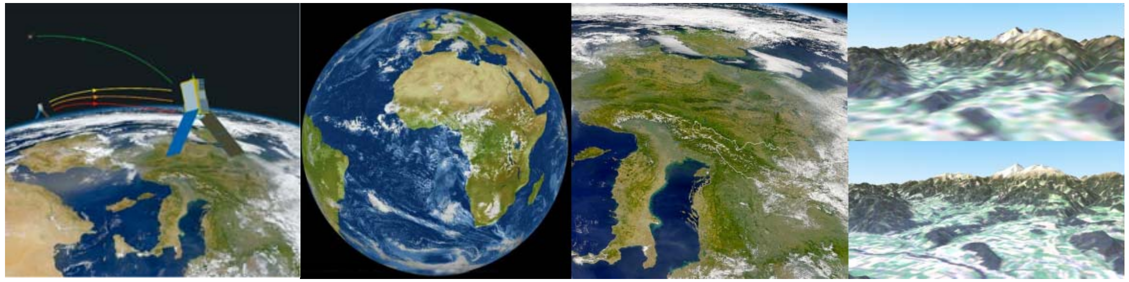

ACCURATE—climate benchmark profiling of greenhouse gases and thermodynamic variables and wind from space

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thanks to
all colleagues supporting the ACCURATE concept

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and quite a number more internationally and at the Wegener Center/Univ. of Graz;
and partners from industry (SSC, Thales, RUAG, Kayser Threde,…)

> twenty scientific partners from > ten countries. Thanks all!

what's the question ACCURATE addresses?
obtain a consistent set of climate benchmark data

- Is it possible to simultaneously observe, with global coverage, high accuracy, and long-term stability, a complete set of atmospheric variables including on thermodynamics (temperature, pressure, humidity), dynamics (wind), and climate/chemistry (greenhouse gases and isotopes)? Perhaps complemented with simultaneously measured aerosol, cloud, and turbulence information? As one consistent state in any observed air volume, independent of a priori information?

- Yes. To an unprecedented level of quality and comprehensiveness with the ACCURATE concept. Aim is profiling of all variables above over the upper troposphere-lower stratosphere (UTLS) region and beyond as function of altitude with ~1 km vertical resolution.

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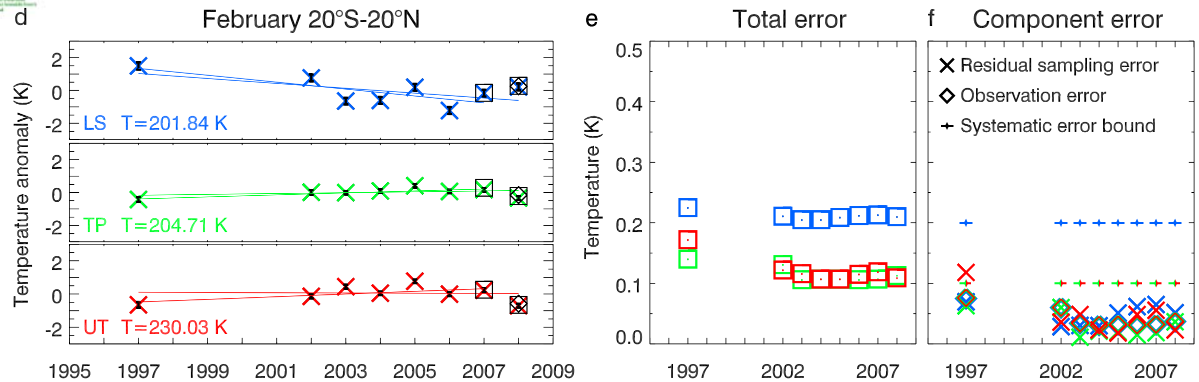
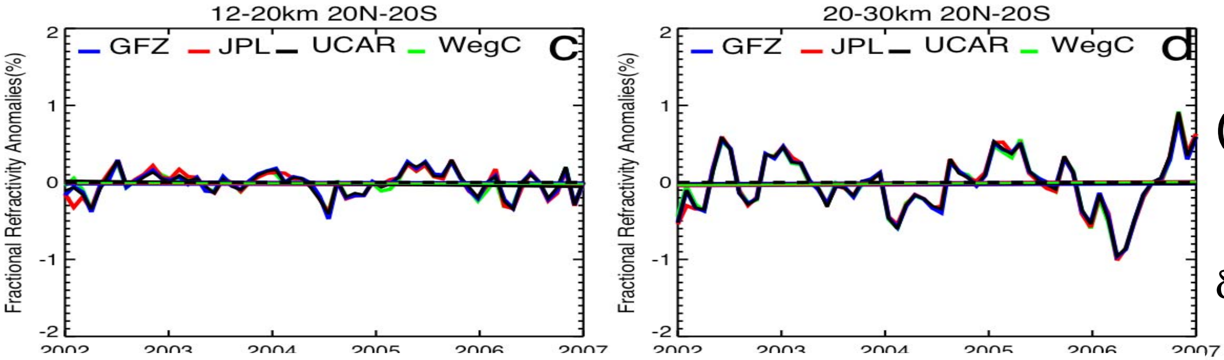
get a feel: how do climate benchmarks look like?

example GPS radio occultation data 1997/2001-2008



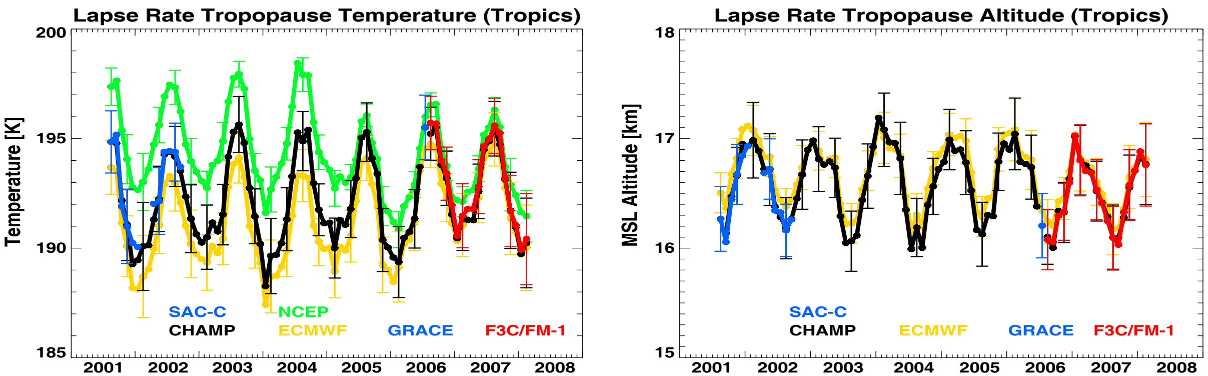
(Steiner, Kirchengast, Lackner, et al. GRL, 2009)

δT < 0.1-0.2 K



(Ho, Kirchengast, Leroy, Wickert, Mannucci, Steiner, et al., JGR, 2009)

δN < 0.05-0.1%

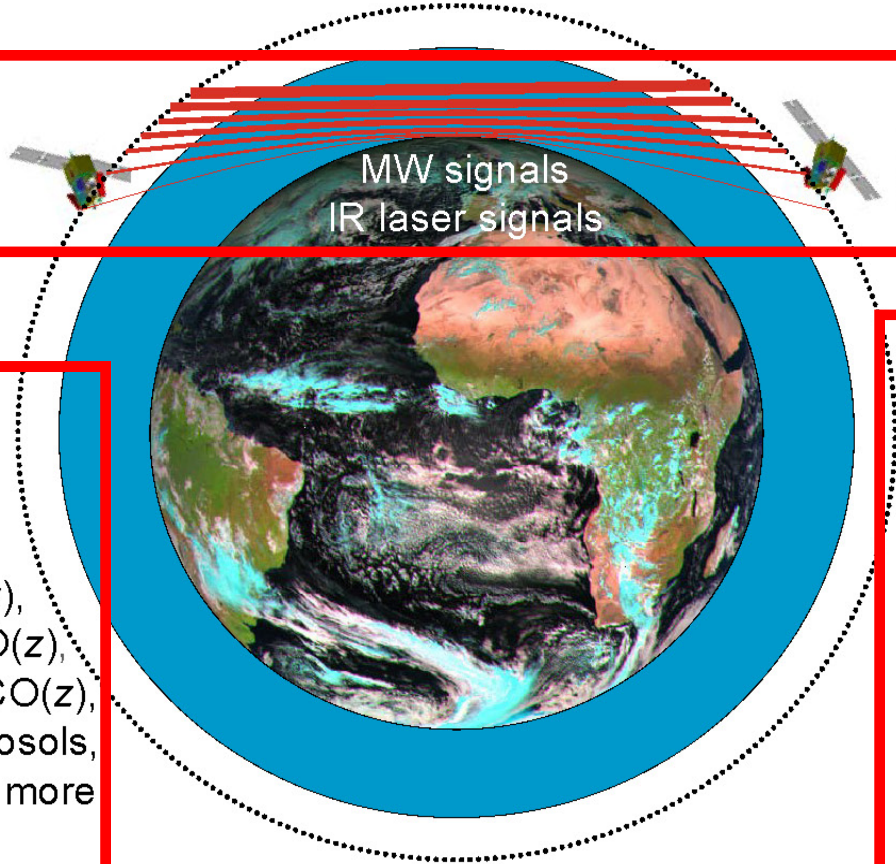


(Foelsche, Kirchengast, Borsche, et al. ECMWF Proc, 2008)

δTP < 0.5 K/0.05 km

what are the key elements of the concept?

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



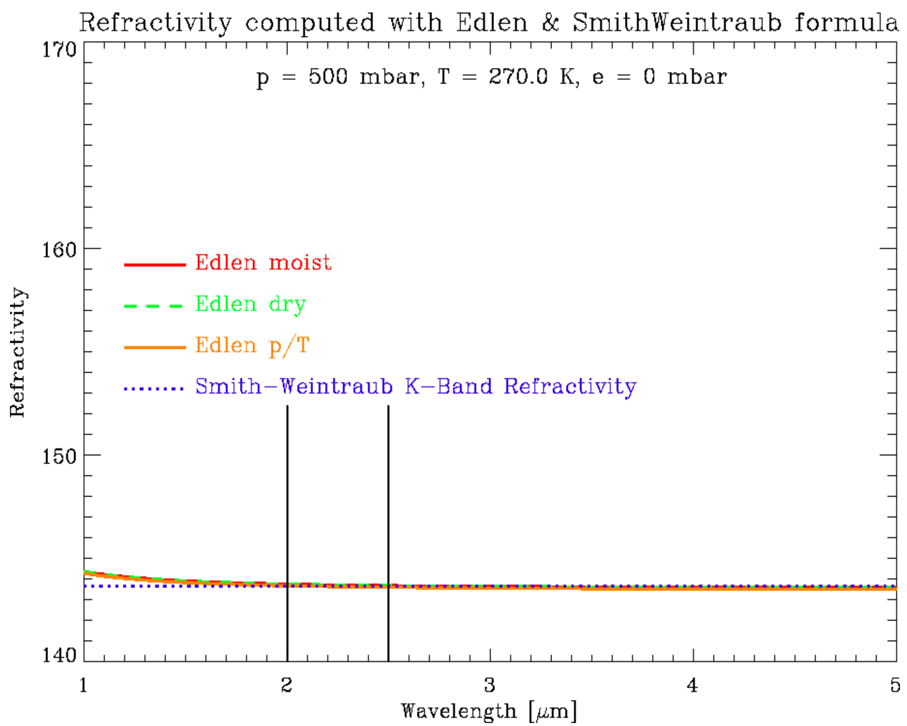
ACCURATE
climate benchmark
quality UTLS profiles:
$z(t)$, $N(z)$, $p(z)$, $Z(p)$,
$T(z)$, $q(z)$, $H_2O(z)$, $V_{los}(z)$,
$CO_2(z)$, $^{13}CO_2(z)$, $C^{18}OO(z)$,
$CH_4(z)$, $N_2O(z)$, $O_3(z)$, $CO(z)$,
$HDO(z)$, $H_2{}^{18}O(z)$ & aerosols,
clouds, turbulence (and more
below & above UTLS)

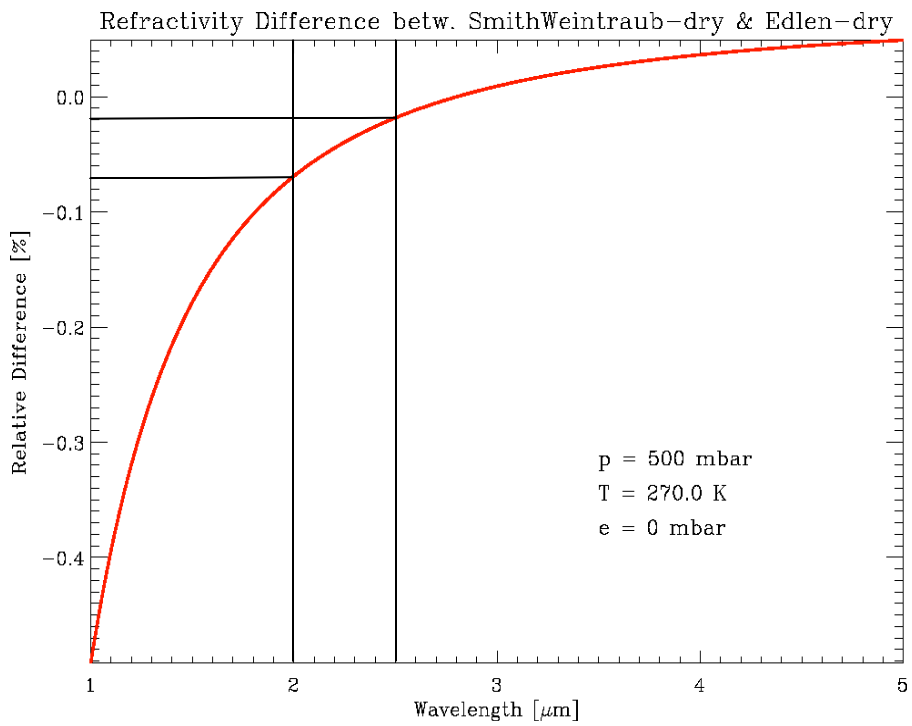
ACCURATE
LMIO=LMO&LIO
measurement techniques:
LMO: LEO-LEO microwave
occultation (MW cross-links
at 17.25, 20.2, 22.6 GHz;
optional 179+182 GHz)
LIO: LEO-LEO infrared
laser occultation (SWIR
cross-links at 21 selected
frequencies in 2–2.5 μm)

just one note on ACCURATE LIO&LMO synergy

SWIR refractivity (LIO) vs MW band (LMO) dry air refractivity

MW dry-air refractivity ("Smith-Weintraub formula") is to < 0.1% difference equal to SWIR refractivity ("Edlen formula") within 2–2.5 µm, so that LIO and LMO signal travel paths are very closely the same. In moist air (5-12 km) the difference can increase to 10-20% near 5 km under moist tropical conditions, so that the LMO-derived atm.state is used to accurately align signal travel paths.

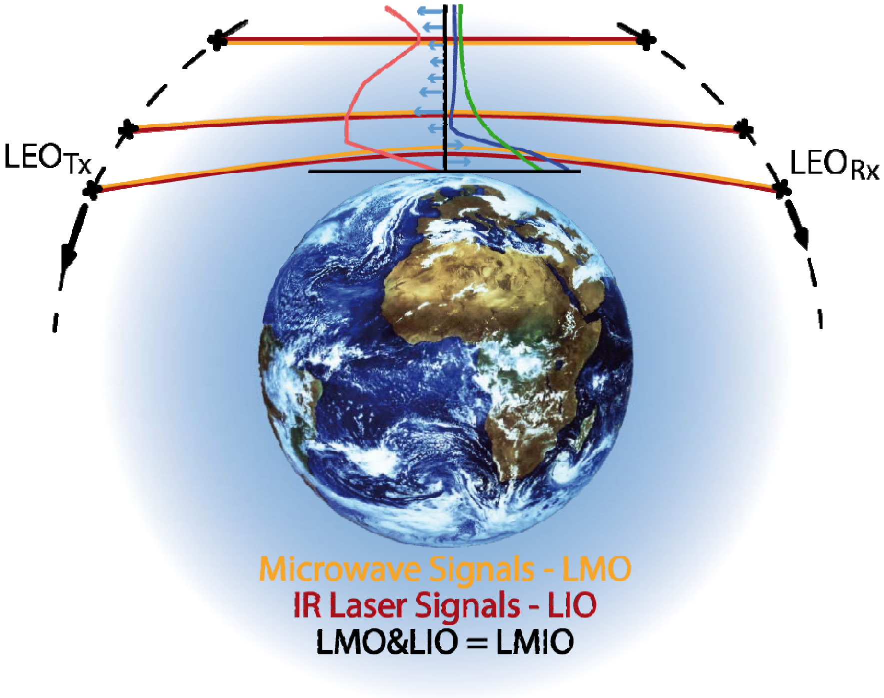


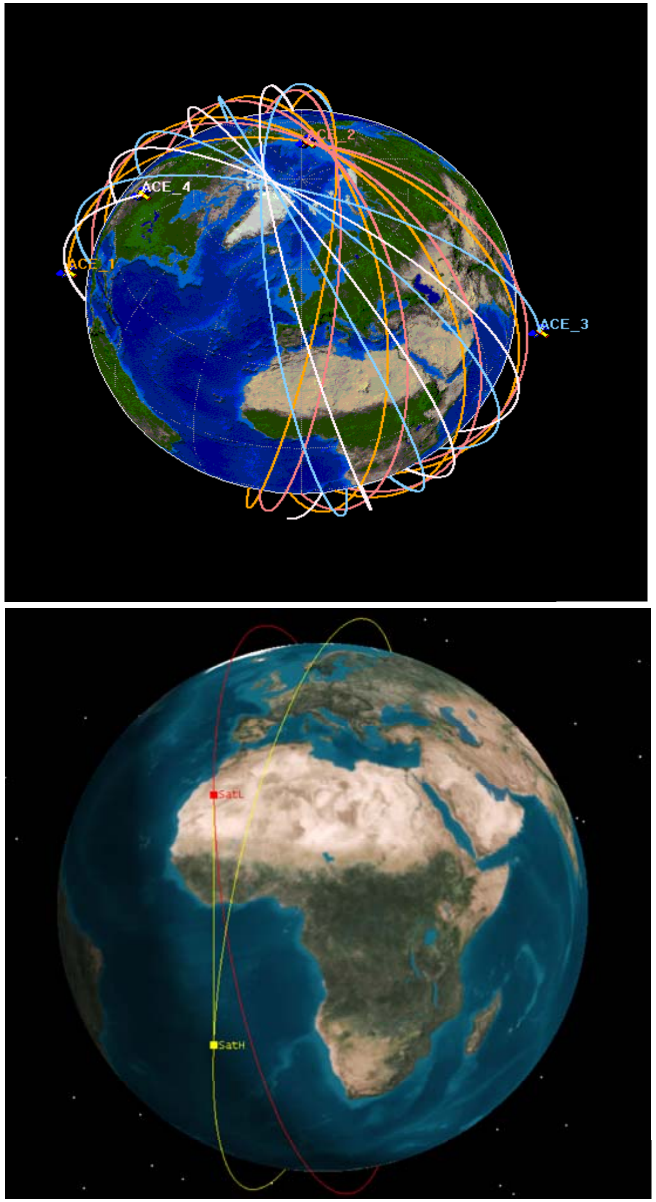


ACCURATE satellite system concept
enhanced from earlier ACE+ mission studies

Baseline constellation concept:

- 2 orbit planes, counter-rotating Rx vs Tx sats
- 1-4 satellites/plane (1 demo, 2-4 full), planes drifting through all local times (i ~ 80°)
- 2 orbit heights (Tx ~595 km, Rx ~512 km; in-orbit separation to suitably spread events)





(Images: Deimos, 2010; Alcatel, 2004)

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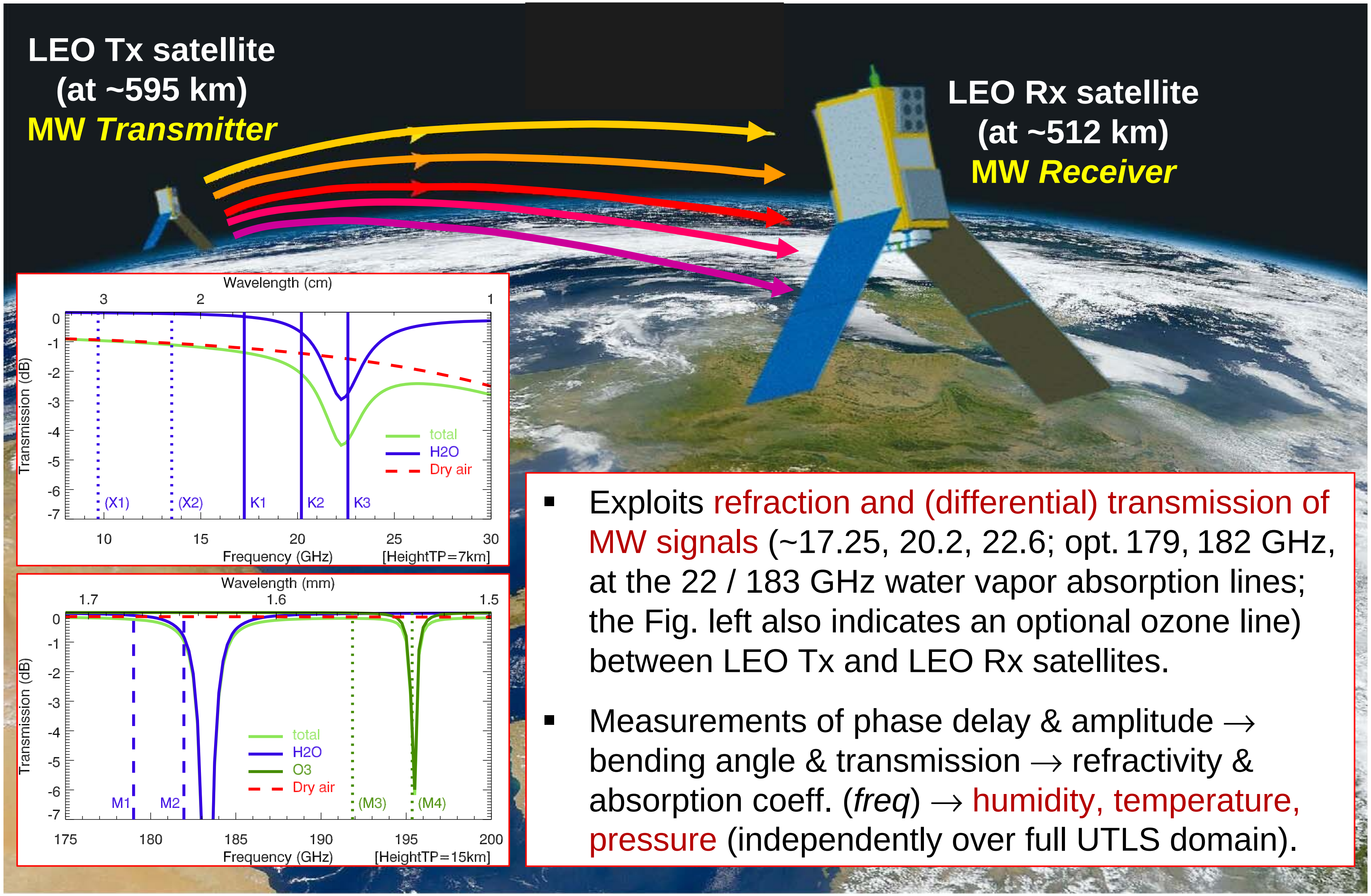
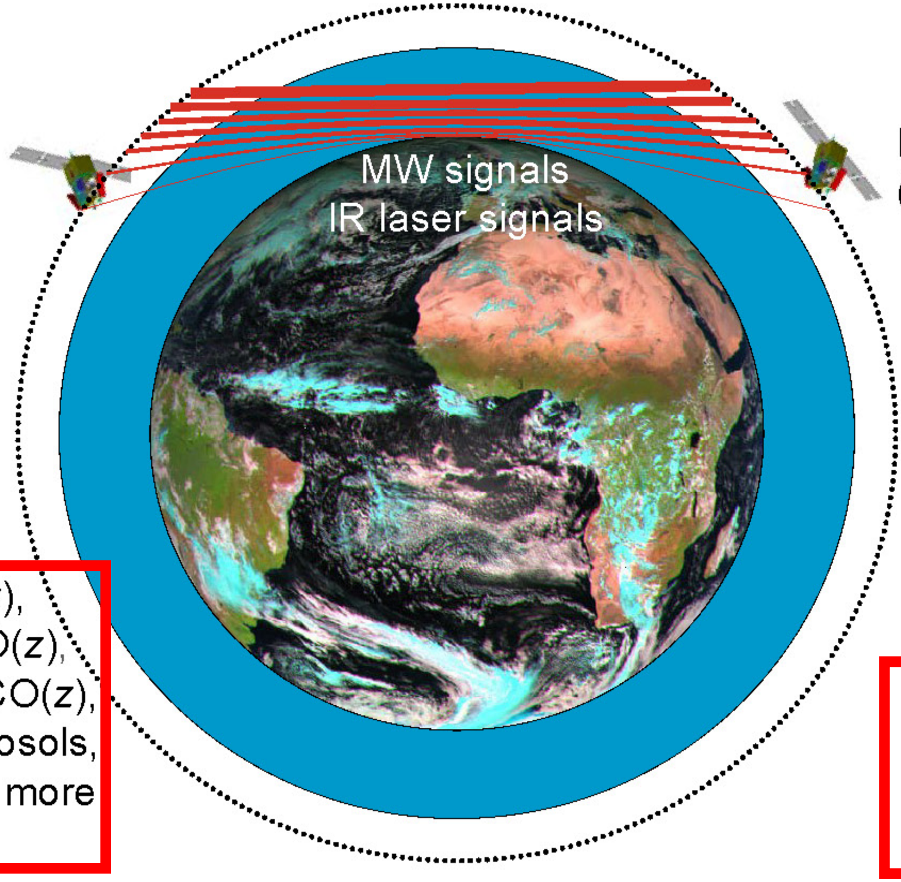
how does the LMO method work?

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



- 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).

…thus let's right turn to the new LIO part of LMIO
ACCURATE IR laser occultation – overview



ACCURATE
climate benchmark
quality UTLS profiles:
z(*t*), *N*(*z*), *p*(*z*), *Z*(*p*),
[$T(z)$] $q(z)$, $H_2O(z)$, $V_{los}(z)$,
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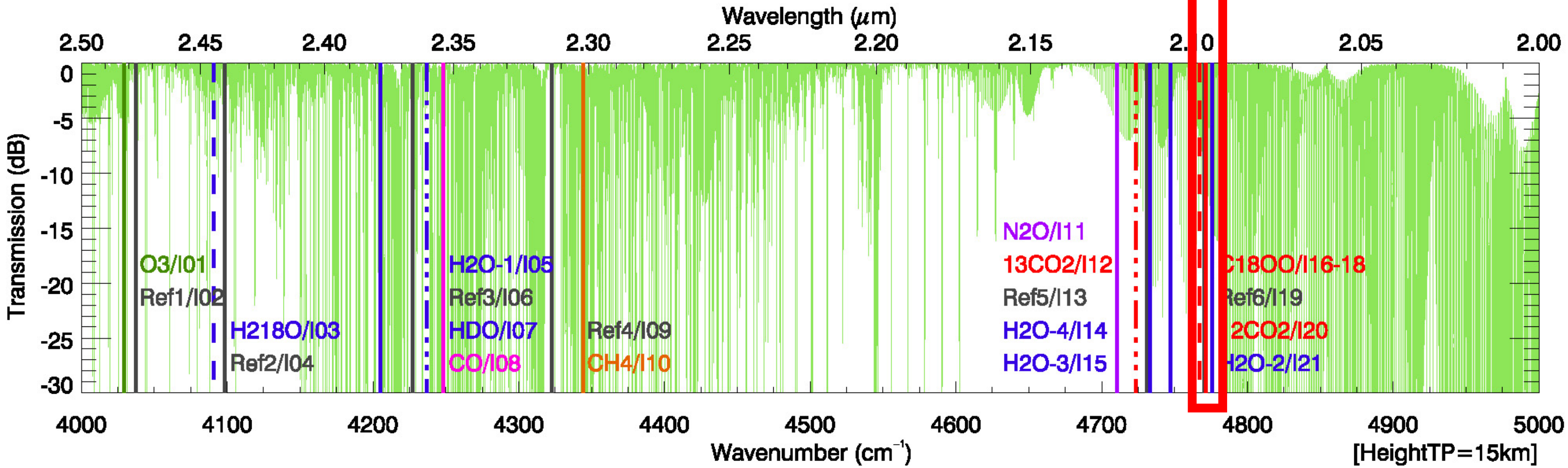
$HDO(z)$, $H_2{}^{18}O(z)$ & aerosols,
clouds, turbulence (and more
below & above UTLS)

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

LIO design: how to properly select LIO lines and create a working payload?

ACCURATE laser line selection within 2–2.5 μm for
differential log-transmission trace species and wind measurements

inspect a 10 cm^{-1} sub-range for CO_2 / H_2O, as an example…

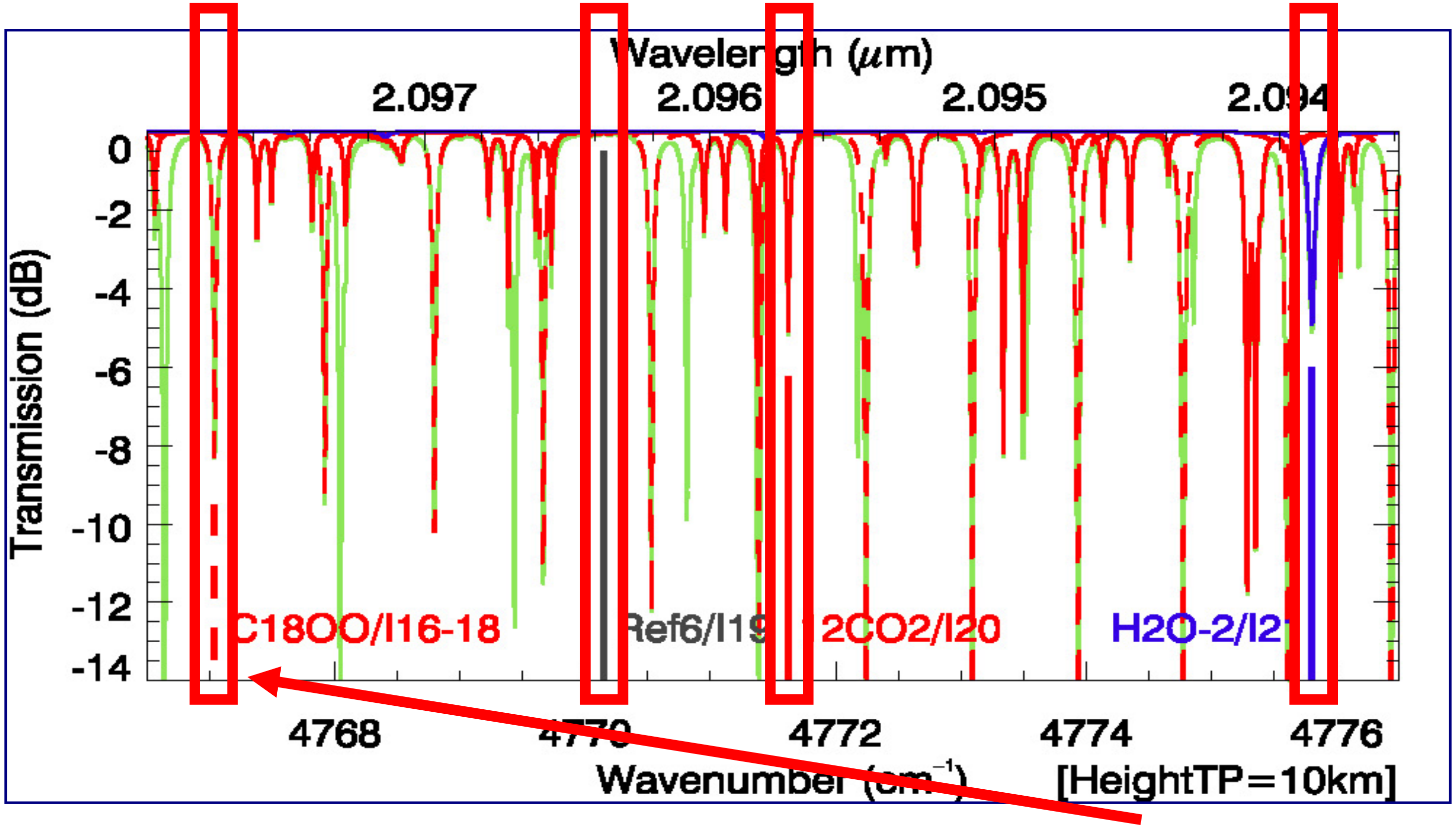


(The RFM fast LBL radiative transfer model of A. Dudhia et al. was used for LIO SWIR transmission simulations, such as for the channel selection indicated above: www.atm.ox.ac.uk/RFM; RFM takes line data from the HITRAN 2004 / 2008 data base of Rothman et al.: www.harvard.edu/HITRAN)

payload: how do measure trace species with LIO?

differential log-transmission over *narrow delta-freq*

abs. channel $C^{18}OO$ **ref. channel** **abs. channel $^{12}CO2$** **abs. channel H_2O**



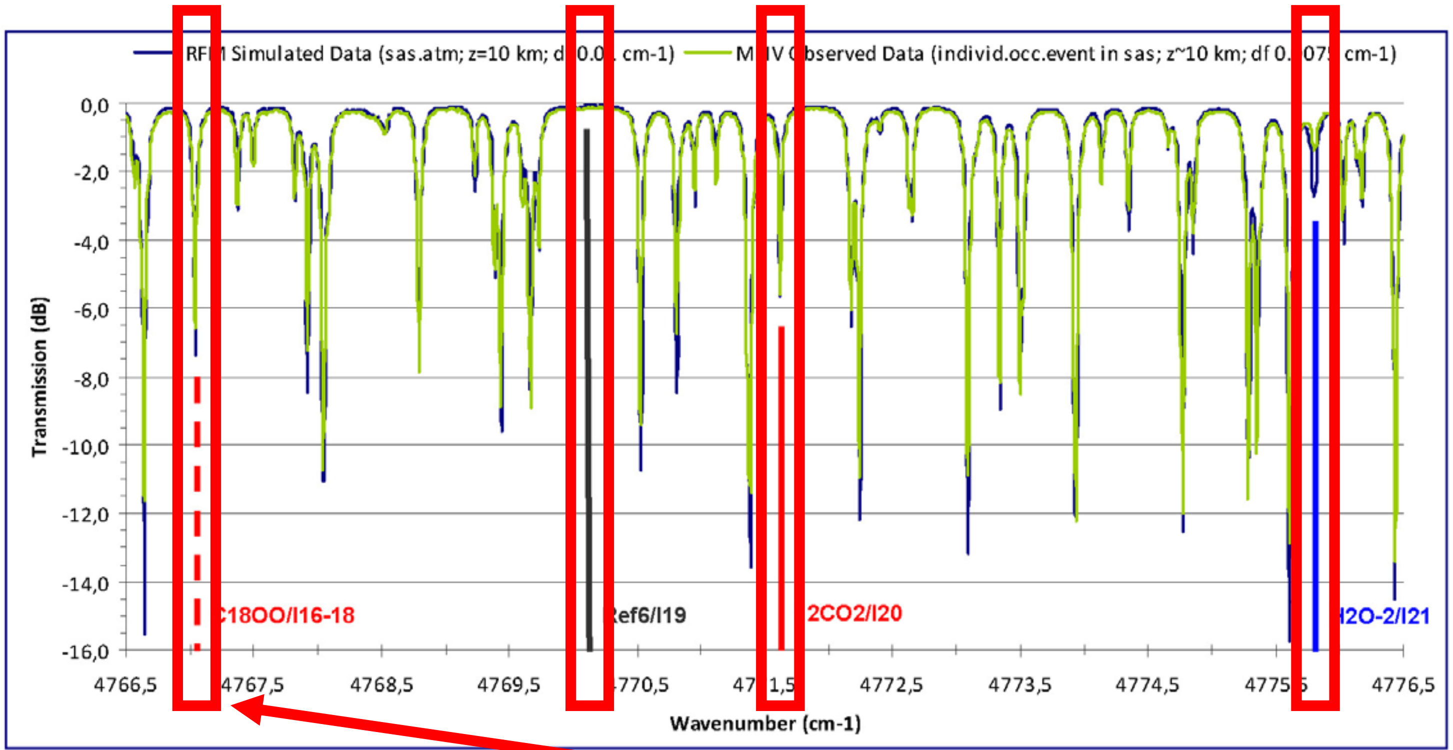
Inspect next a 0.1 cm^{-1} sub-range about the $C^{18}OO$ line center, to see how line-of-sight wind is measured…

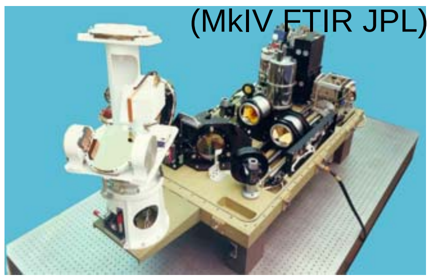
<u>… check the present range with real data before…</u>

payload: real limb spectra confirm selections

comparison RFM to balloon-borne MkIV solar occultation spectrum
(MkIV source G.Toon/JPL; P.Bernath-J.Harrison/UoY)

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





(MkIV FTIR JPL)

Inspect now the 0.1 cm^{-1} sub-range about the $C^{18}OO$ line center (via RFM data), to see how line-of-sight wind is measured…

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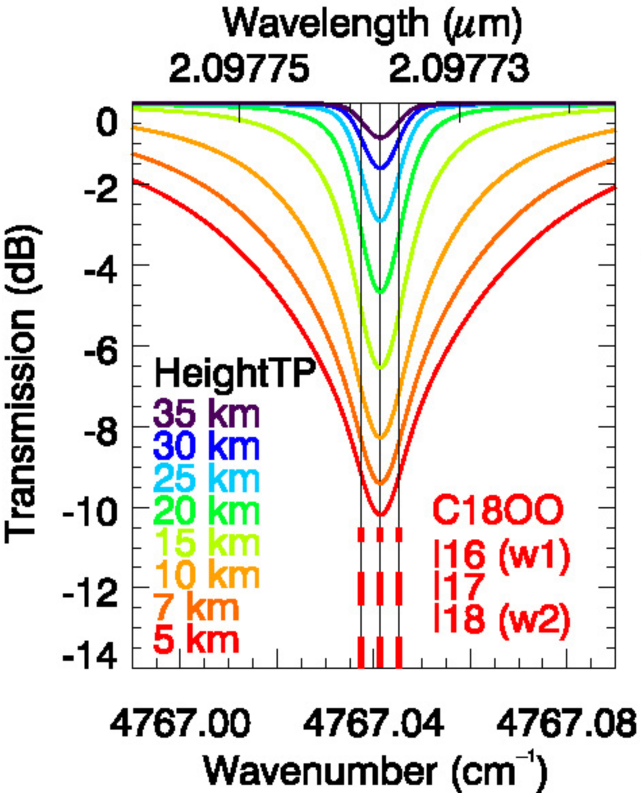
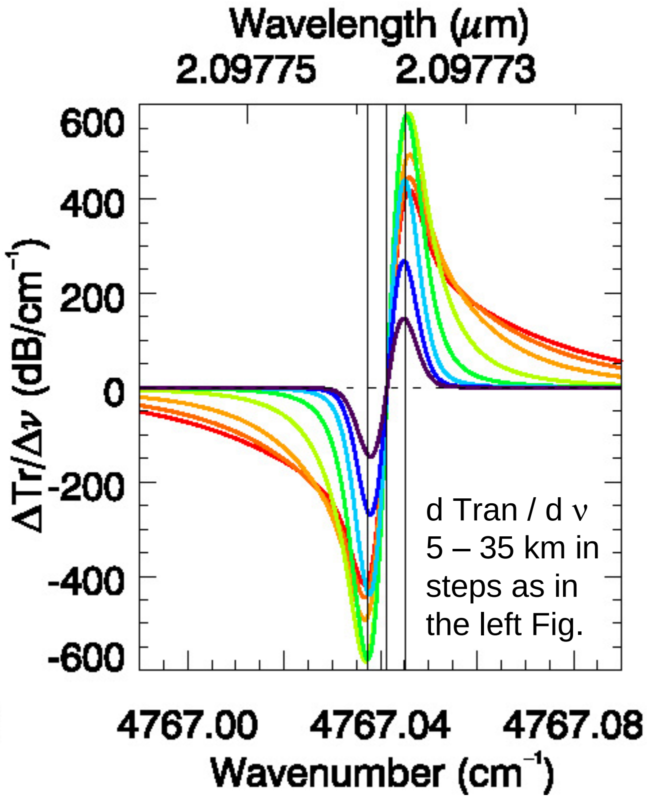
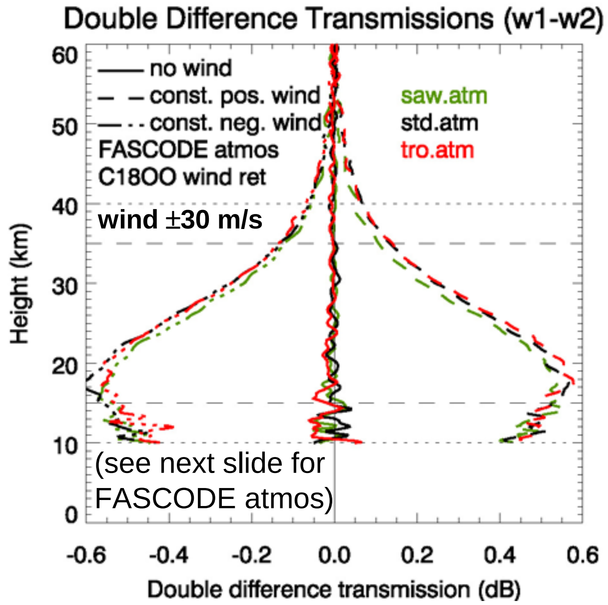
payload: how to measure winds with LIO?

differential log-transmission over *very narrow delta-freq,*
spanning ~ the Doppler FWHM of the symmetric $C^{18}OO$ line



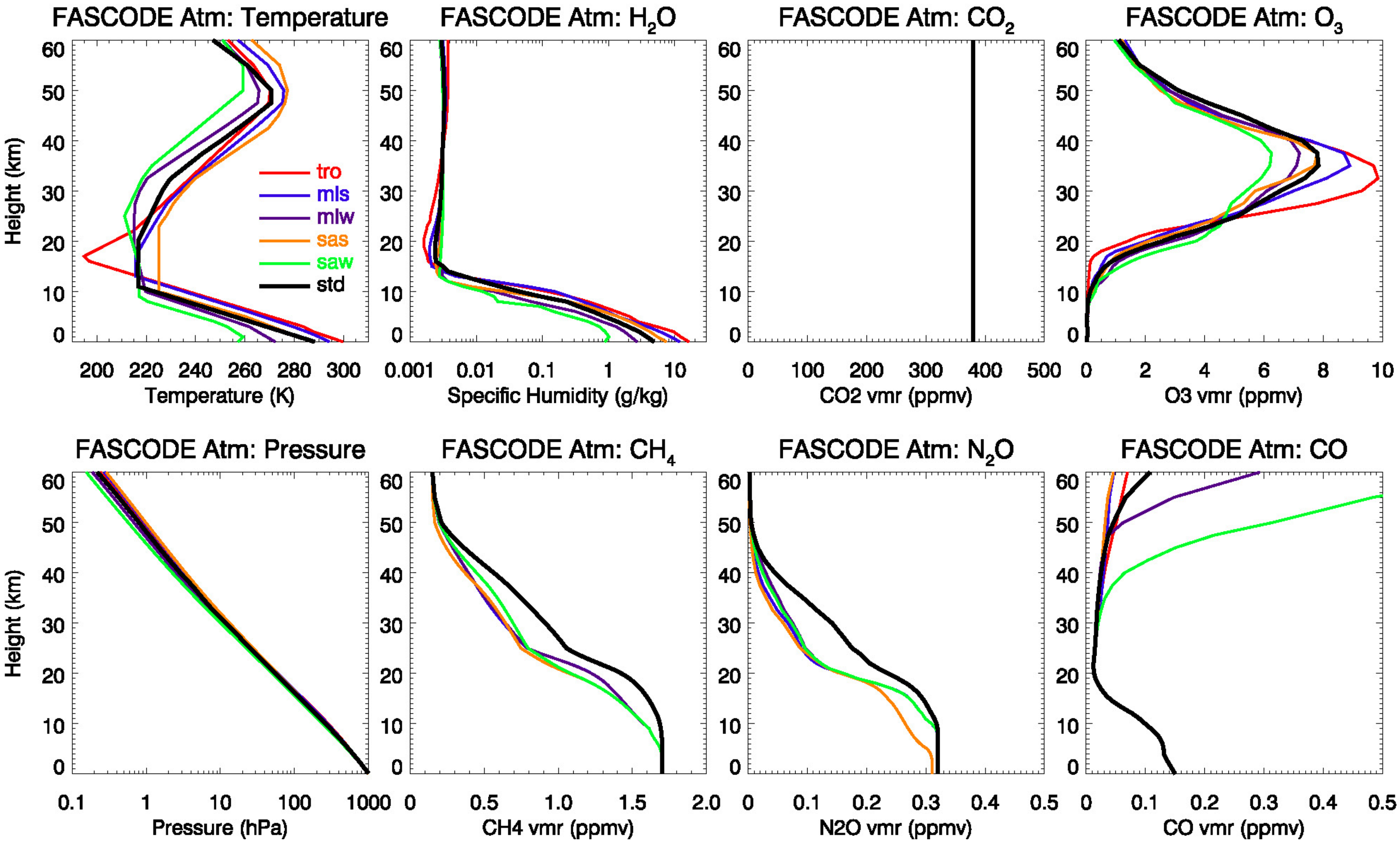




(wind line spacing: df/f = +/-0.83 x 10^{-6} about $C^{18}OO$ line center frequency, ~ Doppler FWHM;
Laser: FWHM < 3 x 10^{-8}, frequency knowledge < 1 x 10^{-8}, intensity stability < 0.1%)

study of the performance by end-to-end simulations (1)

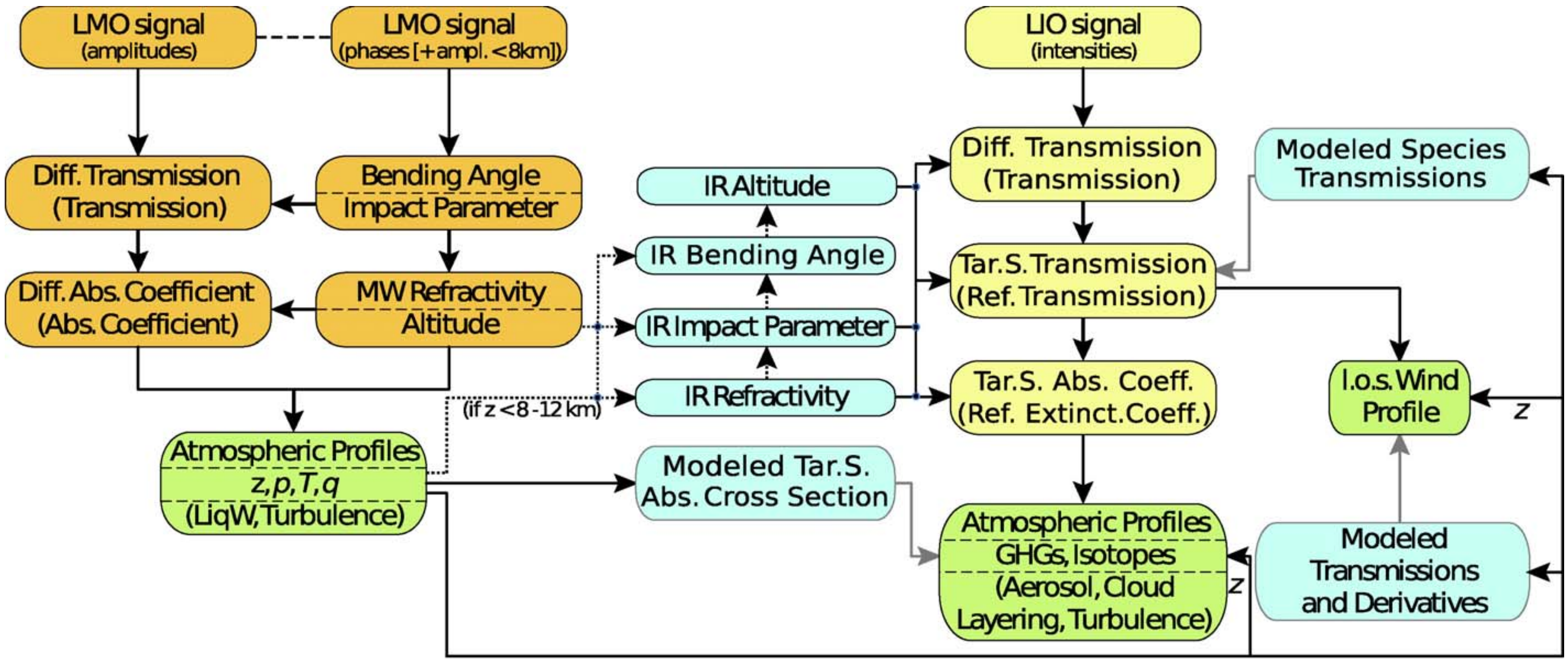
LMIO simulations, using basic & advanced atmospheres



study of the performance by end-to-end simulations (2)

also EGOPS does LMIO meanwhile; but here mainly ALPS LIO results shown, are consistent with EGOPS;

=> see Proschek et al. LMIO retrieval pres. for EGOPS results



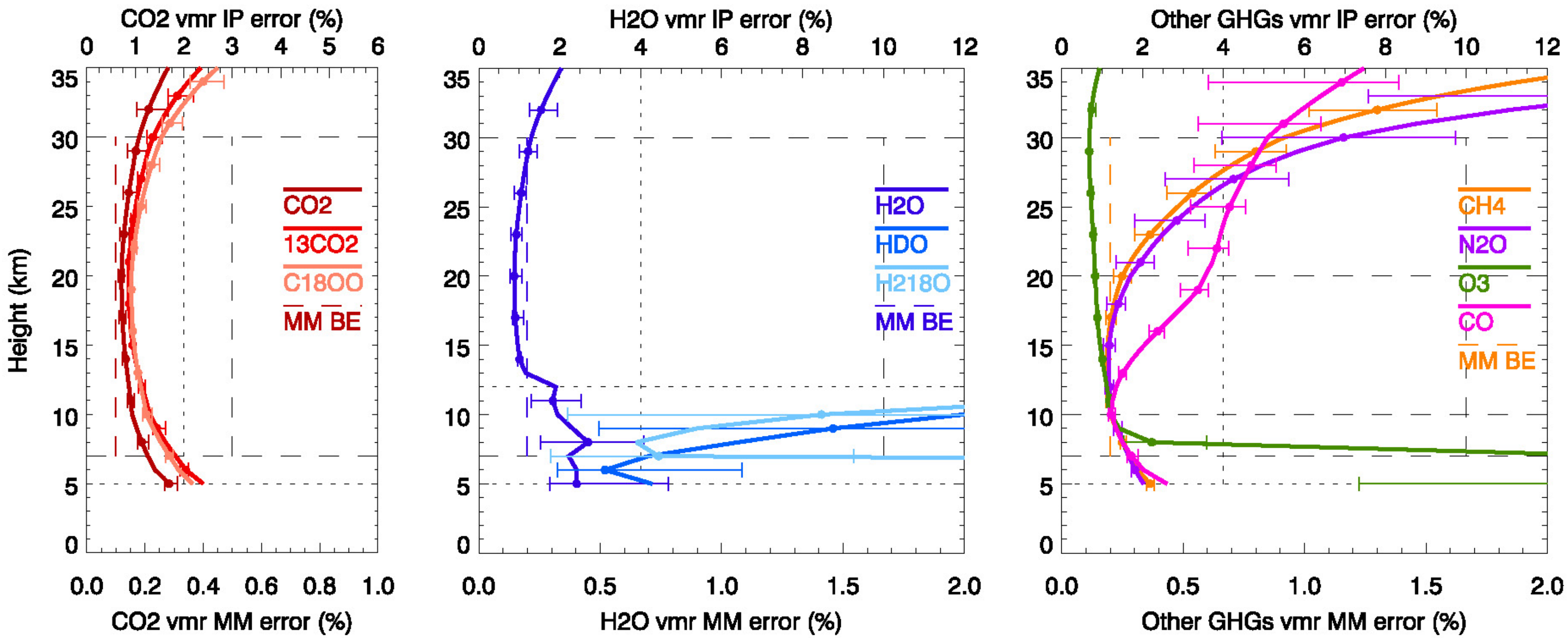
xEGOPS/EGOPS LMIO L1b/L2 retrieval chain, based on L1a simulated observables

what is the LMIO retrieved profiles accuracy? (1)

LMIO requirements & scientific 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)])

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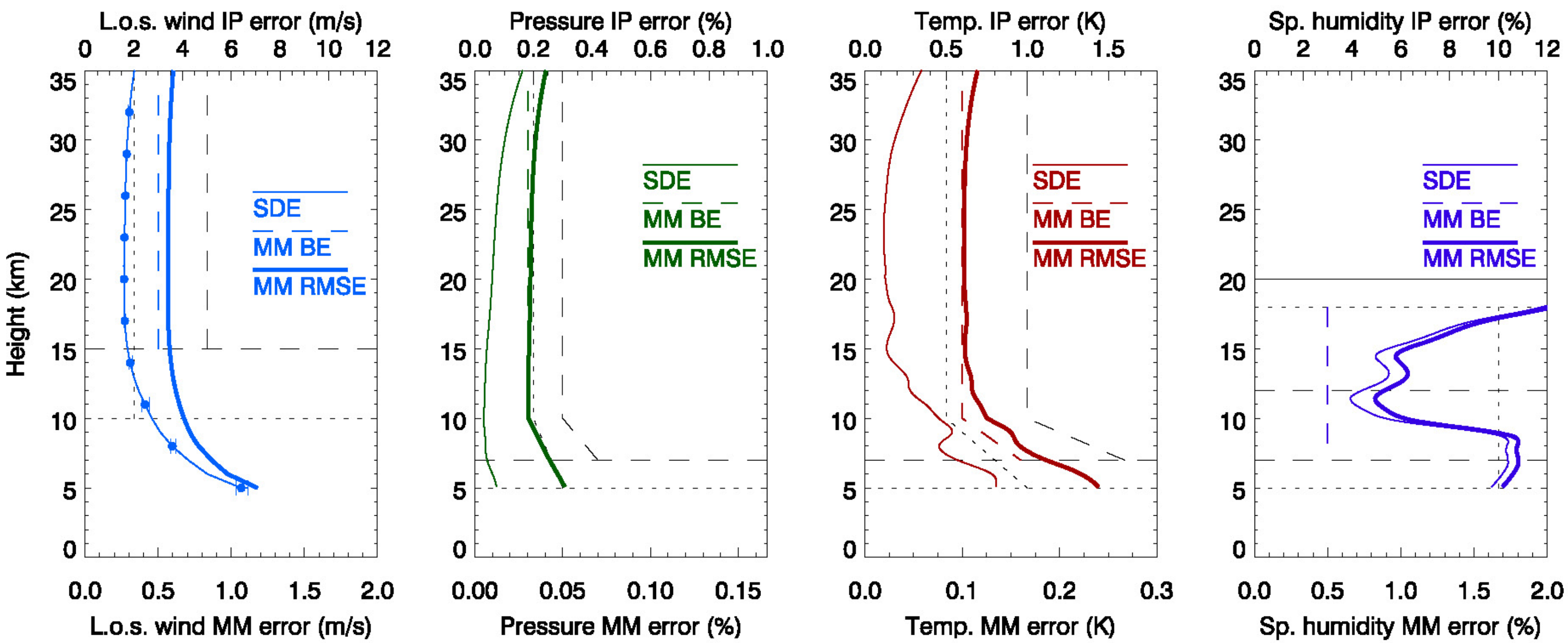
what is the LMIO retrieved profiles accuracy? (2)

LMIO requirements & scientific performance: individual-profile and monthly-mean error estimates

- Monthly-mean l.o.s. wind profiles unbiased and generally accurate to < 0.5-1 m/s. Pressure/temperature/humidity profiles from LMO accurate to < 0.1%/< 0.1-0.2 K/< 2-3% (incl. in clouds) (ALPS2 and EGOPS5 results)

Example results: line-of-sight-wind and thermodynamic retrieval, IP and monthly-mean errors



(Profiles: l.o.s. wind err. from 6 FASCODE&basic wind profiles; p, T, q err. from ECMWF profile ensemble/EGOPS5)

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Ground-based initial demo experiment IRDAS-EXP

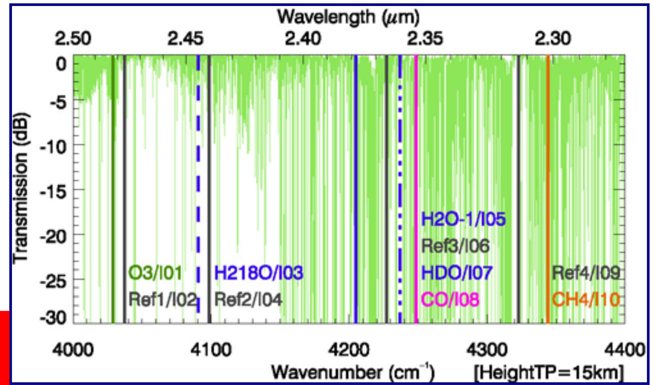
CO_2-H_2O-V_{los} 2.1μm + CH_4 2.3μm LIO demonstration

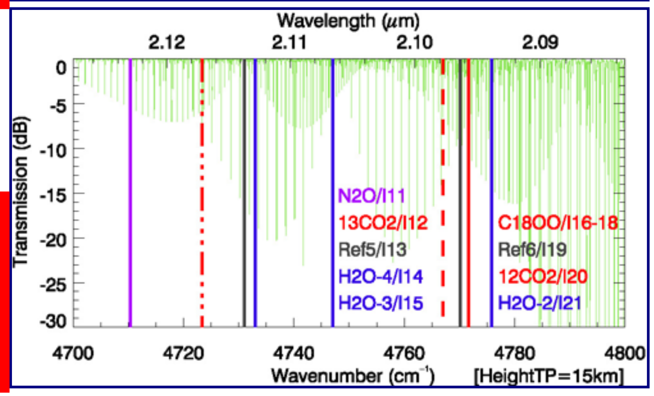
line selection for ACCURATE LIO demo breadboard

Ch.ID	Frequency	Wavelength	Channel Utility	$\Delta\lambda_{ar}/\lambda_r$ (%)
	(GHz)	(cm)	LMO X/K band 8–30 GHz	
(X1)	9.70	3.0906	p, T, Ref[H_2O] ~2–7 km	(Ref)
(X2)	13.50	2.2207	p, T, Abs/Ref[H_2O] ~2–7 km	–28.15
K1	17.25	1.7379	p, T, Ref/Abs[H_2O] ~5–12 km	(Ref)
K2	20.20	1.4841	p, T, Abs/Ref[H_2O] ~5–12 km	–14.60
K3	22.60	1.3265	Abs/Ref[H_2O] ~5–12 km	–10.62
	(GHz)	(mm)	LMO M band 175–200 GHz	
M1	179.00	1.6748	Ref/Abs[H_2O] ~10–18 km	(Ref)
M2	181.95	1.6477	Abs[H_2O] ~10–18 km	–1.618
(M3)	191.85	1.5626	Ref[O_3]	(Ref)
(M4)	195.35	1.5346	Abs[O_3]	–1.792
	(cm^{-1})	(μm)	LIO SWIR-B band 2.3–2.5 μm	
I01	4029.110	2.481938	Abs[O_3]	+0.2006
I02	4037.21	2.47696	Ref[O_3]	Ref1
I03	4090.872	2.444467	Abs[$H_2{}^{18}O$]	+0.1876
I04	4098.56	2.43988	Ref[$H_2{}^{18}O$]	Ref2
I05	4204.840	2.378212	Abs[H_2O-1] ~13–48 km	+0.5259
I06	4227.07	2.36571	Ref[H_2O, HDO, CO]	Ref3
I07	4237.016	2.360151	Abs[HDO]	–0.2353
I08	4248.318	2.353873	Abs[CO]	–0.5027
I09	4322.93	2.31325	Ref[CH_4]	Ref4
I10	4344.164	2.301939	Abs[CH_4]	–0.4912
	(cm^{-1})	(μm)	LIO SWIR-A band ~2.1 μm	
I11	4710.341	2.122989	Abs[N_2O]	+0.4373
I12	4723.415	2.117112	Abs[$^{13}CO_2$]	+0.1610
I13	4731.03	2.11371	Ref[N_2O, $^{13}CO_2$, H_2O]	Ref5
I14	4733.045	2.112805	Abs[H_2O-4] ~4–8 km	–0.0426
I15	4747.055	2.106569	Abs[H_2O-3] ~5–10 km	–0.3387
I16	4767.037	2.097739	Abs[$C^{18}OO$-w1], l.o.s. wind	+0.0653
I17	4767.041	2.097737	Abs[$C^{18}OO$]	+0.0652
I18	4767.045	2.097735	Abs[$C^{18}OO$-w2], l.o.s. wind	+0.0651
I19	4770.15	2.09637	Ref[$^{12}CO_2$, $C^{18}OO$, H_2O, wind]	Ref6
I20	4771.621	2.095724	Abs[$^{12}CO_2$]	–0.0308
I21	4775.803	2.093889	Abs[H_2O-2] ~8–25 km	–0.1185

~2.3 μm (I09–I10)

~2.1 μm (I16–I21)

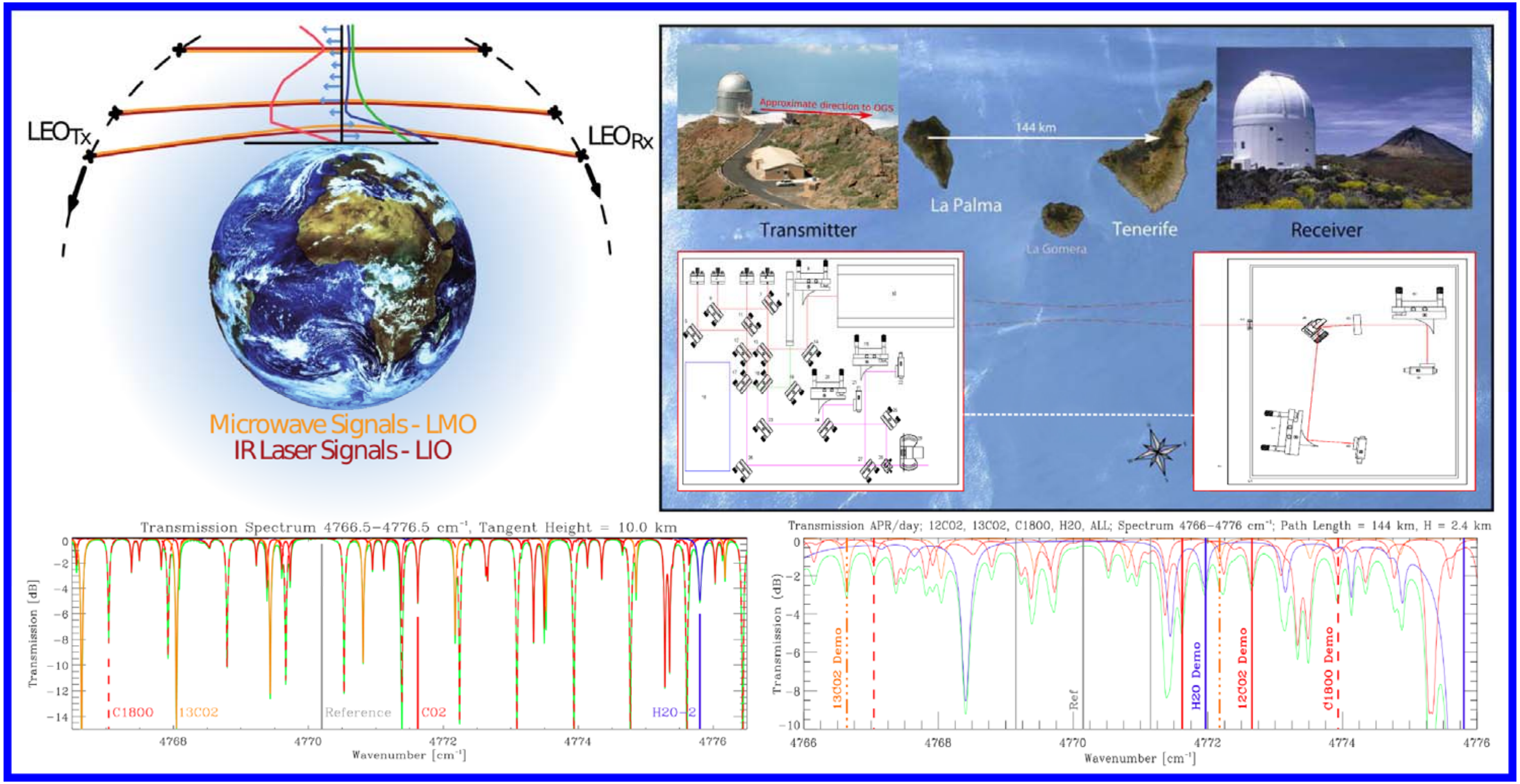




CO_2-H_2O-Wind+CH_4 LIO demo IRDAS-EXP 2010/11

Canary Islands link…where the ESA “QIPS experiment” was run

=> see Schweitzer et al. IR link experiment pres. for more details



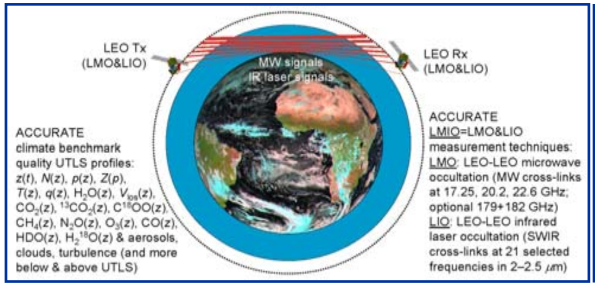
(fig backdrop upper right from Weinfurter et al., ESA-QIPS FinRep, 2007)

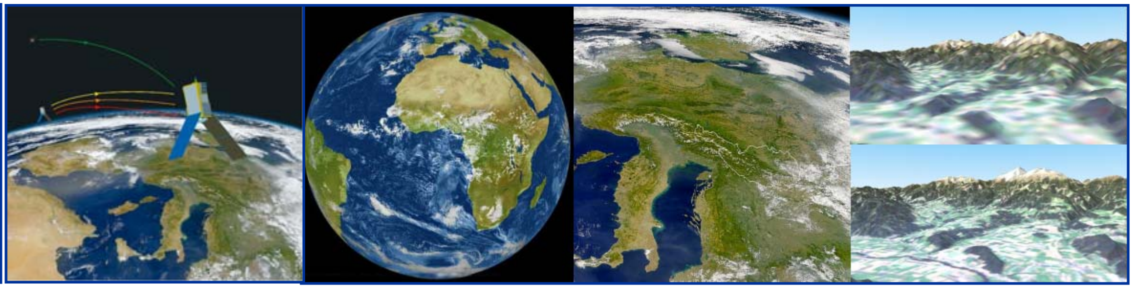
what's next? – …on the road to ACCURATE
towards a demonstration mission

- complete LMIO scientific performance analyses for all parameters, thermodynamic, greenhouse gases and isotopes, wind; as well as for the complementary aerosol, cloud, and turbulence information (projects ACTLIMB, IRDAS; on-going/next ACCU-Clouds/-EXP,…)

- produce and demonstrate a first breadboard of the LIO transmitter-receiver system (IRDAS-EXP CO_2-H_2O-Wind ~2.1 μm, CH_4 ~2.3 μm) (LMO currently proven by a stratospheric aircraft crosslink exp. in U.S.)

- start implementation of ACCURATE as space mission:
  + ACCURATE LMIO demonstration mission (1Tx+1Rx satellite complete demo, e.g., ESA EE-8 mission…)
  + full 4-8 sats climate benchmarking mission (e.g., Europe, U.S.,...)





what's next? – …on the road to ACCURATE
towards a demonstration mission

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- start imple[illegible] CURATE as space mission:
  + ACCURA[illegible] emonstration mission (1Tx+1Rx satellite complete de[illegible] .g., ESA EE-8 mission…)
  + full 4-8 sats climate benchmarking mission (e.g., Europe, U.S.,...)

Thank You! ☺