CEOI EO Mission Development Study:

LOCUS

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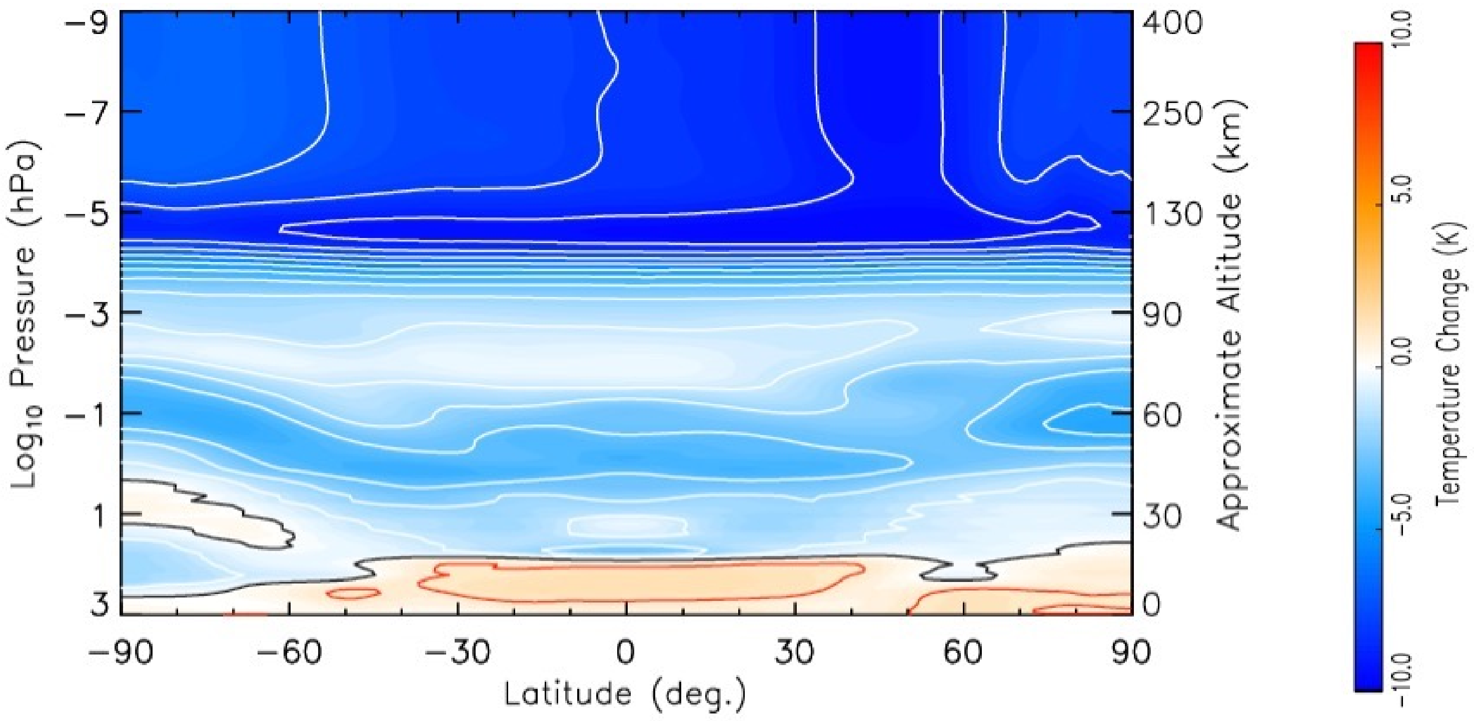
1. Short Summary of the Science Case

2. Demonstrating the Earthwatch Mission Potential

3. Presenting the Strategic Outline Case for LOCUS

Climate Change in the Upper Atmosphere

There is a clear cooling trend in the MLT (**-10ºC**) – much stronger than the Tropospheric warming (**+2ºC**) – but we have no idea how much of it is from an increase in greenhouse gases.



[Solomon et al. 2018]

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Greenhouse Gas Cooling

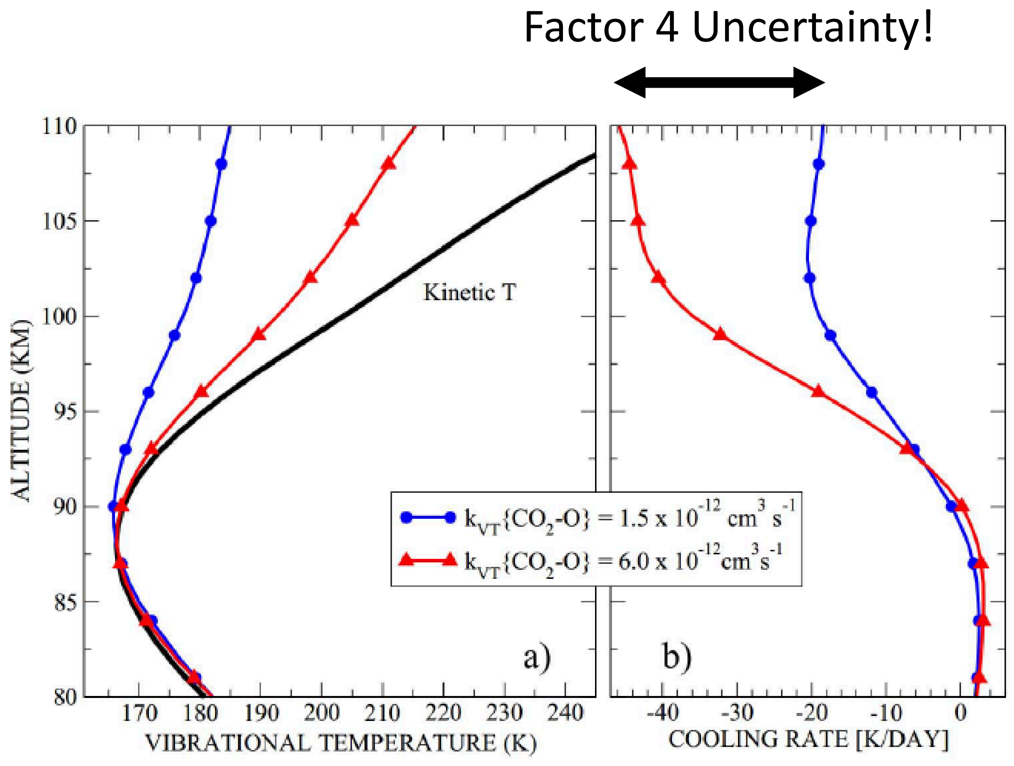
- Upper Atmospheric cooling comes from radiative heat loss from climate gases (i.e. gases that emit/absorb *"heat"* in the infra-red)
  - Optically **thick** Lower Atmosphere: Heats gets **trapped** (*"Climate Change"*)
  - Optically **thin** Upper Atmosphere: Heat **escapes** to Space (Climate change too!)

Rank	Species	Wavelength	Origin
1st	CO_2	15 µm	Anthropogenic greenhouse gas
2nd	NO	5.3 µm	Natural occurrence; Enhanced by Space Weather
3rd	O	63 µm	Natural occurrence

- Current instruments (i.e. SABRE) estimate cooling rates by measuring the heat flux at these wavelengths

The Quenching Rate Conundrum

- To convert heat fluxes to cooling rates and Temperatures, one has to know the collision rates, aka. *quenching rates*
- Upper atmospheric collision rates are dominated by O, by far the most abundant species at altitudes above 120km, but:
- → We've never measured the global distribution of MLT O, so our estimates of collision rates, aka. quenching rates, is highly inaccurate!



[Feofilov et al. 2012]

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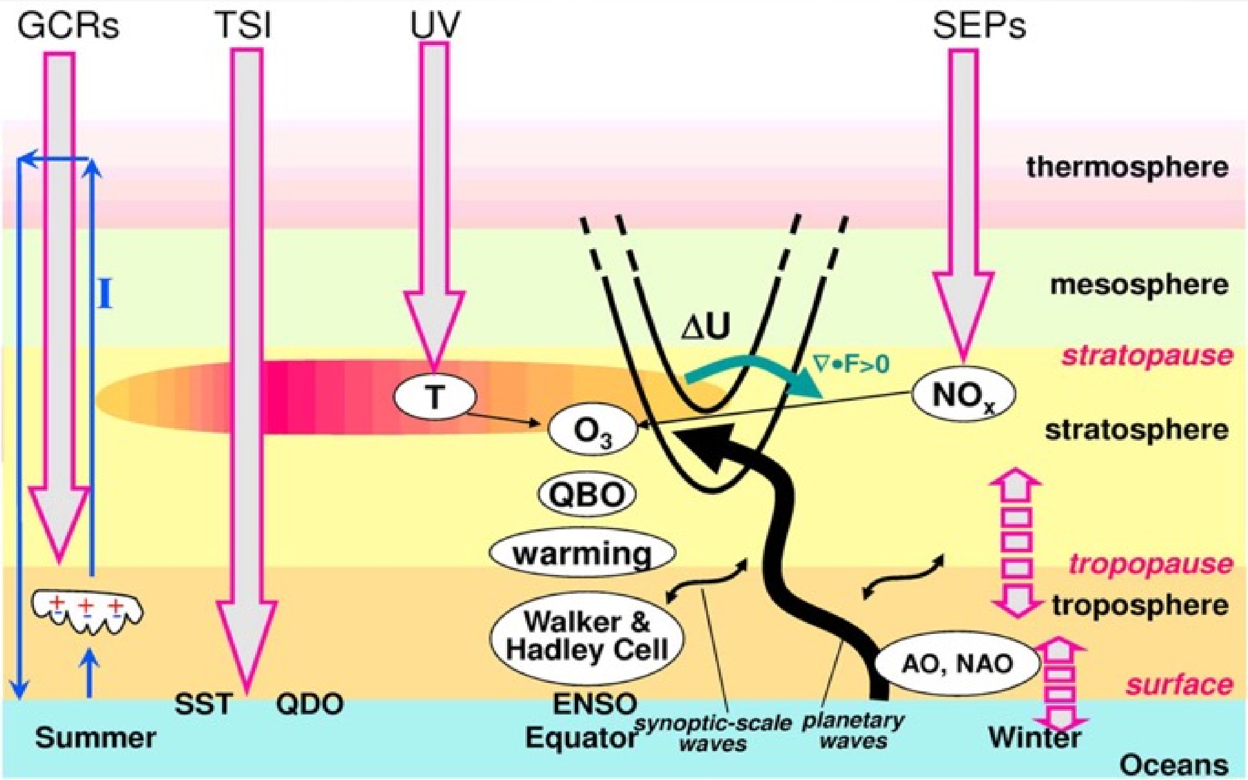
Space Weather Links to Surface Weather

- There are established teleconnections from the Upper Atmosphere to surface climate via O_3
- MLT NO_X from space weather events leads to increased O_3 formation
- Research suggests that the NO_X impact could match the direct UV solar forcing

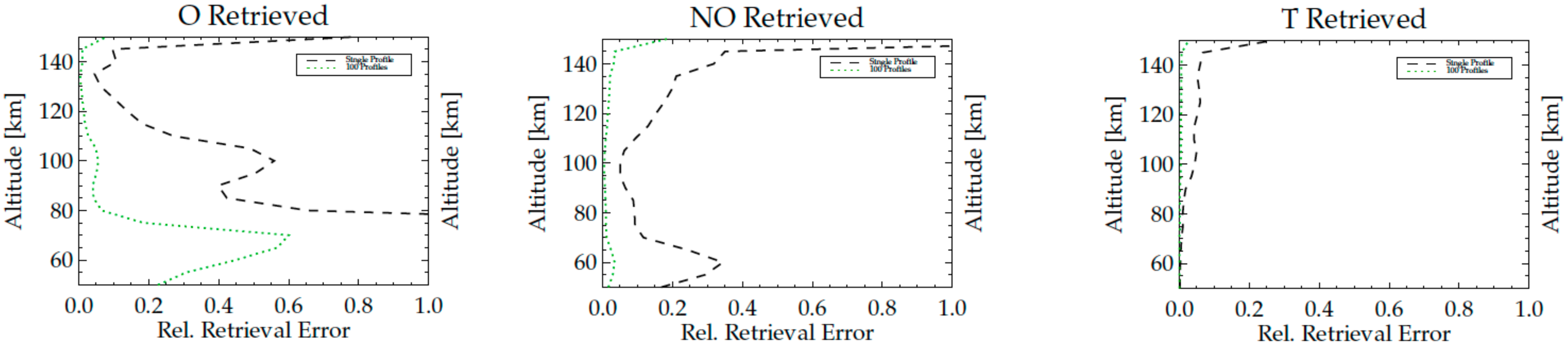


[Gray et al. 2010]

Why we Need LOCUS

- Infrared heat flux measurements are not enough to understand the impact of climate change in the Upper Atmosphere; We also need to know the abundance of O, and ideally measure Temperature directly
- For a full picture, we also want to measure the chemical proxies of Space Weather forcing

Expected Measurement Precision of Key Products (from Retrieval Simulations)



[CEOI EE-9 Preparatory Activities] *[CEOI EE-10 Preparatory Activities]*

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Earthwatch Mission Requirements

- TRL min 3

→ TRL 4 attested in EE-10 review panel report

- SRL min 3

→ SRL 4 attested in EE-10 review panel report

- Mission cost (incl. launch and operation) less than £280M to UK

→ Scalable with mission complexity and build quality (€120M - €400M)

- Keep UK technology at leading edge

→ Reap benefits of CEOI technology development activities

- Mission attractive to other EU members

→ Connections to various European science networks/communities

TRL/SRL Compliance & EU Integration

"LOCUS does not present clear technical showstoppers. However, the performance in terms of noise figure of the mixers at the 4.7 THz frequency band is currently unknown. Such uncertainty could potentially lead to a degradation of the mission performance or, in the worst case, to an unfeasible implementation of the 4.7 THz band using this type of technology. The current state of technology is likely to be sufficient to raise the critical technologies to TRL 5 at the end of phase B1 and hence retire the above mention risk before entering into the development phase."

TRL assessment by the ESA EE-10 Review Panel

"The SRL of all mission objectives is assessed to be 4, because all conditions required according to the ESA Scientific Readiness Levels Handbook are fulfilled. A credible roadmap for reaching SRL 5 by the end of phase A is provided. The risk of not reaching SRL 5 by the end of phase A is considered low."

SRL assessment by the ESA EE-10 Review Panel

"A scientific community capable of addressing all elements required for reaching SRL 5 exists."

European science community assessment by the ESA EE-10 Review Panel

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Supporting UK Technology

1. Quantum Cascade local oscillators (University of Leeds, Figure 2a)
2. THz Schottky diodes and mixers (STFC RAL Space, Figure 2b)
3. Miniature space-coolers (STFC Technology, Figure 2c)
4. Wide-band, digital spectrometers (STAR-Dundee, Figure 2d)
5. THz optics (UCL London)
6. Science case (STFC RAL Space, University of Leeds)

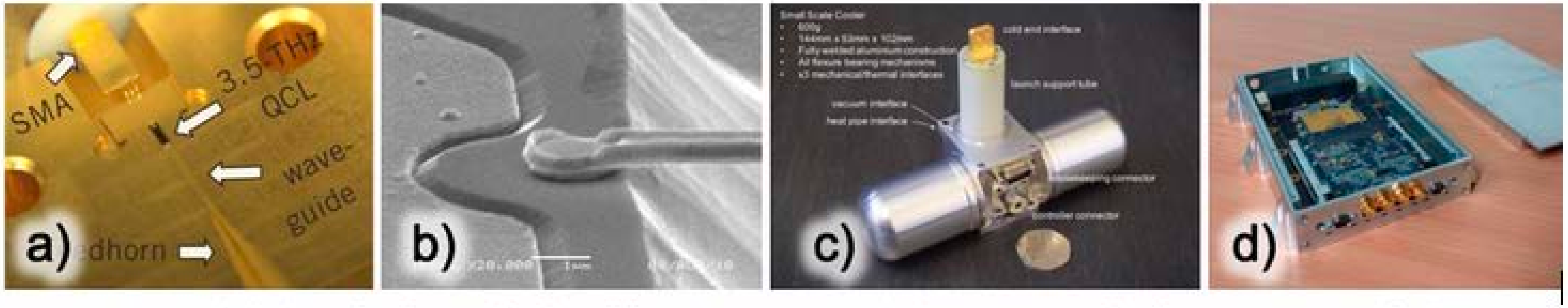


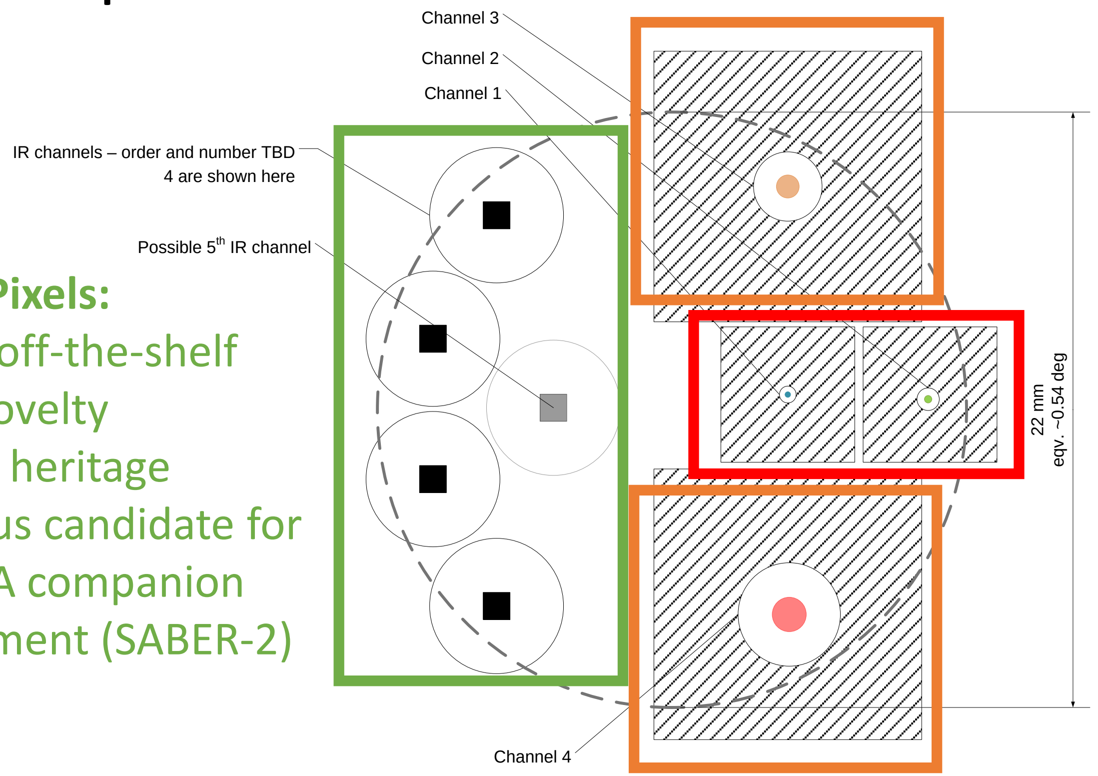
Figure 2: Key LOCUS Technologies developed by UK institutes: a) Quantum-cascade frequency source, b) Supra-THz Schottky diodes, c) Miniature space coolers, d) Wideband, digital spectrometer

Meeting the Earthwatch Cost Envelope

- It is clear that LOCUS in its EE-10 configuration does not meet the financial restrictions of the current Earthwatch Call. There are however several ways to scale the cost of the mission to the UK:
  1. Bilateral Partnership: Parts of the instrument payload could be sourced from a bilateral partner as in-kind contribution. This would reduce the mission cost to the UK without jeopardizing the science return.
  2. Reduced Number of Science Objectives: LOCUS has a long list of scientific objectives, which require multiple channels. By prioritizing the science objectives, the number of channels - and thus cost - could be reduced.
  3. Flexible Procurement Rules: The ESA cost estimate for a full blown LOCUS under ECSS procurement rules exceed the Earthwatch budget. A major cost factor under ECSS are the parallel industry studies, documentation and testing. If the UK bears the risk, then these rules could be relaxed.

Bilateral Payload Split Options

- Compartmentalisation of LOCUS



Infrared Pixels:
- Quasi off-the-shelf
- Low novelty
- SABER heritage
- Obvious candidate for a NASA companion instrument (SABER-2)

THz Channels (770GHz, 1.14THz)**:**
- Pushing the boundaries, using conventional technologies
- Strong incentive to maintain ownership
- Potential partners: JPL, RPG (DE), Ominsys (SWE)

Supra-THz Channels (2THz, 3.5THz, 4.7THz)**:**
- Novel technology
- Interesting future potential (THz Roadmap)
- **Fight tooth and nail to keep these in the UK!**

Others (Spectrometer, Coolers, Calibration, Platform)**:**
- Unlikely to be attractive for non-UK partner

- To meet UKSA requirement of keeping UK technology at leading edge, we want to maintain ownership of the supra-THz channels, spectrometers and mini-coolers

Scalable Science Objectives

- Fundamental: UA quenching rates → 1-2 THz (O), 3 IR (2x15μm, 4.3μm)
- Limited: Space Weather connection → 2-3 THz (O, NO, O3, CO) + 7 IR
- Ideal: Thermal structure, Space Weather, T profiling → 4-5 THz + 7 IR

	THz Channels [THz]					IR Pixels [μm]								
Wgt	4	4	3	2	2	1	1	1	1	1	1	1		
Opt.	4.7	3.5	2	1.1	0.8	15	15	12	9.4	5.4	4.3	2	Saving	Compromise
1	x	x	x	x	x	x	x	x	x	x	x	x	0%	No compromise, full performance
2		x	x	x	x	x	x	x	x	x	x	x	16%	Worse atomic oxygen retrievals at top of altitude range
3		x	x		x	x	x	x	x		x	x	28%	As above, and no Space Weather science objective
4			x			x	x				x		64%	As above, and no Temperature and humidity profiling

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Strategic Outline Case

- Strategic Case
- Economic Case
  - UK technology exploitation
  - Numerical Weather Prediction (NWP)
  - Climate reanalysis
- Commercial Case
  - Earthwatch
  - Alternative Programmes
- Financial Case
  - Fully UK funded vs. Bilateral approach
- Management Case

Strategic Case

- Two strategic UK interests in LOCUS
    1. New understanding of atmospheric processes linked to climate will benefit both Numerical Weather Prediction (NWP) and climate analysis, all of which are key UK science capabilities (ECMWF, Met Office, NCEO, NCAS, Unis, etc.)
    2. New THz technologies for LOCUS have wide potential applications in other fields: Medicine (cancer screening), biology, spectroscopy, non-destructive testing, etc.
- LOCUS directly addresses 4 out of the 5 future challenges from ESA's Living Planet Programme, namely:
    - A1: Water vapour and its role on the radiation budget
    - A3: Atmospheric composition and climate interactions
    - A4: Interactions between changes in atmospheric circulation patterns and regional weather and climate
    - A5: Impact of transient solar events on Earth's atmosphere
- LOCUS measurements are shown to be: Useful, needed, unique and complementary, innovative and timely

Economic Case

- UK target to capture a 10% share of the global space market, thought to be worth £400bn by 2030
  - Requires full exploiting the significant pool of knowledge and emerging technology found in our own research institutes and companies
- LOCUS caters for both:
  - UK tech companies (receivers, quantum cascade lasers, mini-coolers, spectrometers)
  - UK science and research community (atmospheric research, NWP, climate analysis)
- MLT region displays pre-cursors of weather events (i.e. sudden Stratospheric warming) which is why NWP forecast models reach up to ~80km
  - LOCUS will provide missing measurements for data assimilation at that altitude
- Socio-economic impact of NWP estimated at €60 billion/year (ECMWF, EUMETSAT). Protection of Property and Infrastructure has a likely benefit of €5.5 billion/year
  - Cost:benefit ratio for weather events (storms etc) is between 13.2 and 16.1 to 1, more than £27B/year to the UK economy
  - MLT data for NWP at a cost of £150M - £250M would return a multi-billion profit to the UK

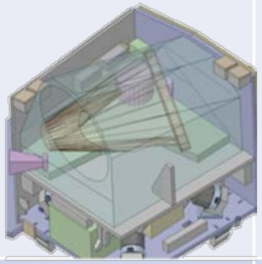
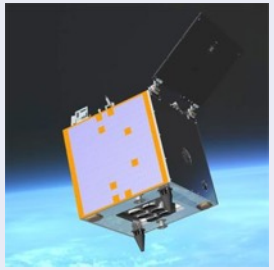
Economic Benefit – Point in Case

- Pre-production runs of the ERA-5 climate re-analysis model from current research activities at ECMWF (private communication by Dr. William Bell) show that:
  - Temperature records above 40km (10hPa) are "*problematic*"
  - These are partly mended post 2006 by GNSS RO assimilation (40km-50km)
  - → A mission that measures temperature in the 50km-80km range would "*pave the way for a more operational monitoring of the atmosphere at that altitude*"
- The trend in NWP is that forecast power increases by 1 day / decade
  - Sum of many model improvements and newly assimilated measurements
  - For that trend to continue, new measurements are needed
  - No composition measurements exist for the Upper Atmosphere, so the impact is likely to be significant (full OSSE is needed to quantify them)

Commercial Case

- Baseline: Implementation as a UK mission in the ESA Earthwatch programme (not the case now)
- Alternative implementation options:
  - Earth Explorer Core Mission: Viable, thanks to positive EE-10 review
    - Core Mission: Unlikely to be selected due to ESA preference for smaller Nations
    - Fast Track Mission: Possibly good change for selection, if cost envelope is compliant
  - ESA Mission of Opportunity: A bilateral mission with NASA, where UK supplies the THz instrument, and NASA contributes the next generation SABER-II IR radiometer could be very appealing to ESA
  - UK National Mission: Could be implemented efficiently with SSTL, but no funding available at the moment
  - ESA Small Sat Challenge: Potentially valid for the most minimalistic LOCUS implementation (1 THz channel & possibly 2-3 IR pixels)

Cost of Various Implementation Options

	1	2	3	4
Configuration	LOCUS with full SABER2	LOCUS (as in ESA EE-10)	LOCUS Reduced Specification	LOCUS Tandem Satellite
Channels	10 IR pixels 5 THz channels	5 IR pixels 5 THz channels	3 IR pixels 1-2 THz channels	1 THz channel
Science & Impact	Full LOCUS science remit + Full SABER science remit	Full LOCUS science remit	Reduced LOCUS science remit (thermal structure and quenching rates)	Reduced LOCUS science remit (thermal structure and quenching rates); Increased geolocation error
Satellite Class	**Astrobus-500** Astrobus-300 	Astrobus-300, **SSTL-150** 	**SSTL-150**, or possibly SSTL-100 (single Thz channel) 	**SSTL-100**, or other SmallSat 
ROM Cost	<€400M	<€300M	<€100M-€150M	<€50M
Possible path to Implementation	- Earth Explorer Core Mission - Earthwatch - ESA Mission of Opportunity	- Earth Explorer Core Mission - Earthwatch	- Earth Explorer Fast Track - UK National Mission	- ESA Small Sat Challenge - UK National Mission

Bilateral Mission with NASA

- Contact established – through intermediary of our Science Team members – with the SABER instrument PIs
  - Dr. James Russel III, Center for Atmospheric Sciences, Hampton University
  - Dr. Martin Mlynczak, Atmospheric Sciences Division, NASA Langley Research Center
- Plans exist for next generation SABER radiometer (SABER-II)
  - Identical performance
  - Compact design (half the weight, half the volume)
- NASA so far unwilling to fund pure continuity missions
- A bilateral UK/USA missions would:
  - Reduce cost to Europe (free IR instrument, US contribution to space segment)
  - Reduce cost to USA (European contribution to space segment)
  - Mitigate the NASA continuity argument (2 instrument mission with scientific synergy will be much more than just an extension of their SABER programme)

Financial Case

- Not possible to fully redo a mission costing for Earthwatch (lack of time, resources, and knowledge of terms and conditions)
- Based on EE-10 costing, the following assumptions apply
  - Space segment is smaller/cheaper with SABER-II than it would be with SABER
  - No parallel industry studies (UKSA to pick UK space prime)
  - Instrument (pre-)development by UK universities and research institutions
- Two cost models:
  - Fully UK funded vs. Bilateral mission with free IR instrument

	Phase A/B1 feasibility study	Phase B2CD implementation	Launch and commissioning	Ground segment development	Service development	Operations (per year)	ESA internal cost	TOTAL COST	Commercial contribution	COST to UK Government
UK only	£25M	£80M	£20	£30M	£25M	£30M	£50M	£260M	N/A	£260M
Bilateral	£25M	£55M	£15	£30M	£25M	£15M	£50M	£215M	£65M	£150M

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Management Case

- Divvy up the mission management into 3 Phases, and 5 Task Segments

	Mission Management Task Force	Payload Development Task Force	Space Segment Task Force	Scientific Exploitation Task Force	Economic Exploitation Task Force
Preparation ↓	Task Forces Coordination **RAL/UKSA**	Instrument Design and Pre- Development **Instrument teams/UK Space Prime**		Climate model pre-development (incl. MLT representation) **Leeds/Reading**	NWP model pre-development (incl. MLT assimilation) **Met Office/ECMWF**
Implementation ↓	Coordination with bilateral partner **RAL/UKSA** Coordination with ESA UKSA	Instrument Build **Instrument teams/UK Space Prime**	Satellite Design and Development **UK Space Prime** Launch Support **UK Space Prime/UKSA**		
Exploitation	Monitoring of Societal Impact Science Team		Commissioning and Operation **UK Space Prime/UKSA**	Operational exploitation in climate models **Leeds/Reading**	Operational exploitation in NWP **Met Office/ECMWF**

Summary

- LOCUS meets (or can be made to meet) all the requirements for implementation as an Earthwatch mission
- The LOCUS mission is modular. 2 separate instruments, with several channels each, contribute to various different scientific objectives. This allows for scalability of the mission:
  - In terms of the extent of targeted science objectives
  - In terms of outsourcing single instruments, or parts thereof
- The most promising bilateral option is to co-fly a UK THz sounder, together with the US next-generation SABER-II IR radiometer