The Keystone Mission: Concept and Objectives

One of four projects selected as a candidate for ESA's Earth Explorer 12

William Ward (on behalf of the Keystone Advisory Group and Keystone PI, Daniel Gerber)

https://www.esa.int/Applications/Observing_the_Earth/FutureEO/Preparing_for_tomorrow/ESA_selects_four_new_Earth_Explorer_mission_ideas

https://www.ralspace.stfc.ac.uk/Pages/keystone-shortlisted-to-be-next-earth-explorer.aspx

Overview

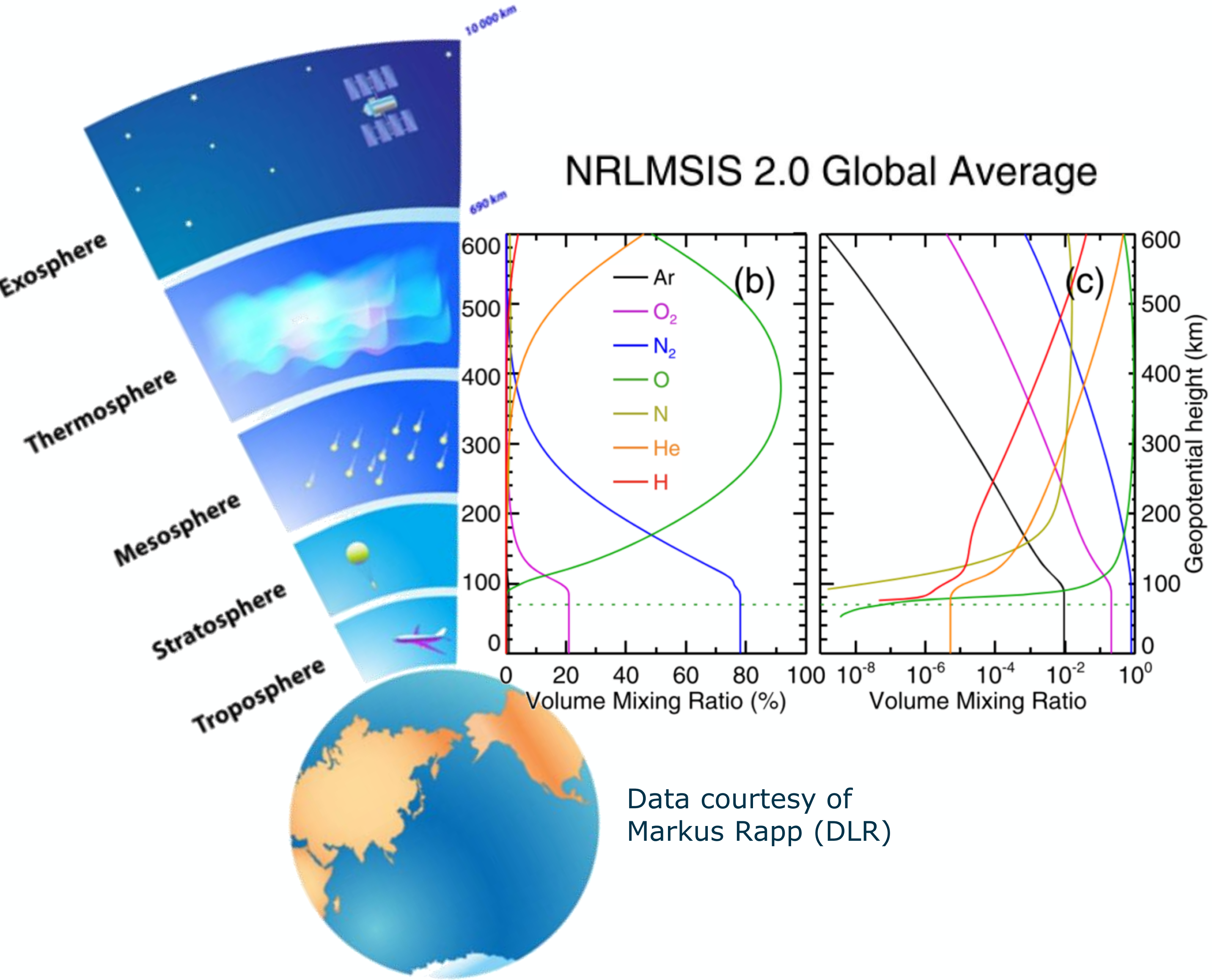
- ESA’s Mission Advisory Group for Earth Explorers
- Mission overview
- Mission objectives and goals
- Measurement requirements
- Summary

Keystone: Mission Advisory Group and ESA Core Team

Mission Advisory Group		
Daniel Gerber	RAL Space – MAG Chair	UK
Patrick Espy	Norwegian University of Science and Technology - NTNU	NO
Maya Garcia-Comas	Instituto de Astrofisica de Andalucia - CSIC	ES
Jörg Gumbel	Stockholm University	SE
Heinz-Wilhelm Hübers	German Aerospace Centre - DLR	DE
John Plane	University of Leeds	UK
Luca Spogli	Istituto Nazionale di Geofisica e Vulcanologia	IT
Claudia Stephan	Leibniz Institute of Atmospheric Physics at the University of Rostock	DE
Christian von Savigny	Institute of Physics at the University of Greifswald	DE
William Ward	University of New Brunswick	CA
Corwin Wright	University of Bath	UK

ESA Core Team	
Mauro Federici	Mission Analyst
Elisabetta Iorfida	Mission Scientist
Fanny Keller	Optical Instrument Engineer
Petronilo Martin-Iglesias	THz Instrument Engineer
Kyle Palmer	System Study Manager
Ben Veihelmann	Mission Scientist
Jonas von Bismarck	Campaign Scientist

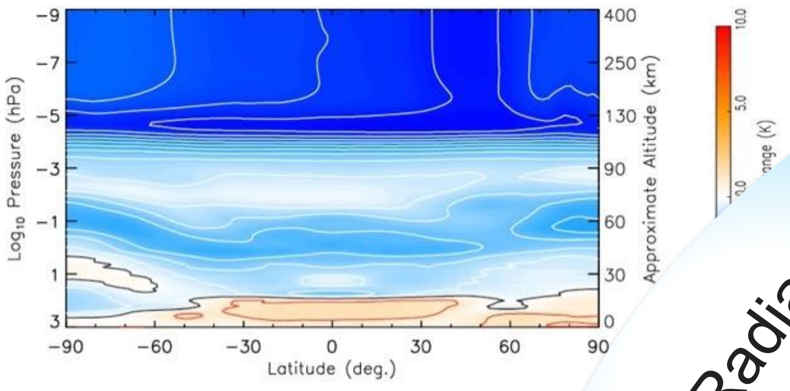
Scientific Motivation and Goals



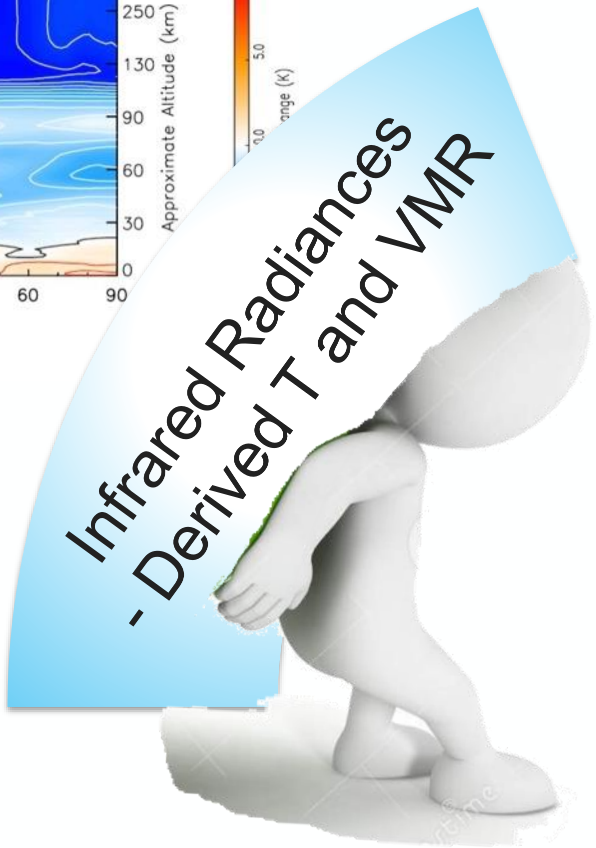
Data courtesy of Markus Rapp (DLR)

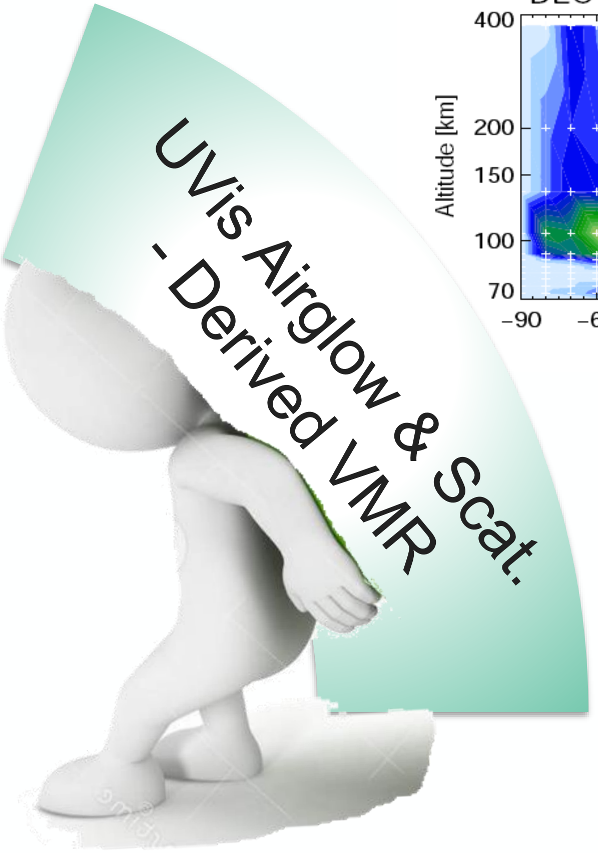
- The Mesosphere—Lower Thermosphere (MLT) is the "**No Fly Zone**" of the atmosphere. Only Remote Sensing techniques are viable
- Atomic oxygen (O) is the dominant reactive species above ~110km, but it can only be observed in the "**THz Gap**" of the electromagnetic spectrum (1THz – 5THz)
- → MLT is the "**Agnostosphere**"
- O is the "**Holy Grail**" of the Upper Atmosphere:
  1. It's the most abundant species
  2. It's involved in almost all reactions
  3. It drives radiative cooling (direct/indirect)
  4. It's the source of all residual drag
  5. It can give neutral winds up to 150km

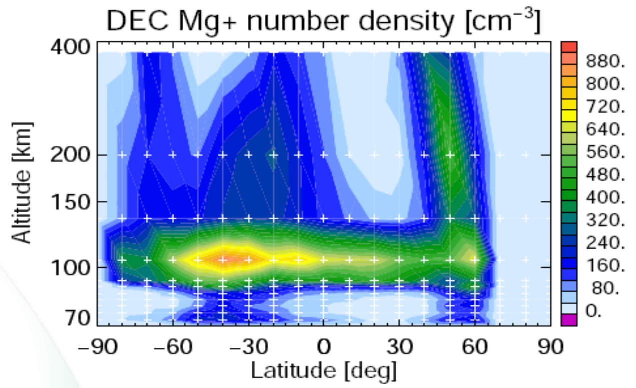
Scientific Motivation and Goals



e.g. MLT cooling trend indicated by IR radiances, [Solomon 2018]





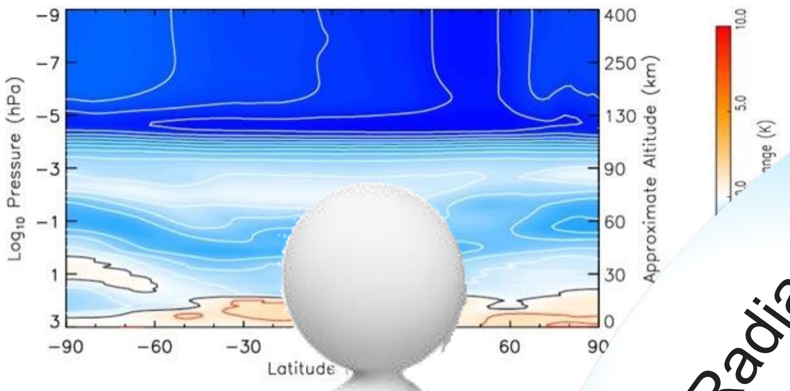


e.g. Mg+ distribution from UVis (SCIAMACHY) [Scharringhausen 2009]

Indirect info on O relying on assumptions on quenching rates

Indirect info on O relying on assumptions on O/O_2 photochemistry

Scientific Motivation and Goals



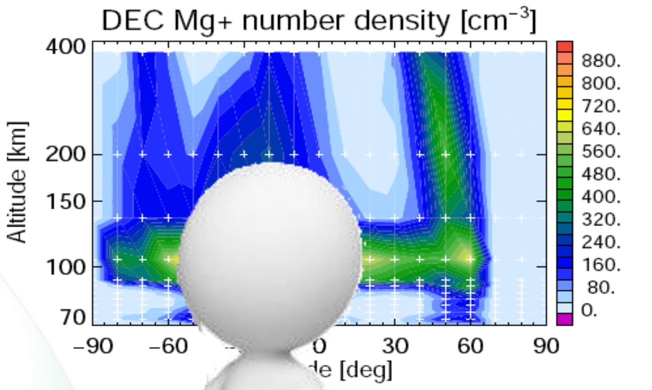
e.g. MLT c
trend indic
by IR radia
[Solomon 20

Infrared Radiances
- Derived T and VMR

THz
Retrieved
O & T

UVis Airglow & Scat.
- Derived VMR

Direct retrievals of O and T are the missing links that combine existing science bites, into a complete picture of the upper atmosphere



g+ distribution
Vis
MACHY)
arringhausen
9]

Mission Requirements

Limb-scanning, medium sized, LEO satellite with 3-instrument payload comprising of:

- Supra-THz radiometers for trace gas, temperature, and wind retrievals
- IR radiometer
- UV-Vis spectrometer

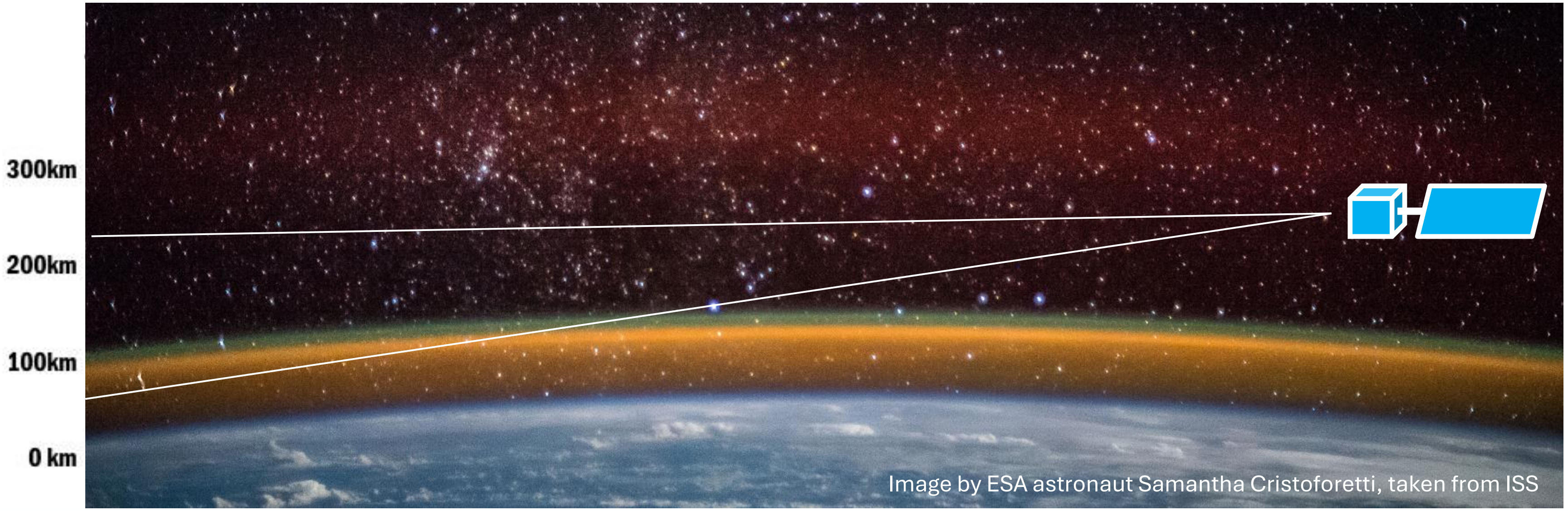


Image by ESA astronaut Samantha Cristoforetti, taken from ISS

Science Objectives

1 — "Thermal balance" Measure O, T, IR heat loss, and airglow to understand MLT (photo)chemistry, and thus upper atmospheric cooling rates, and localised thermal contraction/expansion

2 — "Diurnal variations of the whole atmosphere" Measure O, T, O_3 and ozone related species (e.g., HO_X, H_2O), and neutral winds to obtain a complete picture of MLT variability and tides

3 — "Upward coupling" Measure Temperature, winds, ion density & gravity waves to unveil the vertical propagation of synoptic-to planetary scale disturbances from the middle atmosphere (non-migrating tides and stratospheric sudden warming events) to the MLT

4 — "Downward coupling" Measuring NO_X & HO_X to unveil the vertical propagation of Space Weather (particle precipitation and magnetic storms) to the MLT

5 — "Models & applications" — Measure H_2O, O_3, CO (tracer), O (density), T, and neutral winds as assimilation data products for next generation atmospheric models (and orbit trajectory models)

Past Missions (Dhadly et al., (2023), Neutral winds from mesosphere to thermosphere —past, present, and future outlook)

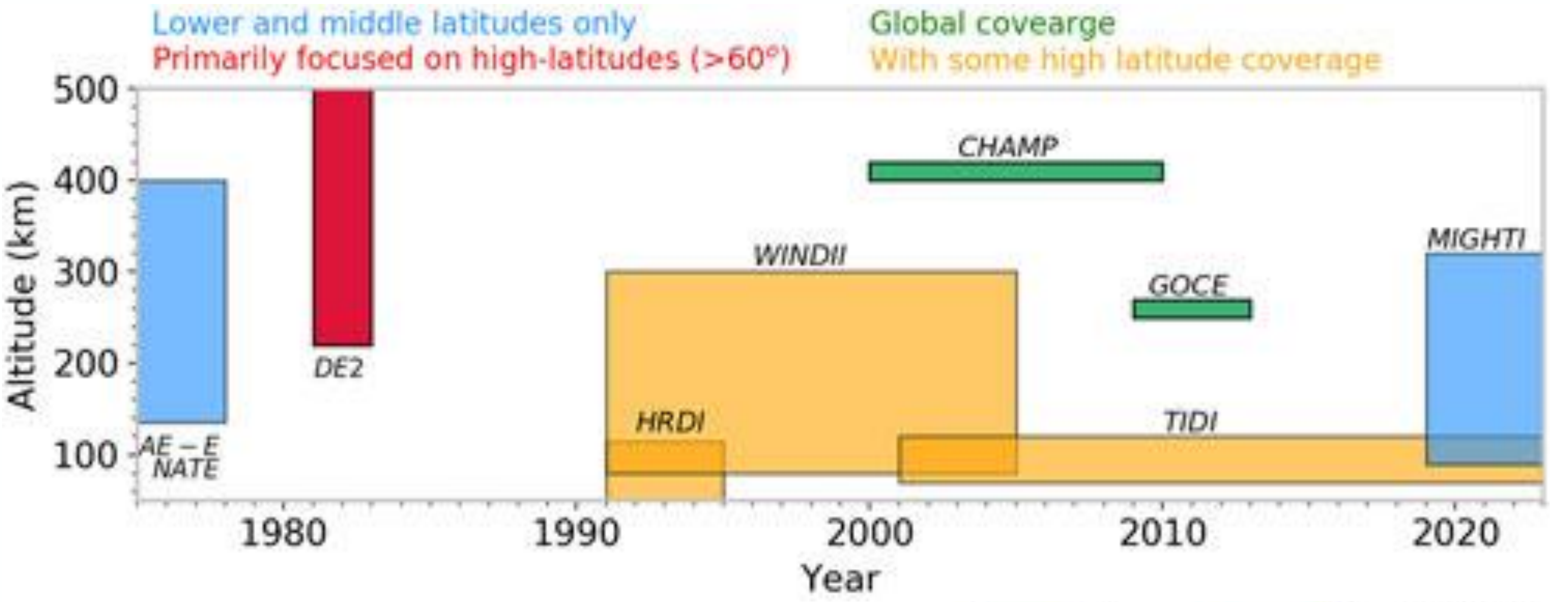


FIGURE 1. The time-line of past ITM missions launched with neutral wind measuring capabilities and their altitudinal coverage. Their latitudinal coverages are indicated with colors on the top.

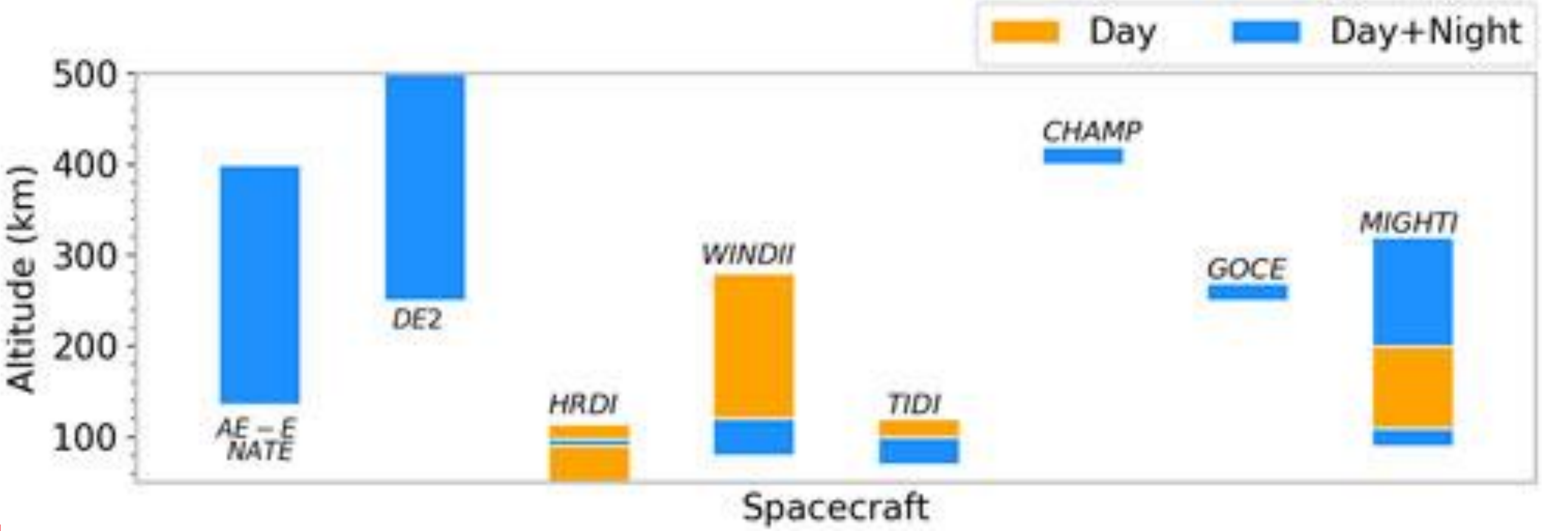
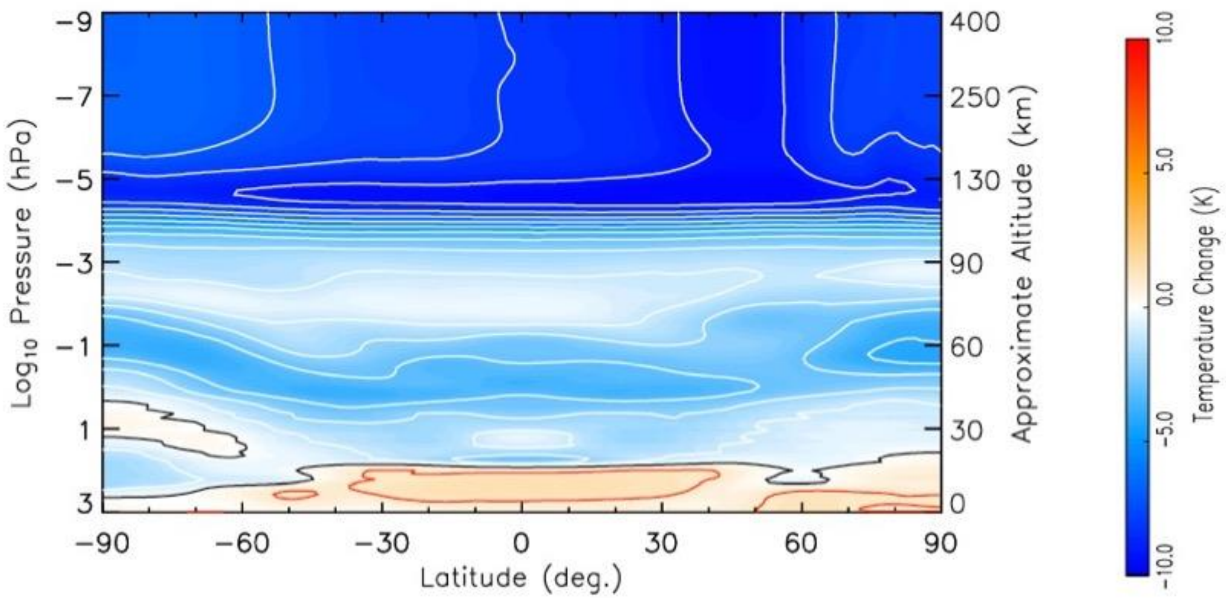


FIGURE 2. Altitudinal and diurnal coverage of the past ITM missions with neutral wind measuring capabilities.

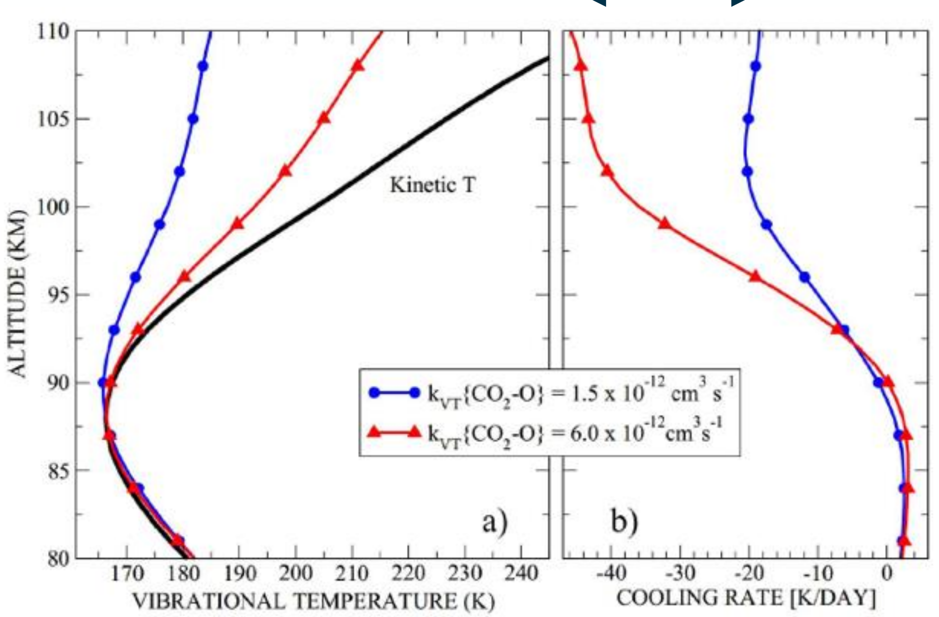
Climatological Trends in the MLT

- Upper atmospheric cooling trend is stronger than surface warming
- Role of GHG unclear, because quenching rates with [O] are unknown



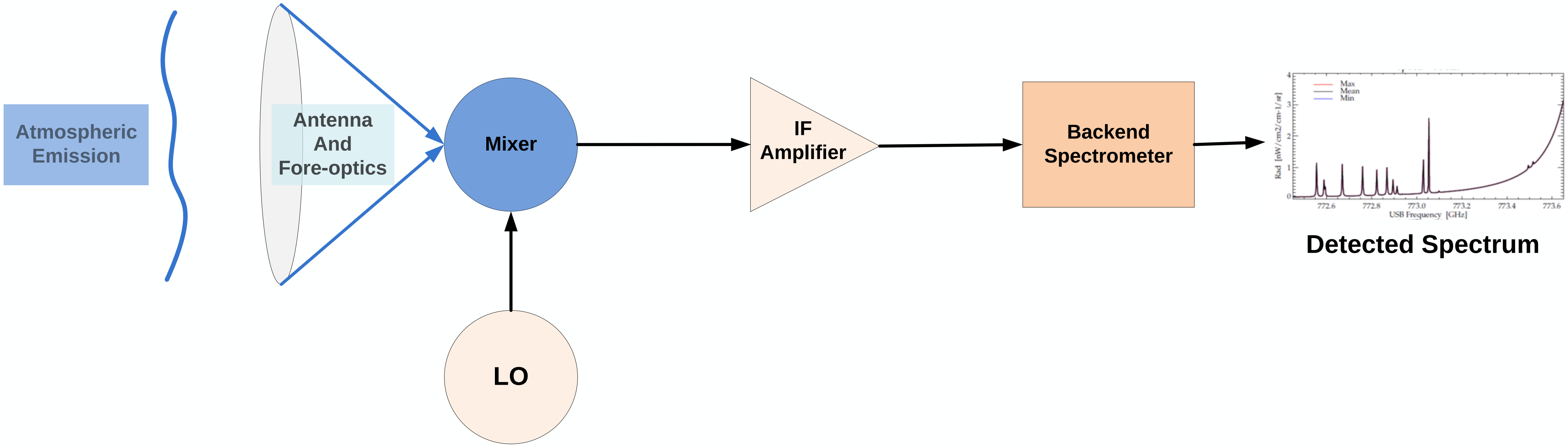
Solomon et al. 2018

Factor 4 Uncertainty!



Feofilov et al. 2012

Terahertz Gap:
Heterodyne Detection for High Frequency Spectroscopy



- The Local Oscillator [LO] needs to match the Radio Frequency [RF]
- Space ready LO for very high THz frequencies (1-5THz) = Breakthrough
- Quantum Cascade Laser LO could bridge the current "THz Gap"

Measurement Requirements: THz

THz Radiometer:

- Passive, heterodyne Schottky radiometers (uncooled)
- High spectral resolution spectrometers (1-3 MHz)
- Key emissions: O, OH, HO_2, H_2O, NO, CO, O_3, O_2
- Heritage: MLS (UARS/Aura), SMR (ODIN), MWS / MWI / ICI (MetOp-SG)

Table 2: Proposed configuration of the Keystone instrument, with three (baseline) to five (optional) spectral bands in the THz region.

Baseline:				
Band	**Target**	**Frequency**	**Bandwidth**	**Comment**
Band B	NO, CO, O_3, H_2O	1.1 THz	1000 MHz	Other NO / CO lines are available, but here they are in a single band
Band C	O	2.0 THz	500 MHz	Weaker line than 4.7 THz, but lower retrieval errors in mesosphere (~90km)
Band D	OH, HO_2	2.5 THz or 3.5 THz	1000 MHz	Trade-off is: More QCL power at 3.5 THz (lower cooling), better Schottky NEdT at 2.5 THz. OH also at 1.8 THz but not combined with HO_2
Optional:				
Band	**Target**	**Frequency**	**Bandwidth**	**Comment**
Band A	O_2, H_2O	770 MHz	1000 MHz	Redundant pointing from O2 (pointing also available from UV-Vis instr.)
Band E	O	4.7 THz	500 MHz	Stronger line than 2 THz. Better for upper thermosphere, but Schottky receivers challenging

Mission Concept, Challenges, and Trade-offs

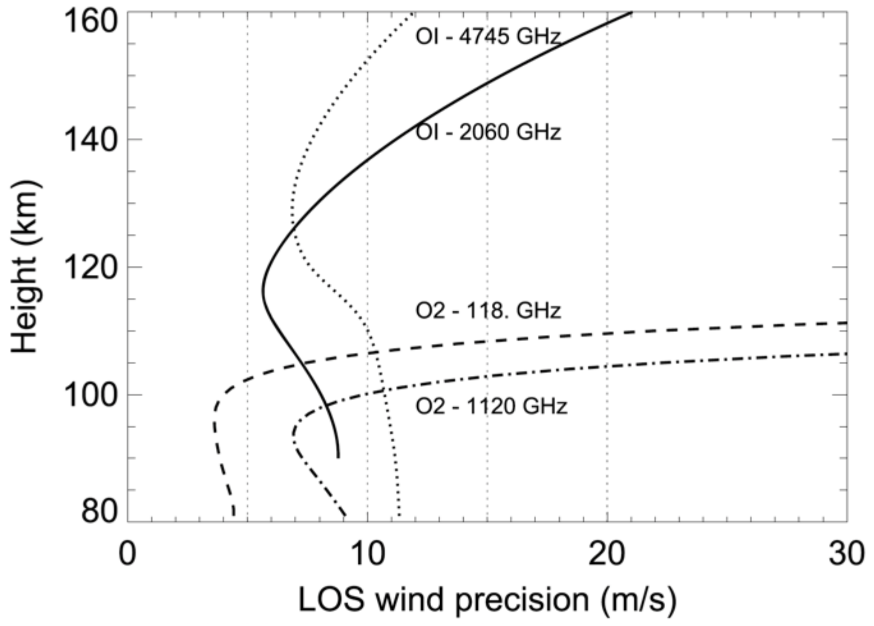
Band selection for atomic oxygen and associated Doppler wind retrieval

2 THz (weaker spectral line)

- performs better at low tangent altitudes (90-110km)
- limited vertical range of density (180km), T (115km), and wind (135km)

4.7 THz (stronger spectral line)

- worse lower limit of vertical range (110km)
- extended vertical range of density (220km), T (130km), and wind (150km)
- technical challenge



Figures/Table: Wu et al. 2016 (JGR)

Table 2. Summary of Estimated Height Ranges of OI and O_2 Sensitivities to Wind, Density, and Temperature

Frequency (GHz)	Molecule	DSB T_{sys} (K)[a]	Doppler (MHz)[b]	Wind[c]	Density (Uncertainty 5%)	Temperature	Note
2060.07	OI	7,000	3.2	90–135 km	<180 km	90–115 km	This work
4745.80		16,500	7.4	110–150 km	<220 km	90–130 km	-
1120.71	O_2	4,000[d]	1.2	<100 km	<100 km	<100 km	-
118.75		1000	0.13	<105 km	<105 km	<95 km	MLS[e]

Measurement Requirements: IR

Infrared Radiometer

- Single pixel IR detectors
- Key emissions: CO_2, NO, OH, O_3
- Heritage: SABER (TIMED)

Table 3: This is the proposed subset of SABER infrared channels that best complement the Keystone THz measurement.

Baseline:						
Channel	**Species**	**λ Cent.**	**Δλ**	**Required emissivity** (W cm^{-2} sr^{-1})	**Required D*** (cm Hz$^{1/2}$ / W)	**Comment**
Chan A	CO_2	15.2 μm	0.632 μm	3.4E-09 ♣	8.5E10 ♣	O quenching rates
Chan B	CO_2	15.14 μm	3.594 μm	2.8E-08	1.7E10	O quenching rates
Chan D	O_3	9.39 μm	0.672 μm	1.1E-08	2.6E10	Indirect method for O
Chan E	NO	5.41 μm	0.309 μm	2.5E-09	1.2E11	Thermal balance
Chan F	CO_2	4.27 μm	0.153 μm	1.3E-09	6.2E11	O quenching rates (mesospheric contribution)
Optional:						
Band		**Target**	**Frequency**		**Bandwidth**	**Comment**
Chan C	Clouds	11.85 μm	2.09 μm	1.0E-09	4.8E11	Sensitive to ice water (can detect PMC/NLC)
Chan G	OH	2.07 μm	0.54 μm	2.5E-09	1.2E11	Night-time evaluation of O, but drives mirror quality

♣ This value is increased by a factor of 5 over SABER, which will extend the top of the measurement range in the infrared from ~100km to 120-130km and guarantee a vertical overlap with the THz retrievals.

Measurement Requirements: UV-Vis

UV-Vis Spectrometer

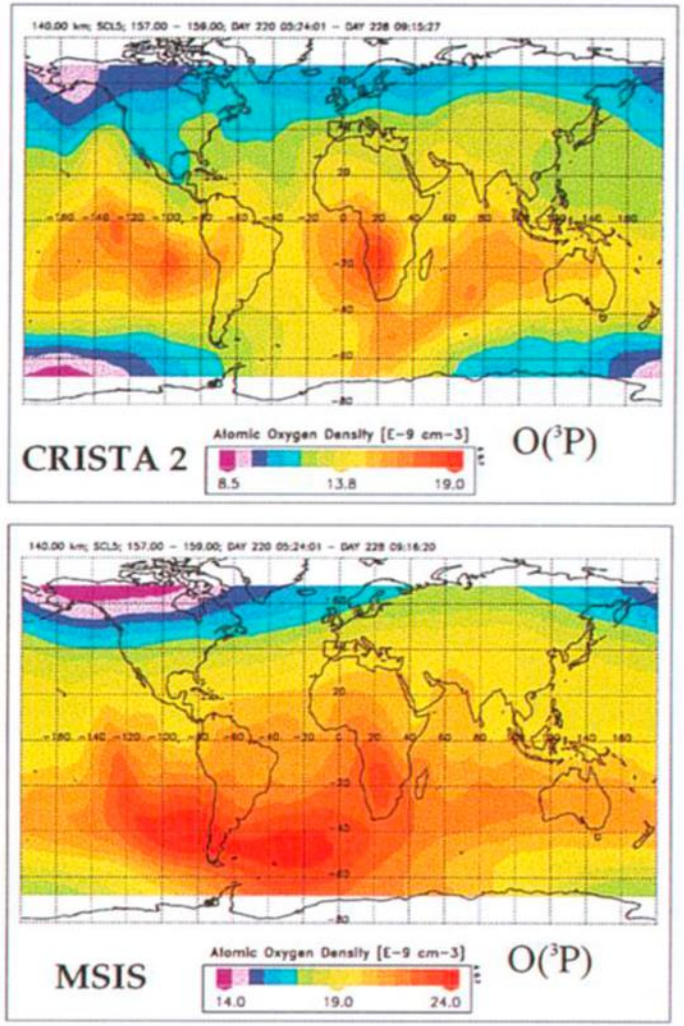
- Broadband spectrometer: 200nm - ~800nm
- Spectral resolution: 1nm
- Heritage: OSIRIS (ODIN), SCIAMACHY (Envisat), NOMAD (ExoMars)

Table 4: Bandwidth coverage of the UV-Vis instrument

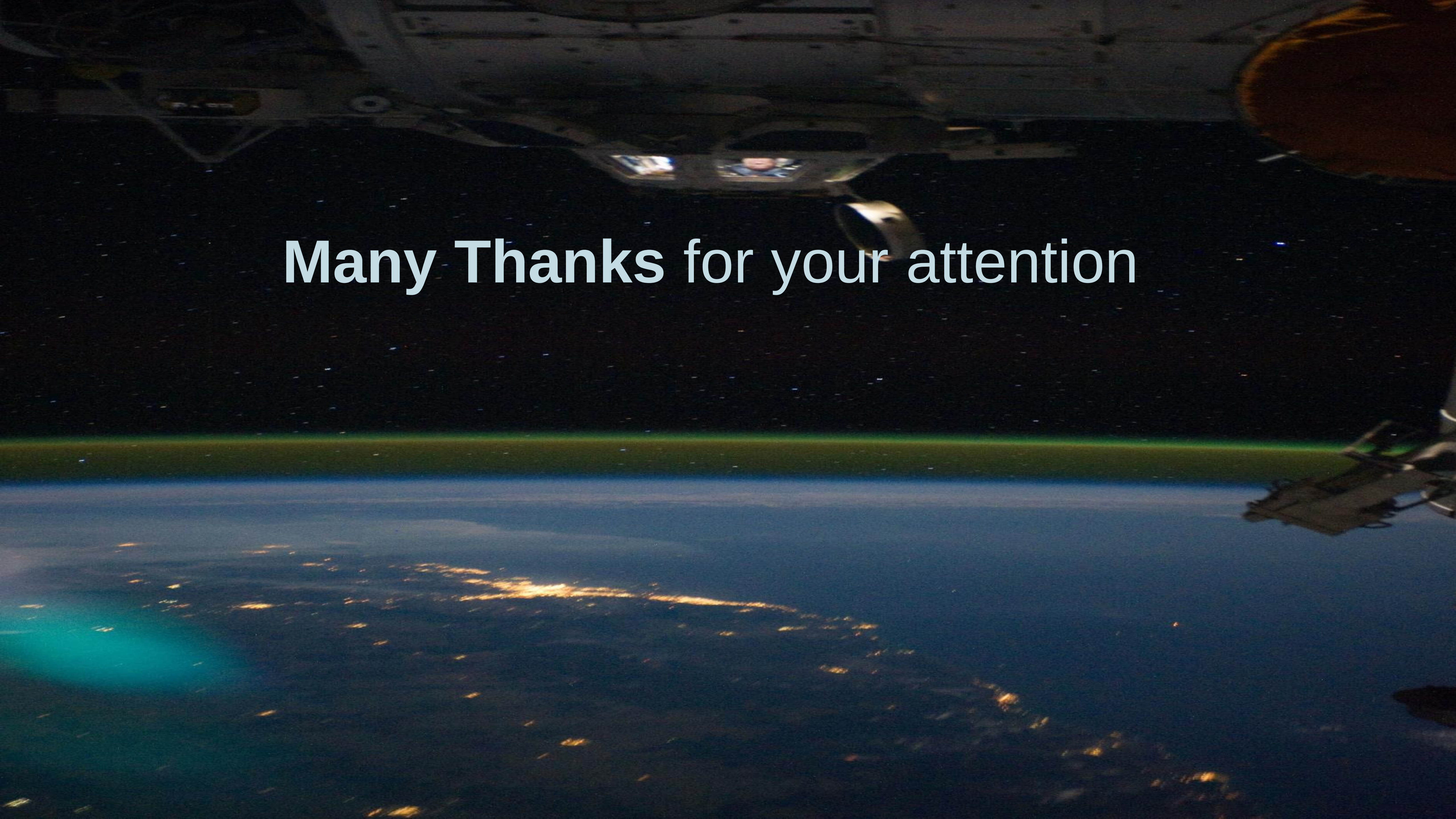
Baseline: 260-770nm **Optional:** 200-800nm				
Species	Spectral range	Resolution	Altitude range	Type of signature
NO Gamma bands	200 - 300 nm	1-2 nm	60 - 110 km	Emission
O_3	250 – 310 nm	< 3 nm	35 - 70 km	Absorption
Pointing information	290 -305 nm	2 nm	N/A	O_3 absorption
Fe / Fe+	272 nm / 240-260 nm	2 nm	unknown	Emission
Mg / Mg+	285 nm / 280 nm	2 nm	70 – 130 km	Emission
O (1S-3P)	297 nm	2 nm	90 – 100 km	Emission (night time)
O_2 Herzberg / Chamberlain bands	300 - 430 nm	2 nm	TBD	Emission (weak)
OH Meinel bands	308 nm	2 nm	60 – 90 km	Emission (weaker than 1500 nm)
Fe (potentially)	372 nm	2 nm	unknow	(potentially)
O (1S-1D)	577 nm	2 nm	85 – 105 km	Emission (green lines)
Na	589 nm	2 nm	80 – 105 km	Dayglow/nightglow with different emissions
O (1D-3P) red	630 nm, 636 nm	2 nm	200 – 250 km	Emission (red lines)
O+	732 nm	2 nm	200 - 250 km	Emission
O_2 A-band (0-0,0-1)	760 nm, 865 nm	2 nm	80 – 100 km at night and 50 – 100 km during daytime	Emission (main band).
Temperature	760 nm	2 nm	80 – 100 km (night) 50 – 100 km (day)	From O_2 A-bands (if spectrally resolved)
K	~770 nm	2 nm	80 – 100 km	(potentially)

Summary

- Atomic oxygen (O) is the missing keystone for our understanding of the upper atmosphere.
- The Keystone mission will provide first global and temporally resolved measurements of the key missing MLT trace gas atomic oxygen (O), together with Temperature, neutral winds (Doppler), and other important trace gases
- Keystone flies a comprehensive payload suite, comprising of a novel THz radiometer in combination with heritage IR and UV-Vis instruments
- The Phase-0 system study will address trade-offs on viewing strategy (wind observations) and temporal sampling of diurnal / seasonal cycles (orbit choice)



Figures: Grossmann et al. 2000 (GRL)


Many Thanks for your attention