wege entstehen, indem wir sie gehen
paths emerge in that we walk them

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Monitoring von Treibhausgasen und Klimawandel mit Satelliten

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Thanks to all colleagues who also contributed to work discussed in here, especially the ESA project partners (see references)

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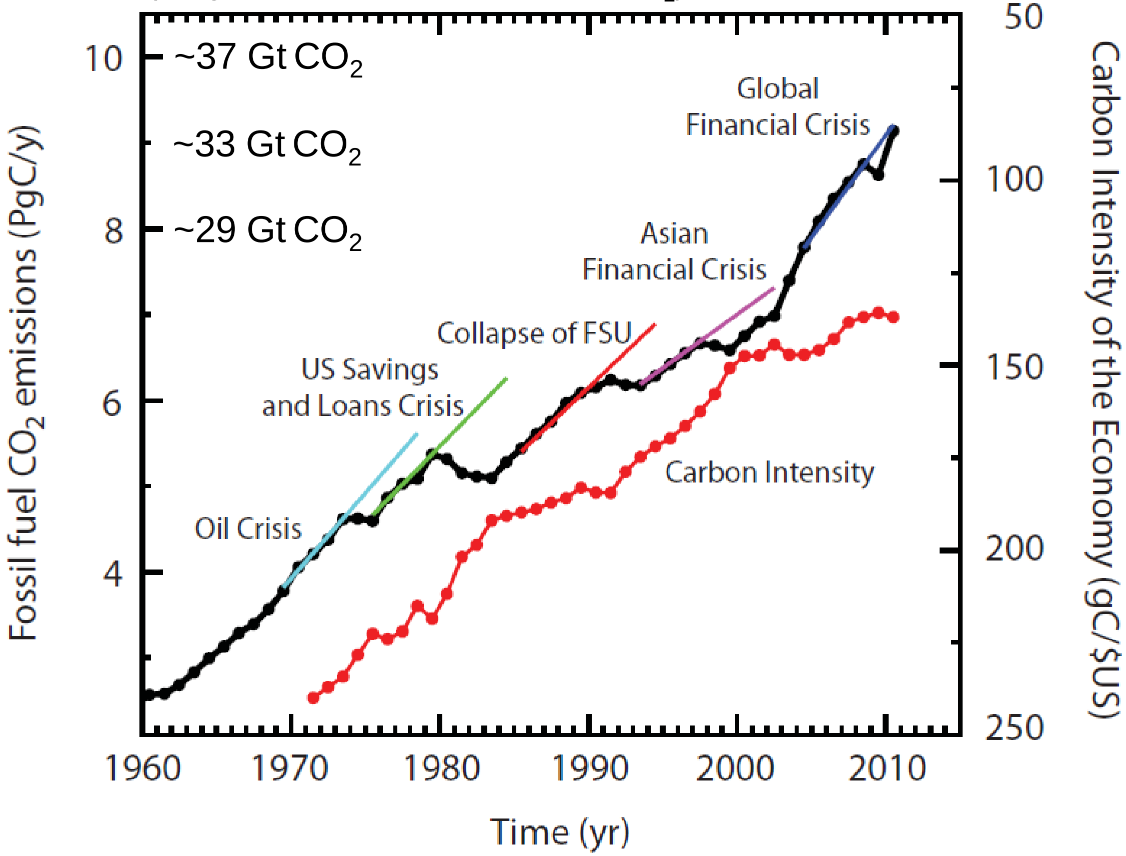
Vortrag bei Graz in Space 2012, IWF Graz, AT, 6. September 2012

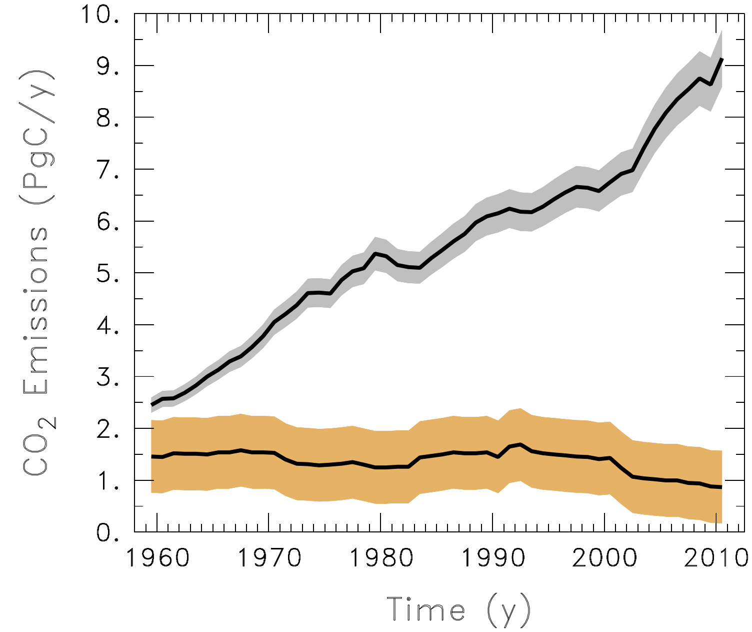
Why care? – Let's check GHGs/CO_2, how did we fare so far?

- Over the most recent decade (2001-2010) CO_2 emissions still rose faster than in any decade before – what's next?

(1 PgC = 1 GtC, 1 GtC = 3.67 Gt CO_2)

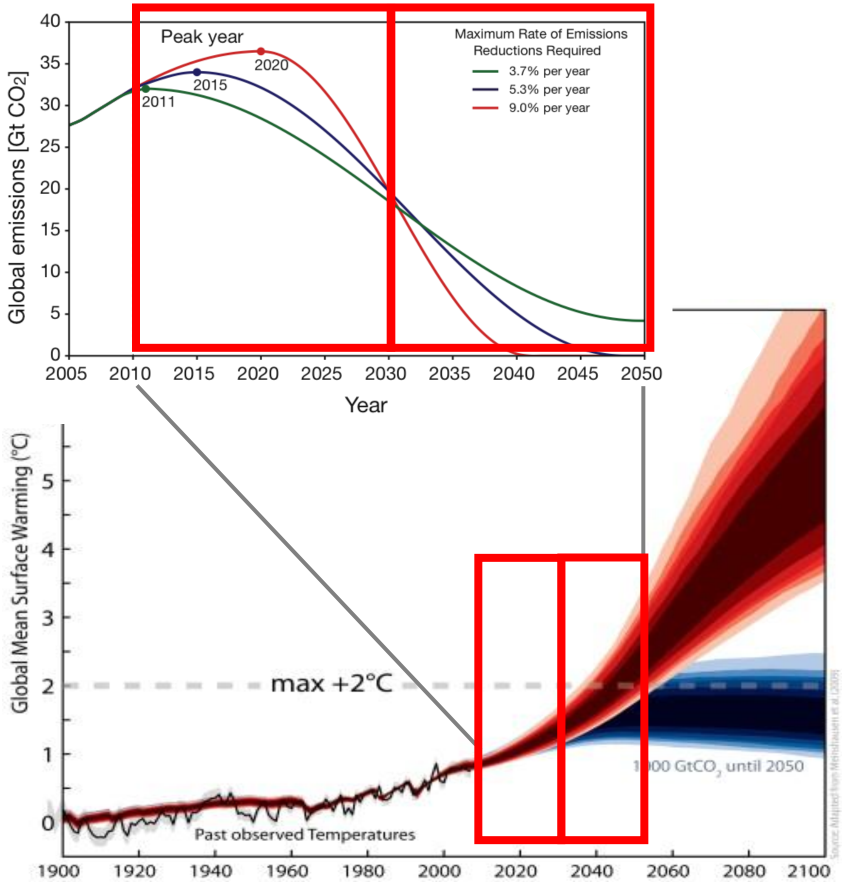


[Peters et al. (GCP data), Dec 2011]

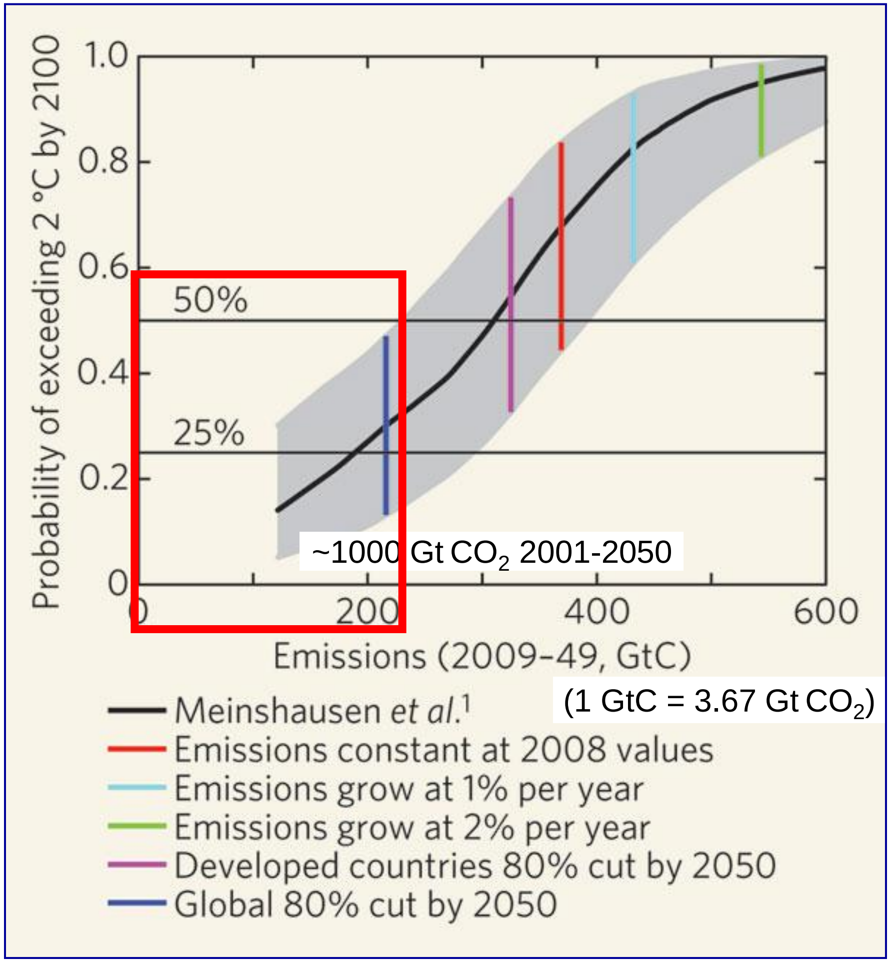


(current land use change emissions ~10% of total CO_2 emissions)

- globally about –60% CO_2 to 2050 (OECD countries –80%) is estimated to be needed for likely keeping max. +2°C



[Allison et al., 2009; Meinshausen et al., 2009]



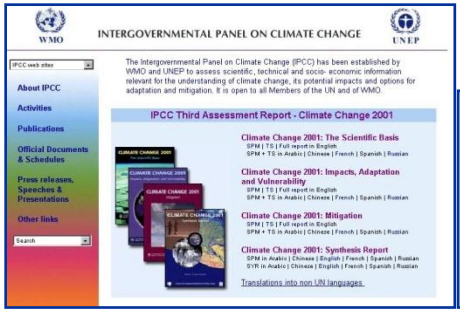
[Schmidt and Archer, 2009]

so we must monitor the atmosphere and climate with benchmark data techniques since…

…these unique data serve as fundamental backbone and "true" reference standard to atmosphere and climate science & services

more specifically, three major reasons:

- to rigorously observe and learn, independent of models, how weather, climate and composition variability and change evolve, over monthly, seasonal, interannual, and decadal scales
- to test and guide the improvement of weather, climate and constituent models and thereby enhance their predictive skills for simulating future weather, climate and chemical composition
- to use the benchmark data as accurate observational constraints for natural and anthropogenic climate and composition change detection and attribution

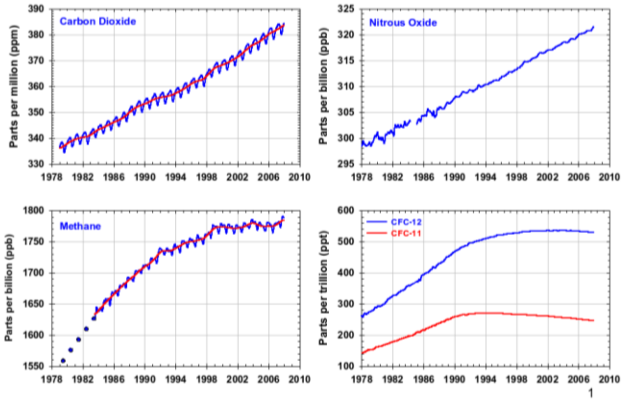


…from the 9 ***"high priority areas for action"*** noted in the ***IPCC 2001 report*** (Summary for Policymakers, IPCC WG I, p. 17) - ***still valid a decade later in 2012:***

"- ***sustain and expand the observational foundation for climate studies by providing accurate, long-term, consistent data including implementation of a strategy for integrated global observations.***"

which properties need such benchmark data to have and which techniques can match these?

key properties:

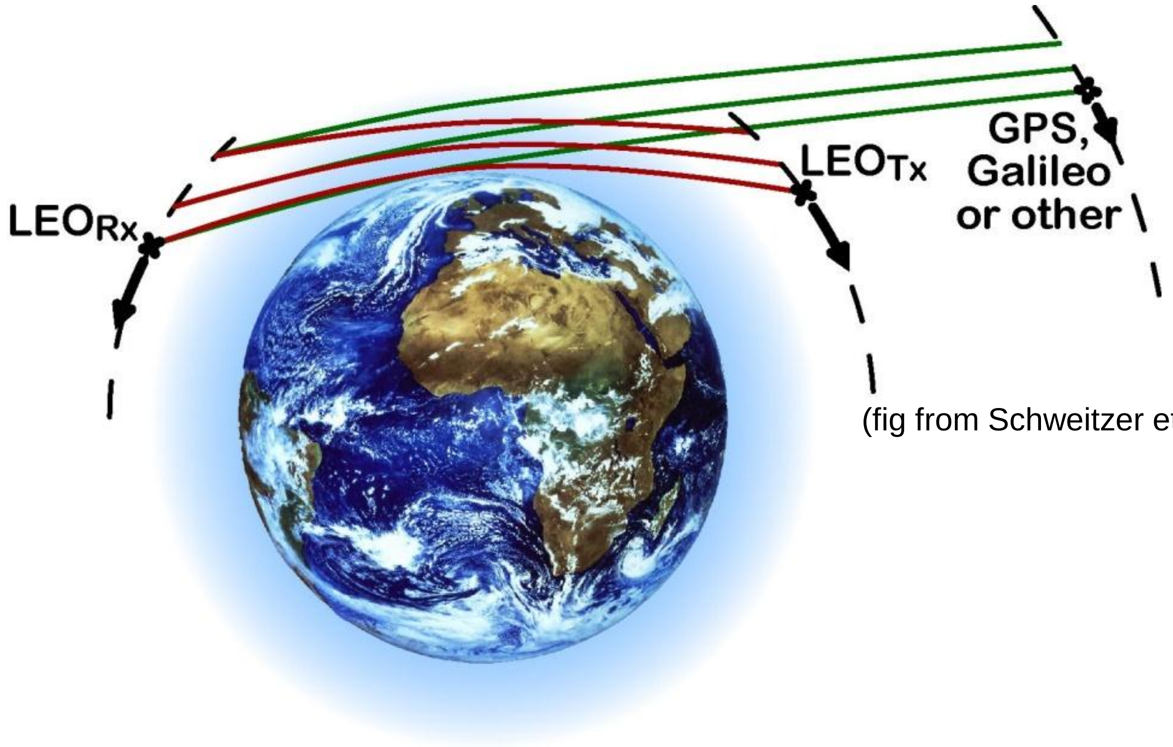


- long-term stable (over decades and longer)
- accurate (traceable to SI standards)
- globally available (same above land and oceans, etc.)
- measure sensitive indicators of atmosphere and climate change, in a physically consistent manner, such as:
  => GCOS Essential Climate Variables (ECVs) (in the atmosphere: temperature, pressure, water vapor, wind, greenhouse gases, etc.)
  [e.g., GCOS Guideline, GCOS-143(WMO/TD No. 1530), May 2010]

…now, GNSS Radio Occultation (GRO) can provide such data for thermodynamic variables over tropo- and stratosphere; the new next-generation technique shall do so for a complete set of ECVs

LMIO ("ACCURATE"):

from GRO decimeter-wave L-band signals to GRO-type coherent signals at cm-, mm-, and µm wavelengths



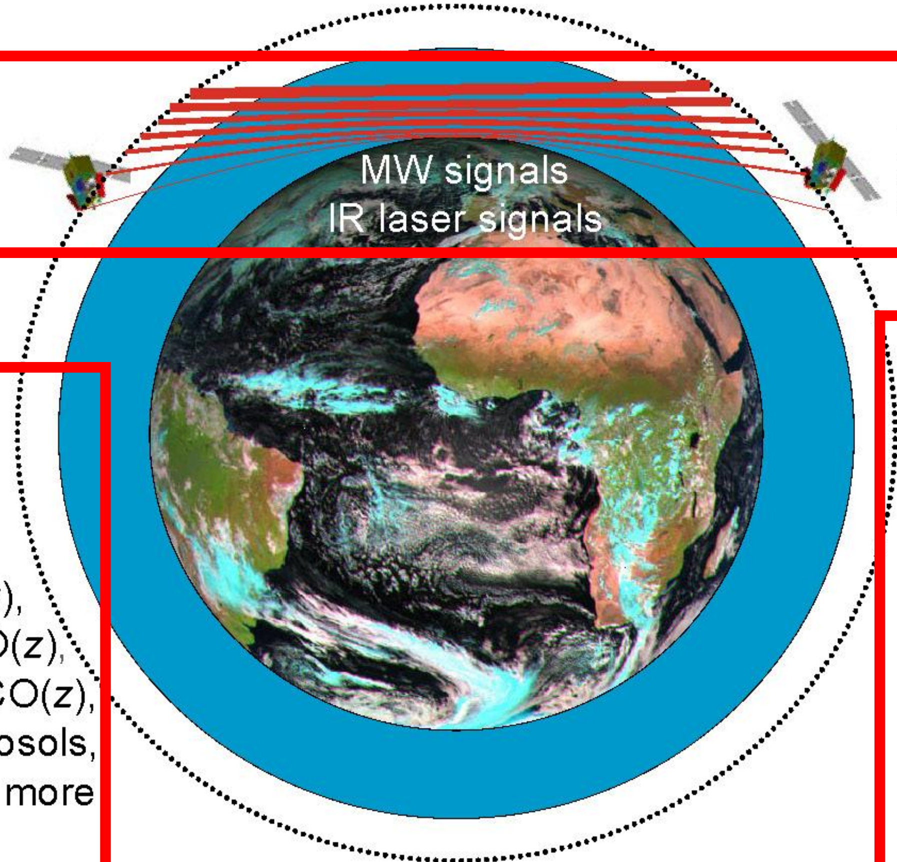
(fig from Schweitzer et al., JGR, 116, D10301, 2011)

= LEO-LEO Microwave and Infrared-laser Occultation

LMIO – ACCURATE measurement concept

LEO-LEO microwave occultation (LMO) combined with LEO-LEO infrared-laser occultation (LIO): LMIO

[Introduction of LMIO: Kirchengast and Schweitzer, GRL 38, L13701, 2011]



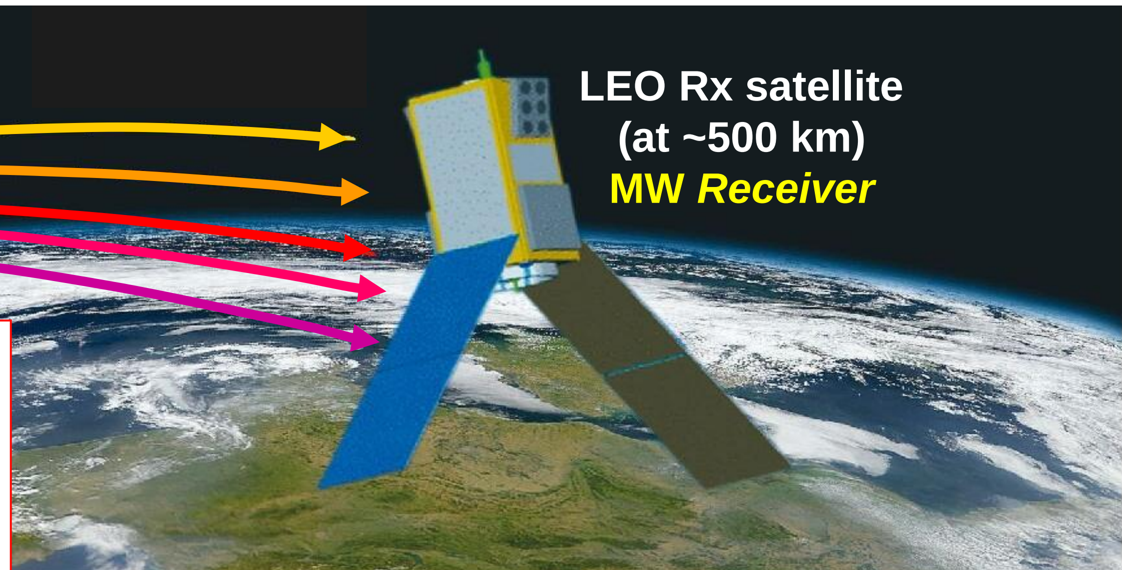
ACCURATE
climate benchmark quality UTLS profiles:
$z(t)$, $N(z)$, $p(z)$, $Z(p)$, $T(z)$, $q(z)$, $H_2O(z)$, $V_{los}(z)$, $CO_2(z)$, $^{13}CO_2(z)$, $C^{18}OO(z)$, $CH_4(z)$, $N_2O(z)$, $O_3(z)$, $CO(z)$, $HDO(z)$, $H_2{}^{18}O(z)$ & aerosols, clouds, turbulence (and more below & above UTLS)

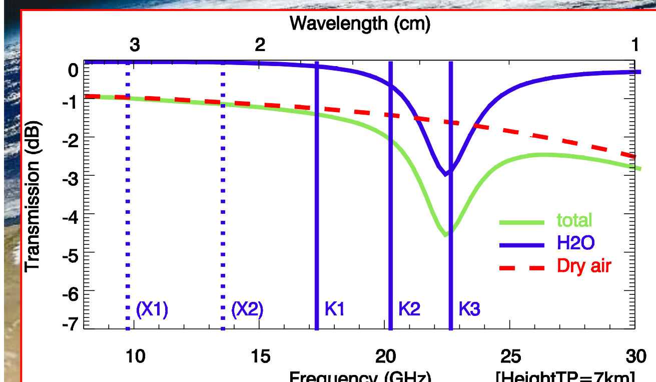
ACCURATE
LMIO=LMO&LIO measurement techniques:
LMO: LEO-LEO microwave occultation (MW cross-links at 17.25, 20.2, 22.6 GHz; optional 179+182 GHz)
LIO: LEO-LEO infrared laser occultation (SWIR cross-links at 21 selected frequencies in 2–2.5 μm)

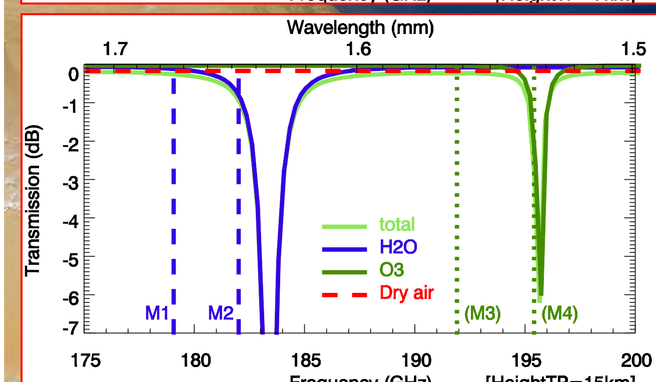
how does the LMO method work?

MW refraction&absorption: established by GRO heritage and ACE+ and ATOM(M)S concepts…

[Recent LMO performance study: Schweitzer et al., JGR 116, D10301, 2011]





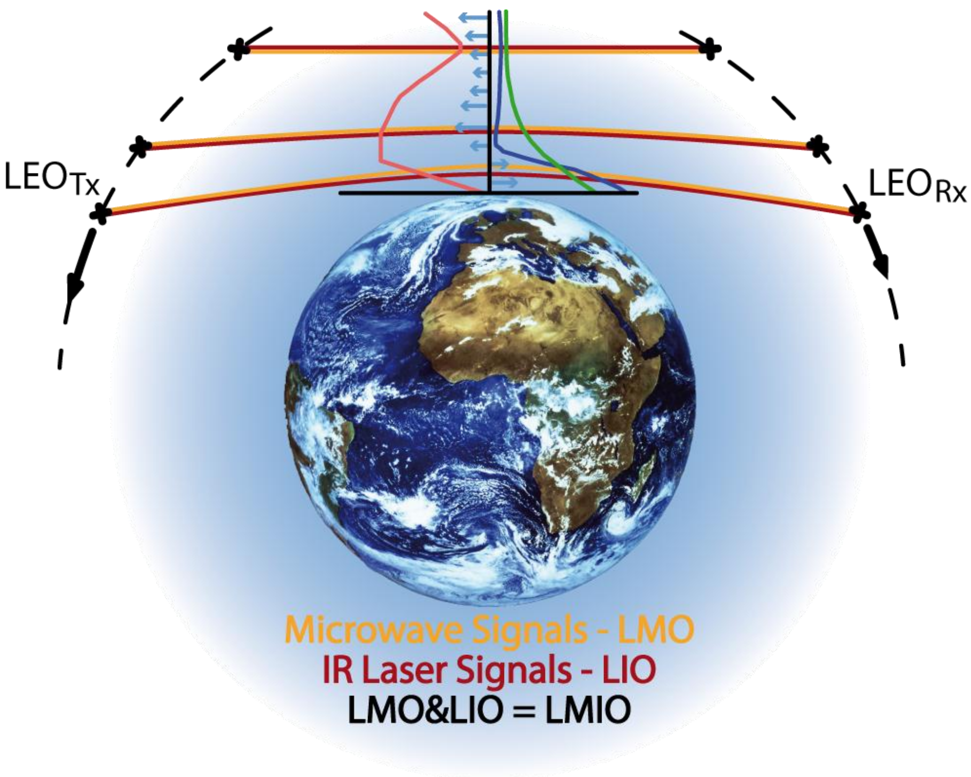


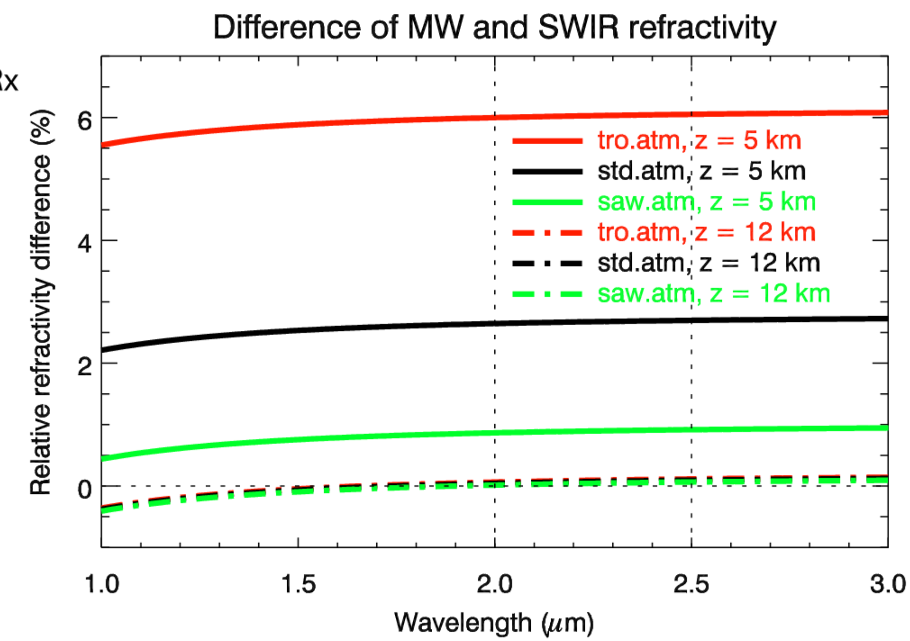
- Exploits refraction and (differential) transmission of MW signals (~17.25, 20.2, 22.6; opt. 179, 182 GHz, at the 22 / 183 GHz water vapor absorption lines; the Fig. left also indicates an optional ozone line) between LEO Tx and LEO Rx satellites.
- Measurements of phase delay & amplitude → bending angle & transmission → refractivity & absorption coeff. (*freq*) → pressure, temperature, humidity (independently over full UTLS domain).

how does LIO join LMO in synergy to form LMIO?

SWIR refractivity (LIO) approx. equals MW dry-air refractivity (LMO)

MW dry-air refractivity ("Smith-Weintraub formula") is to < 0.1% difference equal to SWIR refractivity ("improved-Edlen formula") within 2–2.5 μm, so that LIO and LMO propagation paths are closely the same. In moist air (~5-12 km) the difference can increase to ~10% near 5 km under moist tropical conditions, so that the LMO-derived state *p*,*T*,*z* is used to accurately compute LIO altitudes.





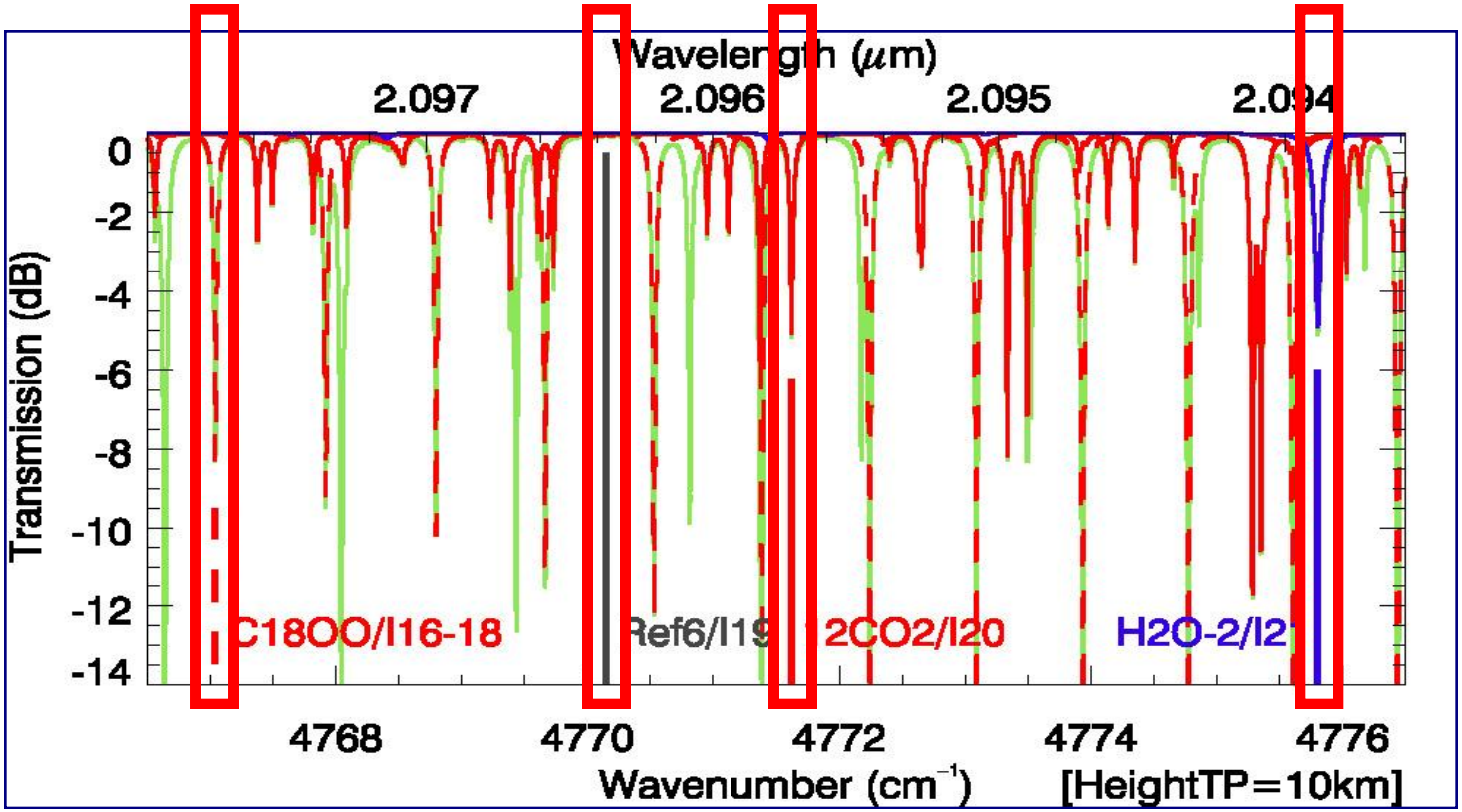
[Details on LMIO signal propagation: Schweitzer, Kirchengast, Proschek, AMT 4, 2273, 2011;
on LMIO retrieval algorithm: Proschek, Kirchengast, Schweitzer, AMT 4, 2035, 2011]

how does LIO then work in LMIO?

differential log-transmission over *narrow delta-freq* ("differential absorption principle")

=> accurate profiles of GHGs and line-of-sight wind speed, building on LMO *T*,*p*,*z*.

abs. channel $C^{18}OO$ **ref. channel** **abs. channel $^{12}CO_2$** **abs. channel H_2O**



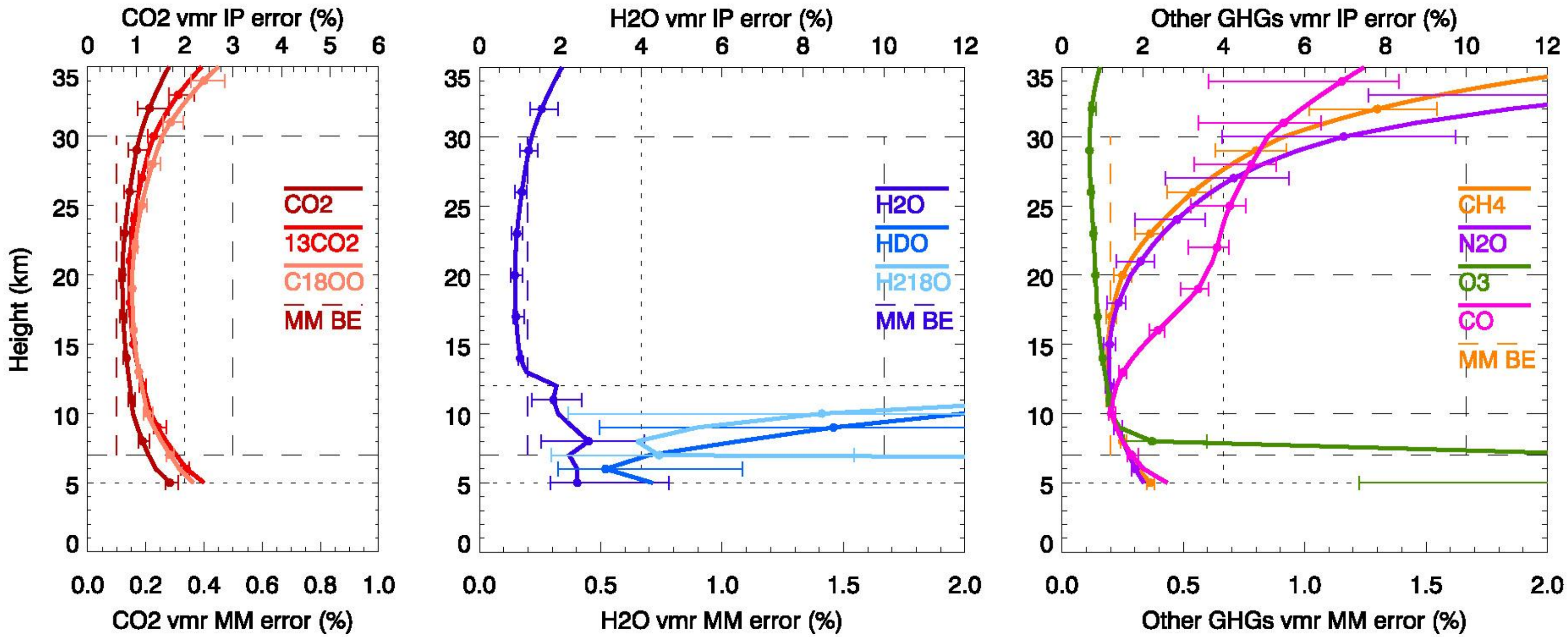
[Details on LIO channel selections etc: Kirchengast and Schweitzer, GRL 38, L13701, 2011;
on accurate line spectroscopy needs: Harrison, Bernath, Kirchengast, JQSRT 112, 2347, 2011]

what is the LIO-retrieved profiles accuracy? (1)

example GHG profiles retrieval performance: individual-profile and monthly-mean error estimates

- Monthly-mean GHG profiles unbiased (no time-varying biases) and generally accurate to < 0.15-0.5% (e.g., CO_2 < 1 ppm) (ALPS2 simulation results)

Example results: GHG and isotope species profile retrieval, IP and monthly-mean errors



(Profiles: Mean.Err[U.S.Std.Atm+5 FASCODE Atms], Range Bars: Spread[Min.Err(6 Atms) to Max.Err(6 Atms)])

[Details from simplified LIO performance study: Kirchengast and Schweitzer, GRL 38, 2011; from quasi-realistic retrieval performance study: Proschek, Kirchengast, Schweitzer, AMT 4, 2011]

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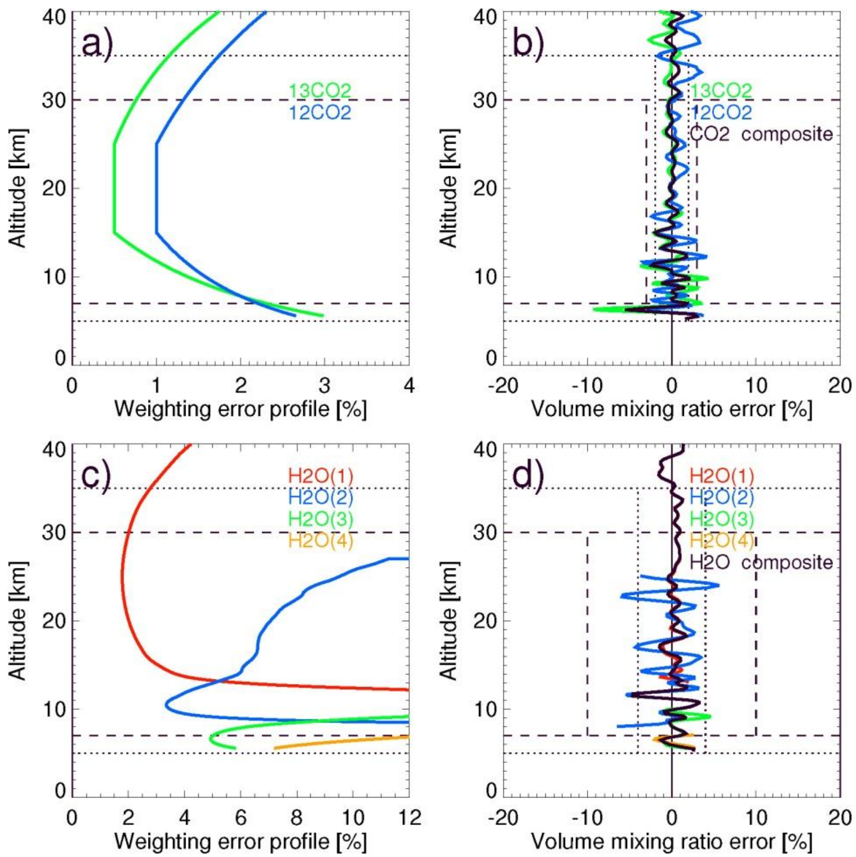
what is the LIO-retrieved profiles accuracy? (2)

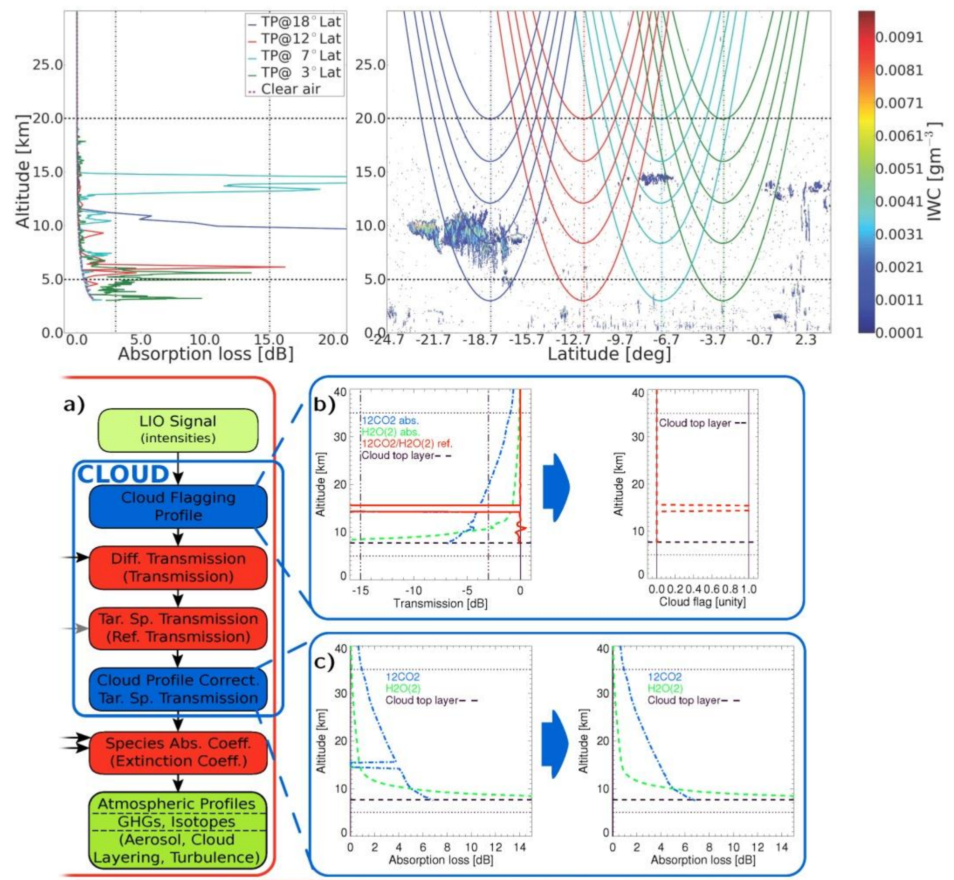
example from the quasi-realistic simulation studies

- Performance found is consistent with the simplified estimates; and these real data processing developments directly prepare for real data

CO_2 and H_2O non-cloudy air performance examples



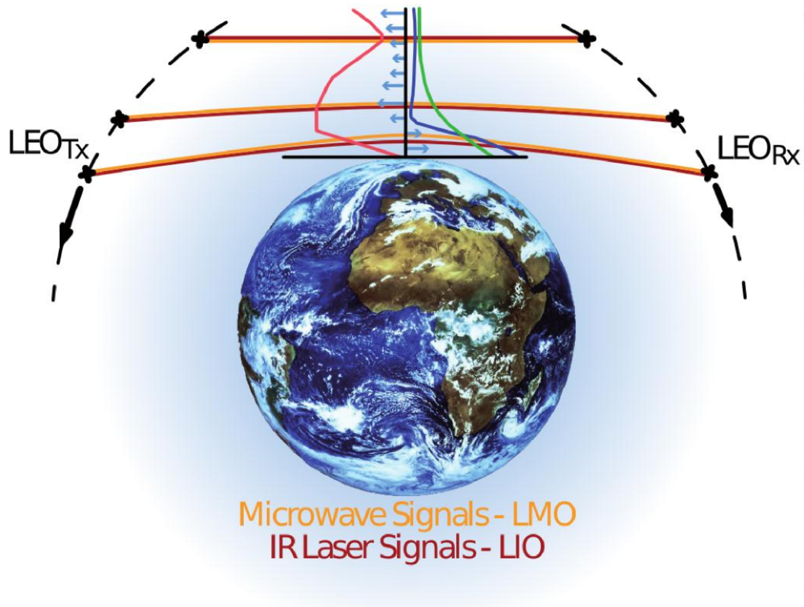
Algorithm development for cloudy air retrievals

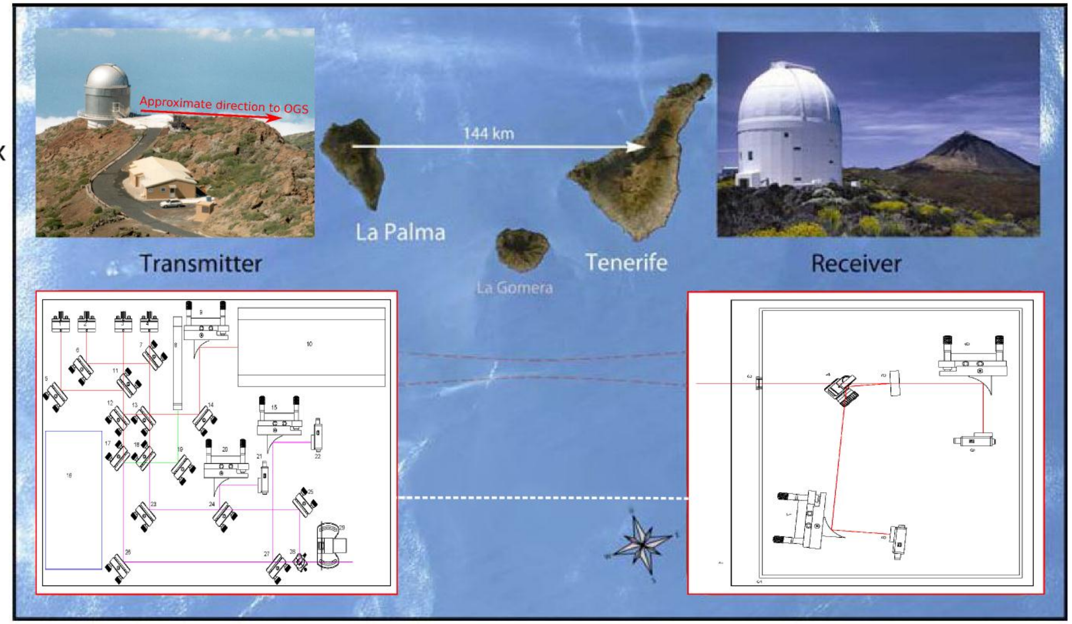


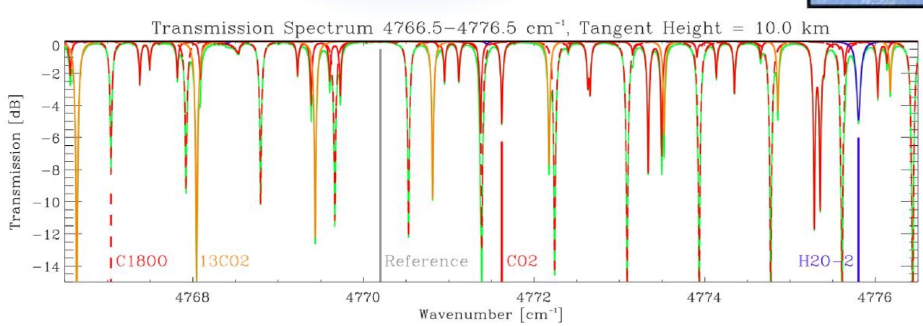
[from Proschek, Kirchengast, Schweitzer, AMT 4, 2035, 2011; and on-going Proschek et al. work]

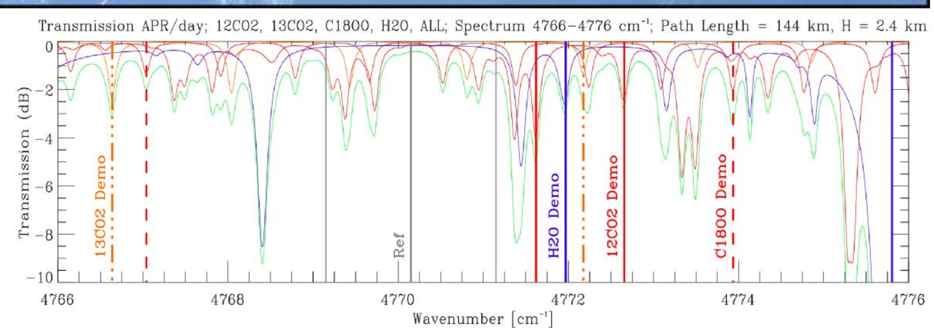
CO_2-CH_4-H_2O LIO demo IRDAS-EXPeriment 2010/11

Canary Islands 144 km link between high-altitude observatories (*z*~2.4 km); Campaign July 2011; learn on LIO from a link somewhat akin to LEO-LEO







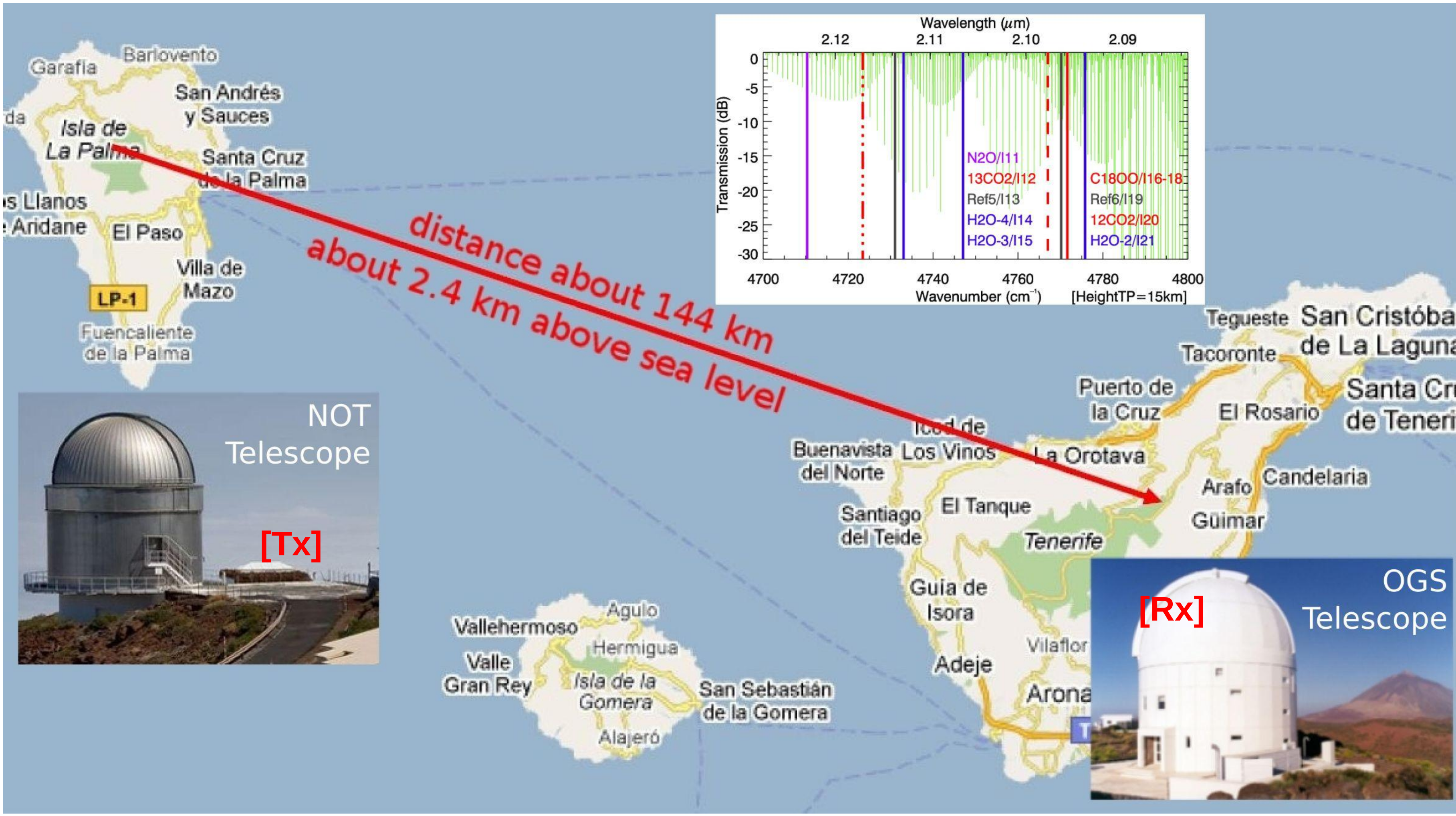


(WegCenter, 2011; fig backdrop upper right from Weinfurter et al., ESA-QIPS FinReport, 2007)

[IRDAS-EXP intro: Schweitzer et al. talk, www.uni-graz.at/opac2010 > Sci.Programme > Fri, pdf; Brooke, Bernath, Kirchengast, et al. (14 further co-authors), AMT, in press, 2012]

IRDAS-EXP campaign 2011 – closer look at the map

IR-laser Tx at parking lot near Nordic Optical Telescope (NOT) La Palma, ESA's Optical Ground Station (OGS) Tenerife 1 m telescope for reception



(WegCenter, 2011; backdrop google maps, telescope pics IAC Spain)

<u>IRDAS-EXP Consortium: U. York, U. Graz, U. Manchester, MPI Jena, IAP Moscow/SCINT-EXP part</u>

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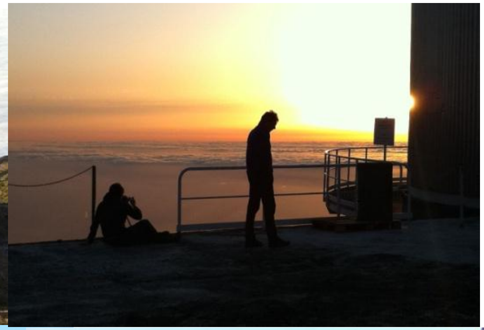
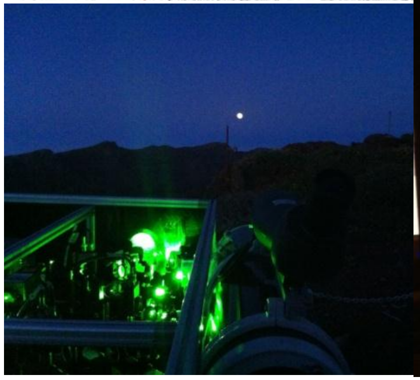
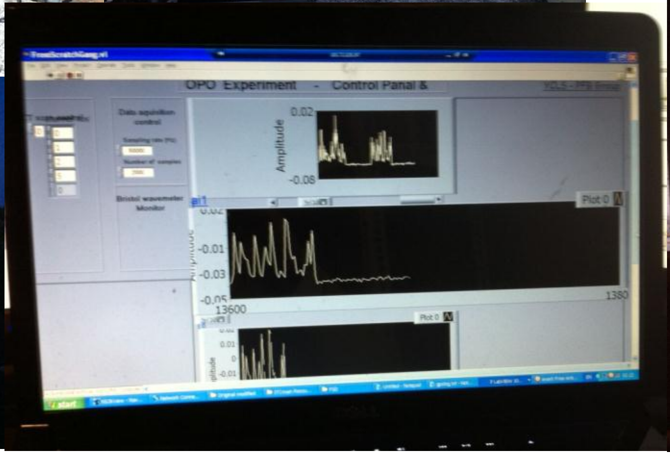
Successful! – first IRDAS-EXP results 17 July 2011

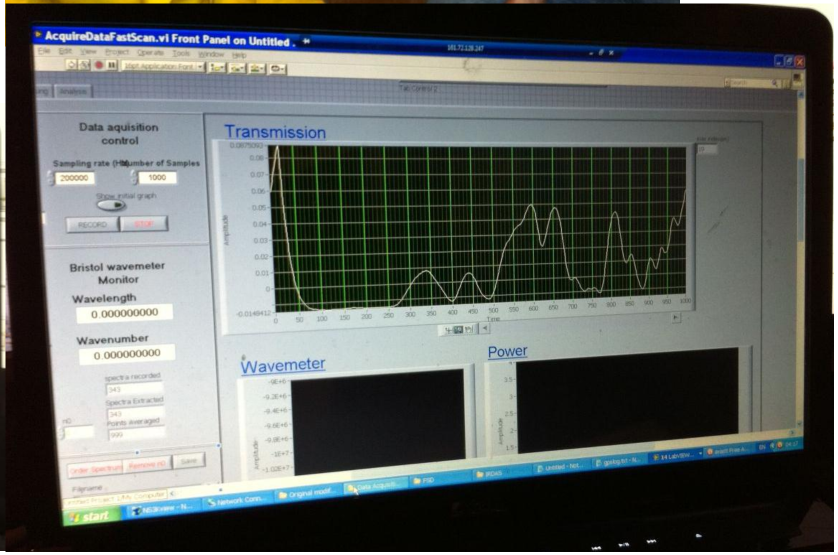
Canary Islands 144 km link: first ever IR-laser occultation signal reception and transmission spectrum, CH_4 near 2.3 µm (lower middle and right)

analysis of data now on-going…



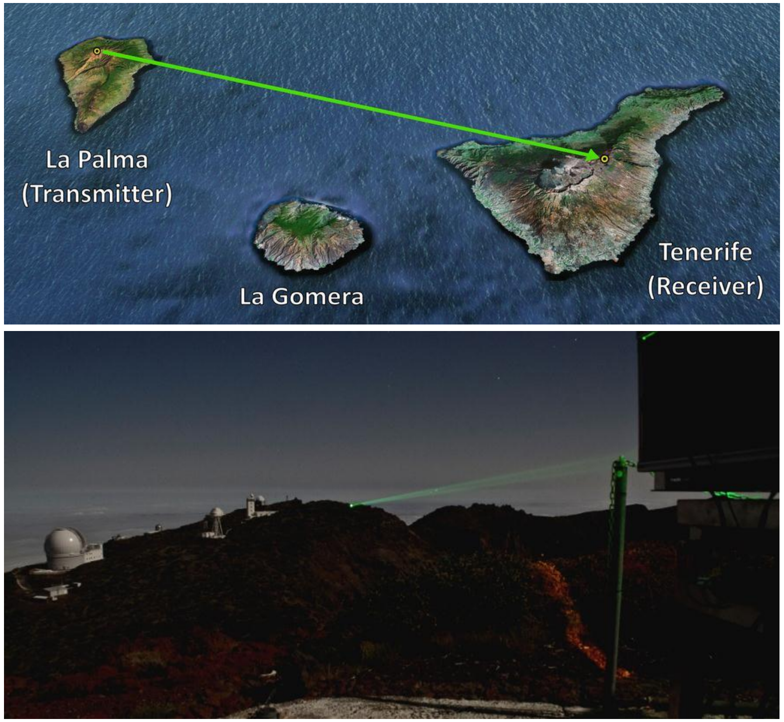



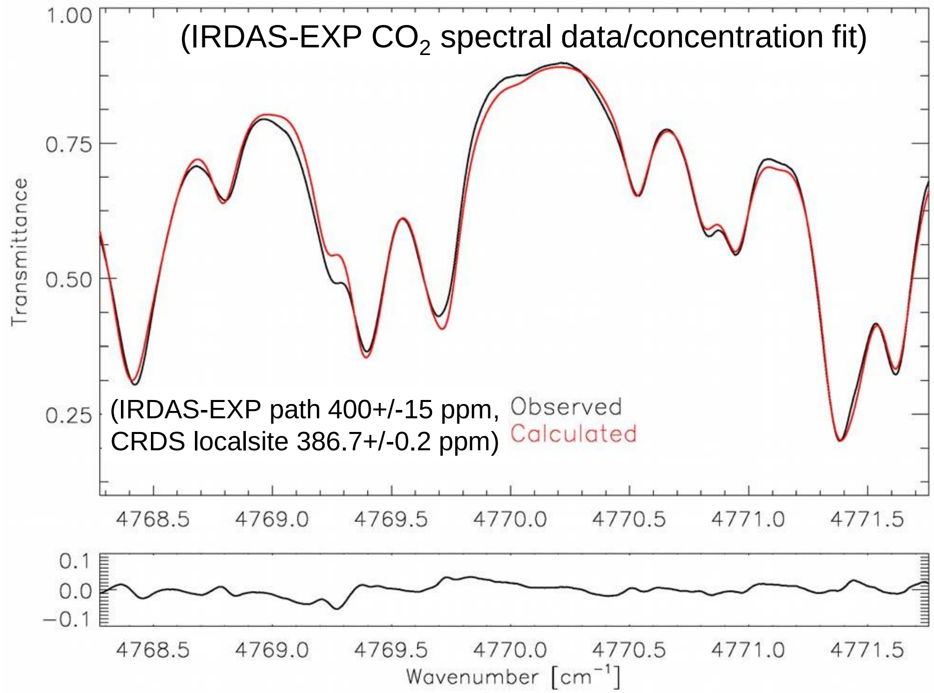


(photos Kirchengast 2011, except upper right: Hargreaves 2011)

First data analysis results, focus CO_2, are encouraging

- CO_2 concentration from the IR-laser data was found consistent within experimental uncertainty with *in situ* validation data (CRDS) in first complete analysis => first experimental demonstration that the IR-laser occultation concept works; currently detailed analyses underway.
- Detailed analysis, incl. CO_2, CH_4, and H_2O retrieval, also encouraging.





[Brooke, Bernath, Kirchengast, et al. (14 further co-authors), AMT, in press, 2012]

Conclusion and next steps

1. LMIO to provide benchmark data of GHGs, thermodynamic variables, and wind in Earth's free atmosphere
   Exploratory scientific studies and technical feasibility work encouraging –> unique scientific potential –> continue work towards LMIO satellite mission

2. IRDAS-EXPeriment July 2011 at Canary Islands
   Pioneering demonstration of CO_2 and CH_4 measurements by inter-island experiment successfully conducted, data analysis on-going. Is one crucial step towards LMIO from space.

[Note if interested in papers: most papers are accessible on-line via *www.wegcenter.at/arsclisys* > *Publications*; otherwise contact gottfried.kirchengast@uni-graz.at or contact the first authors]

Thank You! ☺