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Rutherford Appleton Laboratory
Space Science & Technology Department

Multiplexed LHR for atmospheric composition sounding (Mux-LHR)

Damien Weidmann

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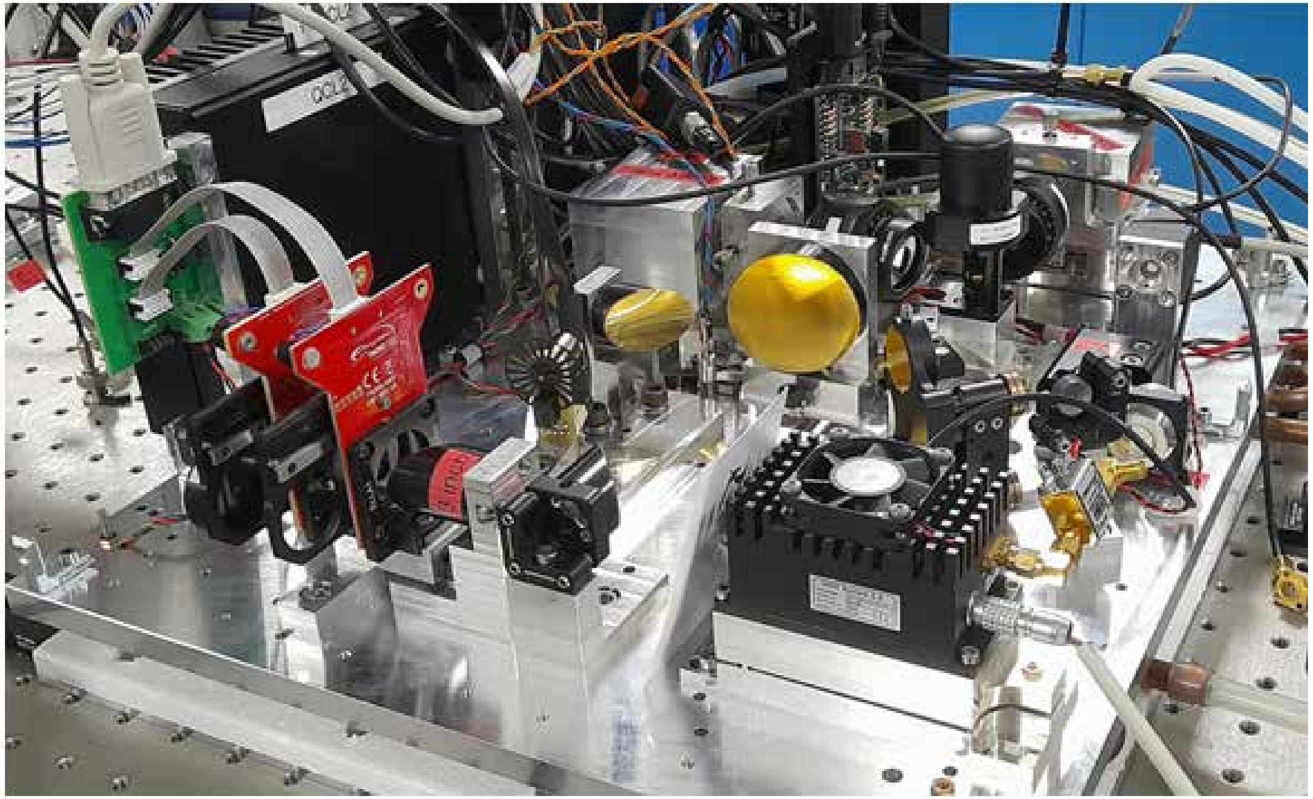
Outline

- Rationale
- State of the art : HIROS
- Emerging : Mux LHR
- Description / roadmap
- Conclusion



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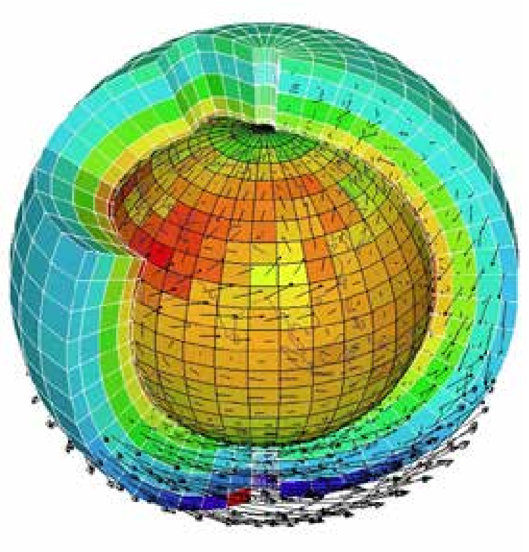
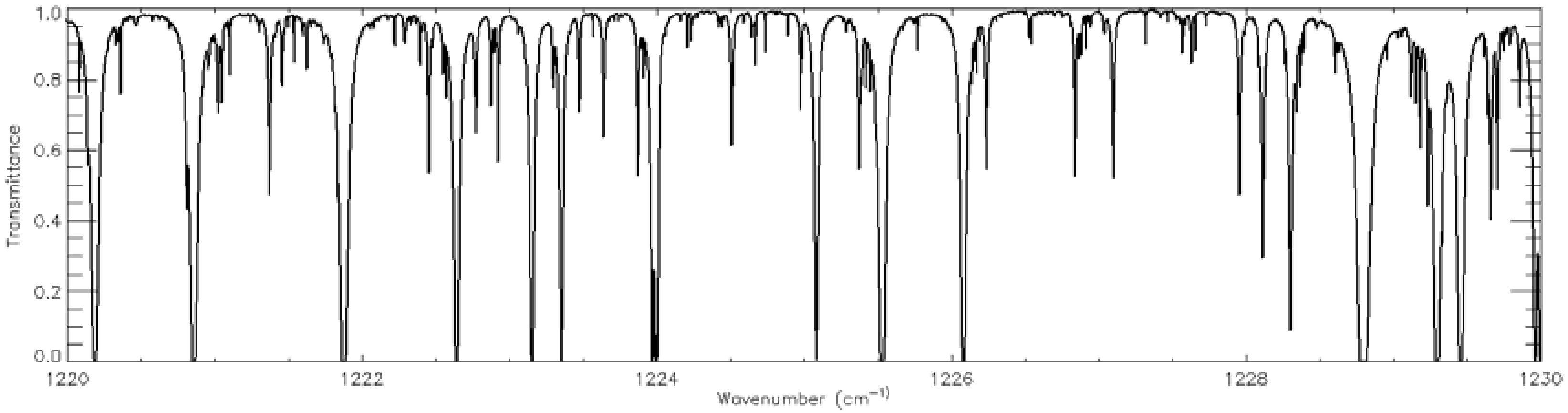
Atmospheric composition sounding

- 4D observation of atmospheric constituents
  - GHG, AQ, NWP, climate and chemistry studies
- Focus on thermal IR (LWIR 8-12 um)
  - Thermal emission (contrast between surface and constituents)
  - Fundamental ro-vibrational bands (“fingerprint”)
  - Lineshape resolution gives height resolution



Credit: https://www.encyclopedie-environnement.org/



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Thermal IR sounders

Nadir : priority to horizontal resolution

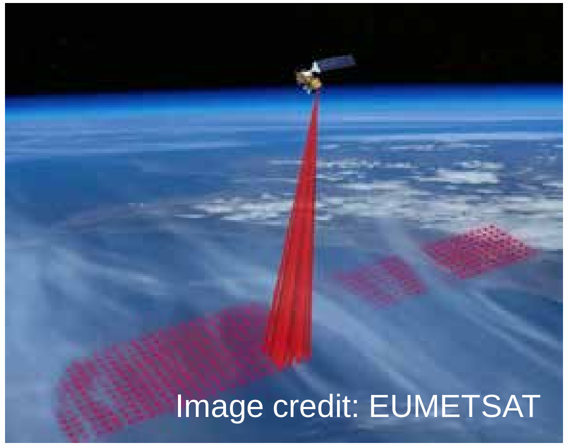


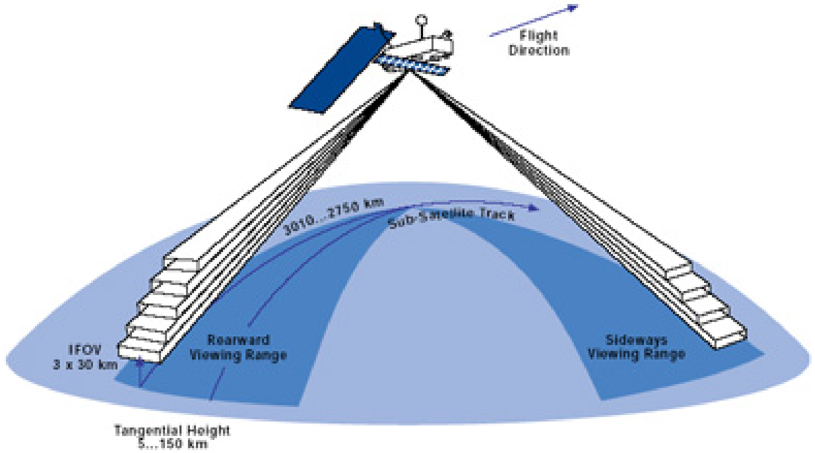
Image credit: EUMETSAT


TES, credit: NASA

IASI NG


CrIS, credit: NASA

Limb : priority to vertical resolution




SCISAT, image credit: CSA


MIPAS, image credit: ESA

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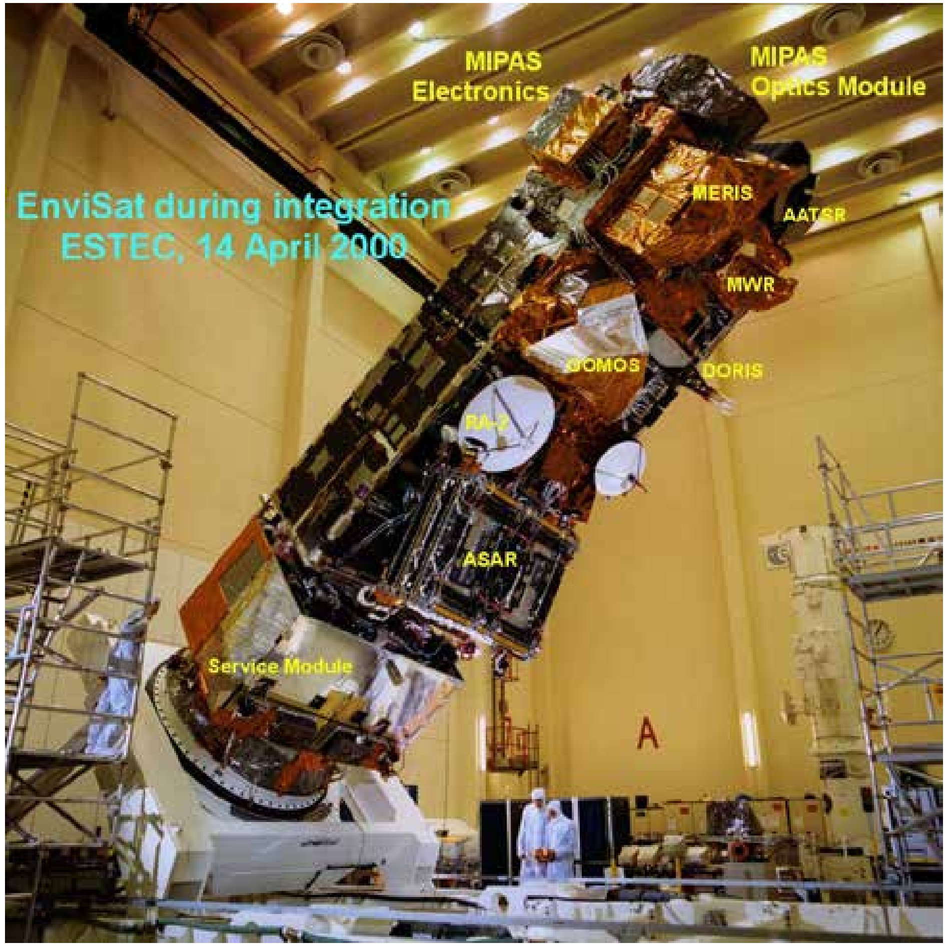
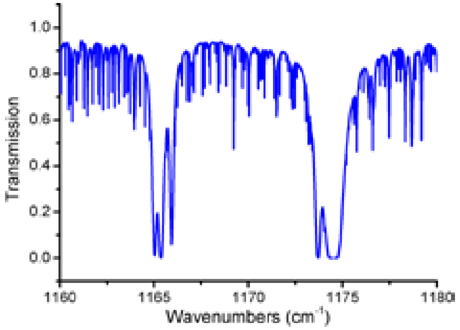
Size - Mass - Cost

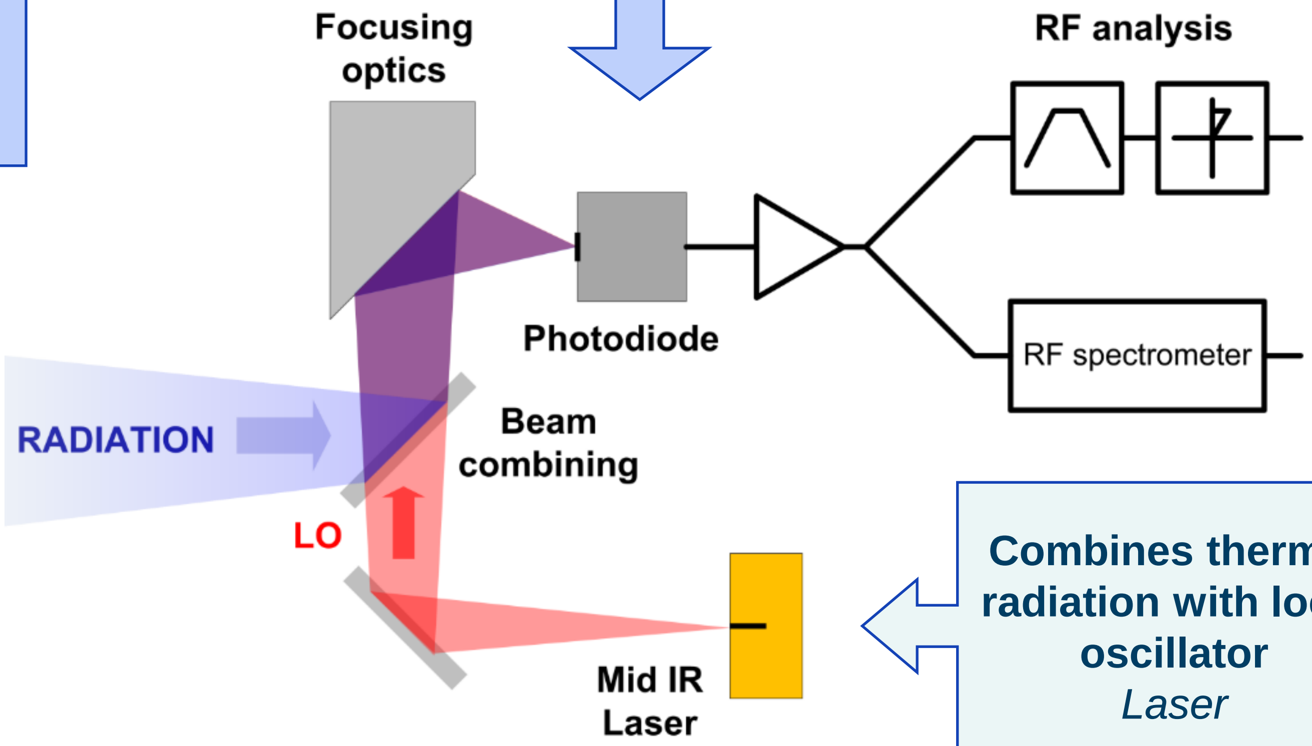


Laser Heterodyne spectro-Radiometry (LHR)

Collects radiation from the scene
contains unique spectral signatures from atmospheric constituents



Non linear mixing
Down conversion into RF domain



Combines thermal radiation with local oscillator
Laser

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Atmospheric trace gas measurements using laser heterodyne spectroscopy, D. Weidmann, in “Advances in Spectroscopic Monitoring of the Atmosphere”, W. Chen, D.S. Venables, M.W. Sigrist (Eds), pages 159-223, Elsevier, 2021. doi: 10.1016/B978-0-12-815014-6.00005-1

Uniqueness & Combined Advantages

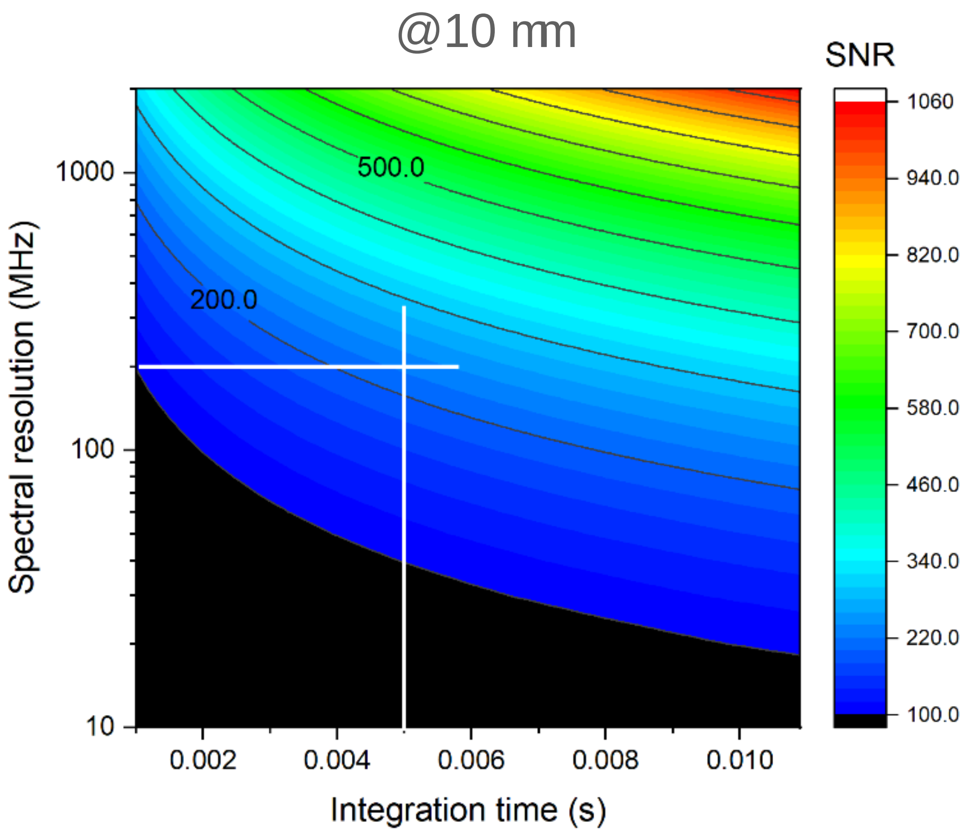
- Radiometric precision
  - Signal to Noise Ratio : ideally shot noise limited

$$SNR = \frac{h \cdot \nu \cdot \kappa \cdot \sqrt{\frac{2B\cdot\tau}{\pi^2}}}{\exp\left(\frac{h\cdot\nu}{k\cdot T_{BB}}\right) - 1} \cdot \frac{1}{\frac{h\cdot\nu}{\eta_d} + \frac{A}{2P_{LO}\cdot {D^*}^2}}$$

- High spatial resolution
  - Coherent FoV

$$\langle i_{IF}^2(t)\rangle = 2e^2 \left| \int \eta(\mathbf{r}) \cdot \mathbf{E_S}(\mathbf{r}) \cdot \mathbf{E}^*_{\mathbf{LO}}(\mathbf{r}) \cdot \mathbf{dr} \right|^2$$

- High spectral resolution
  - Spectral analysis in the RF domain
- Other system benefits
  - Size, Stable spectral response



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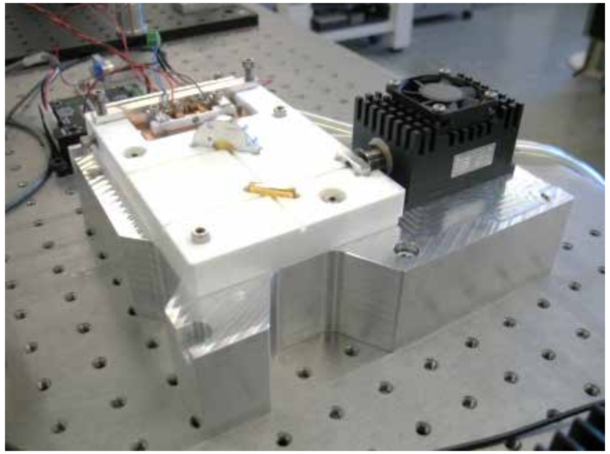
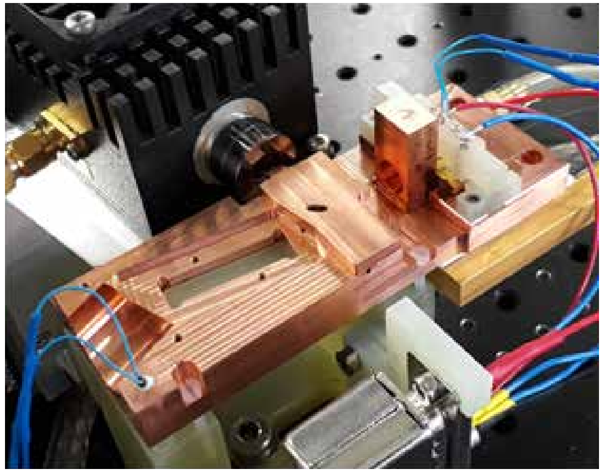
LHR maturation from ground to space

Ozone: 9.7 um

H2O, CO2, CH4 : 10.6, 7.7 um

HW hybrid integration





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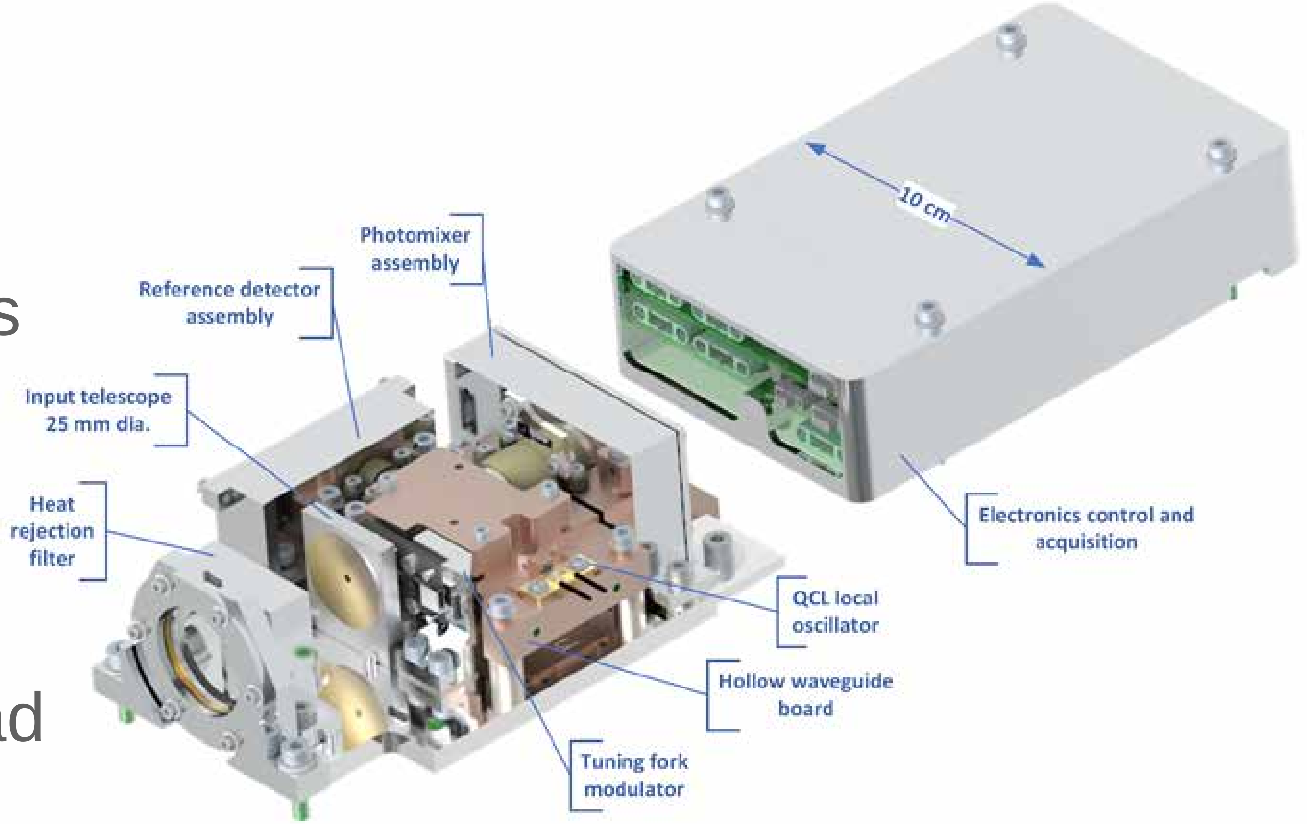
SOLSTICE mission – HIROS payload

Solar Occultation Limb Sounding Transformative Instruments for Climate Exploration

- High accuracy high vertical resolution atmospheric composition
- Complement to Nadir missions
- Constellation coverage
- Highly versatile / configurable
- Productized
- Plug and play scientific payload
- Microsat compatible



High resolution InfraRed Occultation Spectrometer

1 km inst. FoV - Volume <1.5 U - Mass < 2 kg
0.01 cm^{-1} res. - 1 cm^{-1} narrow windows - SNR ~ 140

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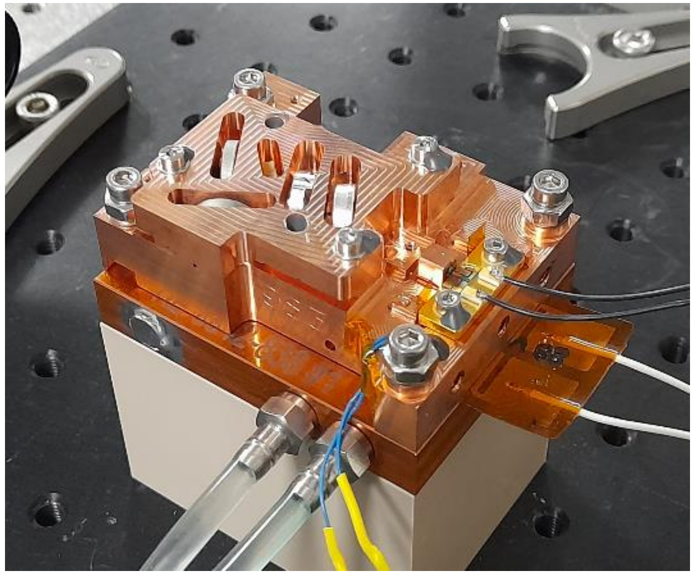
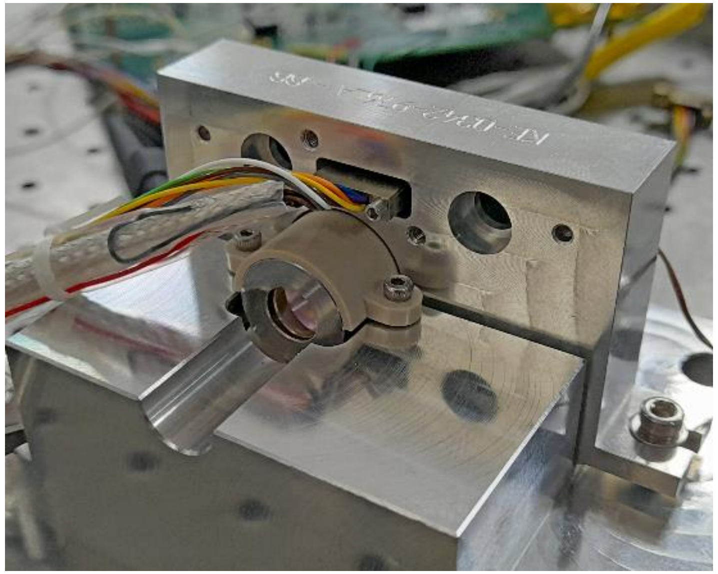
Solstice

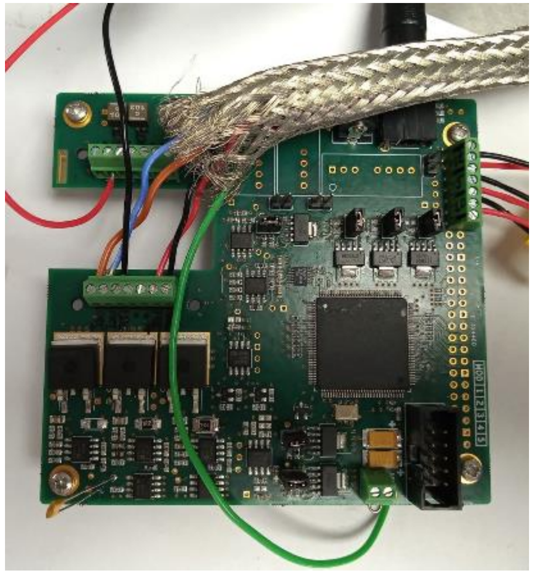
HIROS Development Status



Integrated LHR block tested and functional.
Projected SNR with solar input of 140.

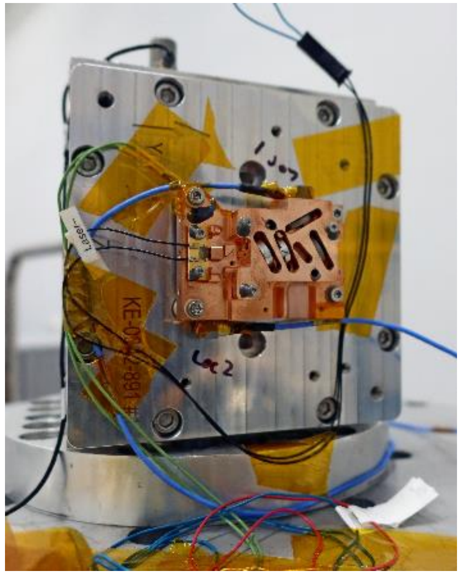


Photomixer in development and testing.
Integrate preamp and RF chain.



QCL digital controller for space application

- Absolute frequency stability 9×10^{-4} cm^{-1} over 30 min
- Relative stability 4×10^{-5} cm^{-1}



HIROS HW board under tests for vibrations and shock
75G @100 Hz
1000G >1kHz.

Front end telescope
25 mm aperture

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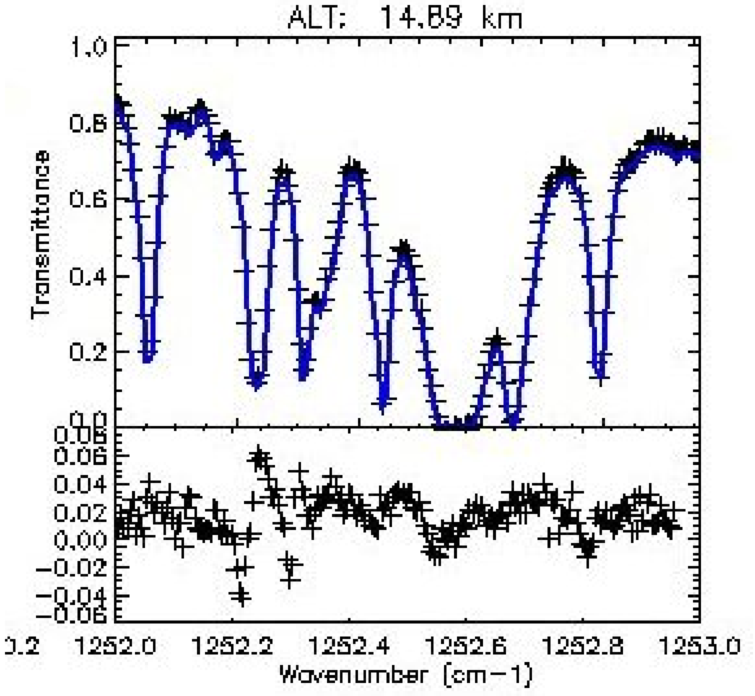
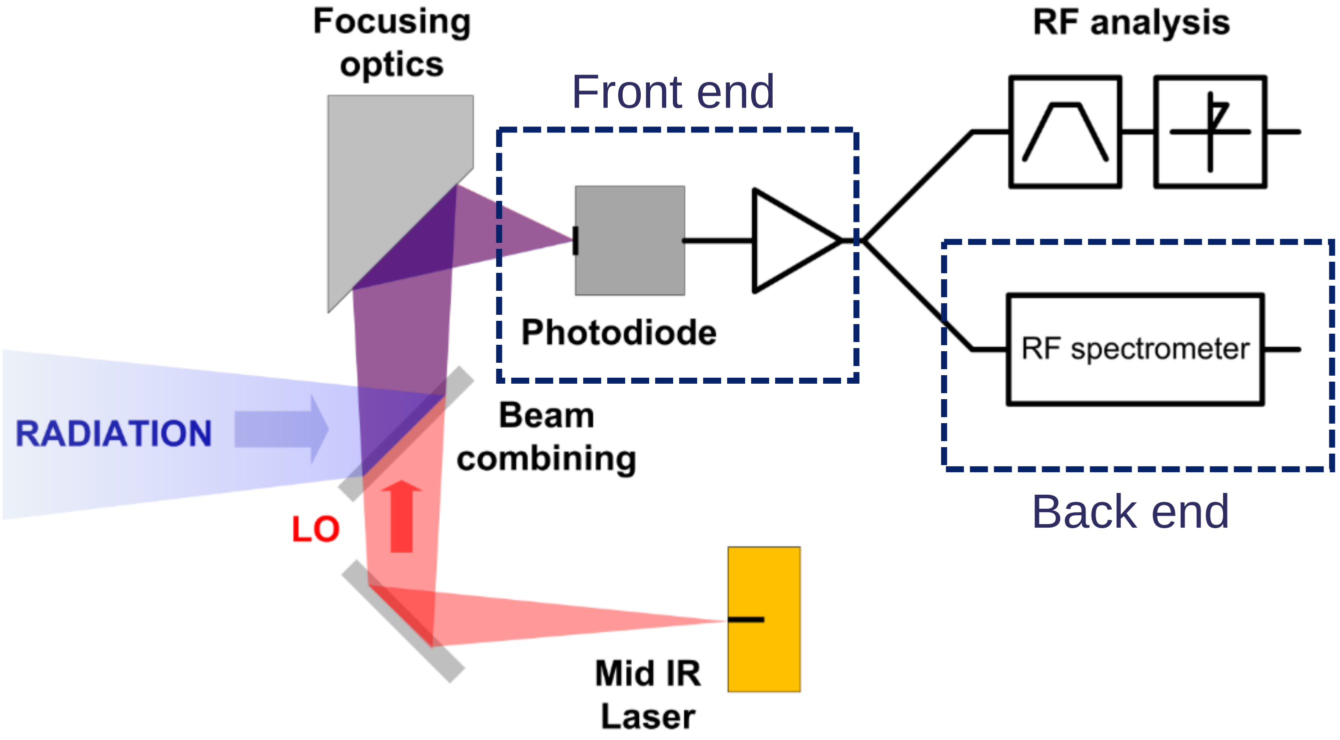
Next and emerging: Multiplexed LHR



Multiplexing ideal SNR gain: x14



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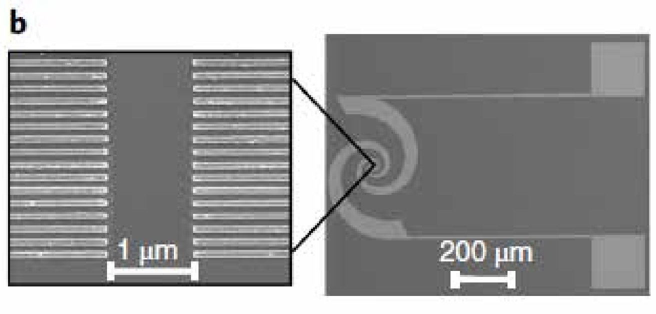
Front end: need for speed

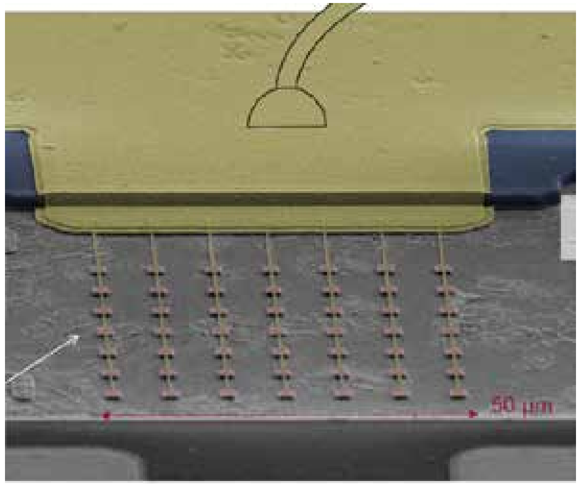
- Resonant optical cavity photodiode (3 GHz)
  - LN2 cooling
- Immersed lens photodiode (1.5 GHz)
  - Thermoelectric cooling

- Plasmon assisted antenna coupled (>1THz)
  - Room temperature
  - Optical pumping



Wang et al., 2019

- Quantum well arrays (>50 GHz)
  - Room temperature



Palaferri et al., 2018

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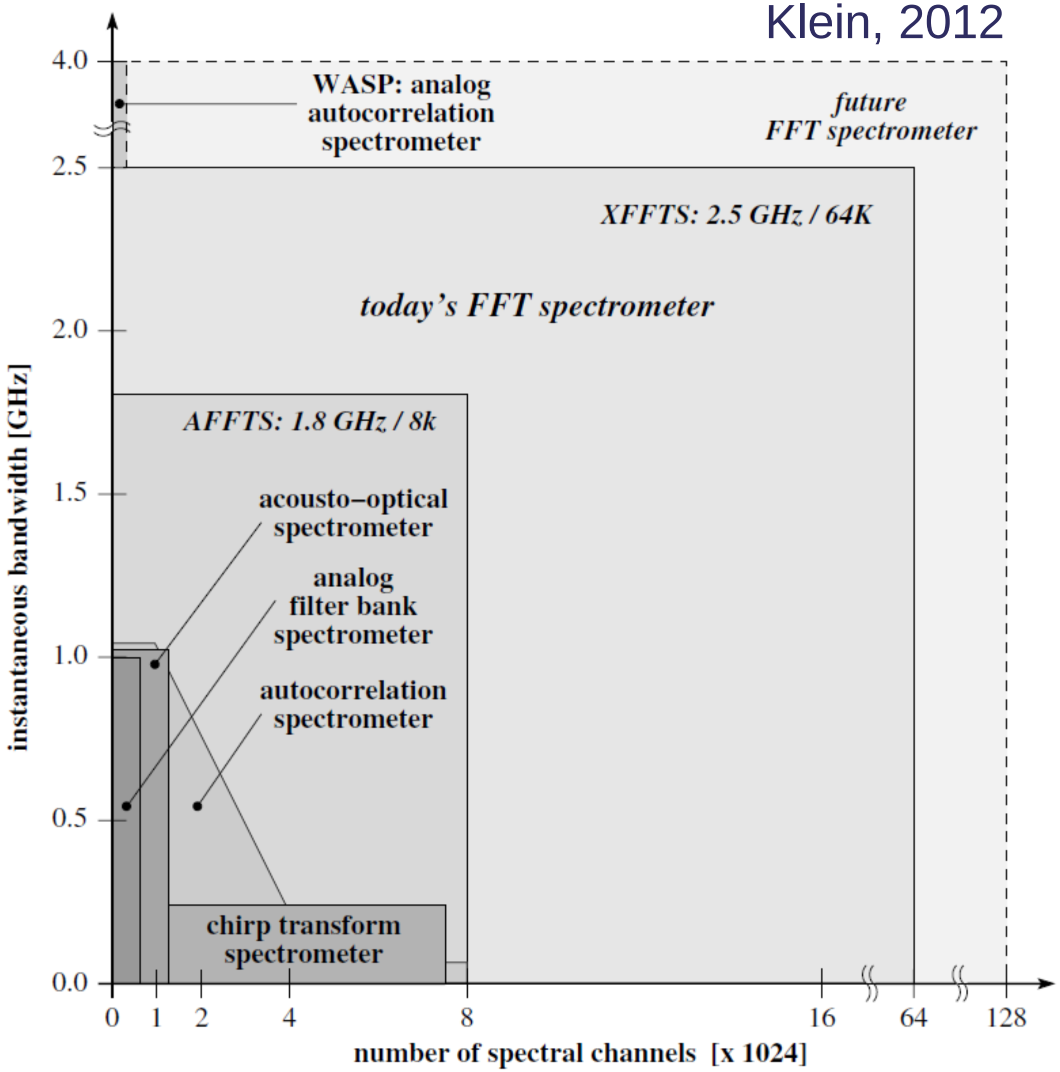
Back end: power efficiency

- Mux LHR requirements
  - Large bandwidth
  - Small number of channels
- Digital approaches
  - Correlators

    < 5 GHz – 1024 ch – 3 W
  - FFT based spectrometers

    < 5 GHz – 16384 ch – 40W

Klein, 2012



Mux-LHR for NWP – IASI comparison

- Study with the Met Office
- Key products
  - Water vapour in the FIR
  - Mesospheric temperature
  - >80 km (NWP / Space weather)
- Best scenario identified
  - LEO
    - Stratospheric sounding
    - Upper atmosphere constrain
  - GEO
    - Targeting sounding
    - Extreme events

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RESEARCH ARTICLE

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Evaluation of laser heterodyne radiometry for numerical weather prediction applications

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This article reports the results of a preliminary mission study to assess the potential of space-borne laser heterodyne radiometry (LHR) for the remote sensing of temperature for assimilation in a numerical weather prediction (NWP) model. The LHR instruments are low cost and small in size, lending themselves to a wide variety of satellite platforms. The impact of different configurations of an idealized LHR instrument is assessed against the Infrared Atmospheric Sounding Interferometer (IASI), via single-column linear information content analysis, using inputs consistent with the background errors of the Met Office 4D-Var assimilation system. Multiplexed configurations give promising results, in particular for sounding of upper-atmospheric temperatures.

KEYWORDS
DFS, IASI, information content, laser heterodyne radiometer, numerical weather prediction, temperature sounding, upper atmosphere

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Conclusion & Forward Look

- Need for atmospheric composition sounding is growing
  - More resolutions, more products and applications
  - TIR LHRs have unique benefits
  - Opportunity for smallsat-enabled novel data products
    - operational
    - Scientific
  - Opportunity to lead in this area
- LHR technology being implemented for solar occultation limb sounding through the SOLSTICE mission
- Mux LHR to unlock nadir and emission limb sounding applications
  - Strong subsystem commonalities with LHR
  - Inherit good heritage from mmW receivers
- Vision
  - To achieve 70% of what a large scale mission achieves at less than 1/10th of the cost
  - To allow novel versatile composition sounding approach and associated products