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

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Progress with LEO-LEO microwave and IR-laser occultation: performance results and Canary Islands greenhouse gases experiment

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Thanks for funds to:

IROWG-2, Session Innovative RO Techniques, Estes Park, CO, USA, 30 March 2012

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

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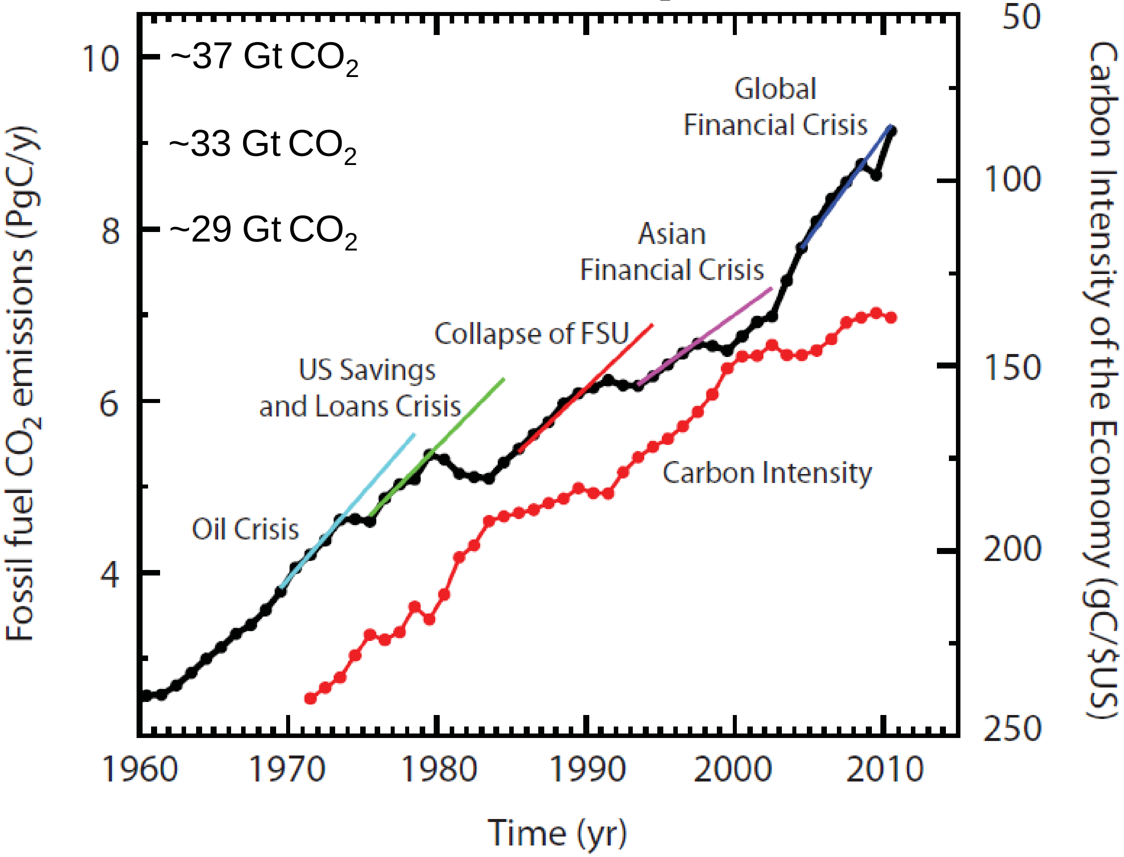
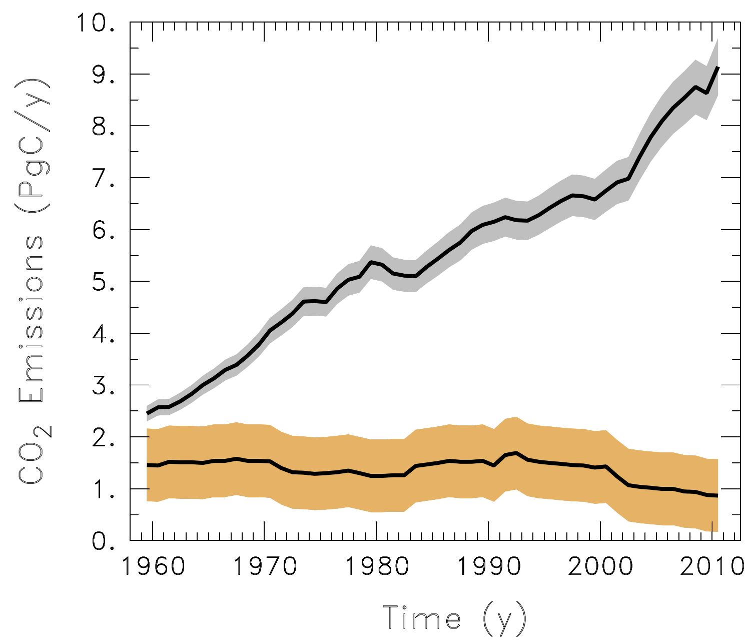
- Over the most recent decade (2001-2010) CO_2 emissions still rose faster than in any decade before – what‘s next?

(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)

Why monitor? – How will GHGs and climate change evolve?

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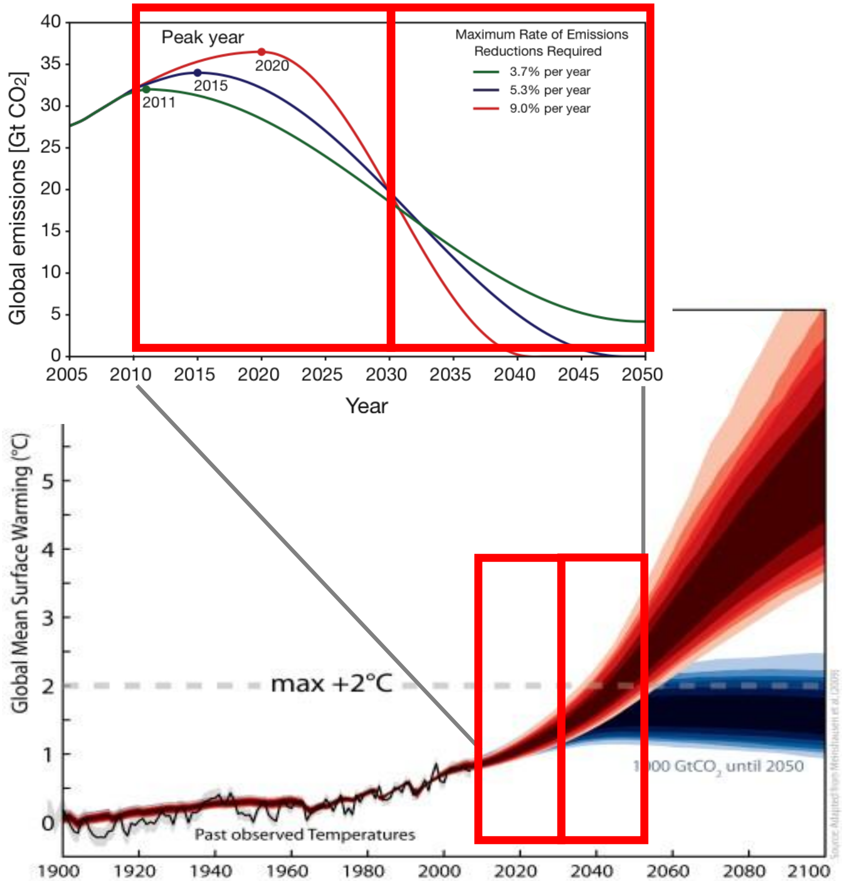
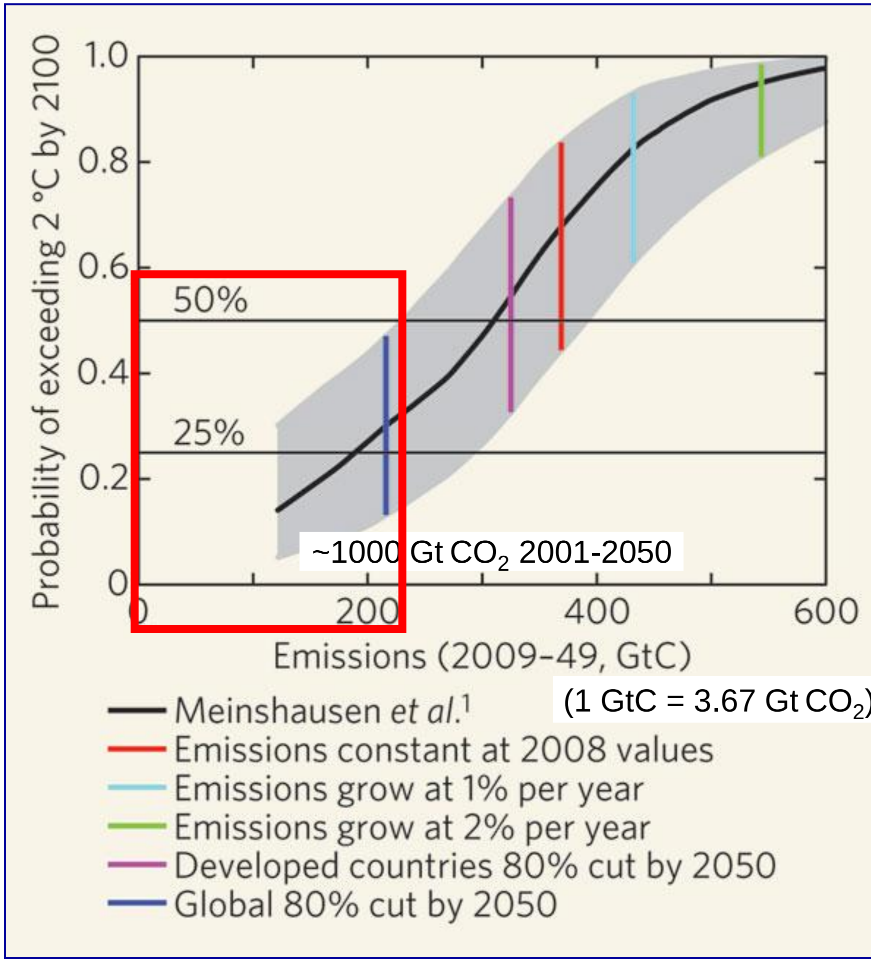
- Globally about –60% CO_2 to 2050 (OECD countries –80%) is estimated to be needed for likely keeping max. +2°C



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



[Schmidt and Archer, 2009]

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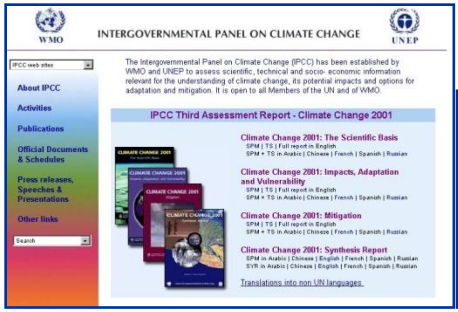
so we must monitor the atmosphere and climate with benchmark data since…

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

more specifically, three major reasons:

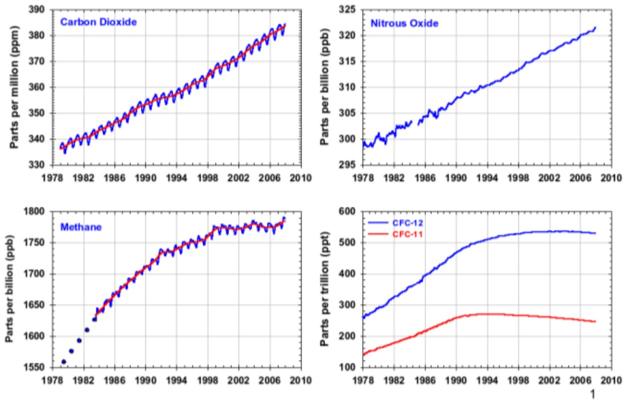
- to rigorously observe and learn, independent of models, how weather, climate and composition variability and change evolve, over monthly, seasonal, interannual, and decadal scales
- to test and guide the improvement of weather, climate and constituent models and thereby enhance their predictive skills 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 climate benchmark data to have?



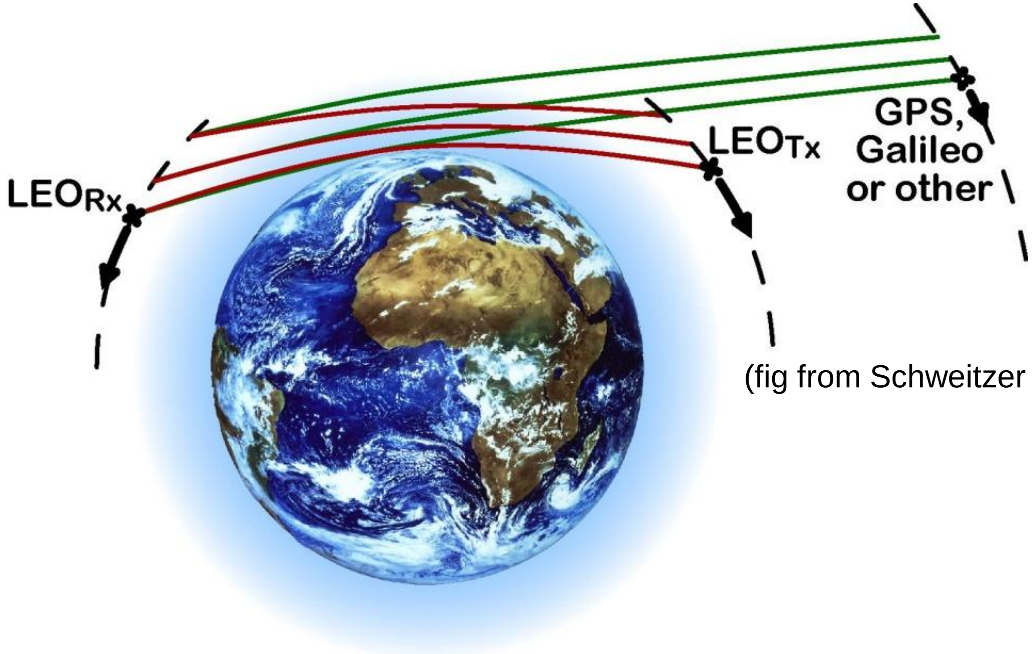
key properties:

- 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 method shall do 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)

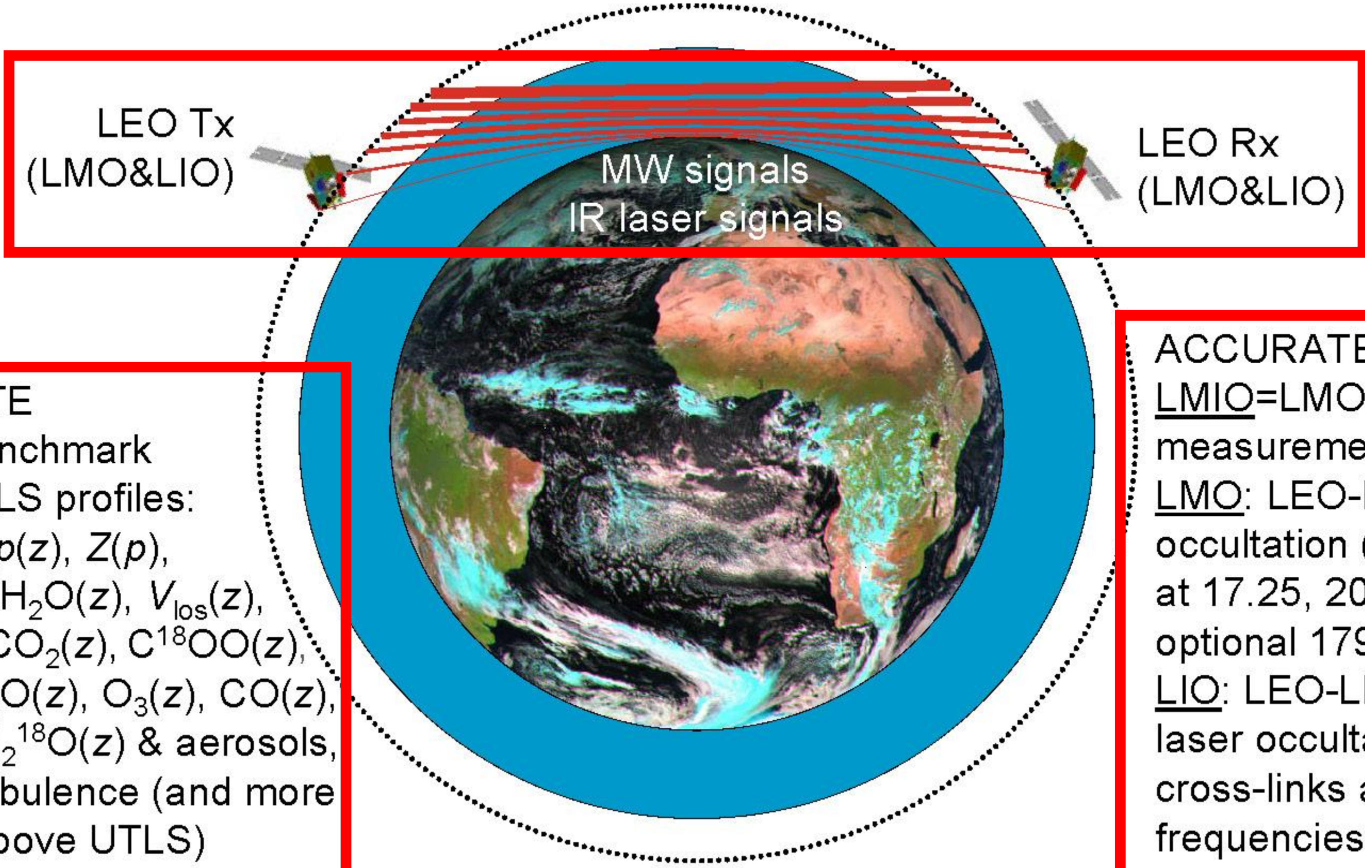
= LEO-LEO Microwave and Infrared-laser Occultation

[LMIO+NIDAR ("ACCU-3G") (…as a footnote, just some final comments then)
most current; extending LMIO by near-surface/lower-troposphere CO_2 and CH_4 sources and sinks monitoring at ~0.1 km native sampling]

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)

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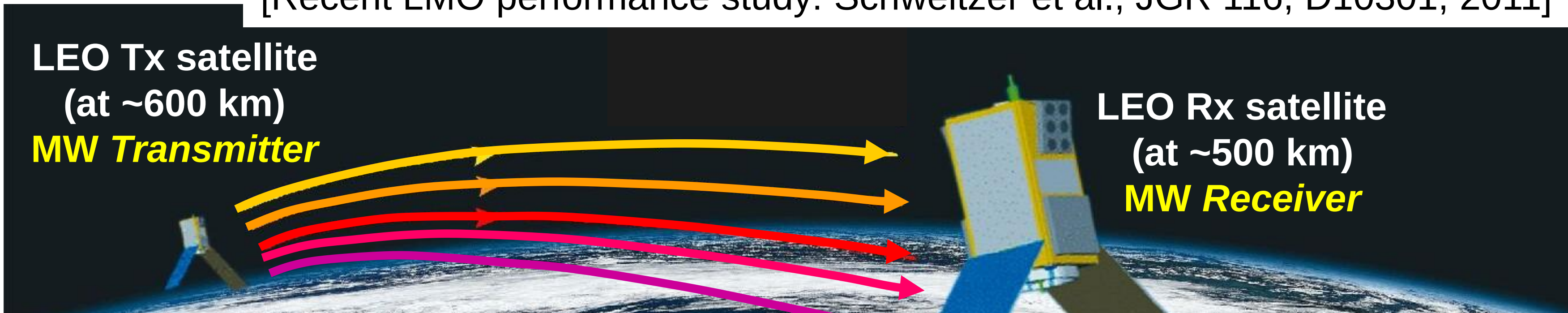
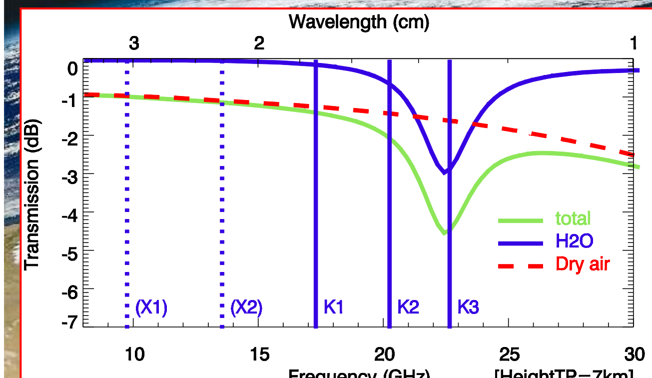
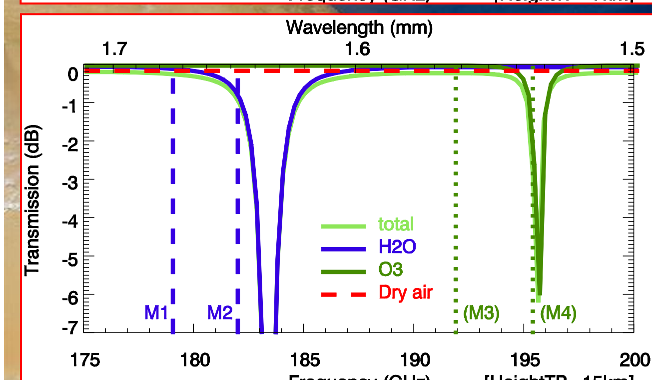
how does the LMO method work?

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]





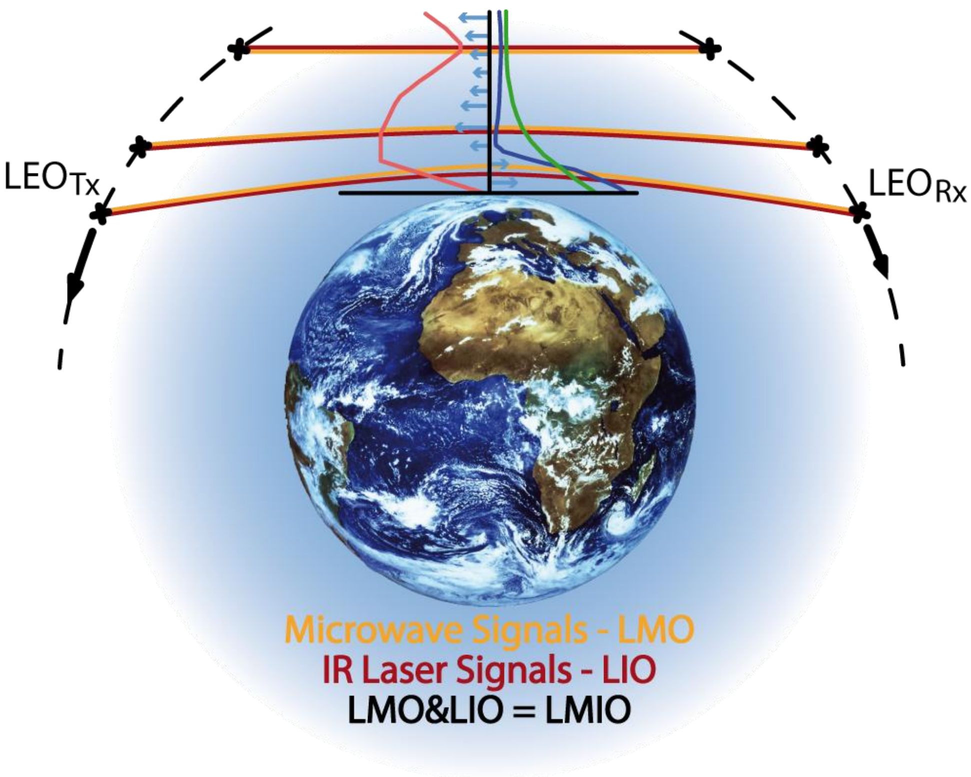


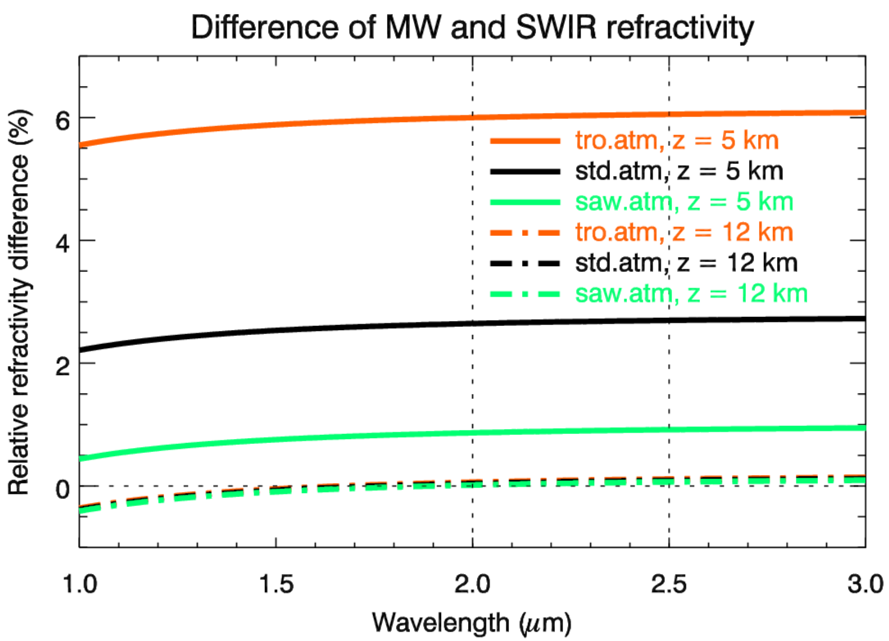
- Exploits refraction and (differential) transmission of MW signals (~17.25, 20.2, 22.6; opt. 179, 182 GHz, at the 22 / 183 GHz water vapor absorption lines; the Fig. left also indicates an optional ozone line) between LEO Tx and LEO Rx satellites.
- Measurements of phase delay & amplitude → bending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



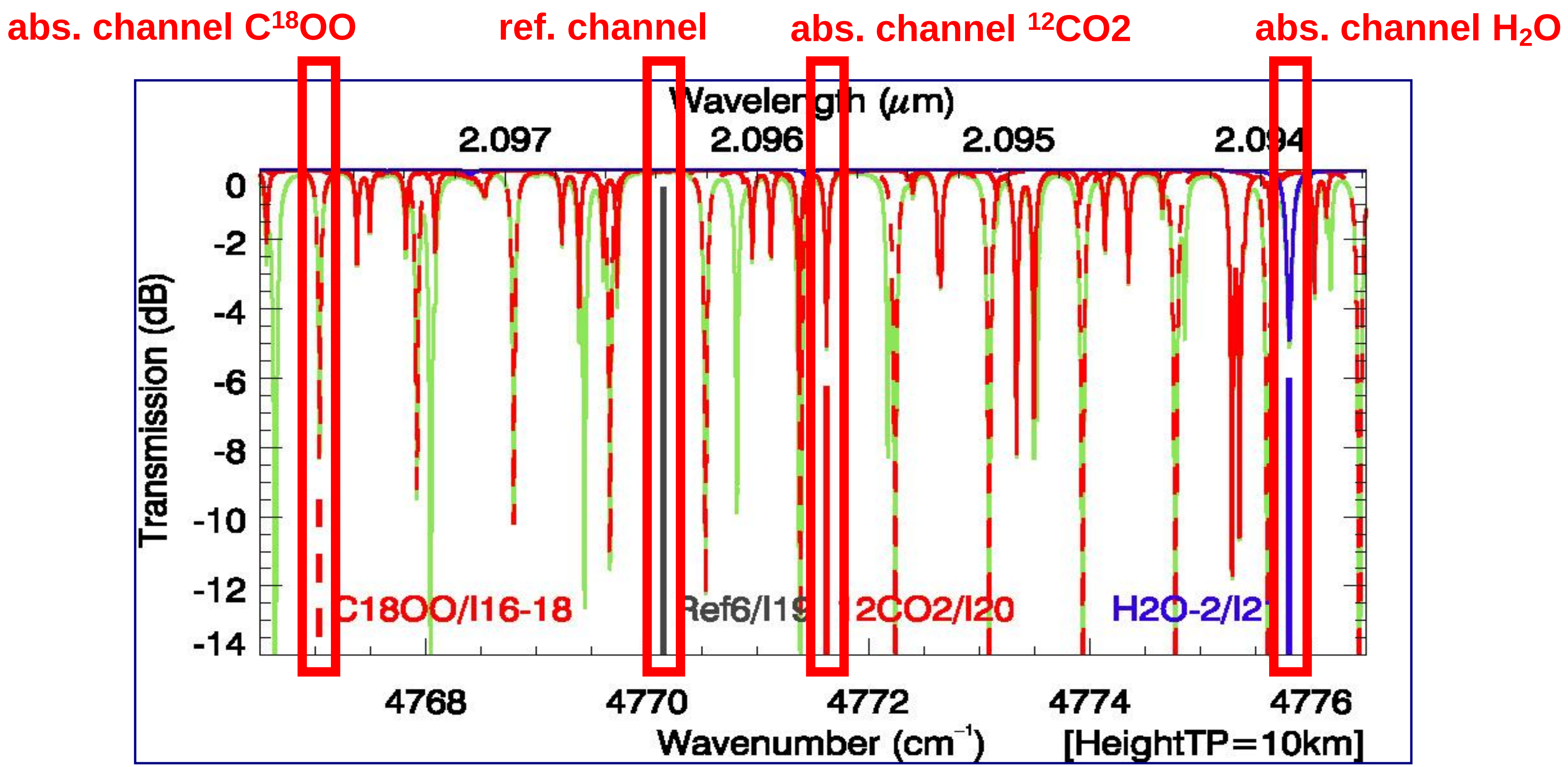


[Details on LMIO signal propagation: Schweitzer, Kirchengast, Proschek, AMT 4, 2273, 2011; on LMIO retrieval algorithm: Proschek, Kirchengast, Schweitzer, AMT 4, 2035, 2011]

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*.



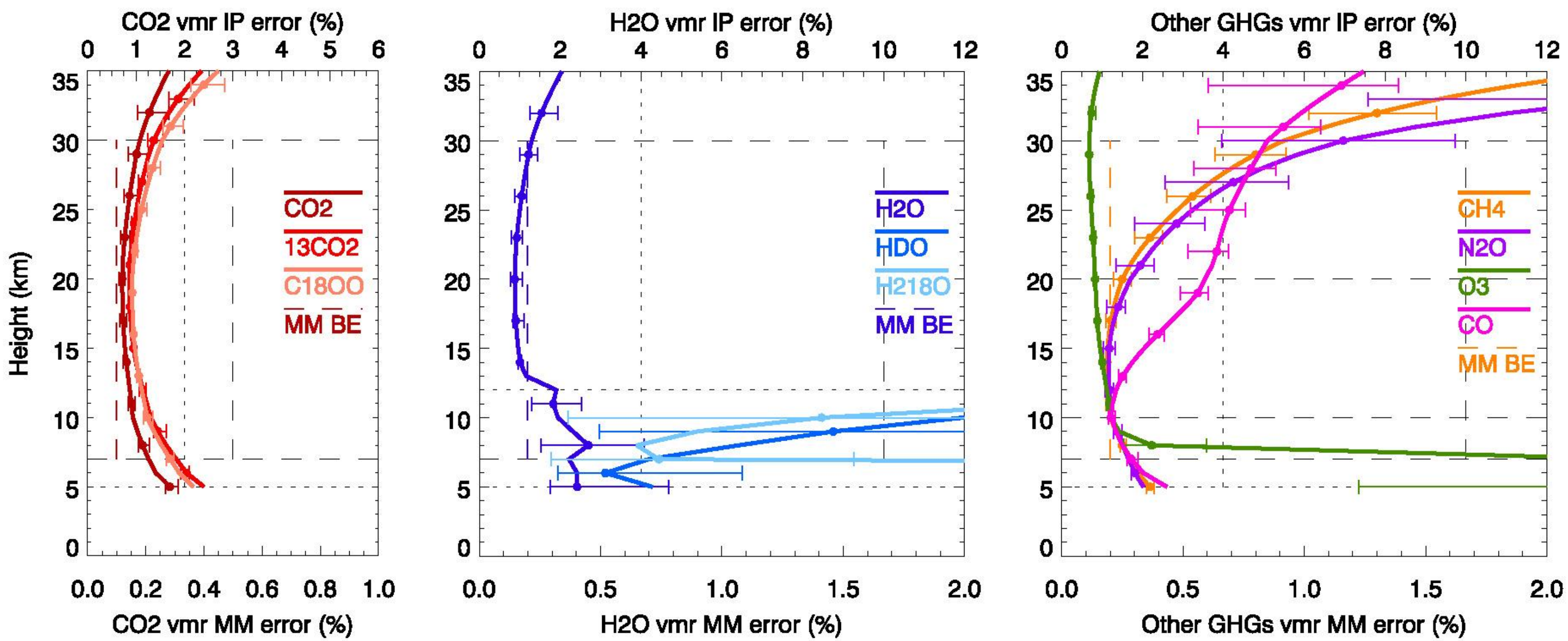
[Details on LIO channel selections etc: Kirchengast and Schweitzer, GRL 38, L13701, 2011;
on accurate line spectroscopy needs: Harrison, Bernath, Kirchengast, JQSRT 112, 2347, 2011]

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)])

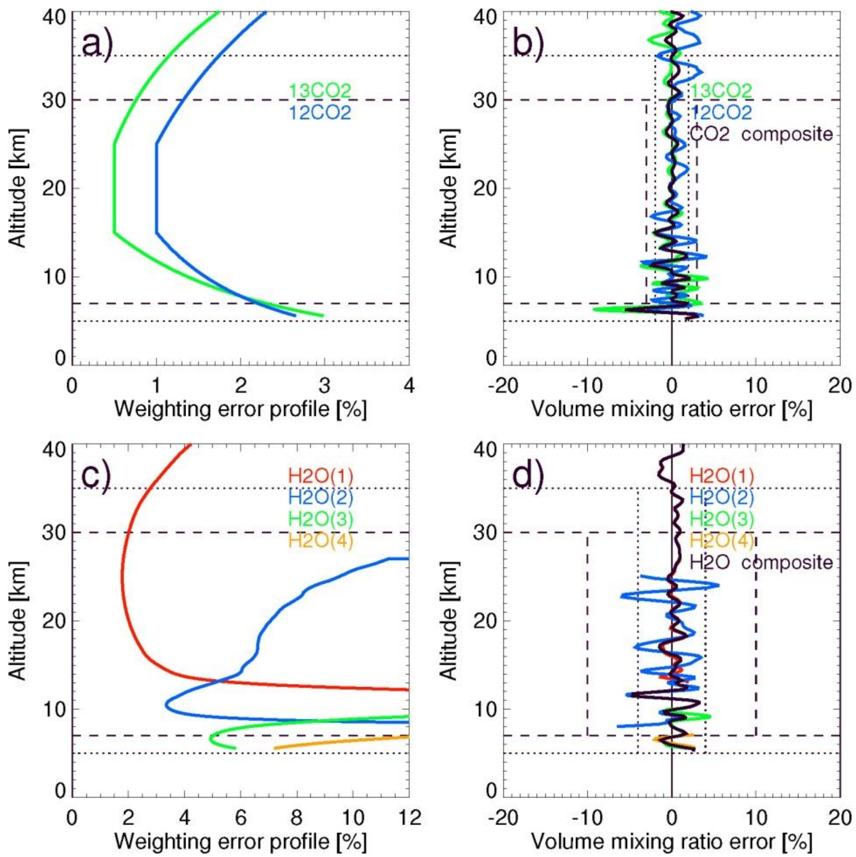
[Details from simplified LIO performance study: Kirchengast and Schweitzer, GRL 38, 2011; from quasi-realistic retrieval performance study: Proschek, Kirchengast, Schweitzer, AMT 4, 2011]

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

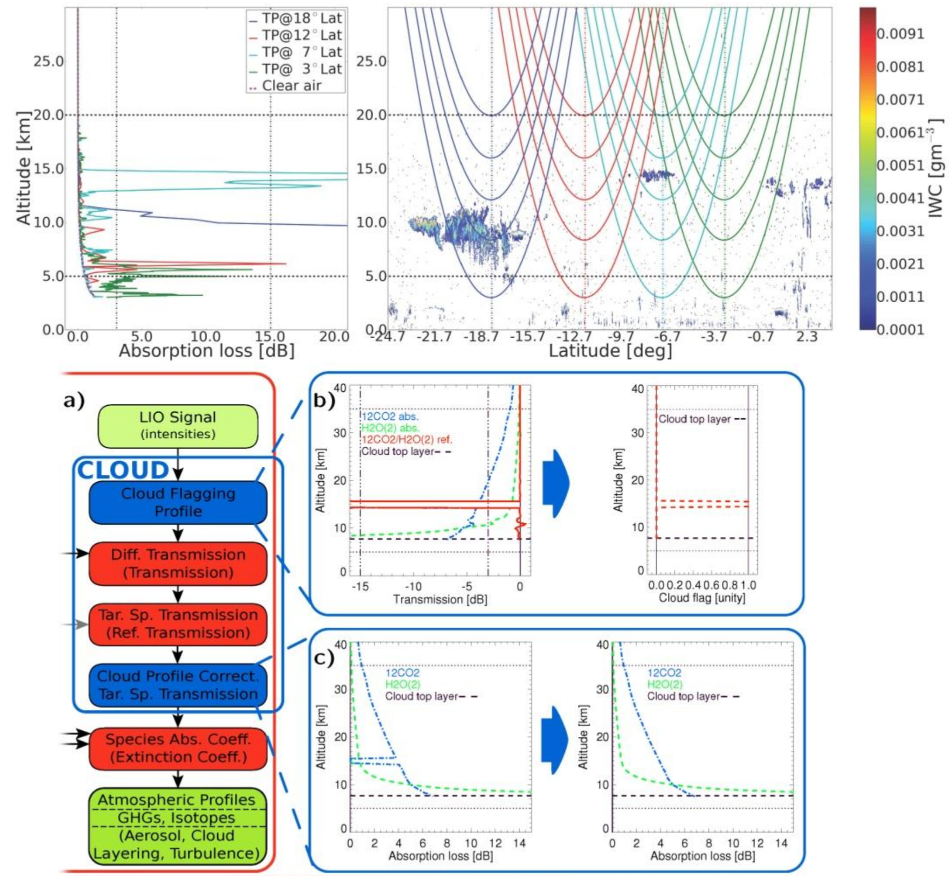
example from the quasi-realistic simulation studies

- 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



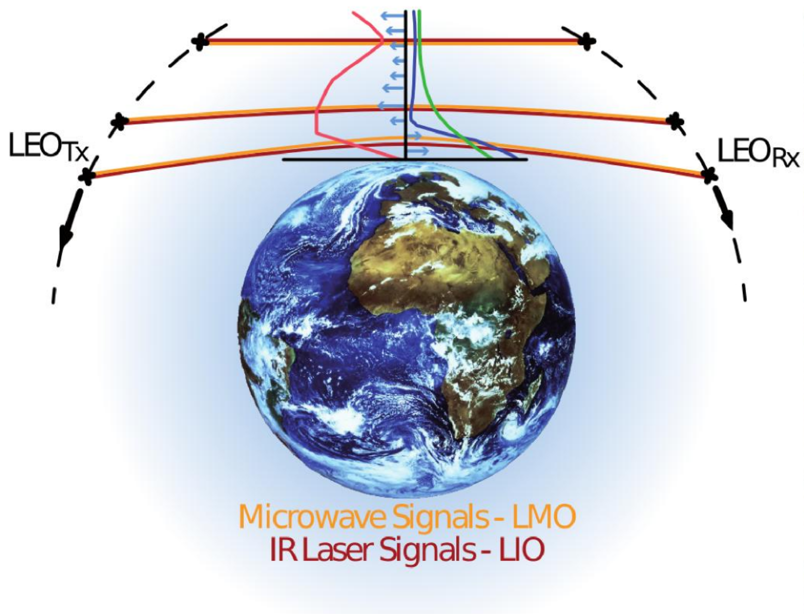
Algorithm development for cloudy air retrievals

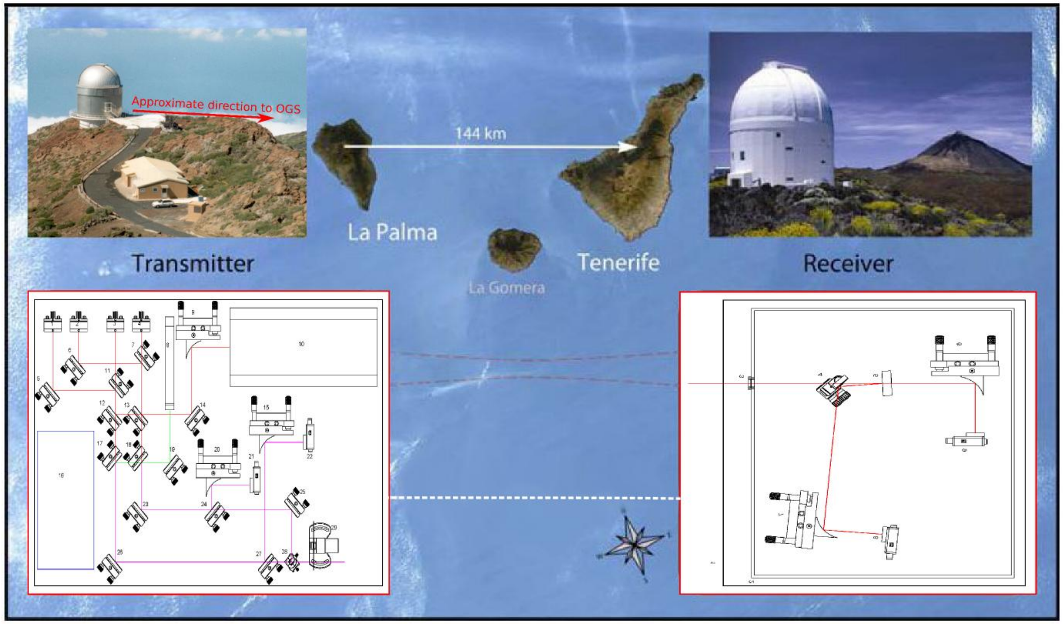


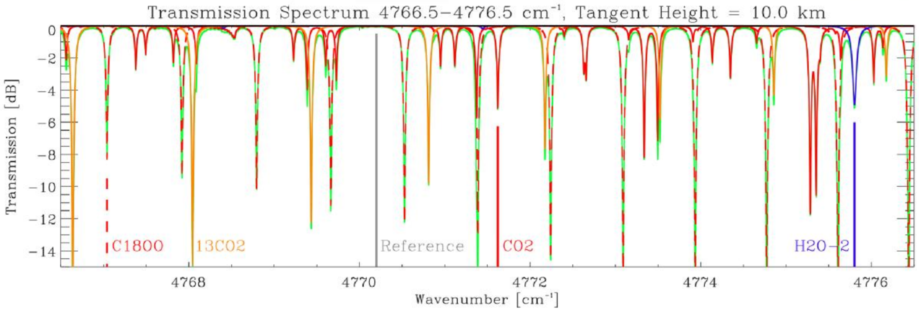
[from Proschek, Kirchengast, Schweitzer, AMT 4, 2035, 2011; and on-going Proschek et al. work]

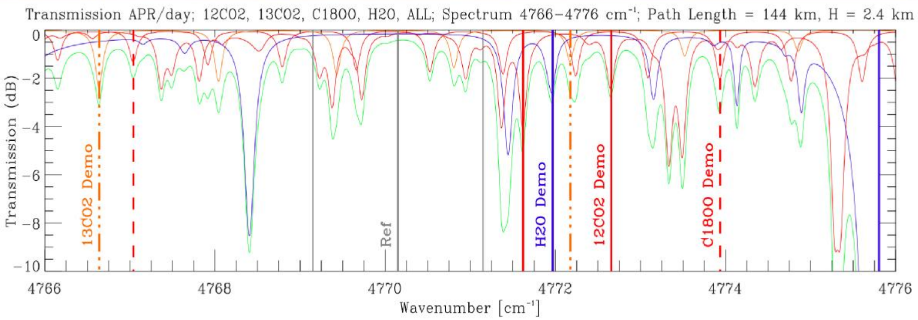
CO_2-CH_4-H_2O LIO demo IRDAS-EXPeriment 2010/11

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), GRL, submitted, 2012]

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☺*Susanne's final slide @ OPAC 2010:*

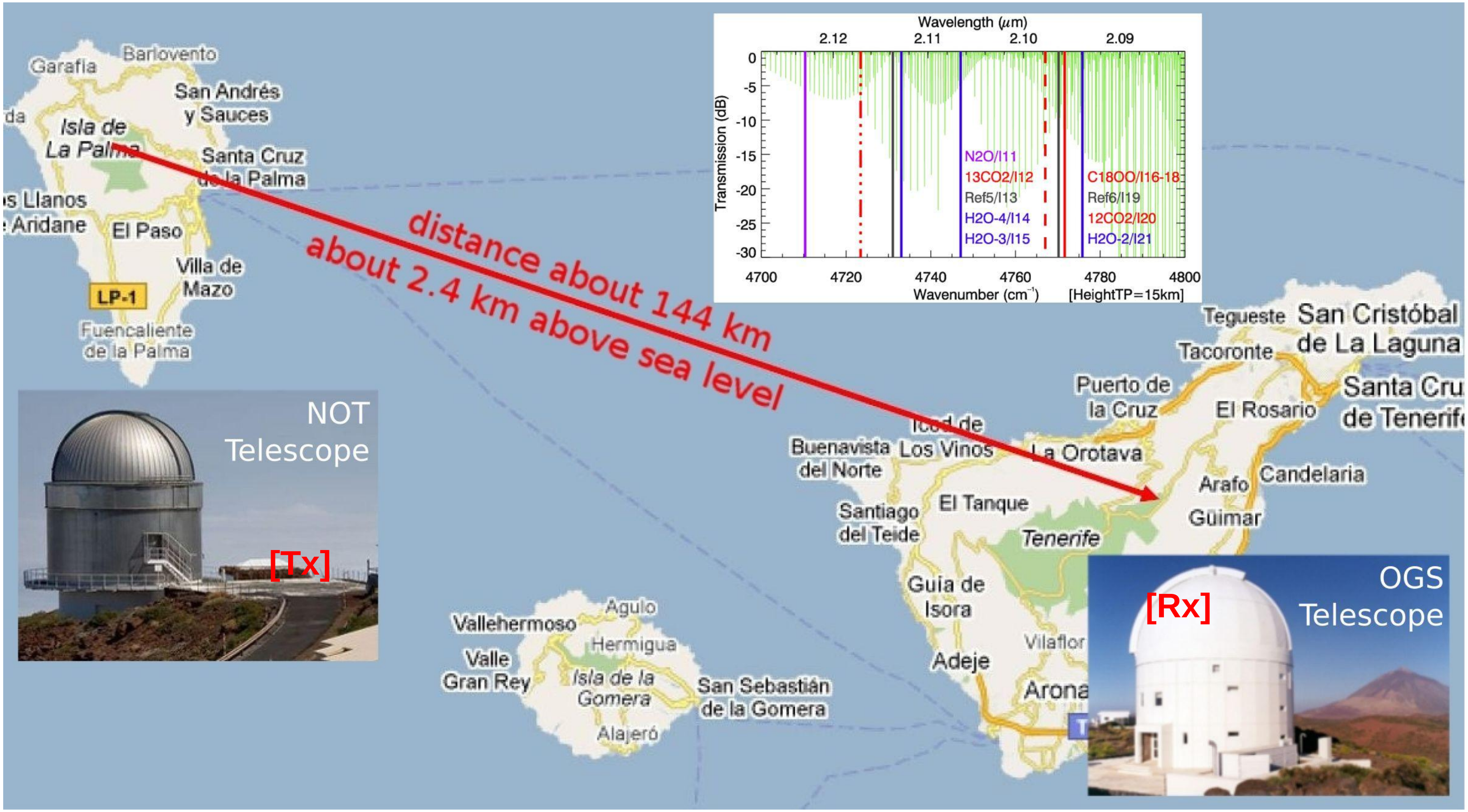
Outlook – Canary Islands, April 2011

a pile of work...

…but we did it!
(in July 2011; and sorry Lidia and all Volunteers…)

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)

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

IRDAS-EXP 2011 – and a range of validation data

Weather station data, GHG data from Cavity Ring-Down Spectrometers (CRDS) & Flasks, webcam, and ECMWF data help validation

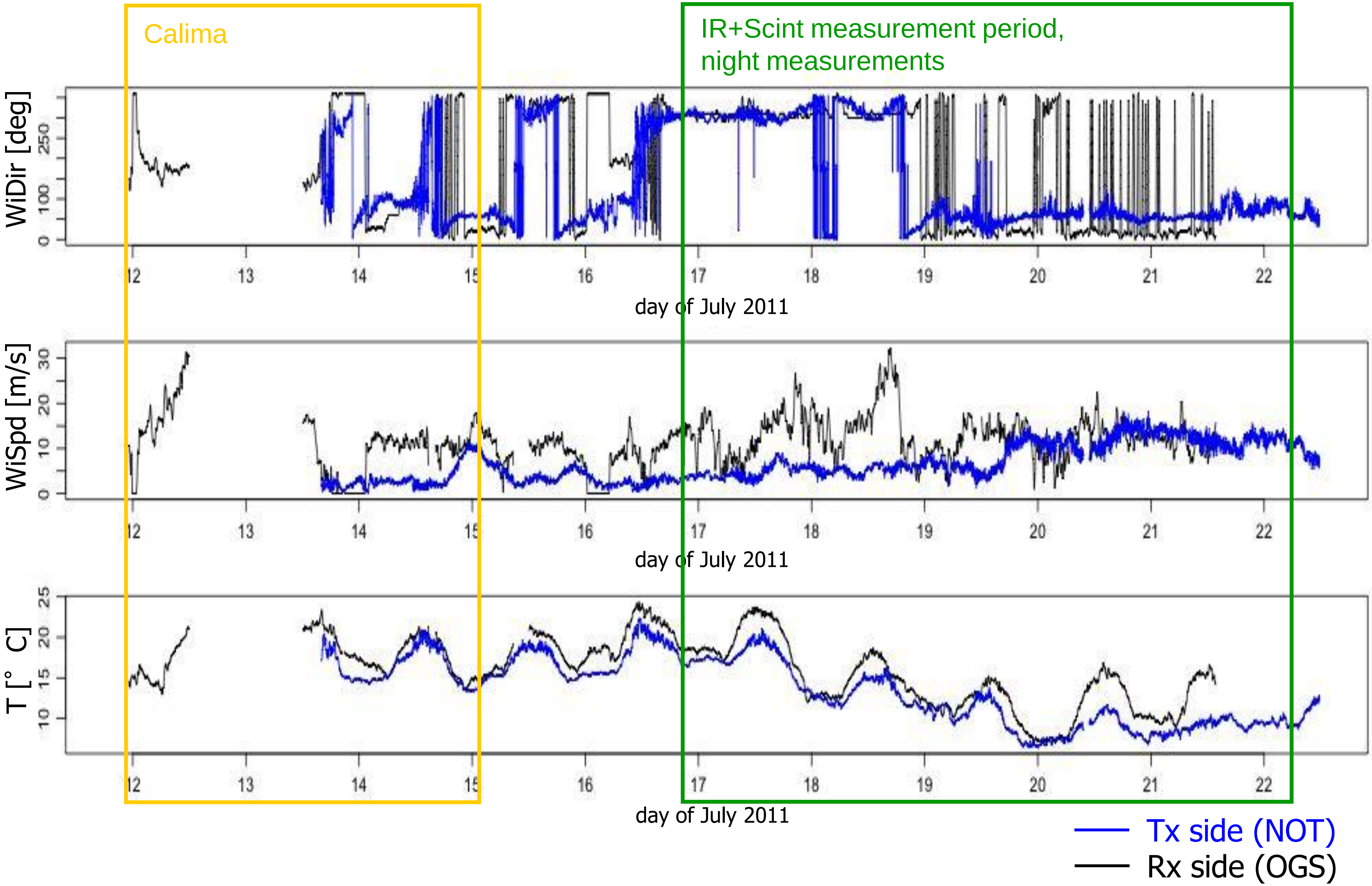
	Transmitter (NOT)	Receiver (OGS)	Notes
meteo data	*NOT station*: p, T, rH, V	*GONG station*: p, T, rH, V, solar radiation *IAC station*: p, T, rH, V, dew point, stability of the air	permanent measurements
Picarro CRDS	CO_2, CH_4, H_2O	CO_2, CH_4, H_2O, CO	continuous measurements; time resolution = 2.5 s, precision = 50 ppb; *instruments from MPI Jena*
camera	*webcam U.York:* l.o.s. vis (not used)	*OGS webcam*: l.o.s. visibility	at Rx continuous recording of pictures; 1 pic every 15 s
sampling flasks	—	*flasks from MPI Jena:* GHG's (esp. CO_2, CH_4)	measurements only if IR signals were received; then 1 sample every 3 hours (21:00, 0:00, 3:00 UTC etc.)

- ECMWF meteo analyses and short-range forecasts over 330 x 330 km Canary Island area @ ~14 km grid (T1279), 91 height levels, 4 UTC layers/day in analysis; 8 UTC layers/day in forecast; p, T, q, u, v, LWC

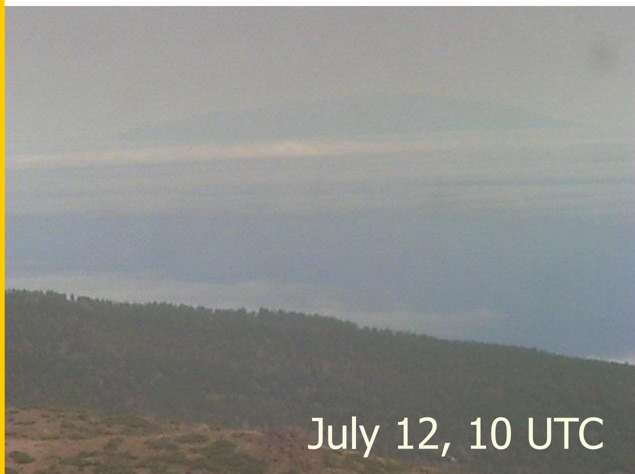
glimpse on-site: weather station near NOT

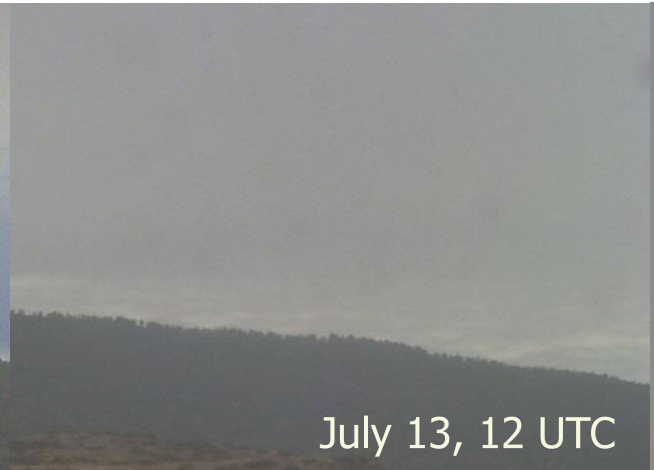
(photos Kirchengast 2011)

Weather data during campaign (Vd, Vs, T)



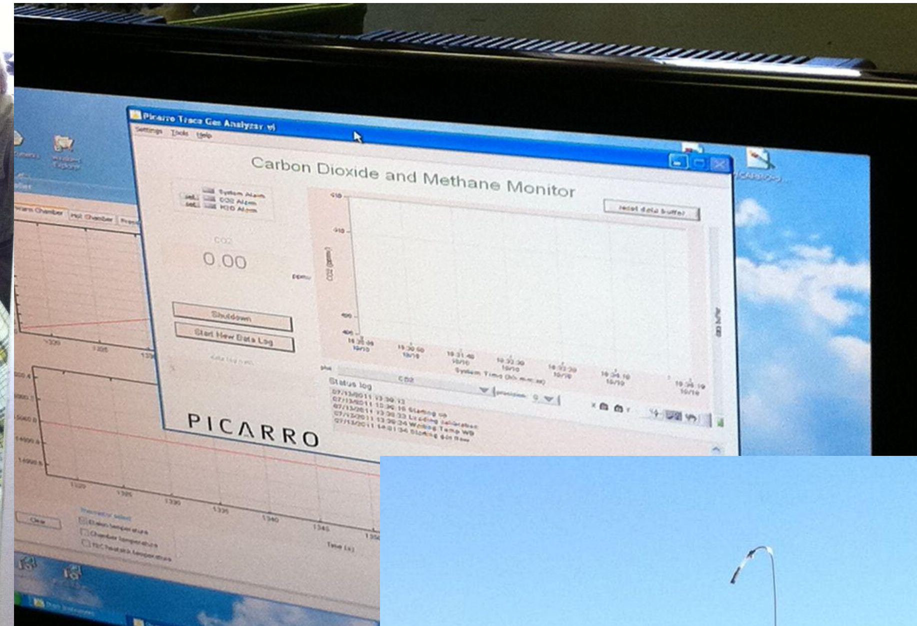
Calima





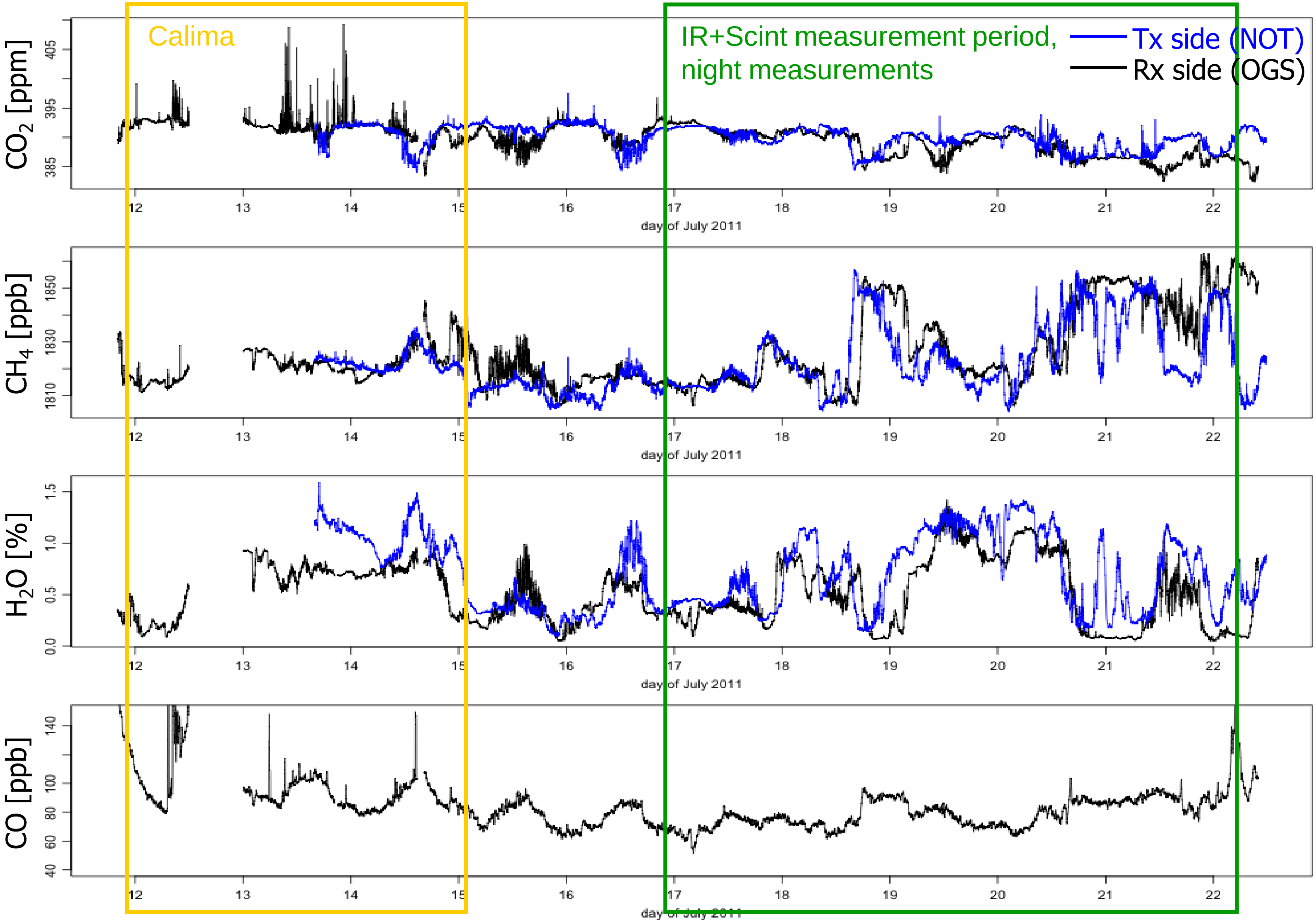
start IR+Scint measurement period, night measurements…

glimpse on-site: Picarro CRDS instrument (NOT)



(C. Gerbig and O. Kolle, MPI Biogeochemistry Jena, setting up the Picarro CDRS in NOT service building, July 2011)

CRDS validation data during campaign

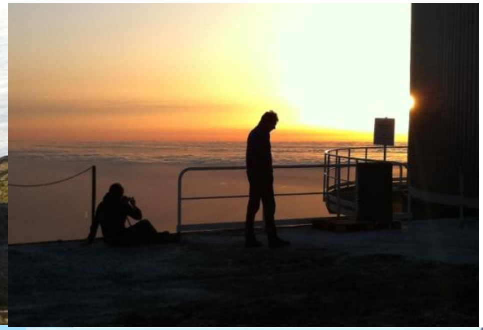


(data Gerbig et al., MPI Jena, 2011)

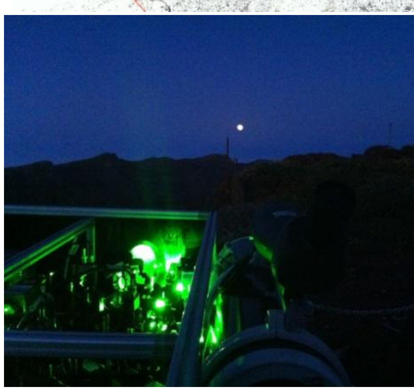
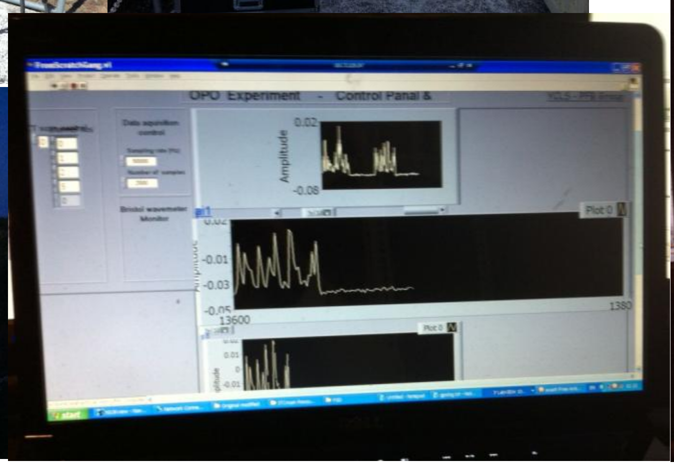
Successful! – first IRDAS-EXP results 17 July 2011

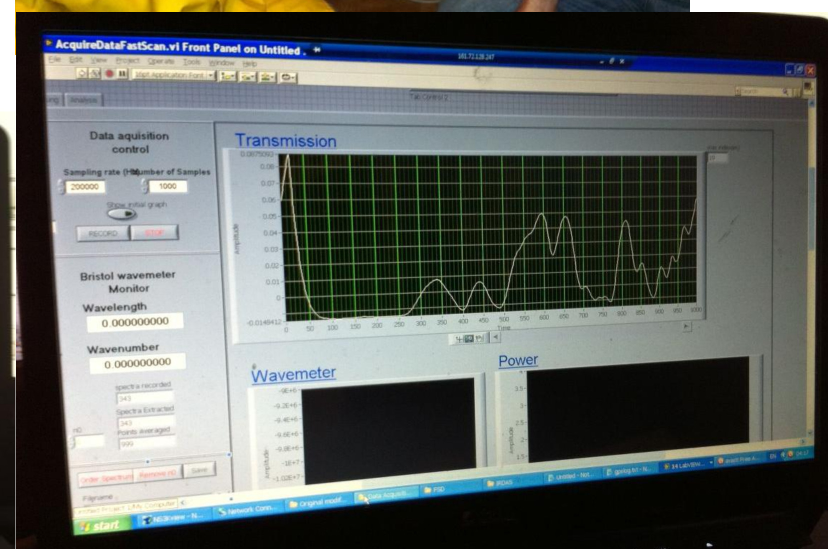
Canary Islands 144 km link: first ever IR-laser occultation signal reception and transmission spectrum, CH_4 near 2.3 µm (lower middle and right)

analysis of data now on-going…



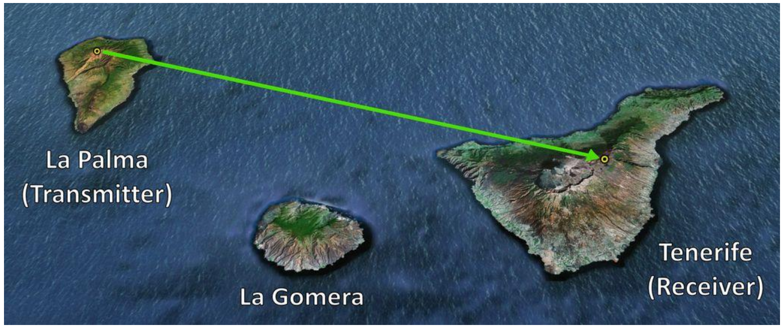



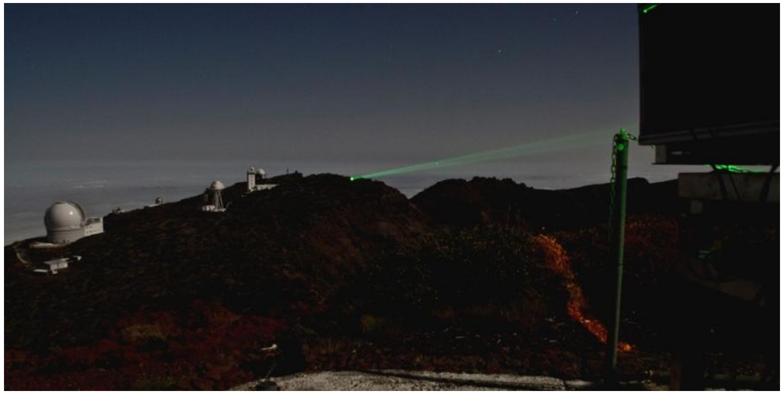


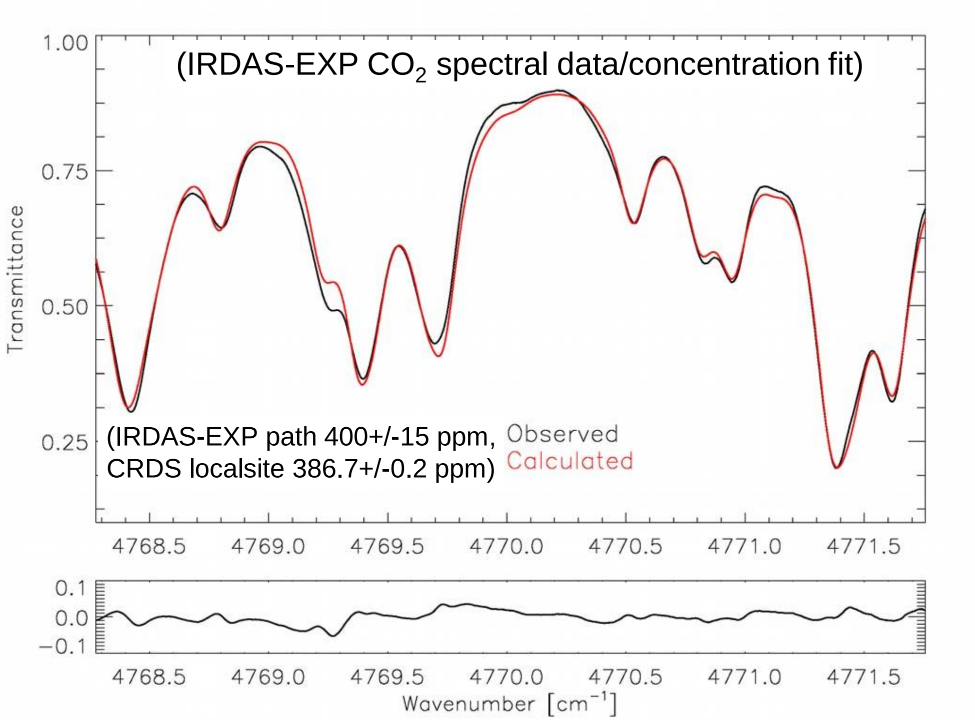
(photos Kirchengast 2011, except upper right: Hargreaves 2011)

Initial 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* CRDS data in first complete analysis => first experimental demonstration that the IR-laser occultation concept in principle works. Currently detailed analyses underway.



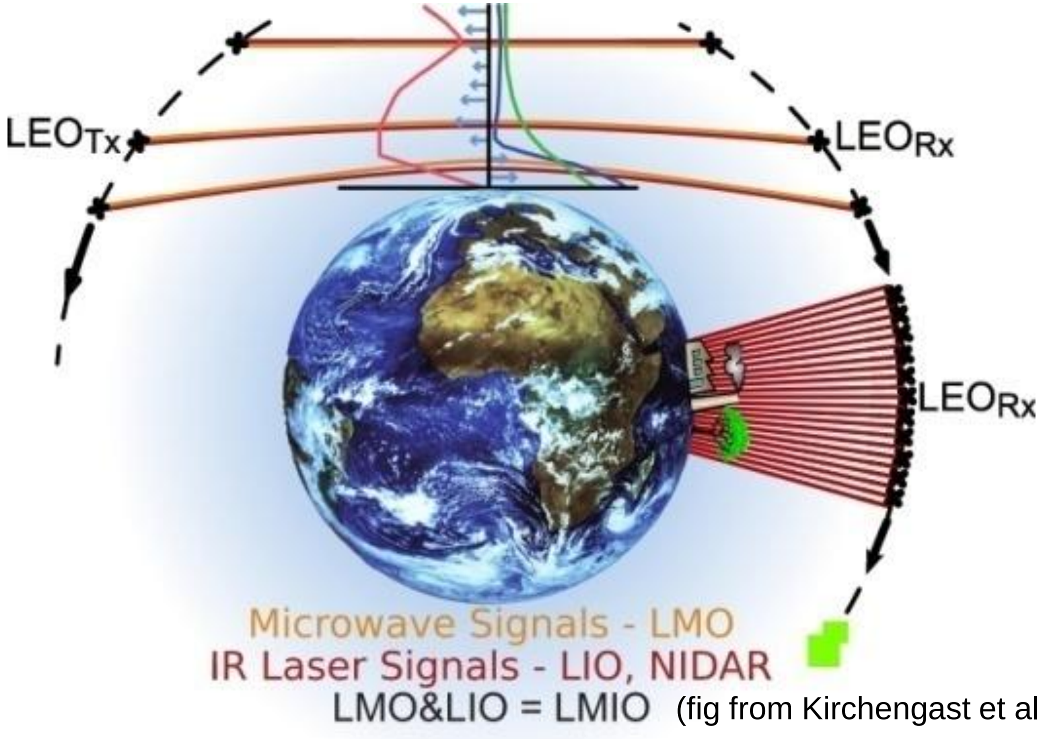




[Brooke, Bernath, Kirchengast, et al. (14 further co-authors), GRL, submitted, 2012]

LMIO & NIDAR:

LEO-LEO microwave and IR-laser occultation (LMIO) complemented by Nadir-looking IR-laser differential absorption reflectometry (NIDAR) – novel global monitoring of atmospheric CO_2 and CH_4 for estimating surface carbon sources and sinks, including anthropogenic emissions…



(fig from Kirchengast et al., ACCUCARBON concept, 2011)

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 sat mission (incl. NIDAR near-sfc CO_2, CH_4)
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! ☺