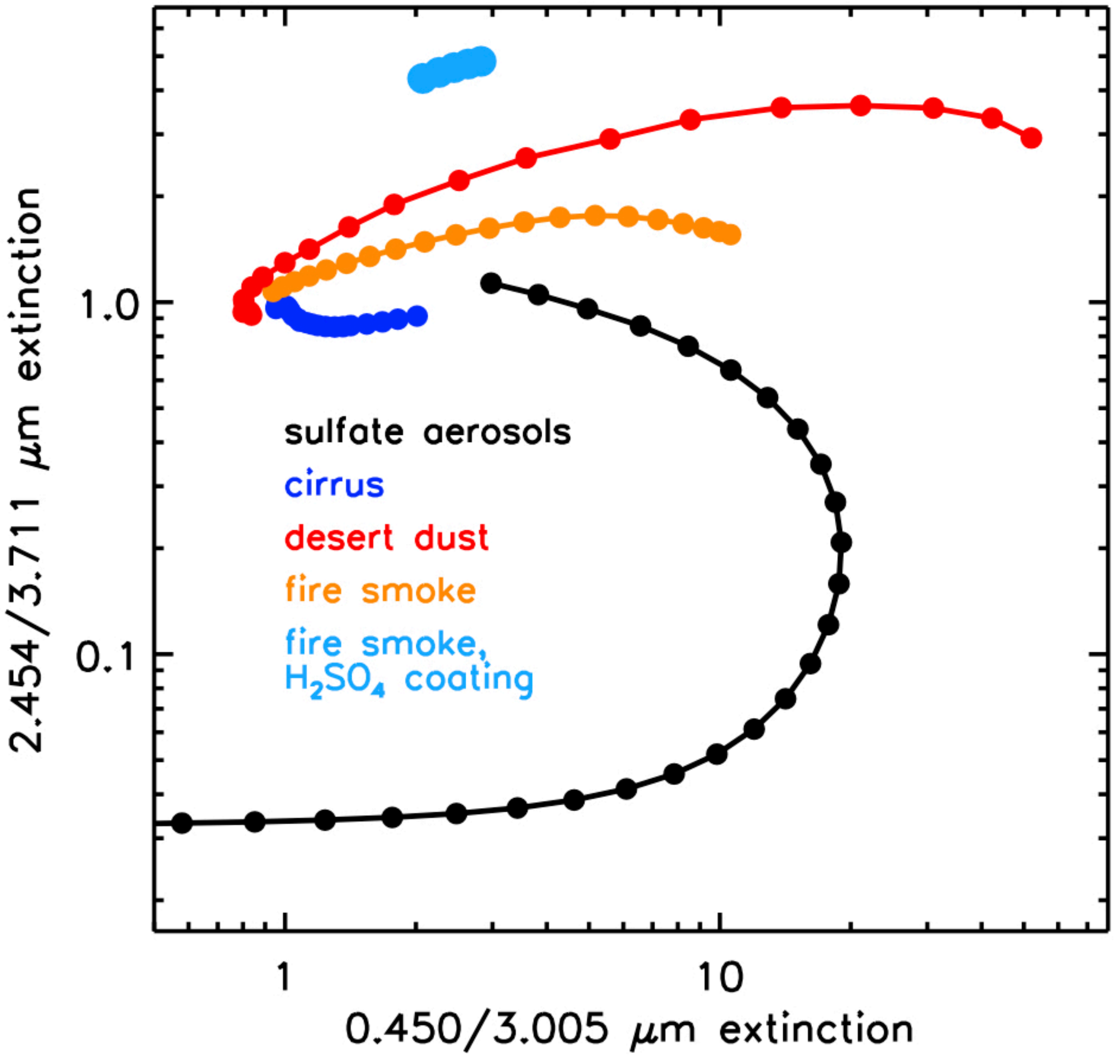
GLO Retrieval Simulation Analysis (Orbital Case)

- 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: t ≈ 3
  - Aerosol retrievals: t ≈ 7 (≤ 5 km)
- Cloud top generally determines lower limit:
  - HALOE measurements showed 50% probability of measuring to >3 km below the tropopause.



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

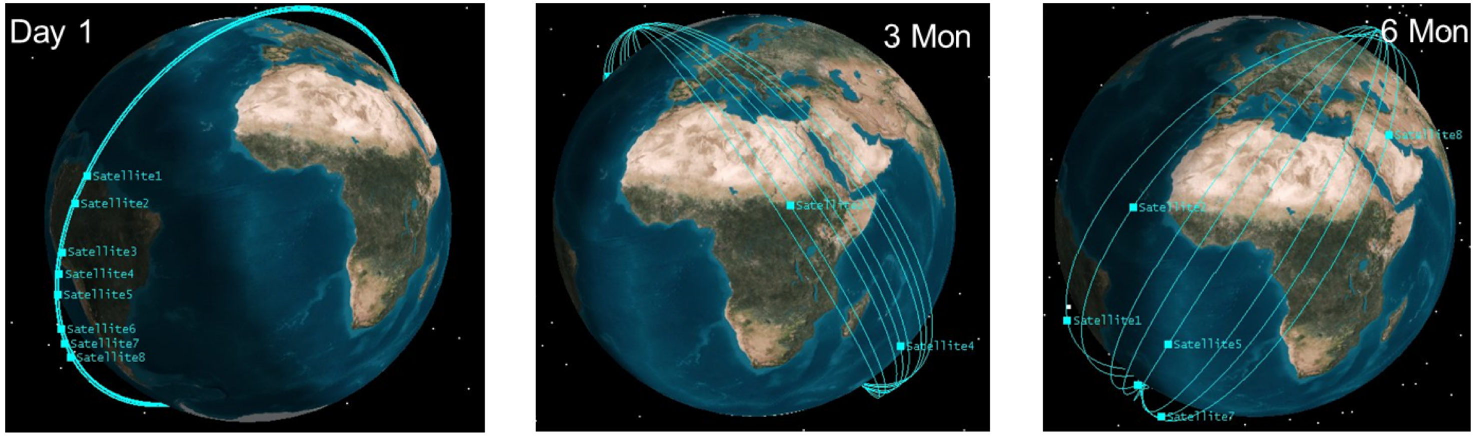
GLO Determination of Aerosol Composition

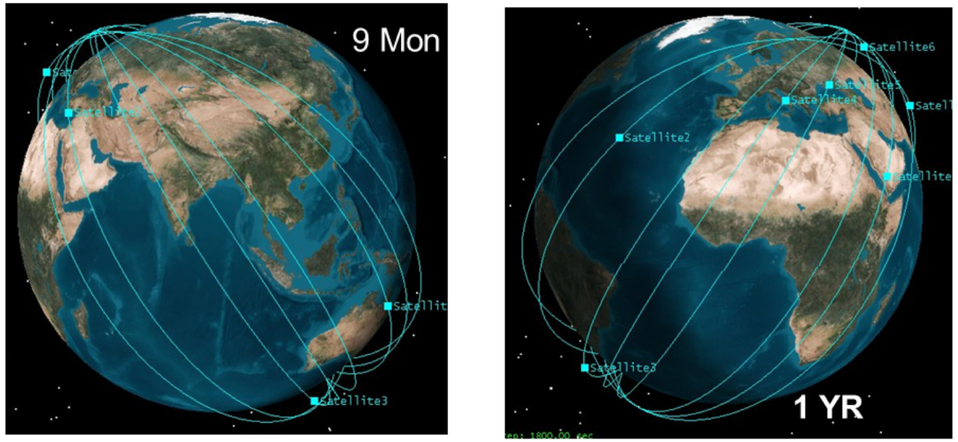


- GLO VNIR and SWIR aerosol extinction measurements contain information on aerosol composition and integrated properties of the size distribution.
- Variation along the curves is due to changing particle size.
- For large particles (rm > ~0.8 μm), the ability to distinguish composition is lost.
- Once composition is identified, it will be possible to retrieve particle size & volume density.
- Optical calculations were from Mie theory for concentric spheres.
- Fire smoke studies use the OPAC soot (BC) refractive index for the core, and P&W sulfate refractive index for the coating.
- Fire smoke aerosols had lognormal distributions with mean radii from 30 to 52 nm, and width = 2, consistent with Ditas et al. [2018].

SOCRATES Mission Implementation I

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

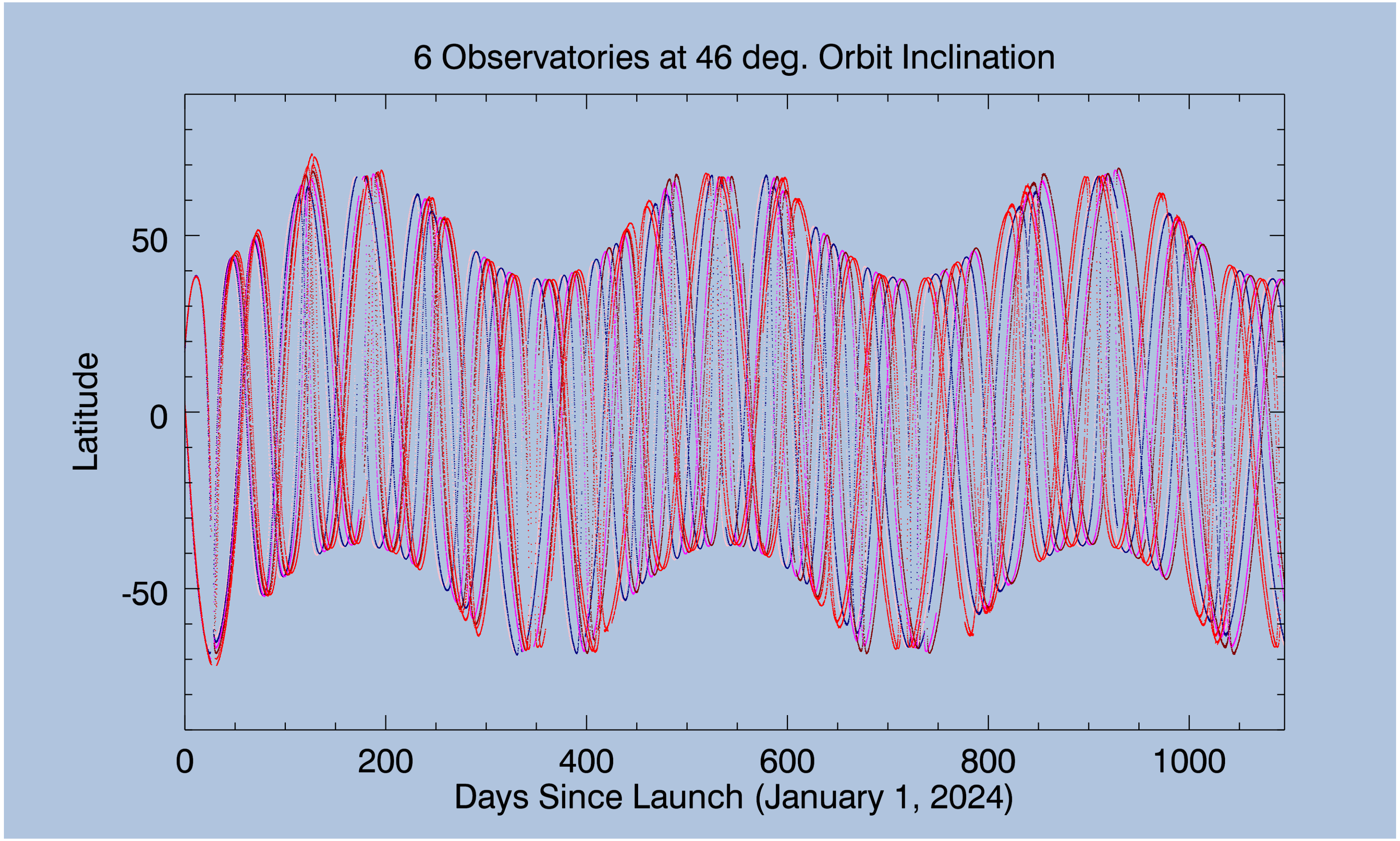




Immediately after launch, all satellites (blue lines) are in the same orbit plane. Due to slightly different precession rates, the satellite orbits spread over time such that within a year they are spread equally over the globe.

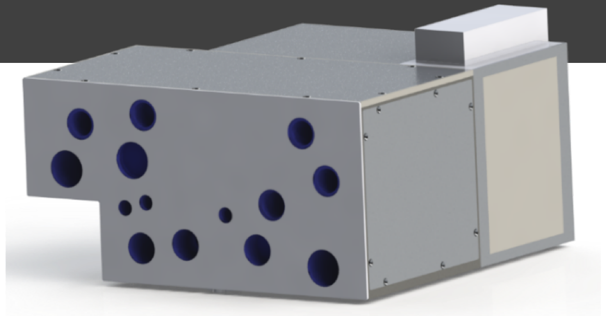
- GLO has the measurement complement, vertical resolution, and precision for UTLS transport studies.
- The sparse solar occultation measurement coverage is mitigated by a constellation approach. SOCRATES plans six satellites.
- All six satellites can be launched from a single rocket, with orbits evolving over six months to one year to allow global coverage.

SOCRATES Mission Implementation II



- All six satellites will have the same orbit inclination.
- The choice of inclination dictates the coverage at different latitudes.
- An inclination of 46 gives good coverage from -50^o to 50^o with coverage in the summer past 65^o in both hemispheres.

GLO Schedule and Status



GLO Schedule	
April 2017	Project Initiation Meeting and SRR
September 2019	Sun tracker test balloon flight
August 2019	GLO Fabrication complete
Fall 2019	GLO checkout and ground-based testing
Spring 2020	GLO Environmental Testing
September 2020	First GLO Balloon flight test
2021	Analysis of Balloon flight test data
September 2021	Second GLO Balloon Flight

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

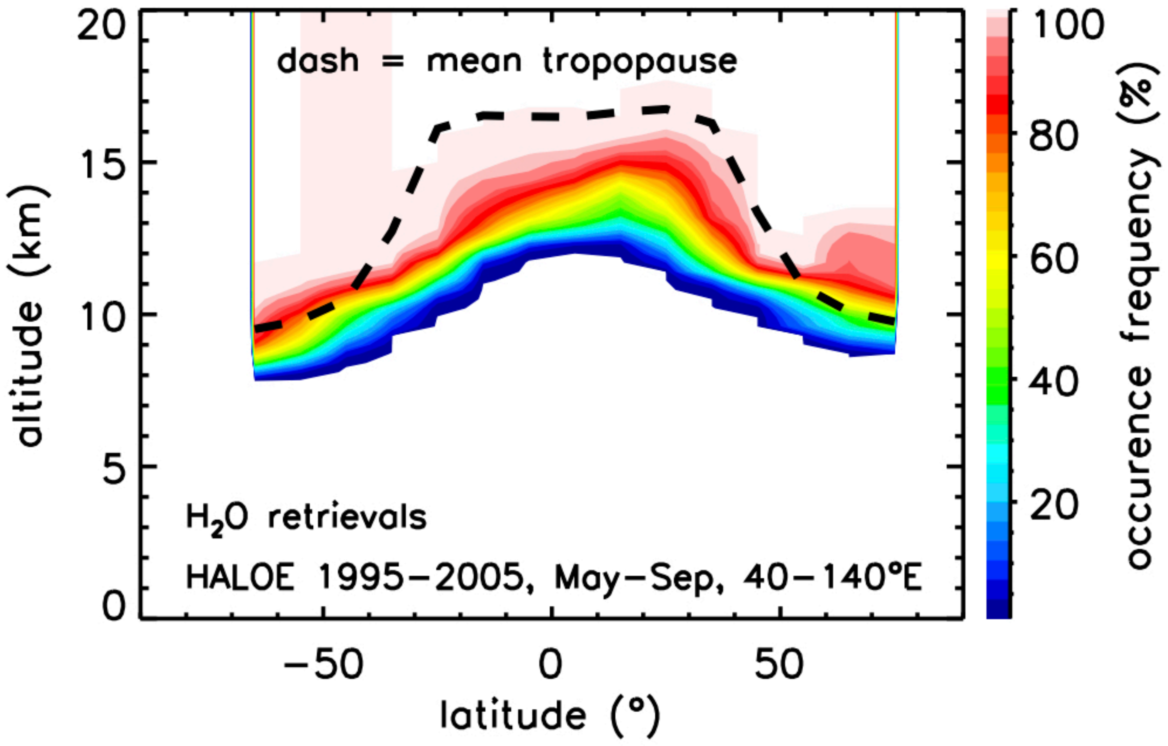
Current Project Status

- Optomechanical design complete.
- IR and SWIR FPAs (Lockheed-Martin SBF207 NBN device) have been tested at AFRL and are currently being integrated in the IDCA.
- Cooler being integrated with IDCA.
- IDCA delivery in July 2019.
- Optical components ordered and most are in-hand.
- Broad-band filters in-hand.
- Gas cell filter delivery imminent.
- For cost considerations going with a COTS FPGA evaluation board for the prototype unit, rather than the rad hardened custom unit envisioned for the orbital version. This is functional and ready for integration.

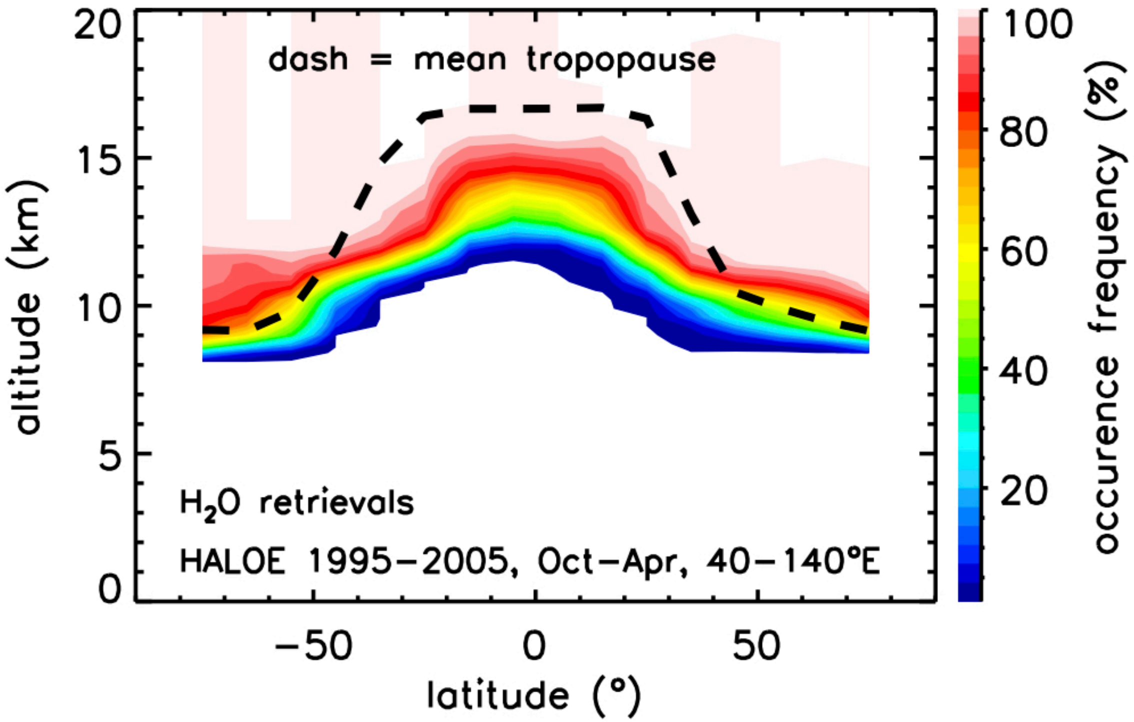
Extra / Backup

HALOE Gas Retrievals Resolve the Tropopause in the Asian Monsoon

Occurrence frequency of H_2O retrievals for the **Asian Monsoon**.



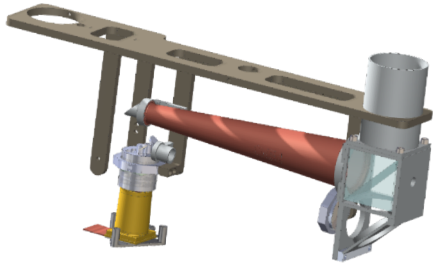
Occurrence frequency of H_2O retrievals for **non-Monsoon period**.



GLO Optomechanical Design

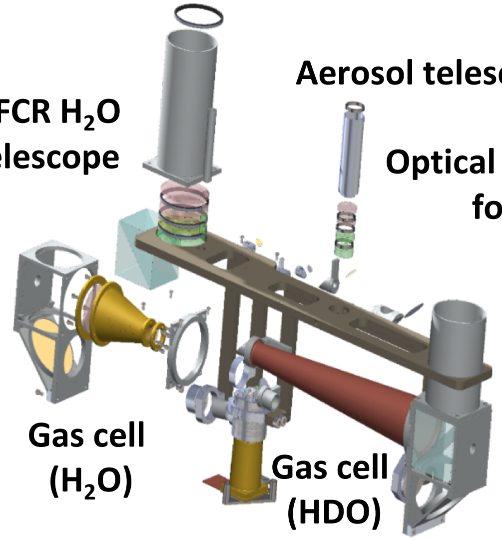
U.S.NAVAL RESEARCH LABORATORY
GATS Global Atmospheric Technologies and Sciences
VIRGINIA TECH

1

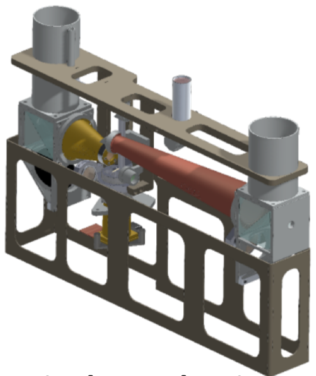


Assembled channel in the Optical Bench structure

2

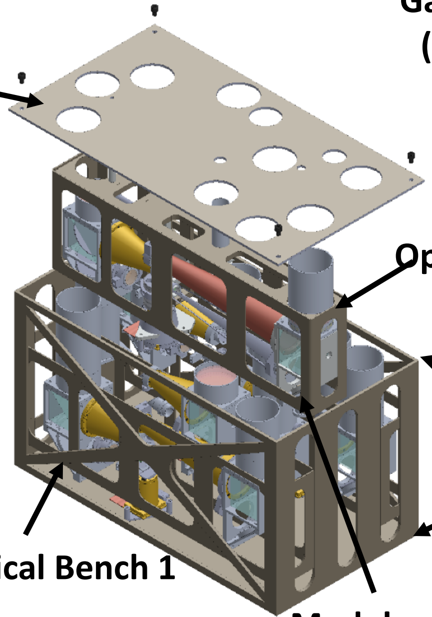


3

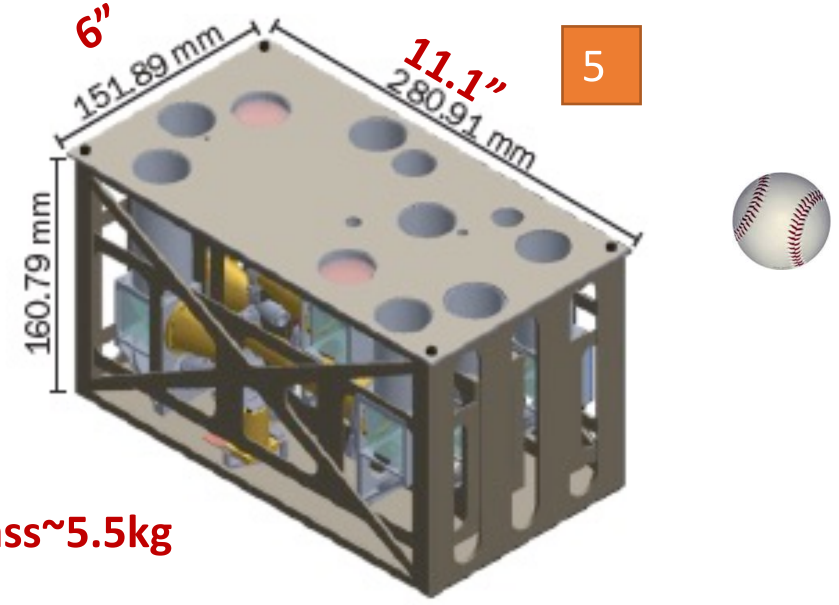


Optical Bench 2 in mounting structure

4

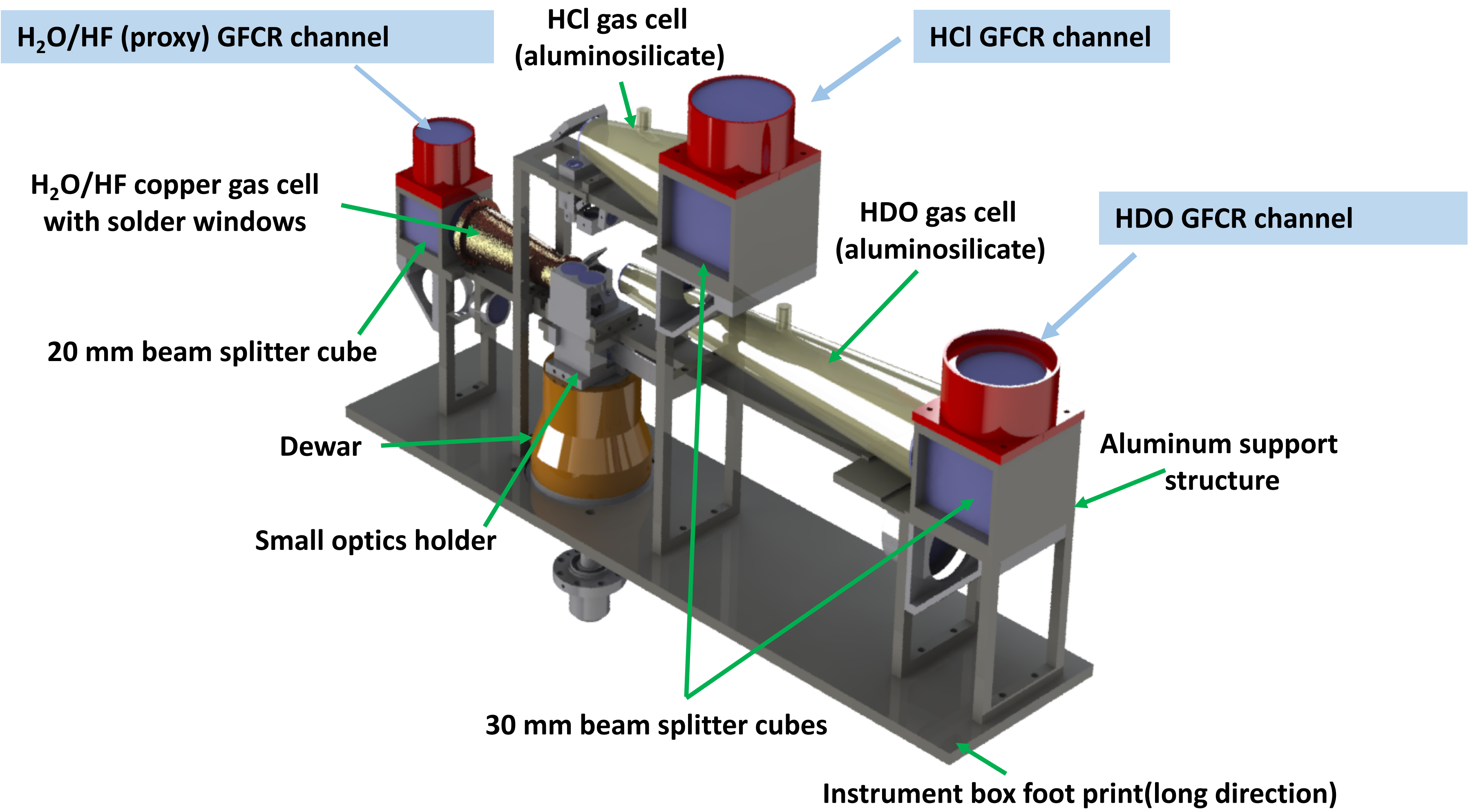


5



Mass~5.5kg

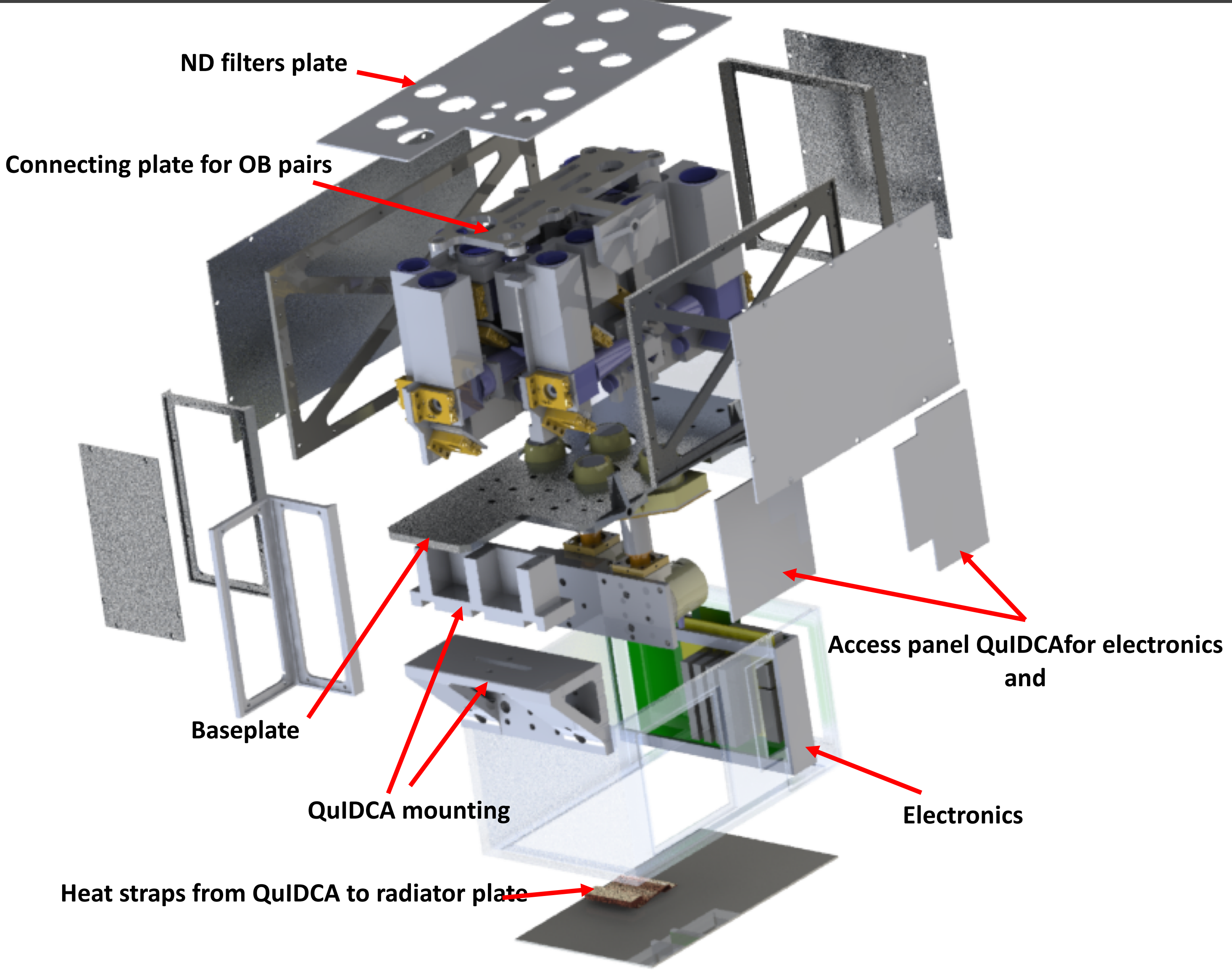
GLO Optomechanical Design



GLO Optomechanical Design

Design:

- Baseplate that interfaces with optical benches structures, QuIDCA mount, and frame and provides anchor point for pan/tilt interface.
- Connecting plate for OB pairs that also provides one of the anchor points for pan/tilt interface.
- ND filter holder plate is removable for lab testing but also functions as the instrument enclosure
- Three mounting locations
- Optical elements, electronics and QuIDCA separated by compartments



GLO is a VNIR/SWIR solar occultation sensor for measuring trace constituents, aerosol and temperature in the upper troposphere and stratosphere at < 1 km vertical resolution.

SOCRATES Measurement Objectives

1. Provide measurement profiles with the vertical resolution and precision necessary to resolve aerosol and trace gas variations below, at, and above the tropopause.

2. Deliver aerosol measurements that, for the first time, enable distinction of the dominant UTS compositions: ice, sulfate, carbonaceous, and mineral dust particles.

3. Deliver a suite of trace-gas measurements that are capable of characterizing UTS radiative sensitivity and of diagnosing transport pathways.

4. Provide near-global sampling to identify composition variations with latitude, longitude, season, and with respect to major weather patterns such as the monsoons.

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