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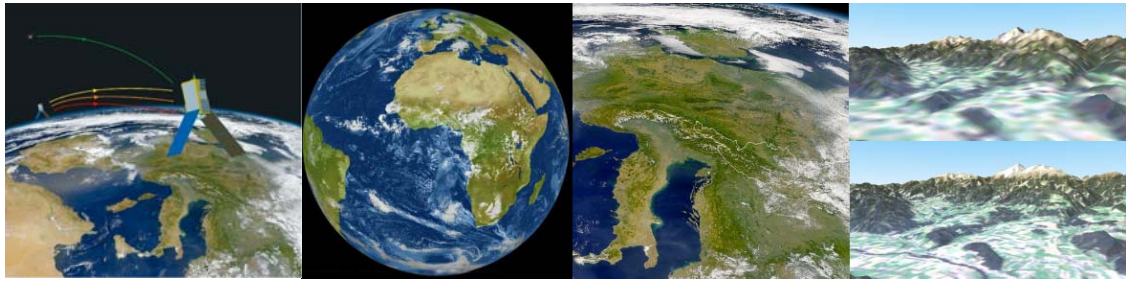

ACCURATE – Observing Greenhouse Gases, Isotopes, Wind, and Thermodynamic Variables by Combined MW Radio and IR Laser Occultation

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…and thanks to all colleagues supporting ACCURATE (see next slide)

Thanks for funds to:

OPAC-3 Workshop – Session “Next-generation Occultation Missions”; September 20, 2007; University of Graz, Graz, Austria.

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thanks to

all colleagues supporting the ACCURATE concept

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Sam Yee, APL/Johns Hopkins University, Laurel, MD, USA
and quite a number more internationally and at the Wegener Center/Uni Graz,
including from industry (A. Deninger TOPTICA, S. Veldman SSC,…)

> two dozen scientific partners from > a dozen countries. Thanks all!

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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 parameters including thermodynamic ones (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 the above parameters over the upper troposphere-lower stratosphere (UTLS) region as function of altitude with 1–2 km vertical resolution.

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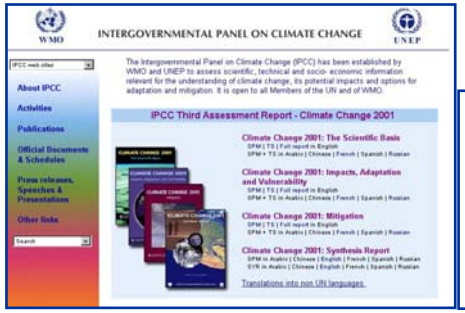
why monitor climate change with benchmark data from space?

three major reasons:

- to rigorously observe and learn, *independent of models*, how climate and chemistry change and variability evolve, over seasonal, interannual, and decadal scales
- to validate and improve climate and chemistry models and thereby enhance their predictive skills for simulating the future climate and chemical composition
- to use the benchmark data as accurate observational constraints for 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 at IPCC 2007 times****:*

"- ***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.****"*

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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 anthropogenic climate change, in a physically consistent manner (e.g., temperature, humidity, wind, composition, etc.)

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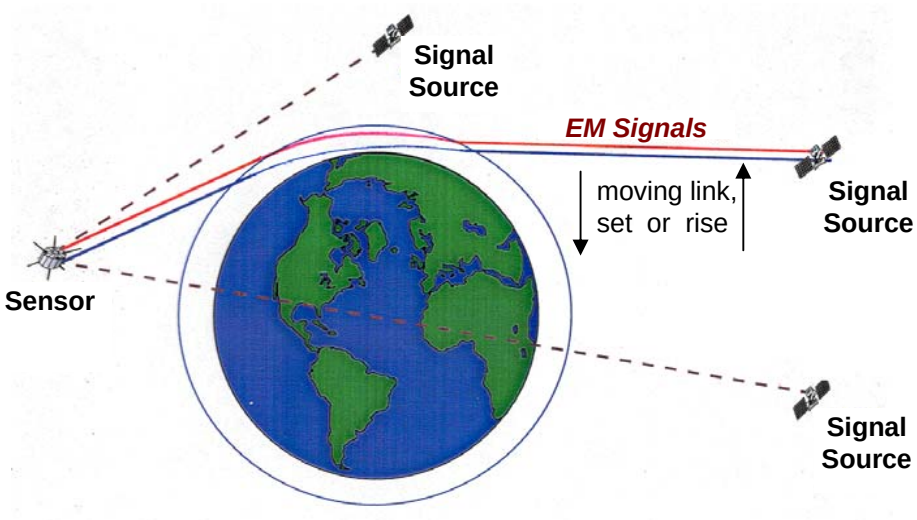
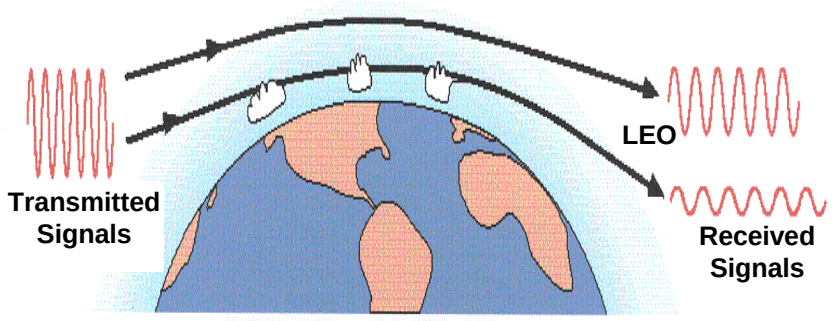
how to make these properties come true?
method of choice – occultation measurements



[basic figures from D. Feng, Univ. of Arizona, priv. communications, 2001 (modified)]



Occultation methods

- exploit refraction and extinction of electromagnetic signals along limb paths
- providing self-calibrated measurements of Doppler shift and transmission profiles
- leading via bending angle, optical thickness, refractivity and absorption coeff.
- to key atmo&climate parameters such as temperature, humidity, geopotential height, ozone, GHGs, wind, and others.

Inversion/processing of occultation data

- is a virtually well-posed and generally close to linear problem solved by
- direct inversion/retrieval or
- data assimilation.

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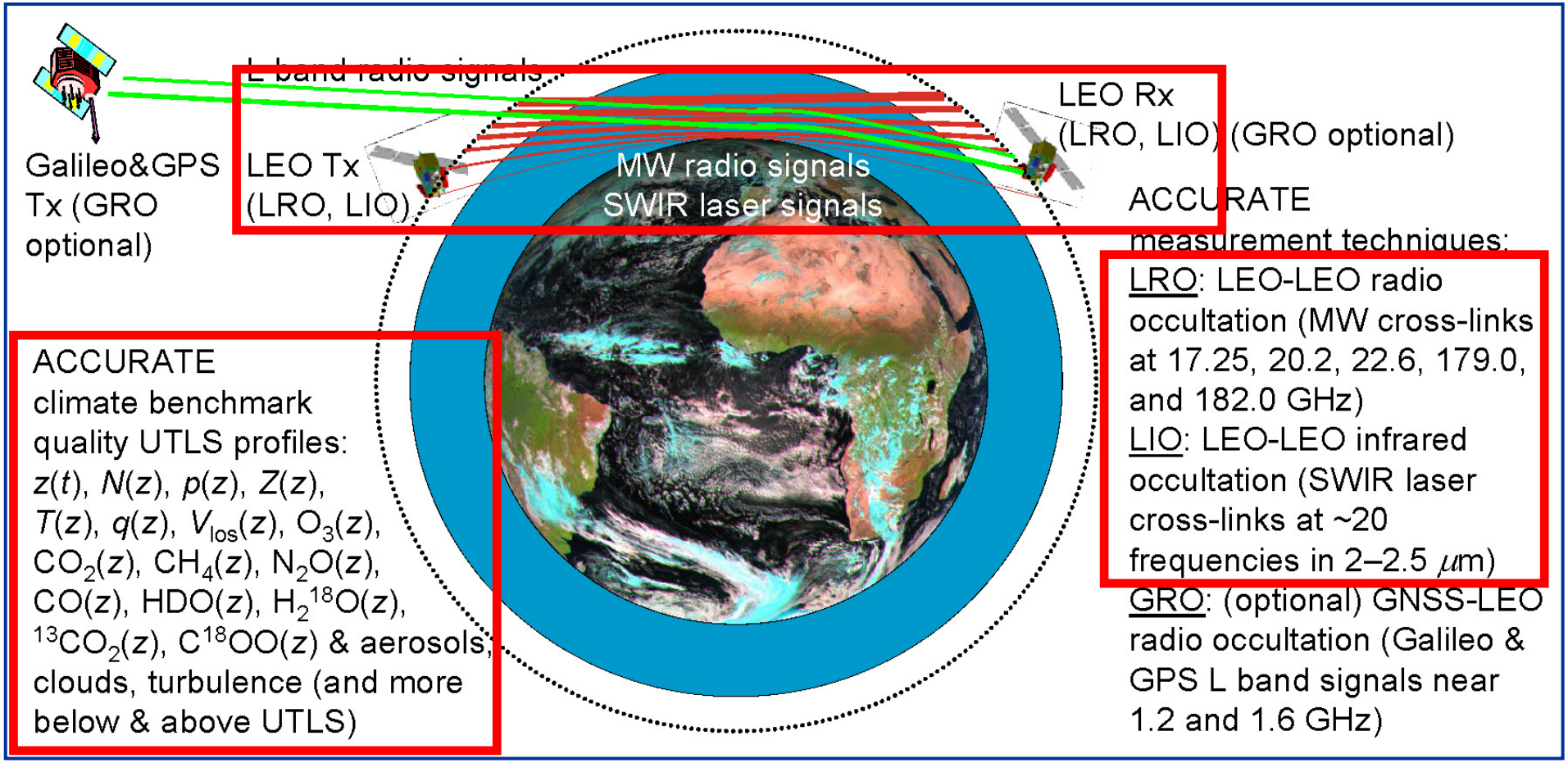
what are the key elements of the concept?

the ACCURATE mission concept

ACCURATE – Atmospheric Climate and Chemistry in the UTLS Region And climate Trends Explorer



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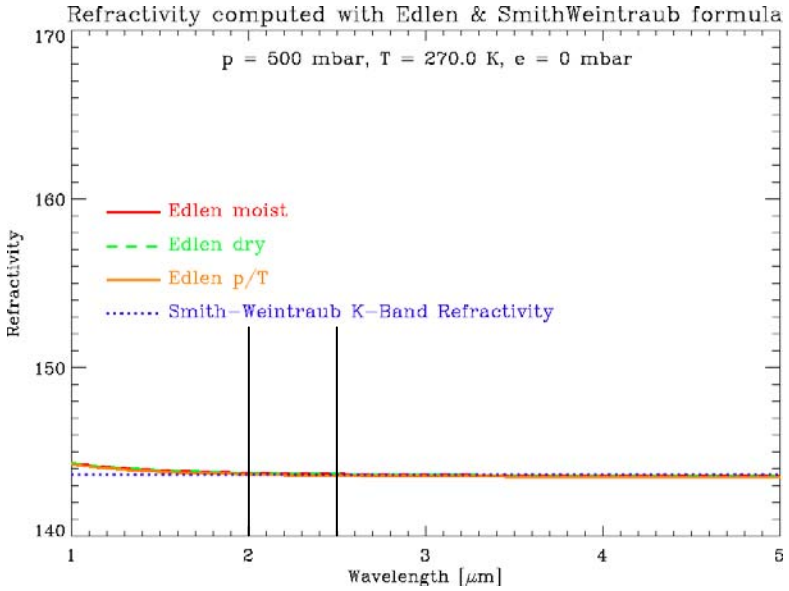
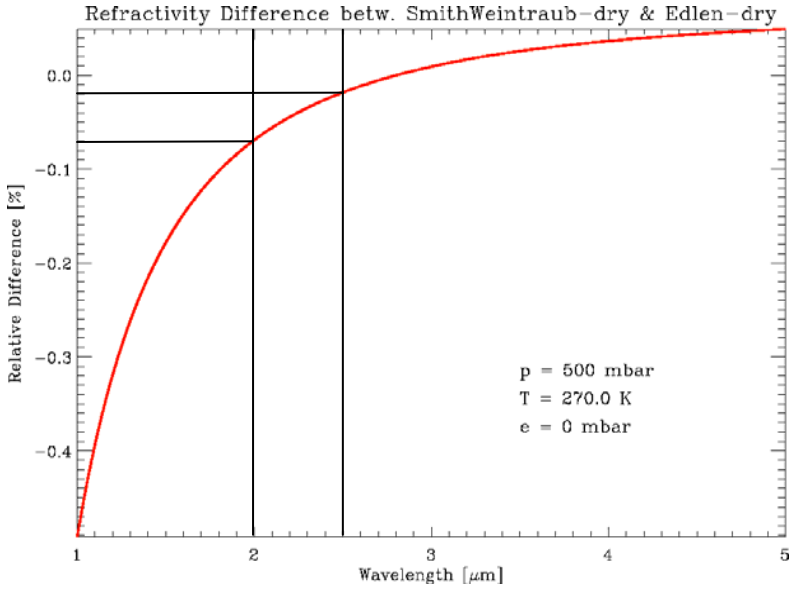
on ACCURATE LIO+LRO synergy (1)

SWIR refractivity (LIO) vs MW band (LRO) 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 LRO 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 LRO-derived atm.state is used to accurately align signal travel paths.





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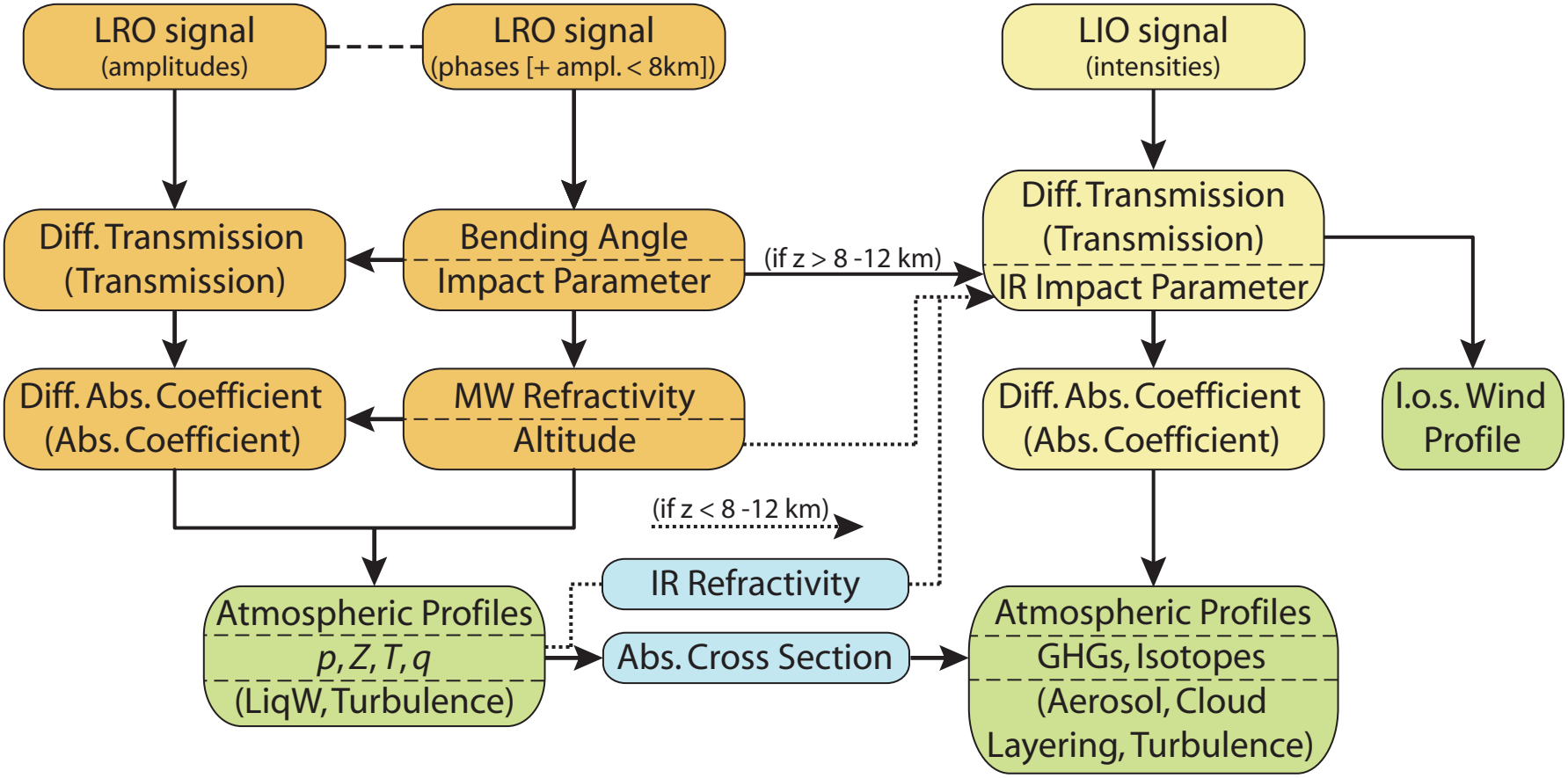
on ACCURATE LIO+LRO synergy (2)
the LRO+LIO retrieval processing



Simplified overview of the LRO+LIO retrieval processing chain.

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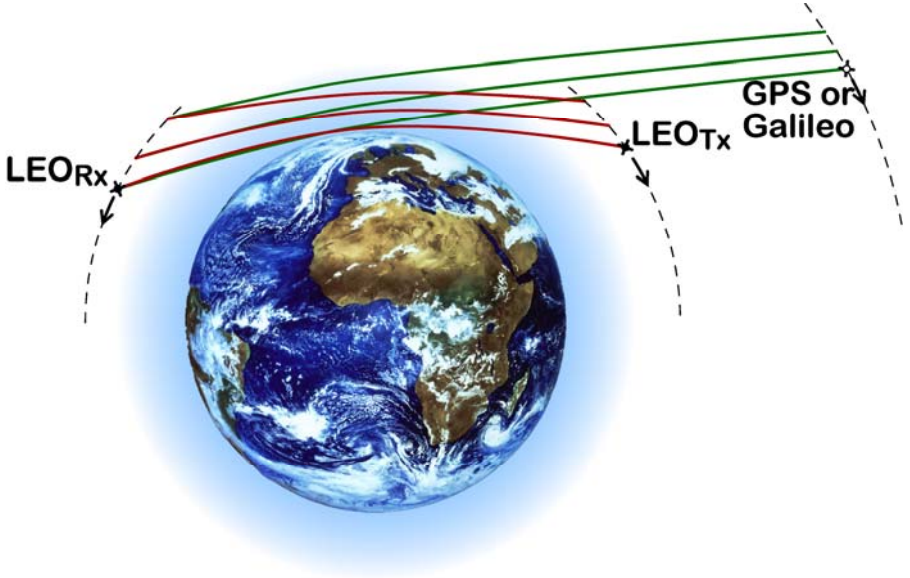
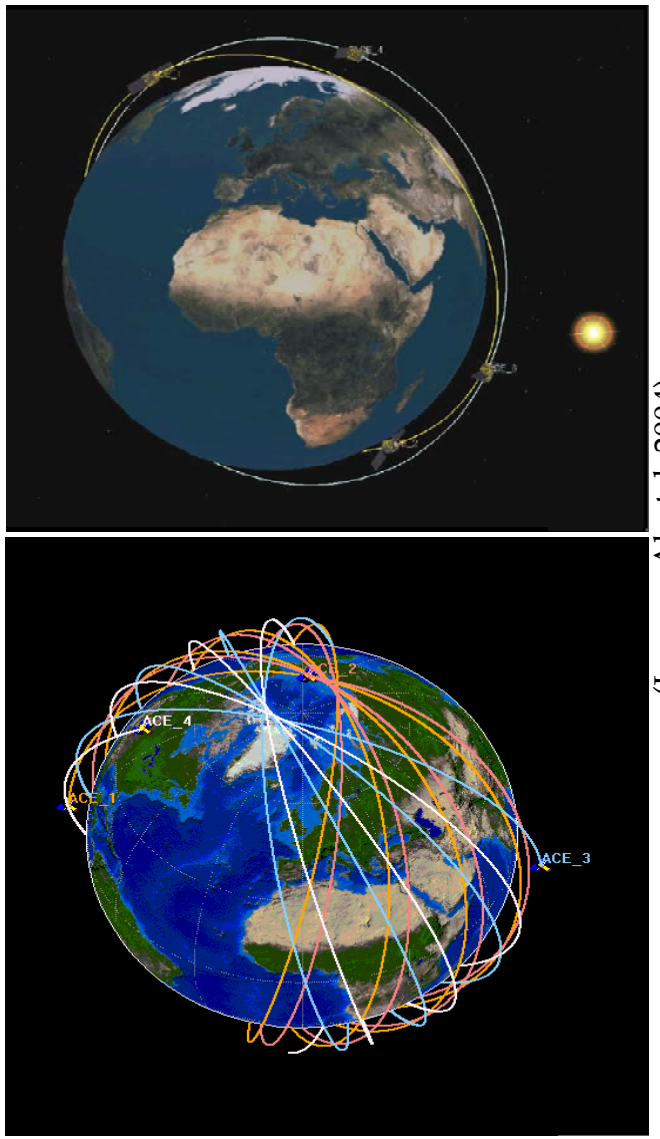
ACCURATE satellite system concept
strong heritage from ACE+ phase A studies

Baseline constellation concept:

- 2 orbit planes, counter-rotating Rx vs Tx sats
- 2 satellites/plane, sun-synchronous (*i* ~ 98°), aligned with MetOp orbit nodes (LTDN 9:30h)
  alternative: near-polar to polar planes (87-90°)
- 2 orbit heights (Rx‘s ~650 km, Tx‘s ~800 km; in-orbit separation Tx‘s ~ 180°, Rx‘s ~ 80°)





(Images: Alcatel, 2004)

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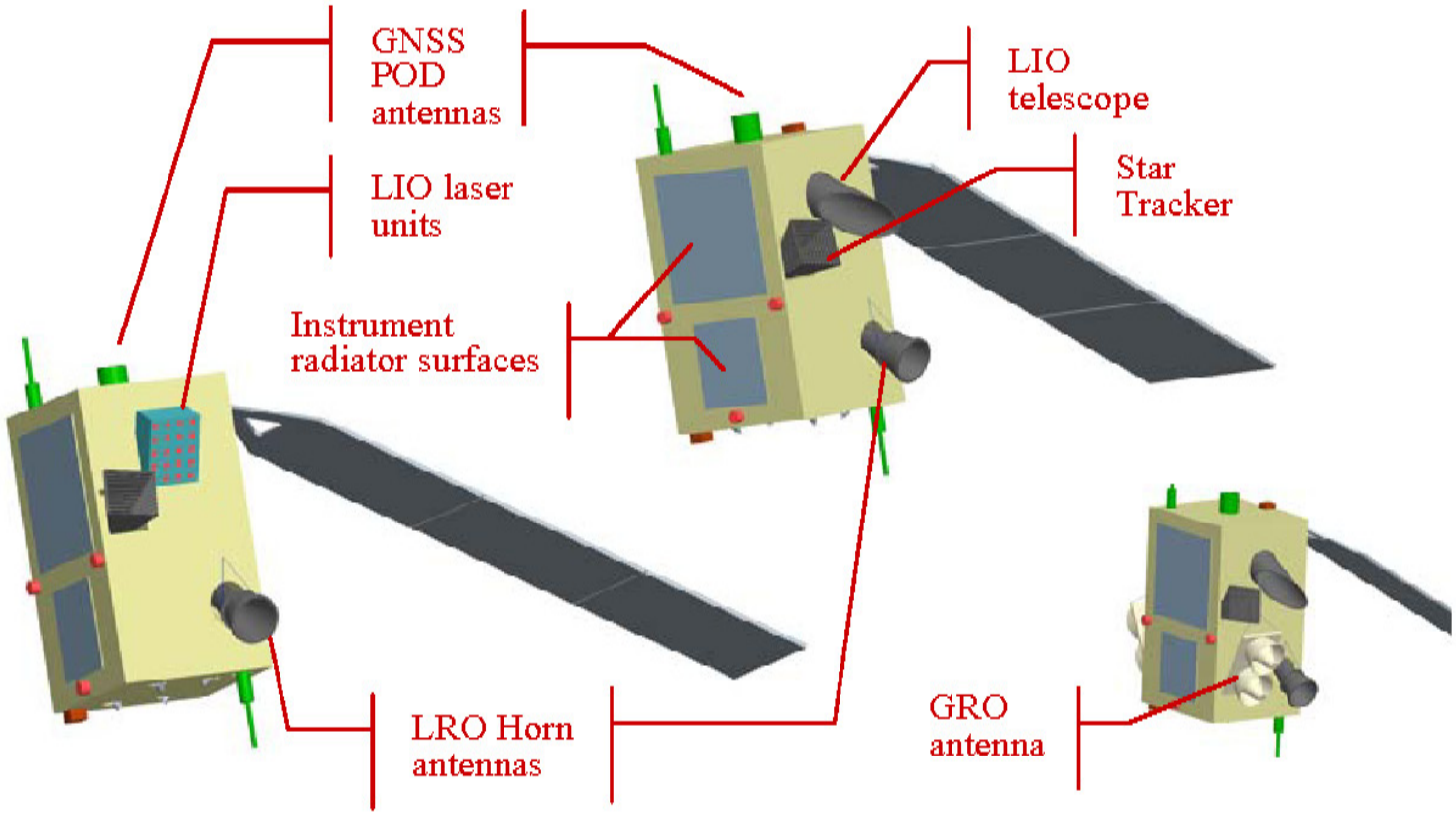
ACCURATE platforms, example design

also using heritage from ACE+ phase A studies

ACCURATE Tx and Rx satellite pair, and option of Rx platform including GRO (model lower right)



(from ACCURATE proposal to ESA, Kirchengast et al., 2005; design SSC, Sweden, 2005)

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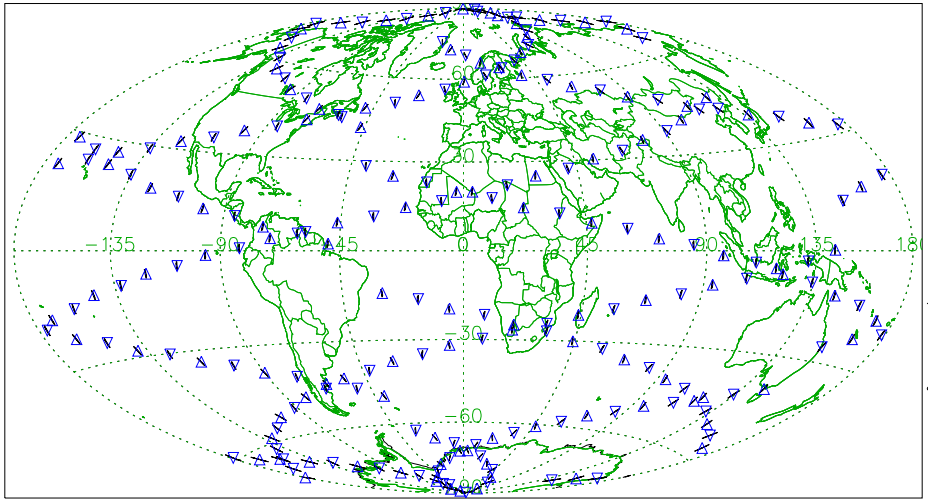
ACCURATE LRO+LIO occ. events coverage

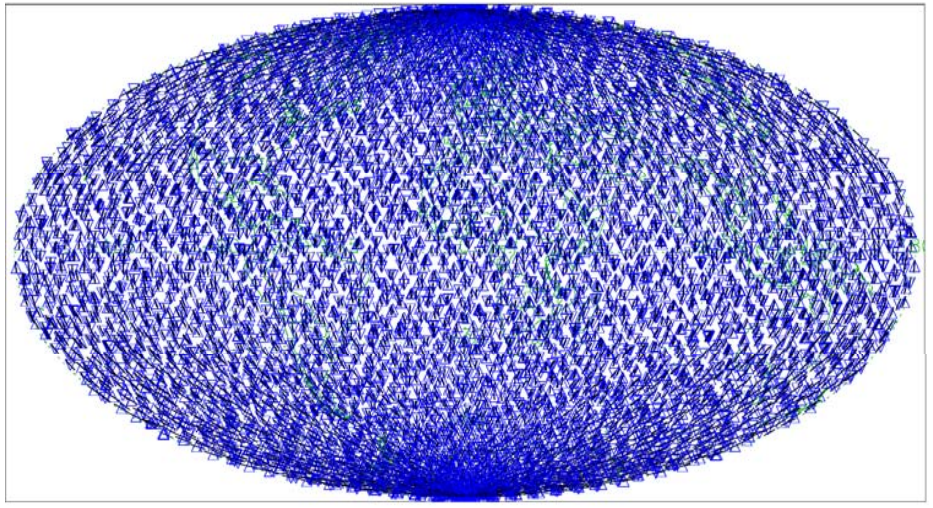
coverage for baseline constellation (2 Tx + 2 Rx)

LRO+LIO coverage within 1 day (top) and within 1 month (bottom):

- ~230 occultation events/day
- ~7000 occultation events/month
- adequate for accurately monitoring the large-scale (> 300–1000 km) evolution of global UTLS climate and greenhouse gases
- ideal event no. for a demonstration mission, as the CHAMP mission has shown for GPS radio occ.

(coverage more than doubles to ~510 events/day, ~15000 events/month, with 3 satellites/plane, i.e., 3Tx+3Rx)





(Kirchengast et al., 2004)

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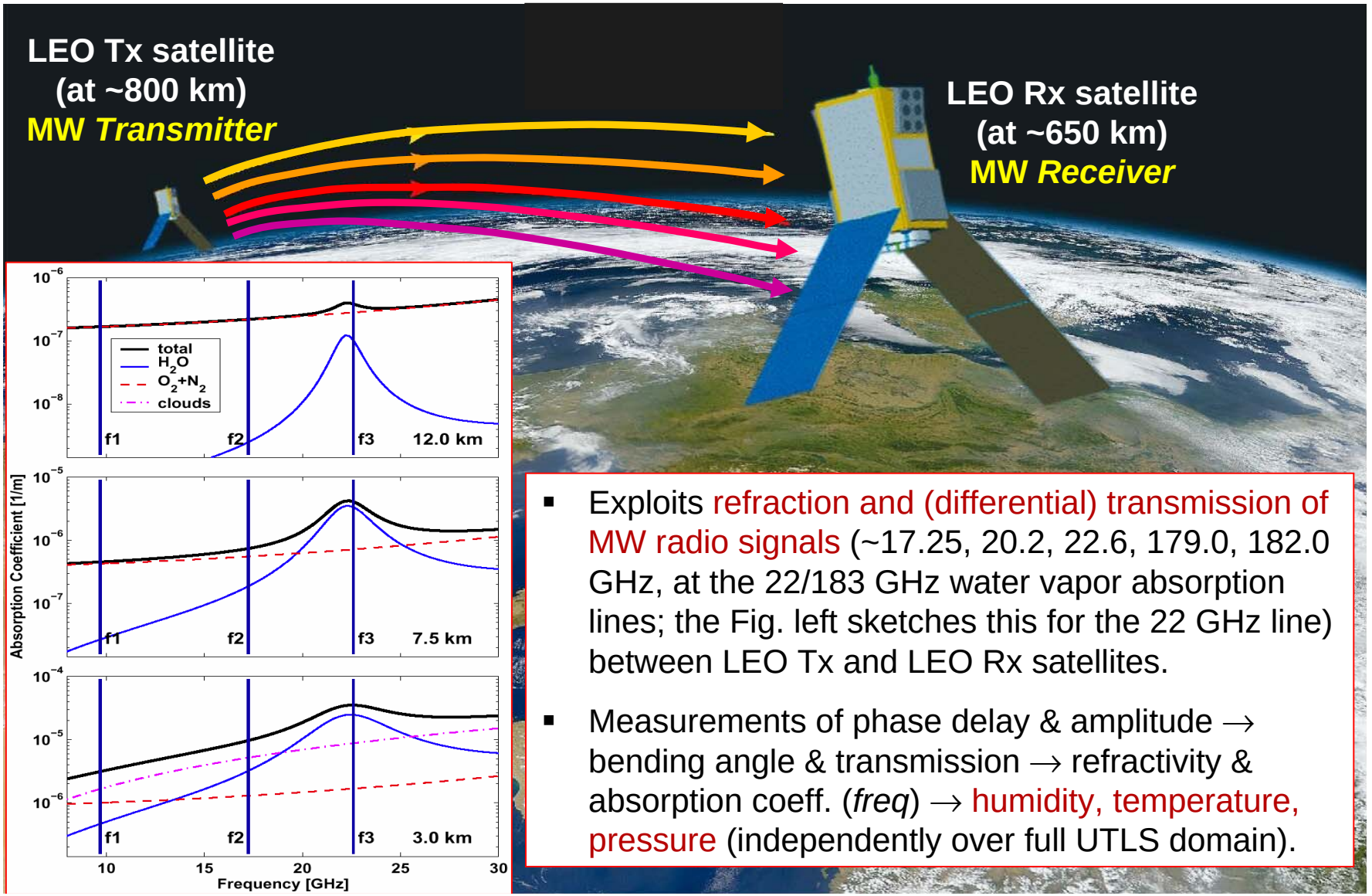
how does the LRO method work?

MW refraction&absorption: well established by ACE+ and ATOM(M)S



- Exploits refraction and (differential) transmission of MW radio signals (~17.25, 20.2, 22.6, 179.0, 182.0 GHz, at the 22/183 GHz water vapor absorption lines; the Fig. left sketches this for the 22 GHz 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).

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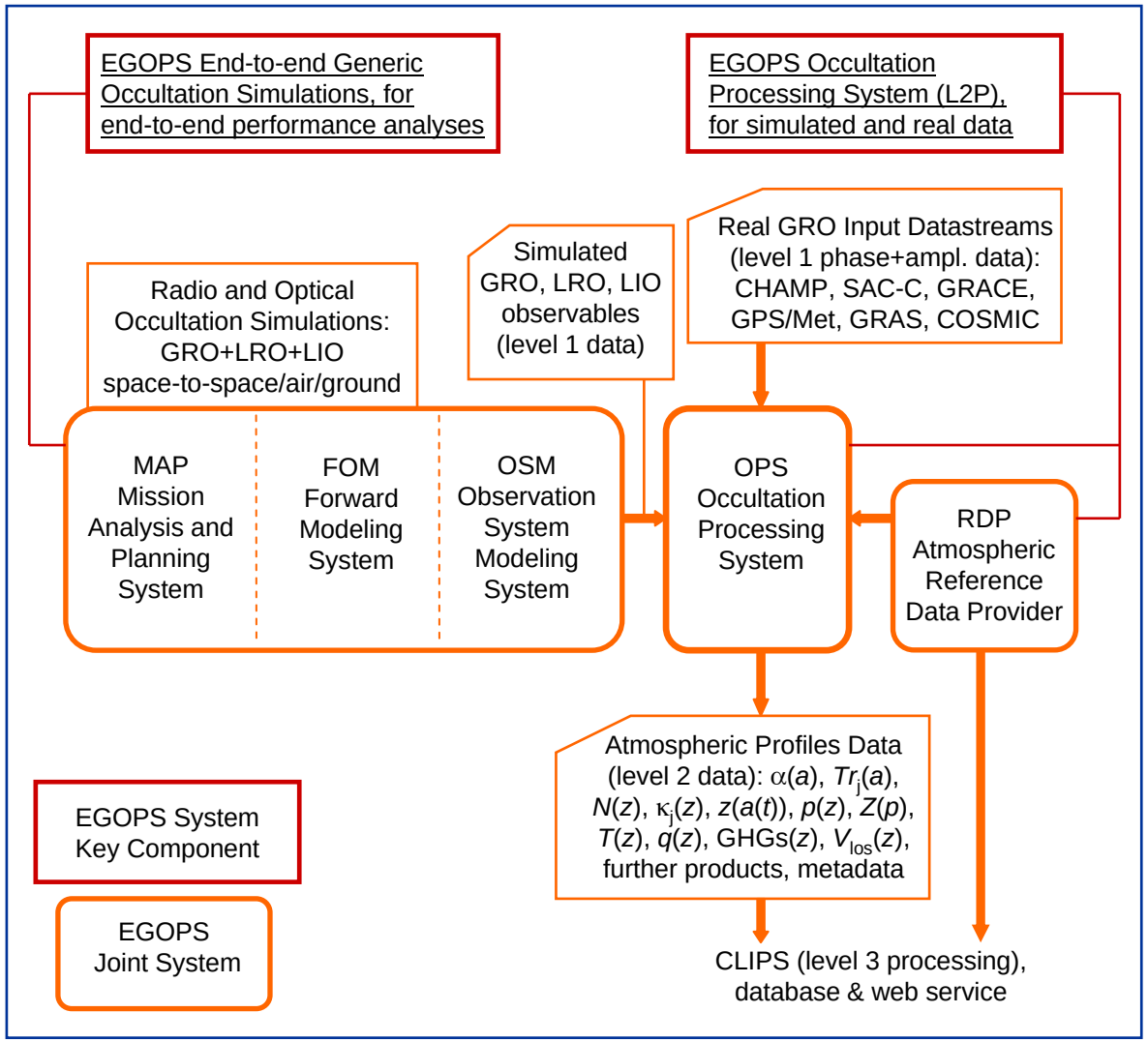
LRO end-to-end performance simulations

• the End-to-end Generic Occultation Performance Simulation and Processing System EGOPS (v5.2) was used for ACCURATE LRO performance evaluation (note: EGOPS LIO is yet in early development)



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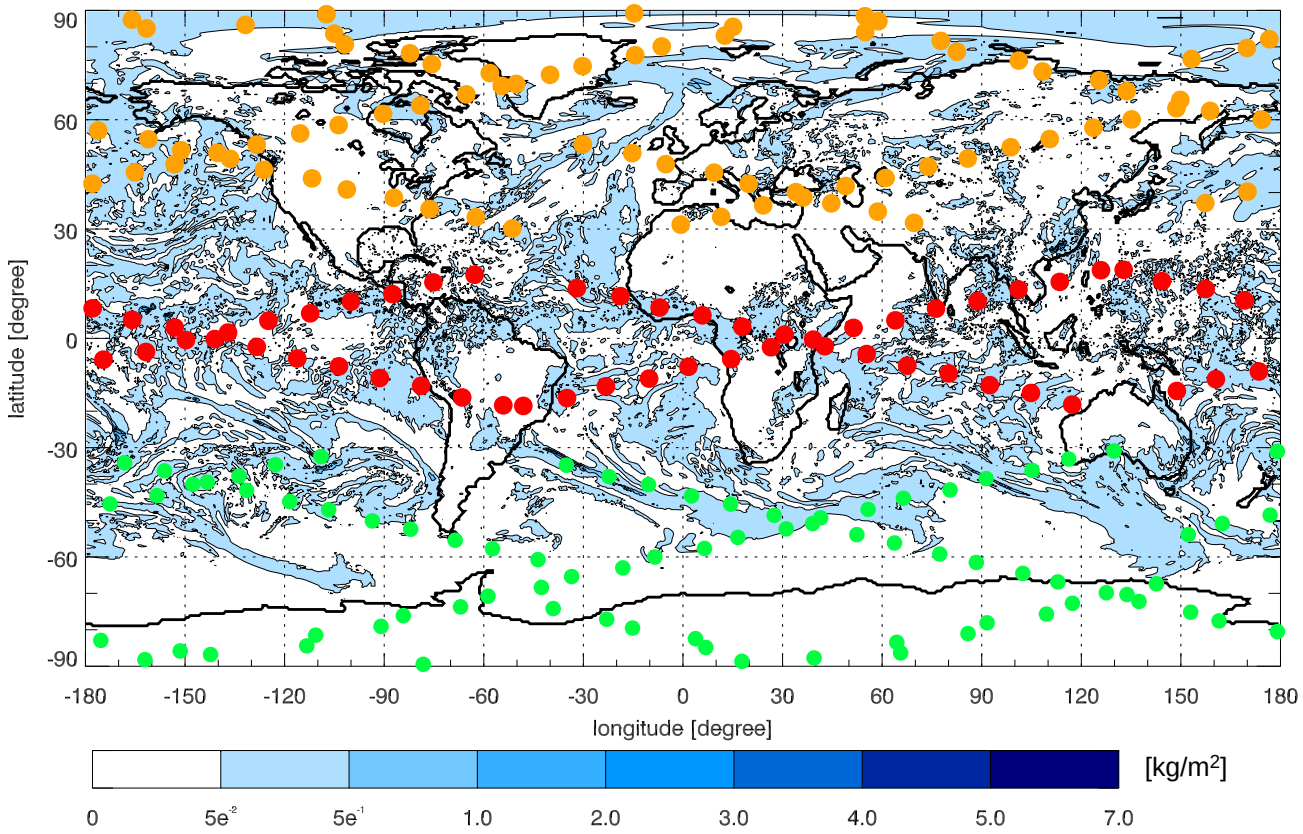
…just two slides on LRO performance (1 of 2)

• end-to-end EGOPS retrieval performance analysis for LRO MW radio links, based on ~230 globally distributed LRO events
comparison of 3-freq. (17.25-20.2-22.6 GHz, ACE+ type) to 5-freq. (additional 179.0-182.0 GHz, ATOMS heritage) performance
(using high-resolution ECMWF analysis as quasi-real atmosphere)



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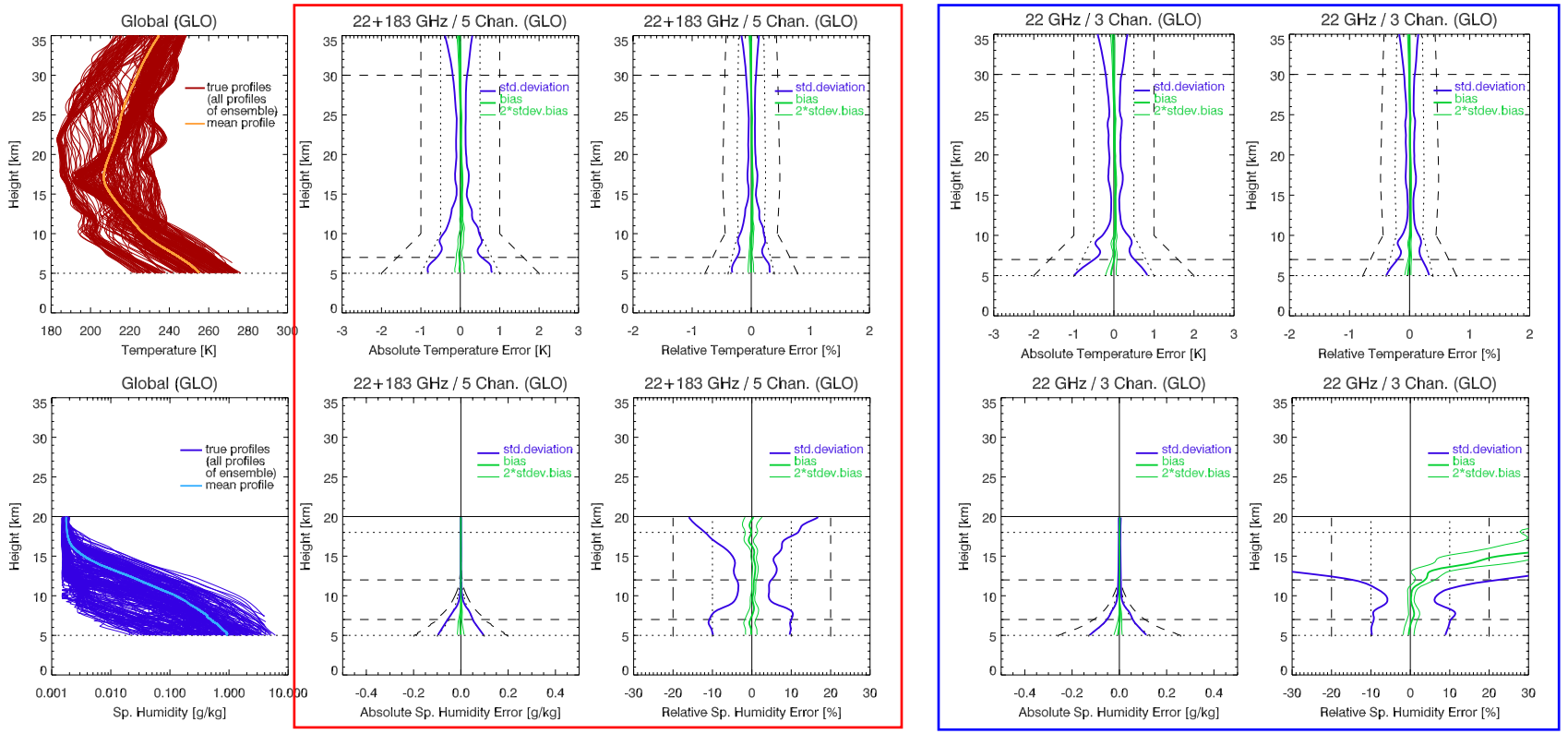
…just two slides on LRO performance (2 of 2)

ACCURATE with 5 frequencies vs. ACE+ type 3 frequencies

- temperature / humidity retrieved well within (ACE+) requirements to an accuracy of < 0.5-1 K / < 5-15% at 1-2 km vertical resolution, including through clouds. The 179.0/182.0 GHz channels (ATOMMS) extend the 3-freq.-based humidity height range from 10-12 km to 18-20 km, thus covering the full tropical tropopause region.



(Retrieval performance study based on ~230-event ensemble and global ECMWF high-res analysis field; done with EGOPS5.2 S/W)

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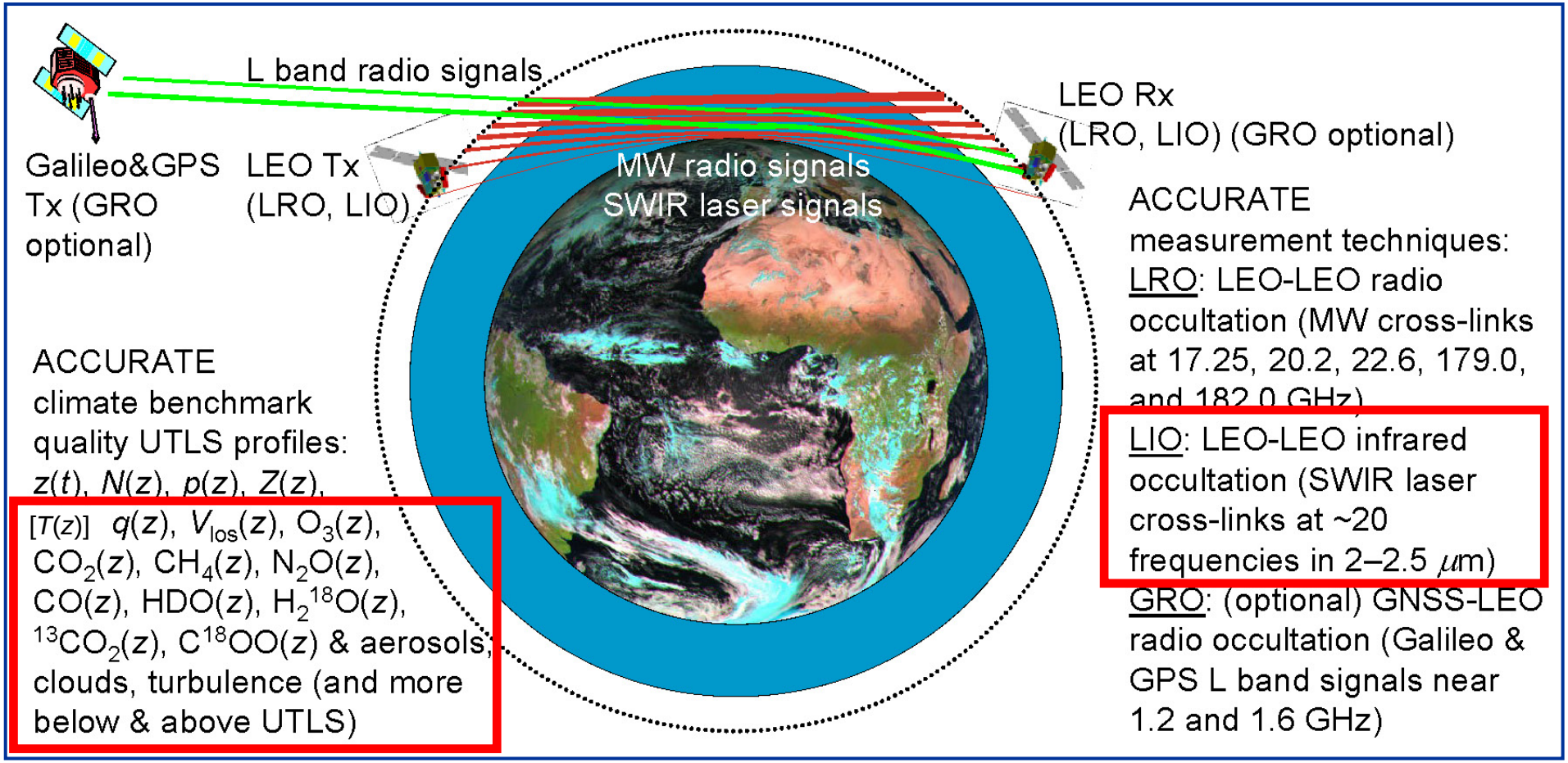
…let's now turn to the new LIO concept

ACCURATE IR laser occultation – an introduction



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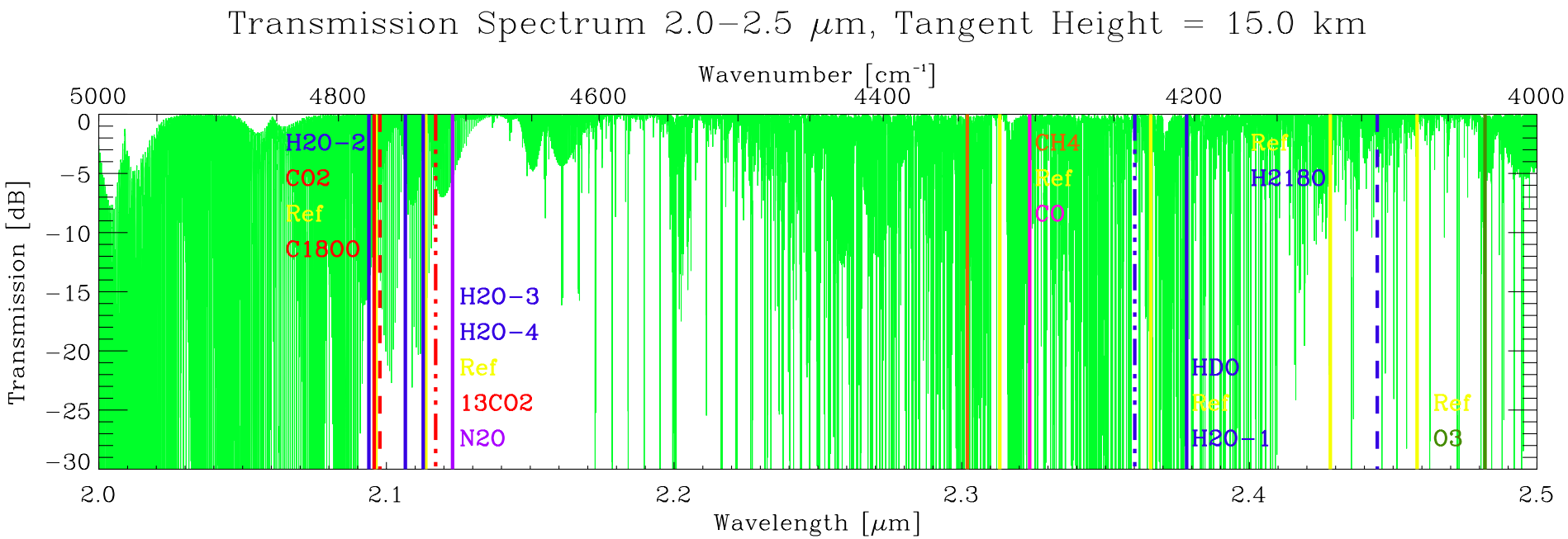
LIO design: how to properly select LIO lines? (1)

ACCURATE baseline laser line selection/2 –2.5 μm



(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.physics.ox.ac.uk/RFM; RFM takes line data from the HITRAN 2004 data base of Rothman et al.: www.harvard.edu/HITRAN)

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how to properly select LIO lines? (2)

ACCURATE line selection summary
(abs and ref lines very close, ratio < 0.1-1%)

Tx Laser Lines Baseline (21 lines in total/incl. 2 CO_2 wind lines)

Trace Gas	Absorption Lines		Reference Lines		Ratio
	$\bar{\nu}_{abs}$ [cm^{-1}]	λ_{abs} [µm]	$\bar{\nu}_{ref}$ [cm^{-1}]	λ_{ref} [µm]	$\lambda_{abs}/\lambda_{ref}$
H_2O(1)	4204.840	2.3782	4227.07	2.3657	1.0053
(2)	4775.803	2.0939	4770.20	2.0963	0.9988
(3)	4747.055	2.1066	4731.05	2.1137	0.9966
(4)	4733.045	2.1128	4731.05	2.1137	0.9996
CO_2	4771.621	2.0957	4770.20	2.0963	0.9997
wind(1)	4771.618	2.0957	4770.20	2.0963	0.9997
wind(2)	4771.625	2.0957	4770.20	2.0963	0.9997
CH_4	4344.164	2.3019	4322.92	2.3133	0.9951
N_2O	4710.341	2.1230	4731.05	2.1137	1.0044
O_3	4029.110	2.4819	4067.80	2.4583	1.0096
CO	4303.623	2.3236	4322.92	2.3133	1.0045
HDO	4237.016	2.3602	4227.07	2.3657	0.9977
$H_2{}^{18}O$	4090.872	2.4445	4118.36	2.4282	1.0067
$^{13}CO_2$	4723.415	2.1171	4731.05	2.1137	1.0016
$C^{18}OO$	4767.041	2.0977	4770.20	2.0963	1.0007

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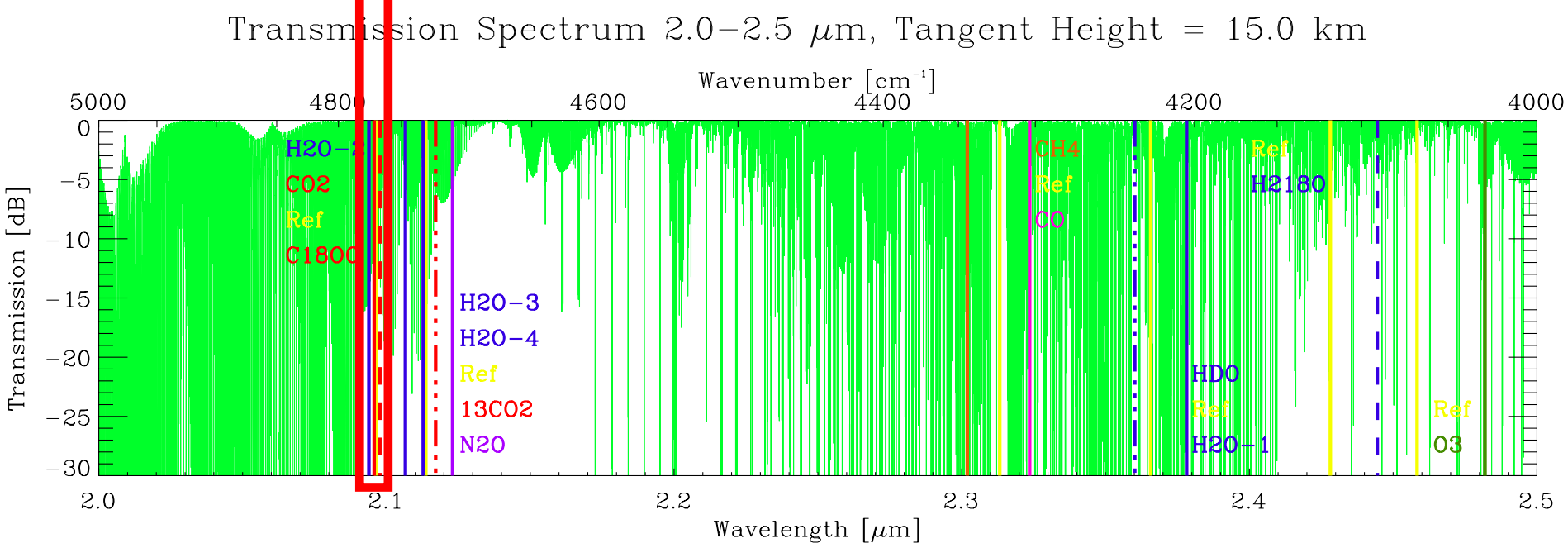
LIO assessment: how to create a working payload?

differential log-transmission trace species measurement

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



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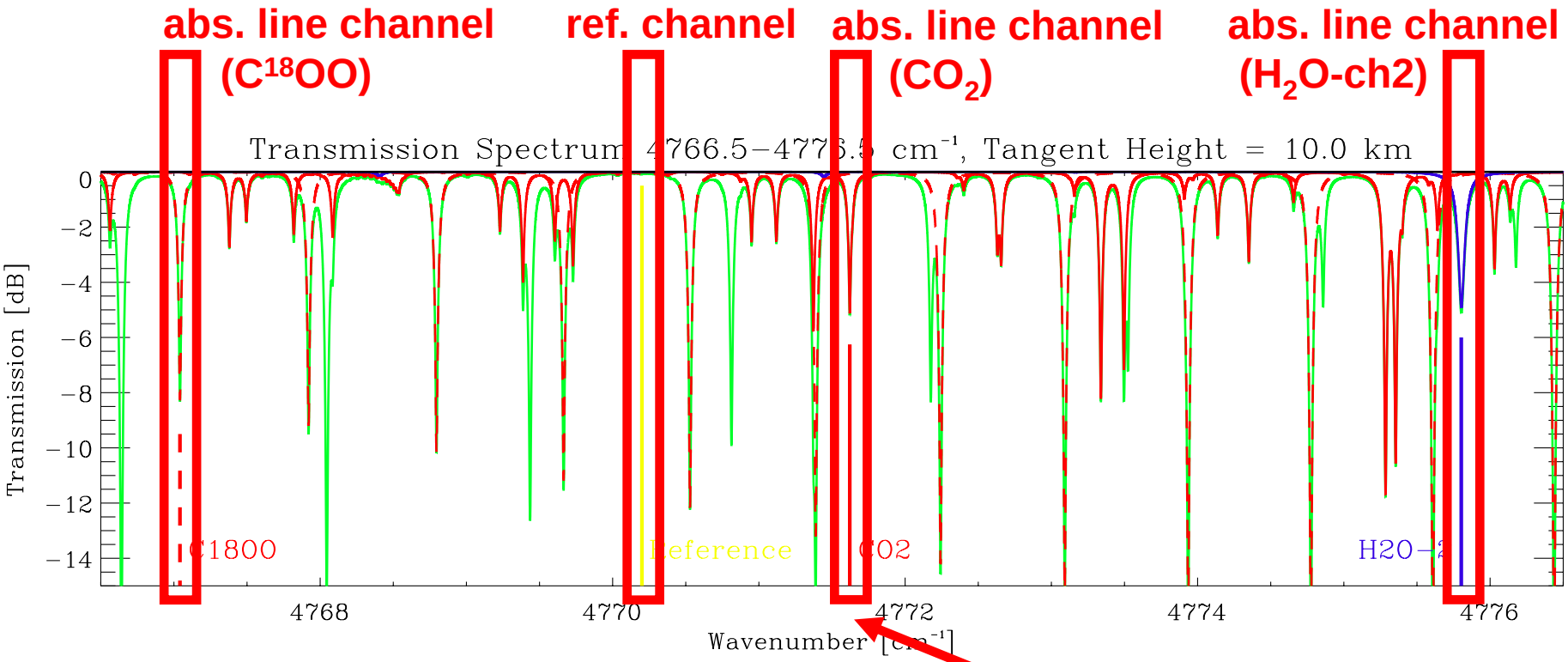
payload: how do measure trace species with LIO?

differential log-transmission over *narrow delta-freq*



Inspect now a 0.1 cm^{-1} sub-range about the CO_2 line center, to see how line-of-sight wind is measured…

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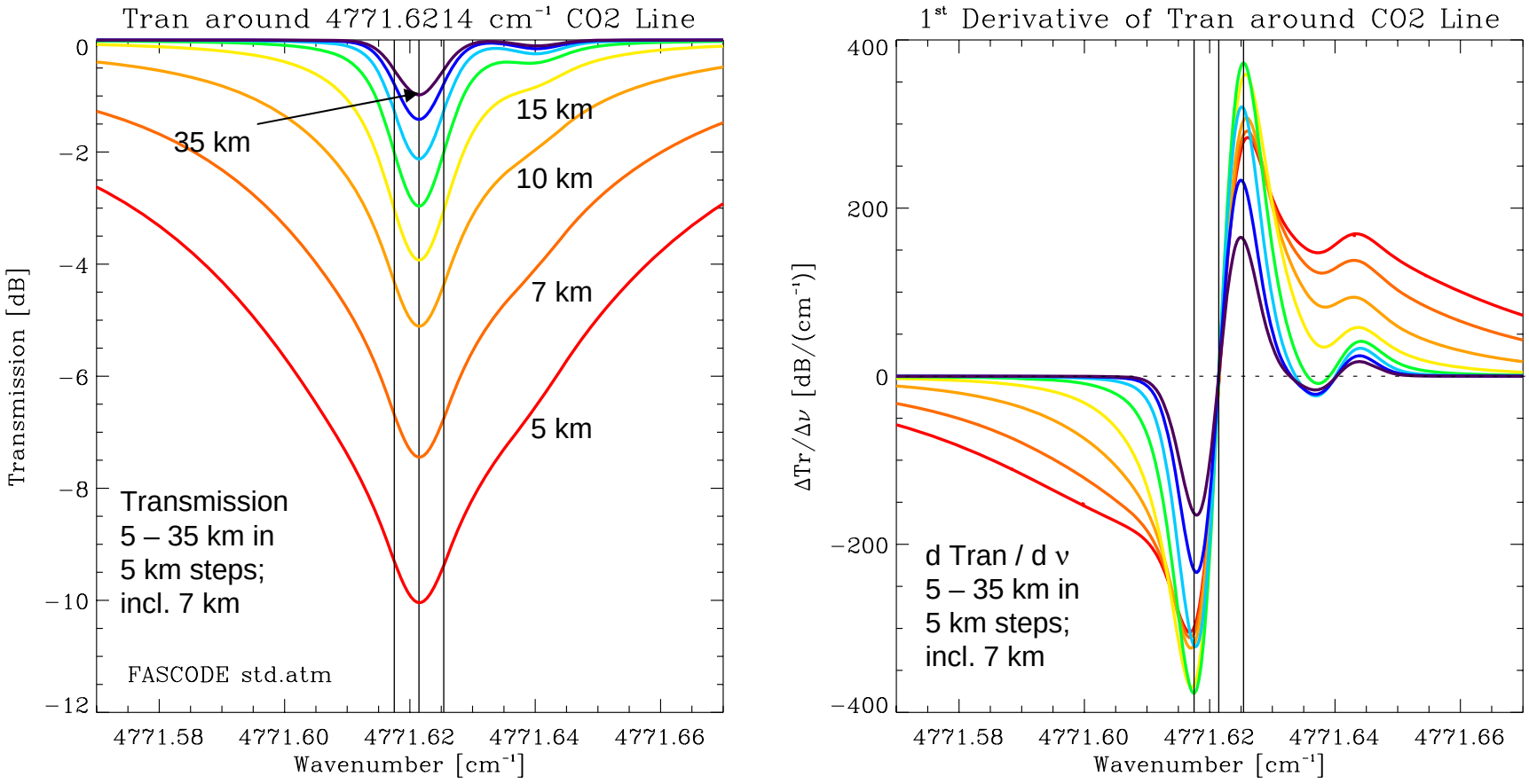
payload: how to measure winds with LIO?

differential log-transmission over *very narrow delta-freq,*
spanning ~ the Doppler FWHM of the symmetric CO_2 line



(wind line spacing: df/f = +/-0.83 x 10^{-6} about CO_2 line center frequency, ~ Doppler FWHM;
Laser: FWHM < 3 x 10^{-8}, frequency stability < 2 x 10^{-8}, intensity stability < 0.1%)

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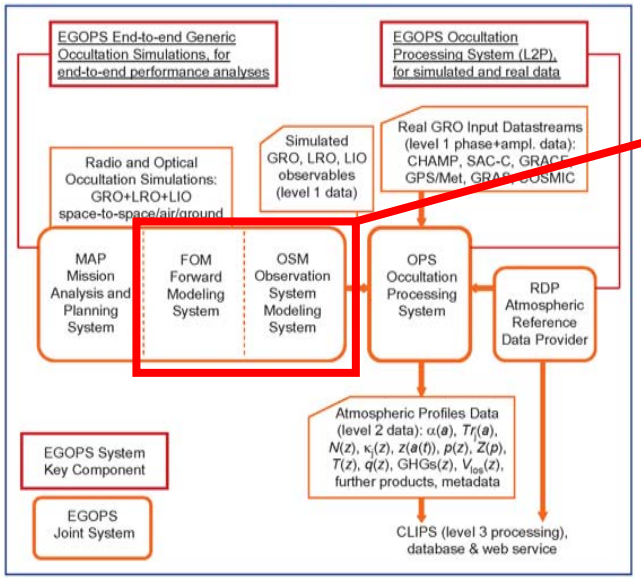
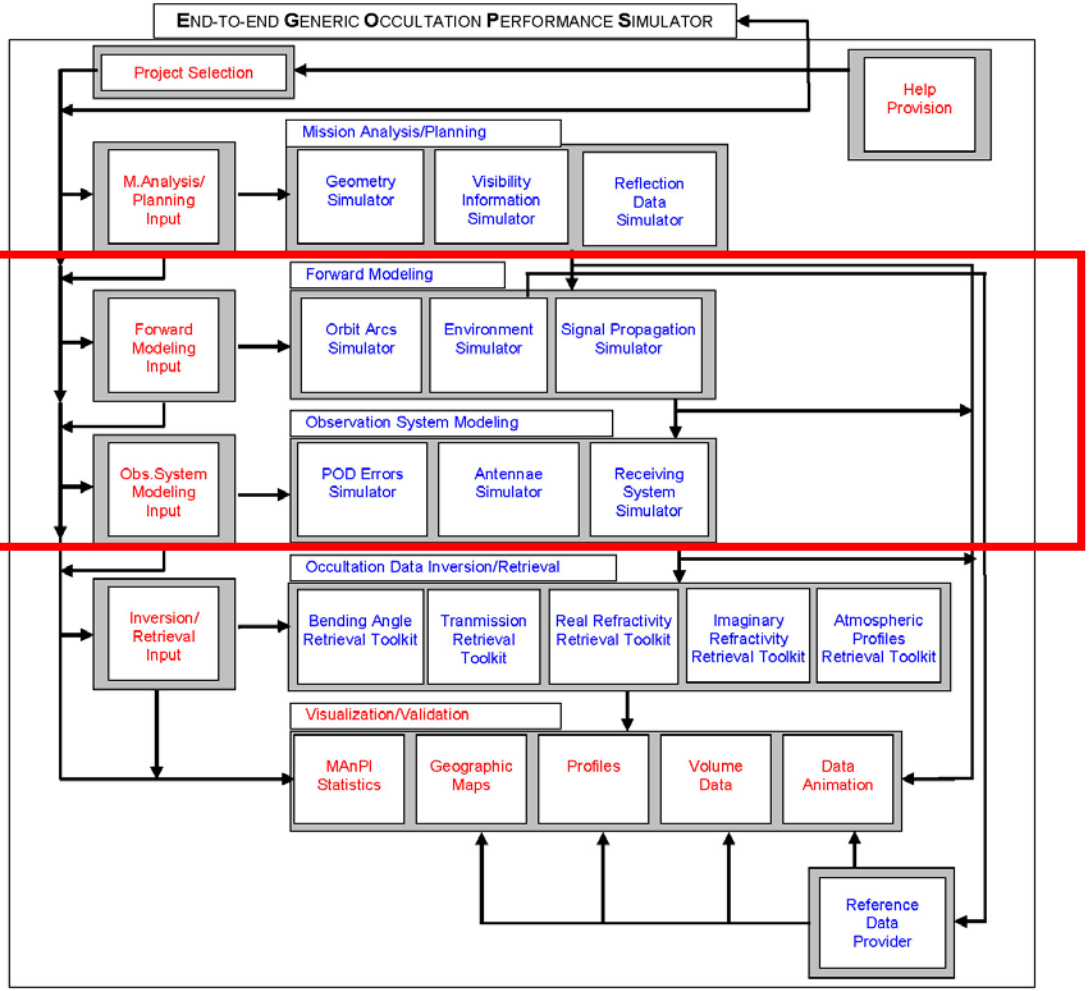
enhancements for LIO in the EGOPS5 system

forward and obs. system modeling capabilities



LIO enhancements to FOM and OSM



Modular view of EGOPS5

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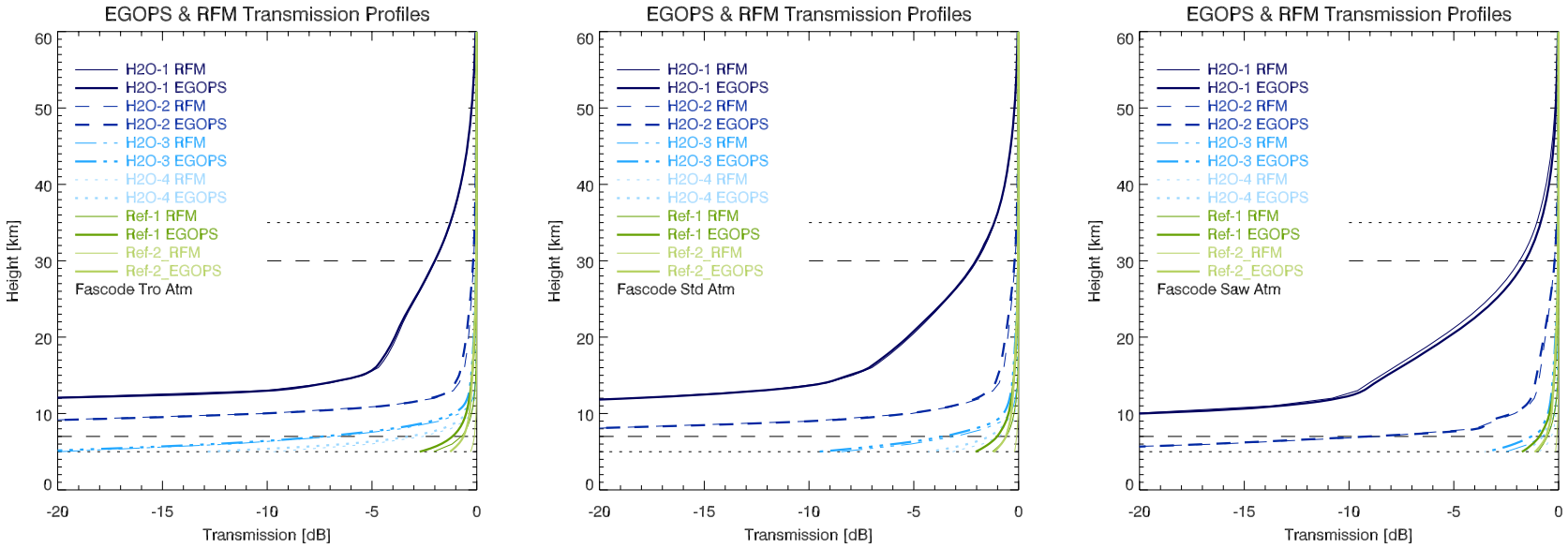
representative EGOPS LIO simulation results

FOM transmission results for H_2O channels



EGOPS transmission calculations in comparison to RFM transmission calculations for the four ACCURATE water vapour channels in a tropical (left), standard (center), and sub-arctic winter (right) atmosphere.

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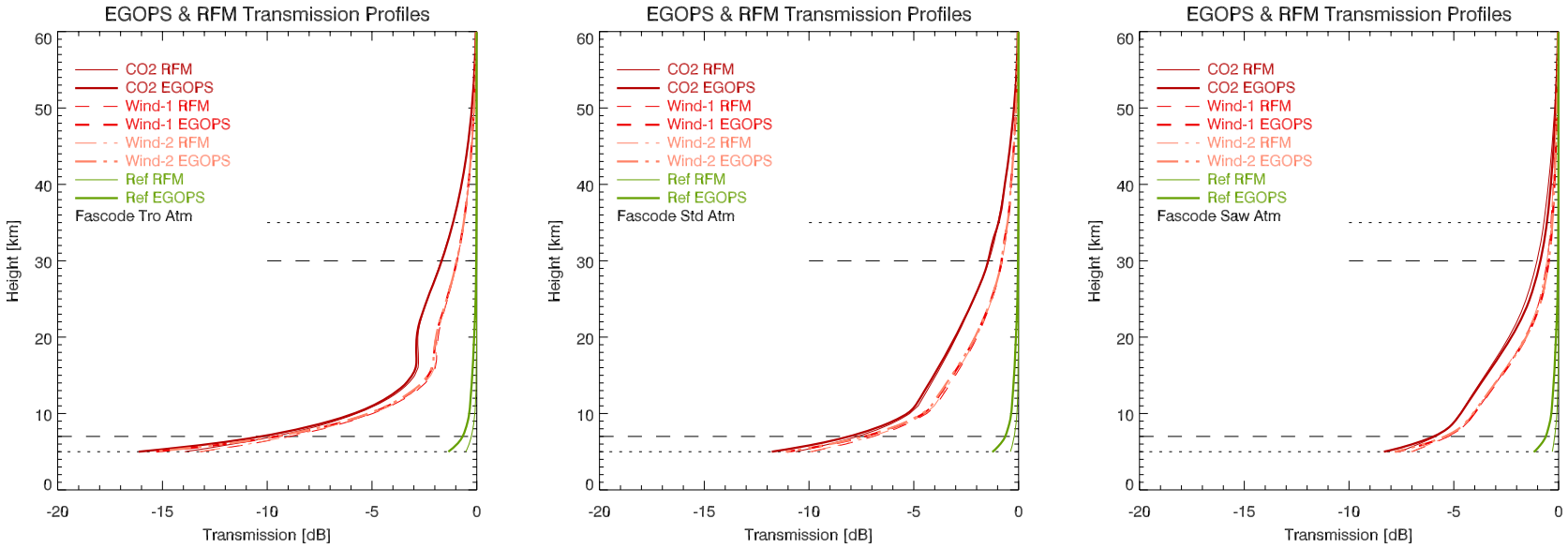
representative EGOPS LIO simulation results

FOM transmission results for CO2 & wind channels



EGOPS transmission calculations in comparison to RFM transmission calculations for the ACCURATE CO_2, Wind-1, Wind-2, and the corresponding reference channel in the FASCODE tropical (left), standard (centre), and sub-arctic winter (right) atmosphere.

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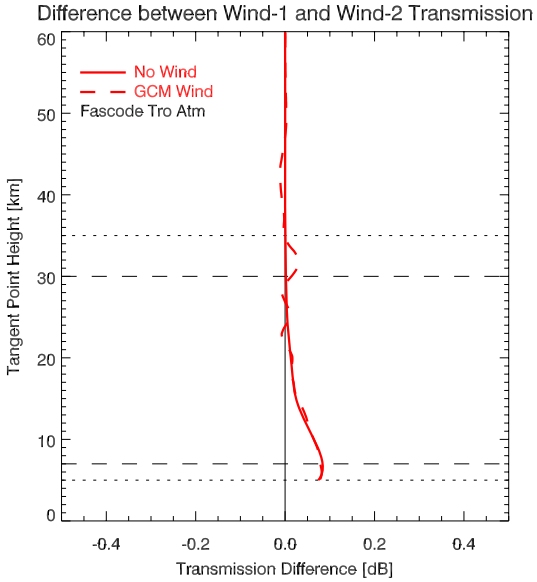
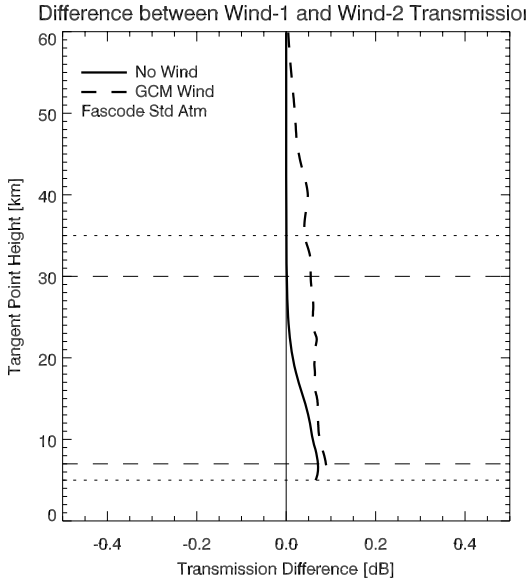
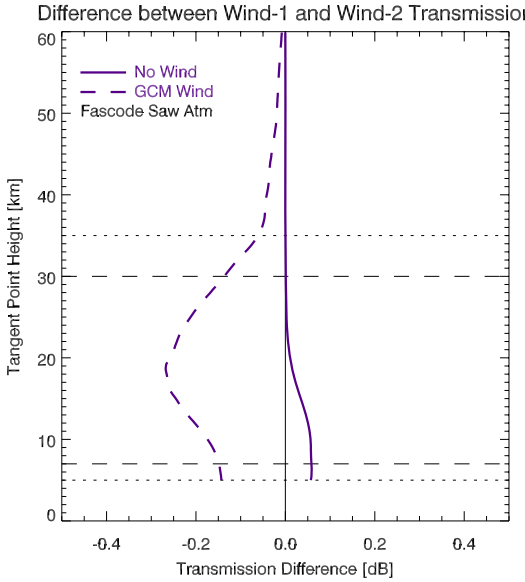
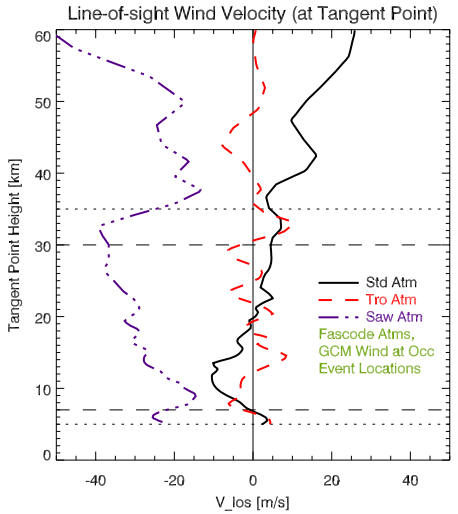
transmission difference between the wind channels (1)

EGOPS results, wind profiles from ECMWF analysis









Transmission difference between the two ACCURATE LIO wind channels (Wind-1 minus Wind-2) for the tropical (left), standard (center), and sub-arctic winter (right) event in windy (dashed line) and calm (solid line) atmosphere.

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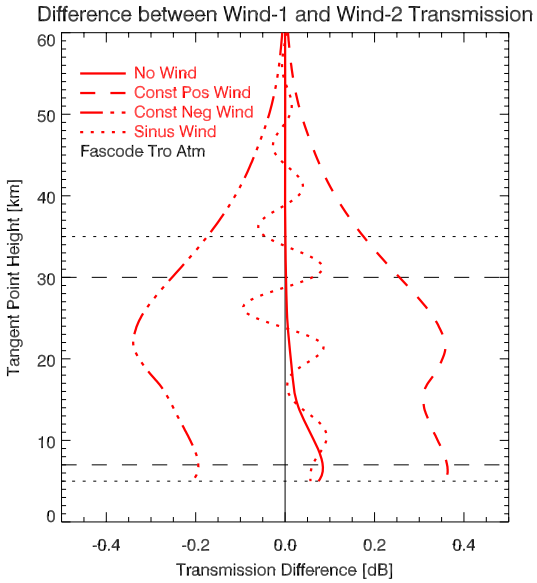
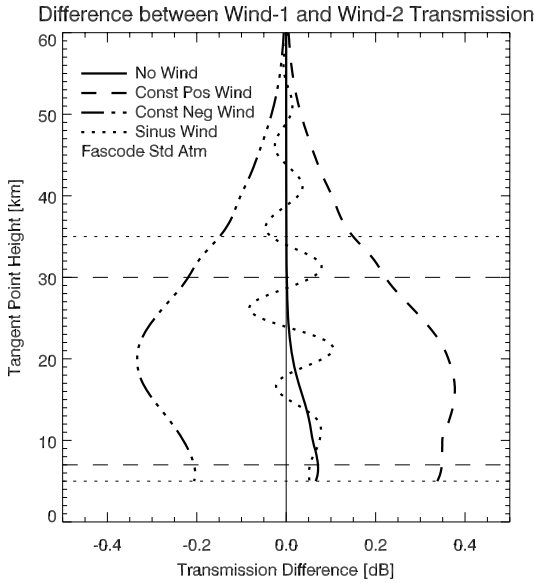
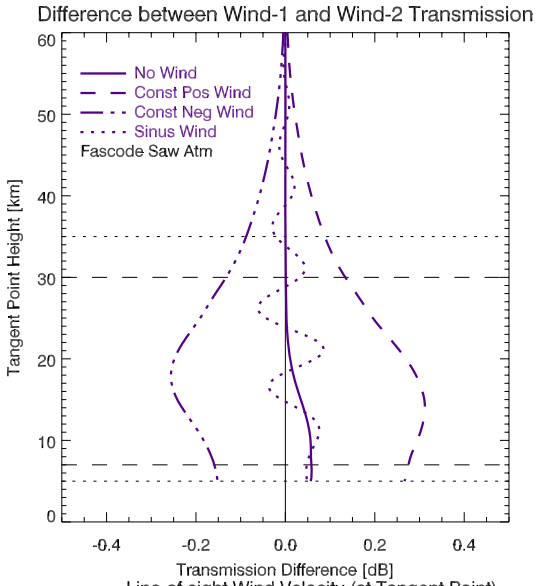
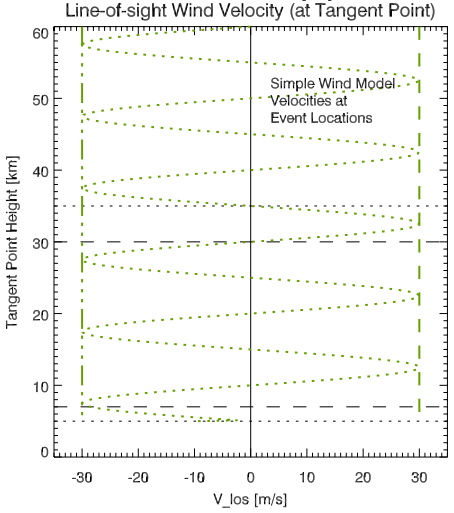
transmission difference between the wind channels (2)

EGOPS results, simple wind profiles aiding physical insight









Transmission difference between the two LIO wind channels assuming three simple wind conditions:

dashed line = constant positive wind
dash-dotted line = constant negative wind
dotted line = sinusoidally-in-height varying wind
solid line corresponds to no wind

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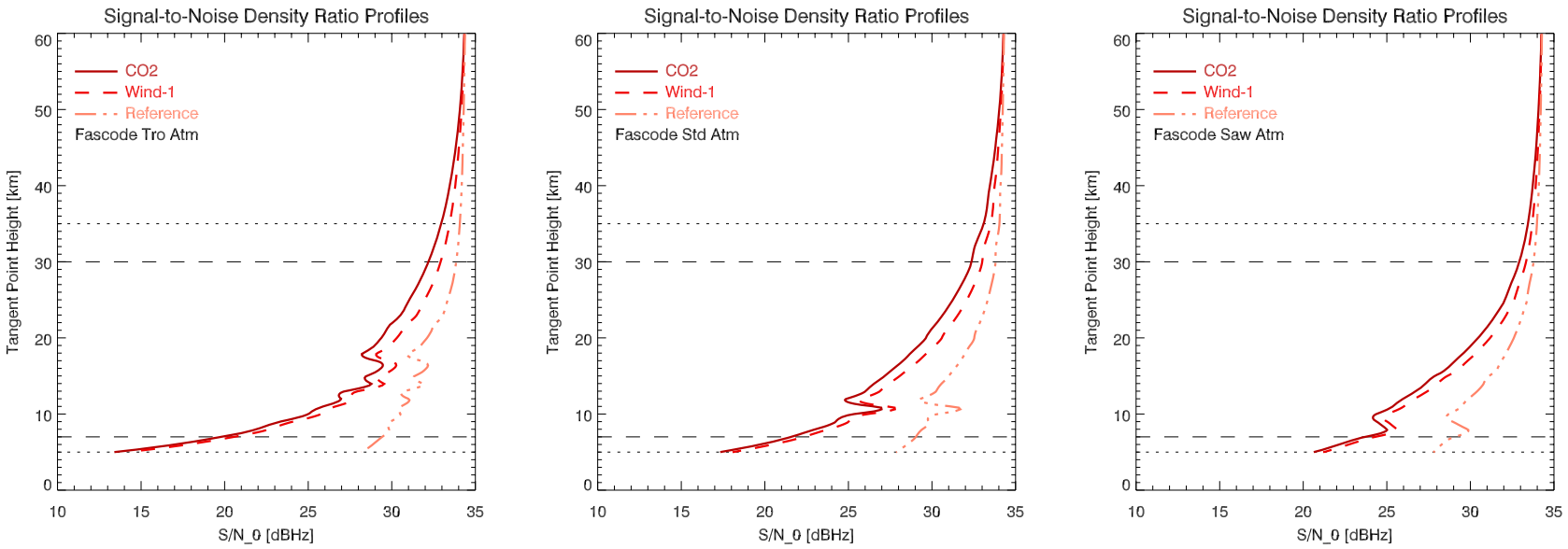
representative EGOPS LIO simulation results

OSM signal-to-noise density ratio for CO_2 & wind channels



Signal-to-noise density ratios (S/N_0) for the ACCURATE CO_2, Wind-1, and the respective reference channel in the FASCODE standard (left), tropical (center), and sub-arctic winter (right) atmosphere.

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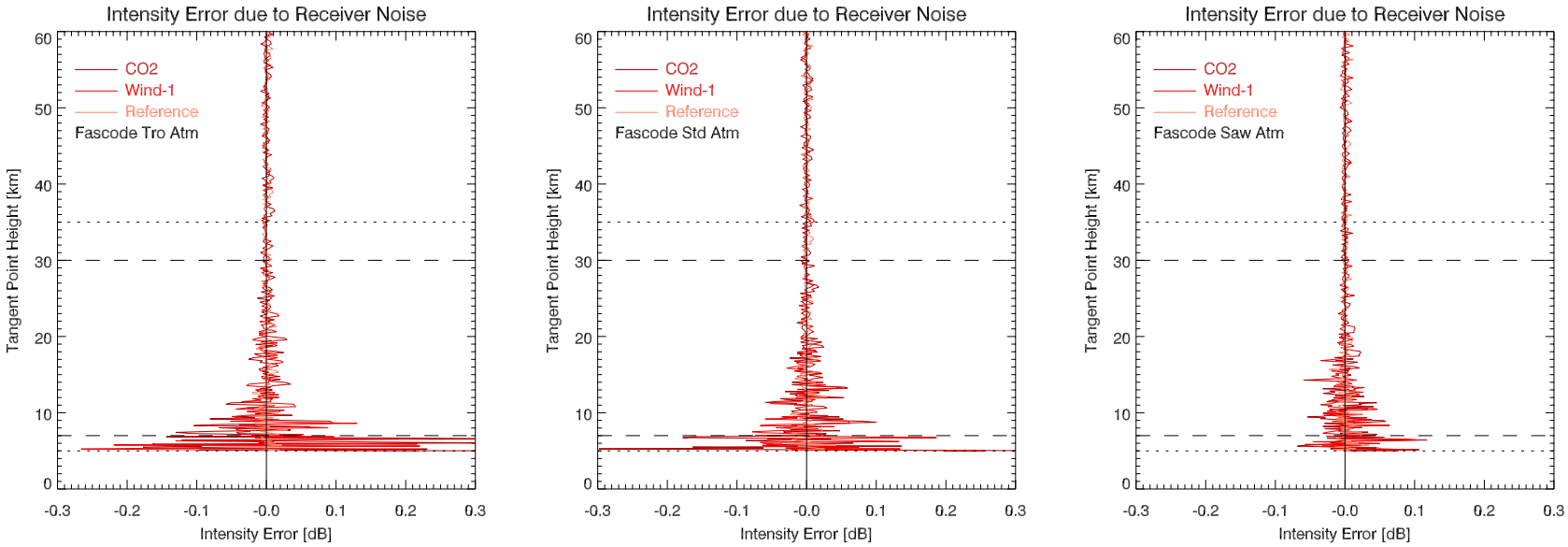
representative EGOPS LIO simulation results

OSM receiver noise for CO_2 & wind channels



Error in received intensity (received power) due to receiver noise at a sampling rate of 10 Hz for the ACCURATE CO_2, Wind-1, and the respective reference channel in the FASCODE tropical (left), standard (center), and sub-arctic winter (right) atmosphere.

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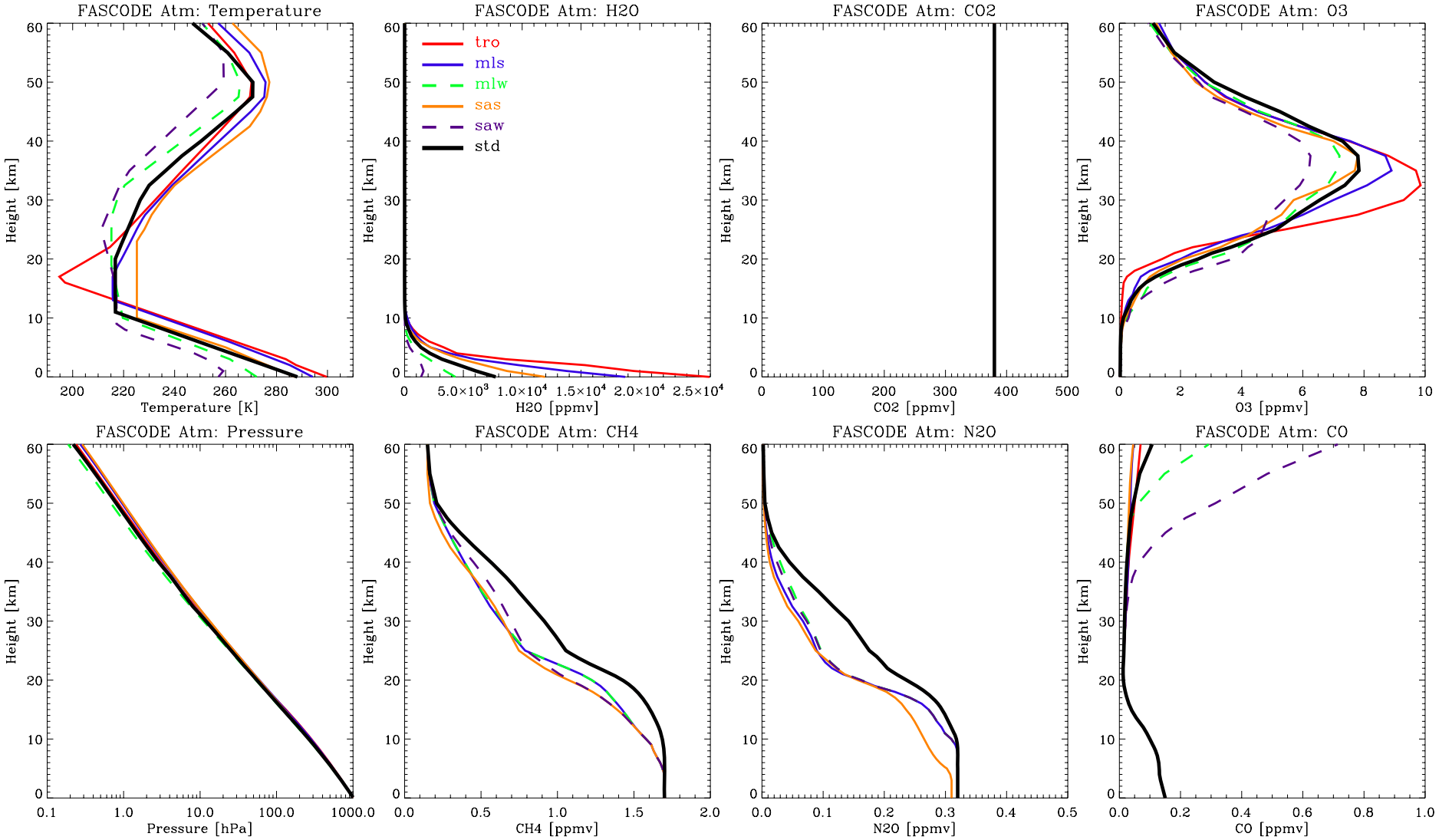
study of the performance by end-to-end simulations

perform LIO simulations, using basic atmospheres



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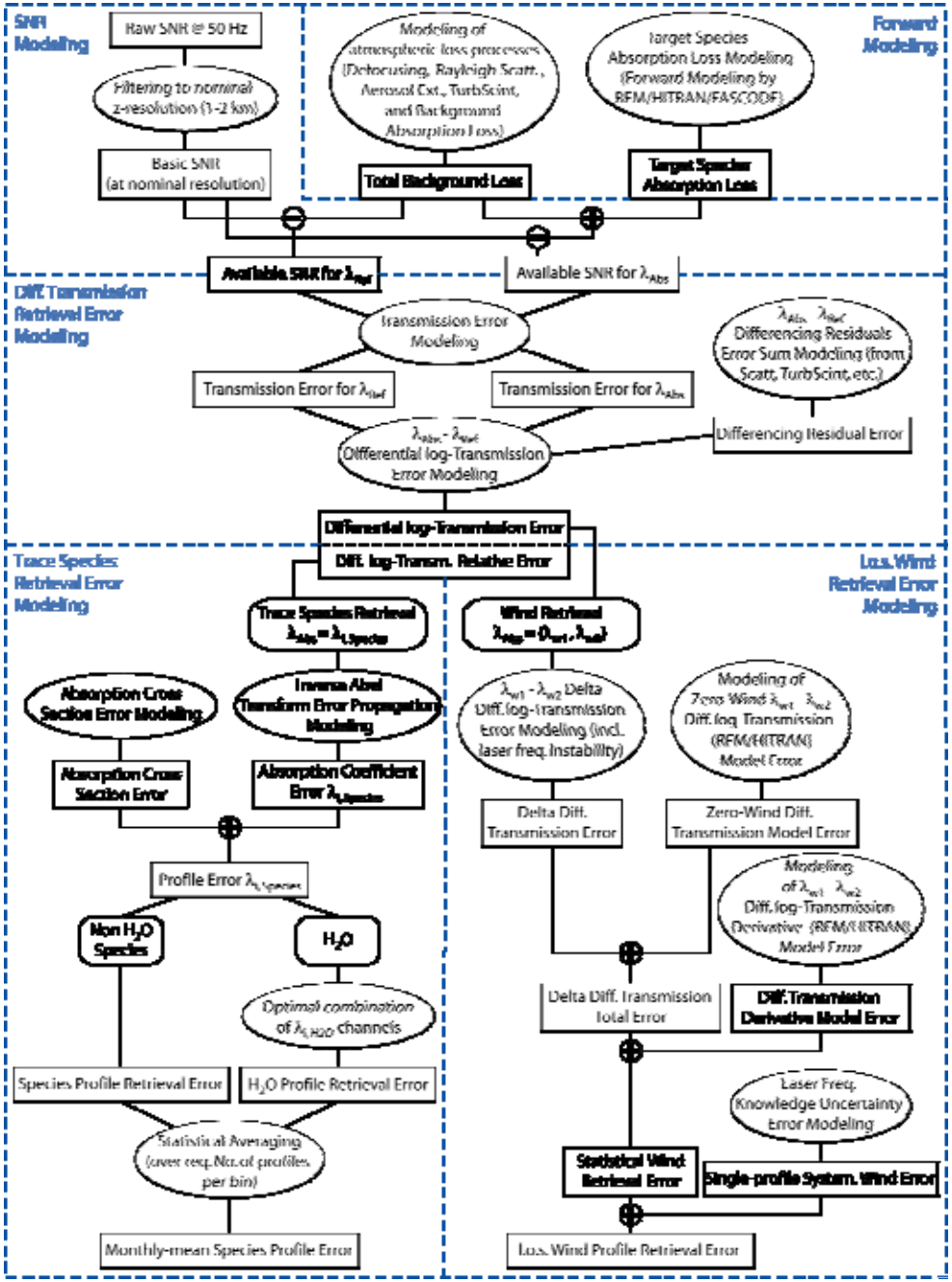
end-to-end simulations by the ALPS system

since EGOPS does not yet LIO retrievals use ALPS (ACCURATE LIO Performance Simulator), an IDL tool for error estimation throughout the LIO retrieval process

[details: Kirchengastner & Schweitzer, 2007]



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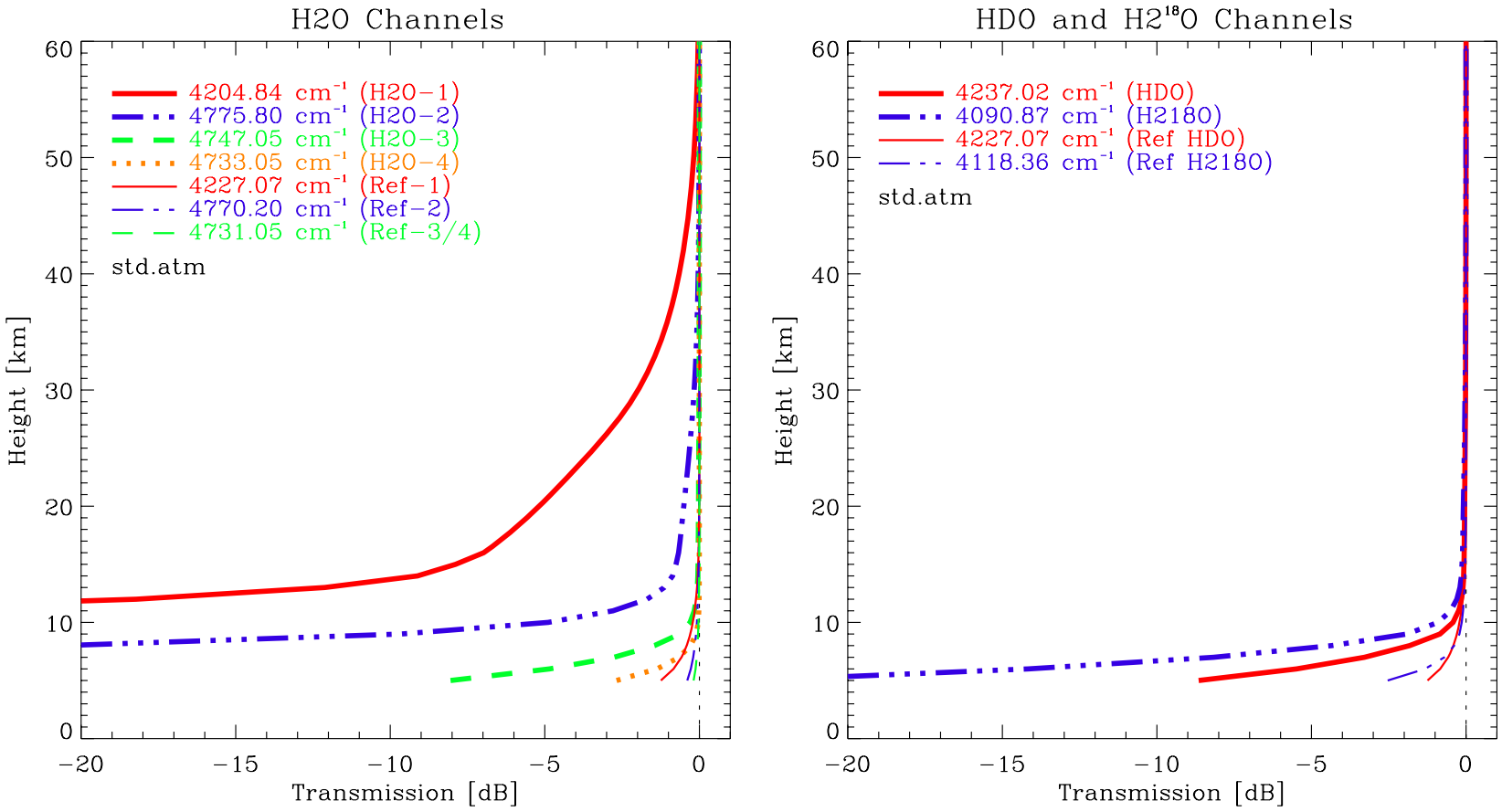
what is the meas. sensitivity as function of height? (1)

on diff. log-transmission sensitivity of H_2O and isotopes



(computed using the RFM fast LBL radiative transfer model of A. Dudhia et al., using line data from the HITRAN 2004 data base of Rothman et al. and the U.S. standard atmosphere, i.e., an RFM/HITRAN/FASCODE system being attached to ALPS)

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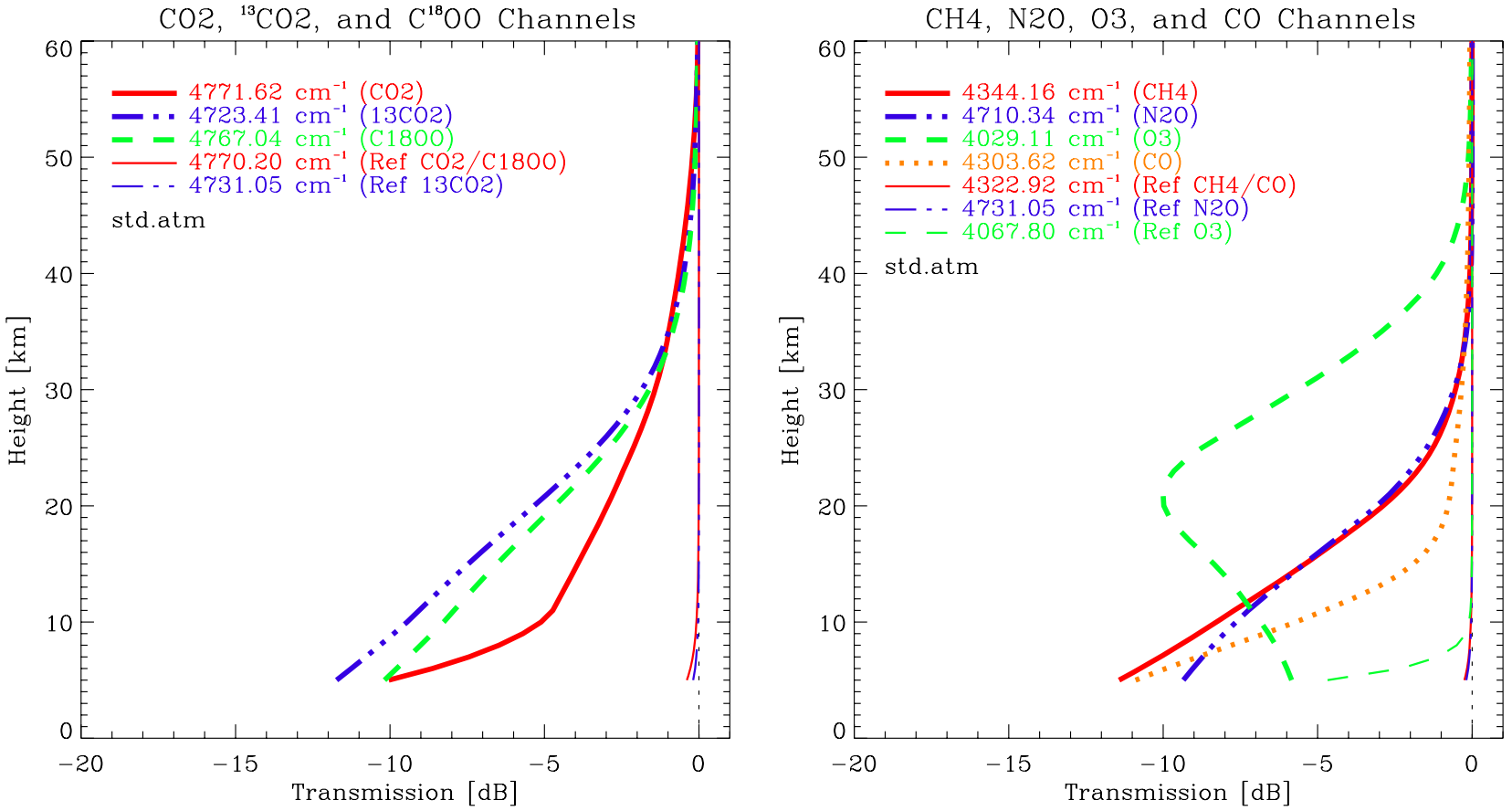
what is the meas. sensitivity as function of height? (2)

on diff. log-transmission sensitivity of CO_2 and isotopes and of the species CH_4, N_2O, O_3, CO



(computed using the RFM fast LBL radiative transfer model of A. Dudhia et al., using line data from the HITRAN 2004 data base of Rothman et al. and the U.S. standard atmosphere, i.e., an RFM/HITRAN/FASCODE system being attached to ALPS)

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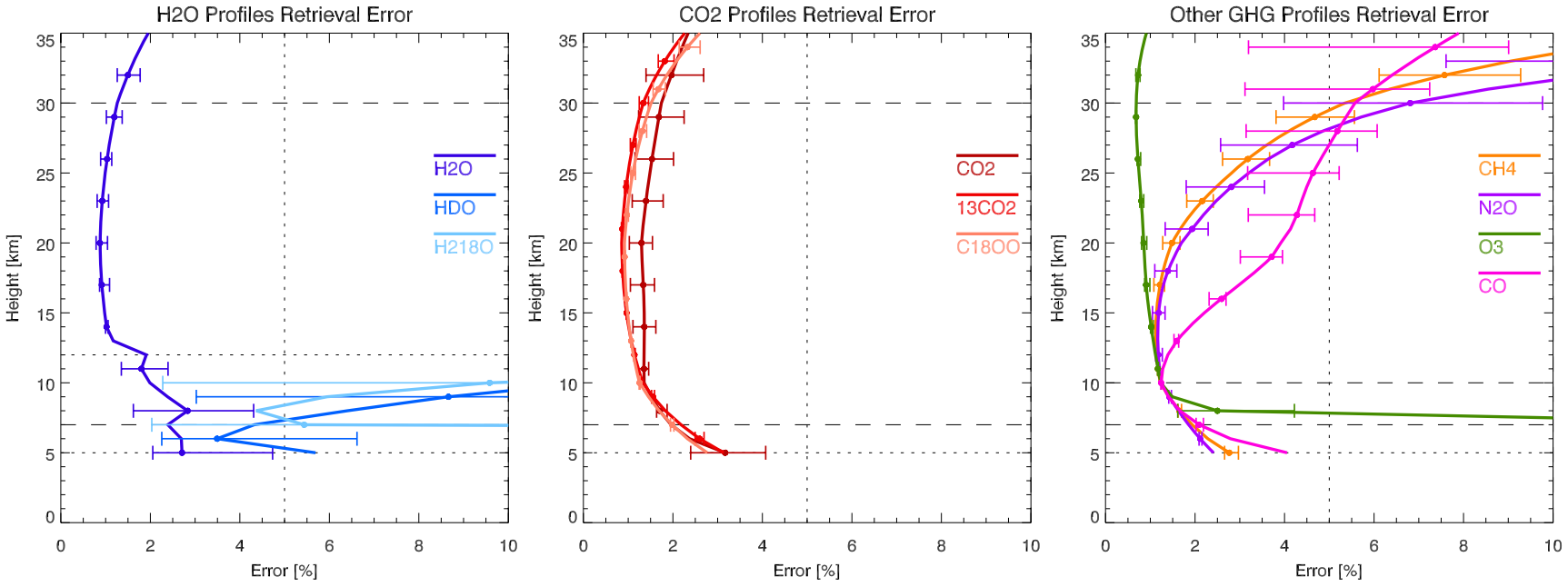
what is the accuracy as function of height? (1)

LIO requirements & scientific performance: individual profiles

- GHGs and isotope species generally retrieved within UTLS outside clouds to an accuracy of < 2-5% (individual profiles accuracy) at 1-2 km vertical resolution. (ALPSv1.8 simulation results)

Example results: GHG and isotope species profile retrieval 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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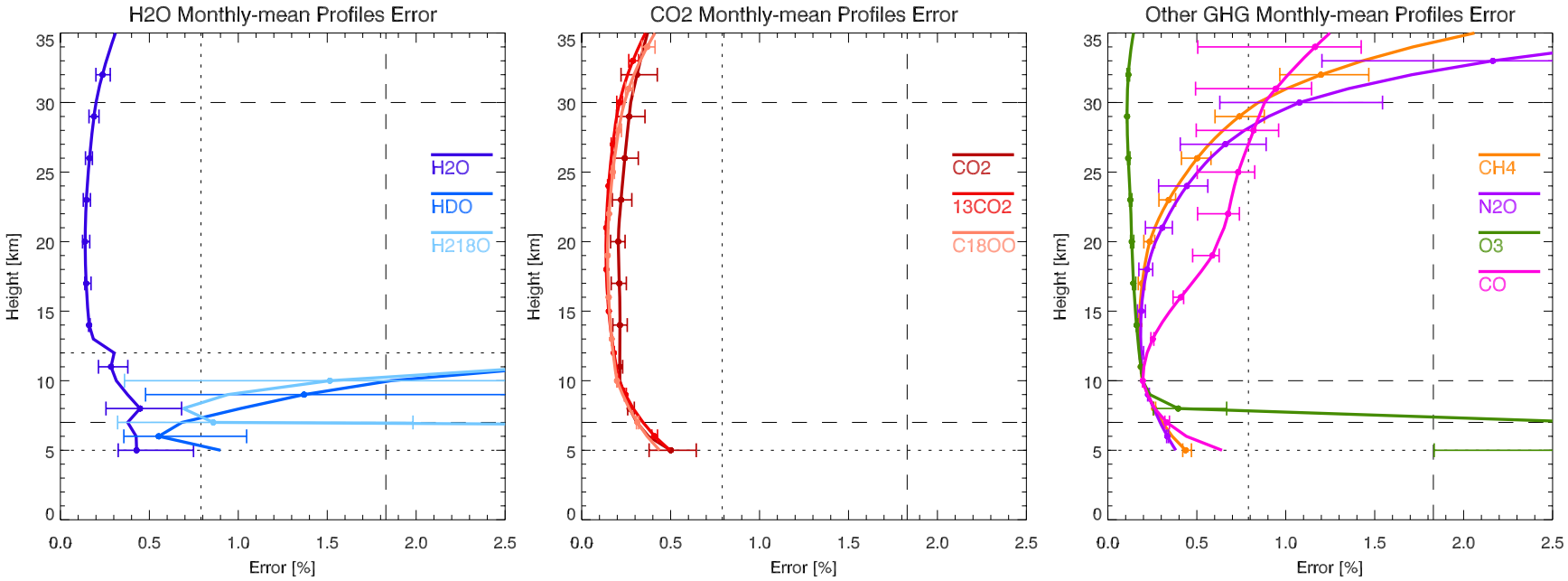
what is the accuracy as function of height? (2)

LIO requirements & scientific performance: monthly-averages

- Monthly-mean species profiles unbiased (no time-varying biases) and generally accurate to < 0.5%, UTLS GHG columns to < 0.25%. (temperature/humidity from LRO to < 0.2 K/< 1-3%, also in clouds)
  (ALPSv1.8 simulation results)

Example results: GHG and isotope species profile retrieval, 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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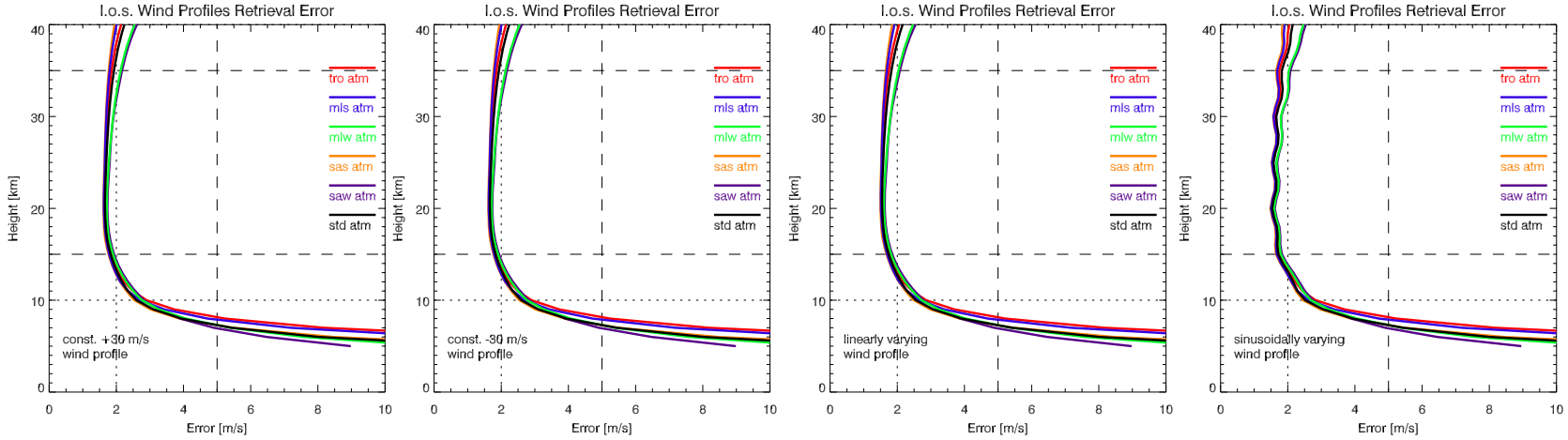
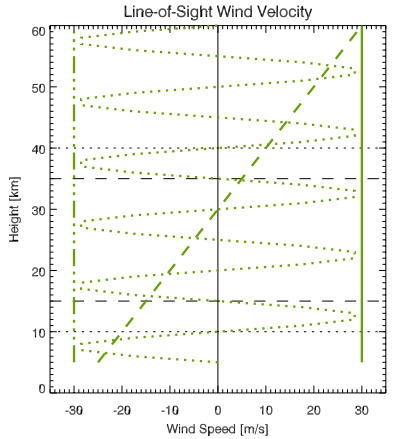
what is the accuracy as function of height? (3)

LIO requirements & scientific performance: l.o.s. wind profiles

- Line-of-sight wind generally retrieved within LS outside clouds to an accuracy of < 2 m/s (individual profiles accuracy). (ALPSv1.8 simulation results)



Example results: Line-of-sight (l.o.s.) wind profile retrieval errors for the 6 FASCODE atmospheres for 4 simple wind profile cases →



each of the result panels (above) illustrates one wind profile case:
left panel → const. positive wind
middle-left panel → const. negative wind
middle-right panel → linearly-in-height varying wind
right panel → sinusoidally-in-height varying wind

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ACCURATE breadboarding concept

CO_2-H_2O-Wind 2.1µm LIO demo breadboard (1)

line selection for ACCURATE LIO demo breadboard

(also for $^{13}CO_2$ demo lines are available within 4770-4775 cm-1, see next slide)

Tx Laser Lines Baseline (21 lines in total/incl. 2 CO_2 wind lines)

Trace Gas	Absorption Lines		Reference Lines		Ratio
	$\bar{\nu}_{abs}$ [cm^{-1}]	λ_{abs} [µm]	$\bar{\nu}_{ref}$ [cm^{-1}]	λ_{ref} [µm]	$\lambda_{abs}/\lambda_{ref}$
H_2O (1)	4204.840	2.3782	4227.07	2.3657	1.0053
(2)	4775.803	2.0939	4770.20	2.0963	0.9988
(3)	4747.055	2.1066	4731.05	2.1137	0.9966
(4)	4733.045	2.1128	4731.05	2.1137	0.9996
CO_2	4771.621	2.0957	4770.20	2.0963	0.9997
wind(1)	4771.618	2.0957	4770.20	2.0963	0.9997
wind(2)	4771.625	2.0957	4770.20	2.0963	0.9997
CH_4	4344.164	2.3019	4322.92	2.3133	0.9951
N_2O	4710.341	2.1230	4731.05	2.1137	1.0044
O_3	4029.110	2.4819	4067.80	2.4583	1.0096
CO	4303.623	2.3236	4322.92	2.3133	1.0045
HDO	4237.016	2.3602	4227.07	2.3657	0.9977
$H_2{}^{18}O$	4090.872	2.4445	4118.36	2.4282	1.0067
$^{13}CO_2$	4723.415	2.1171	4731.05	2.1137	1.0016
$C^{18}OO$	4767.041	2.0977	4770.20	2.0963	1.0007

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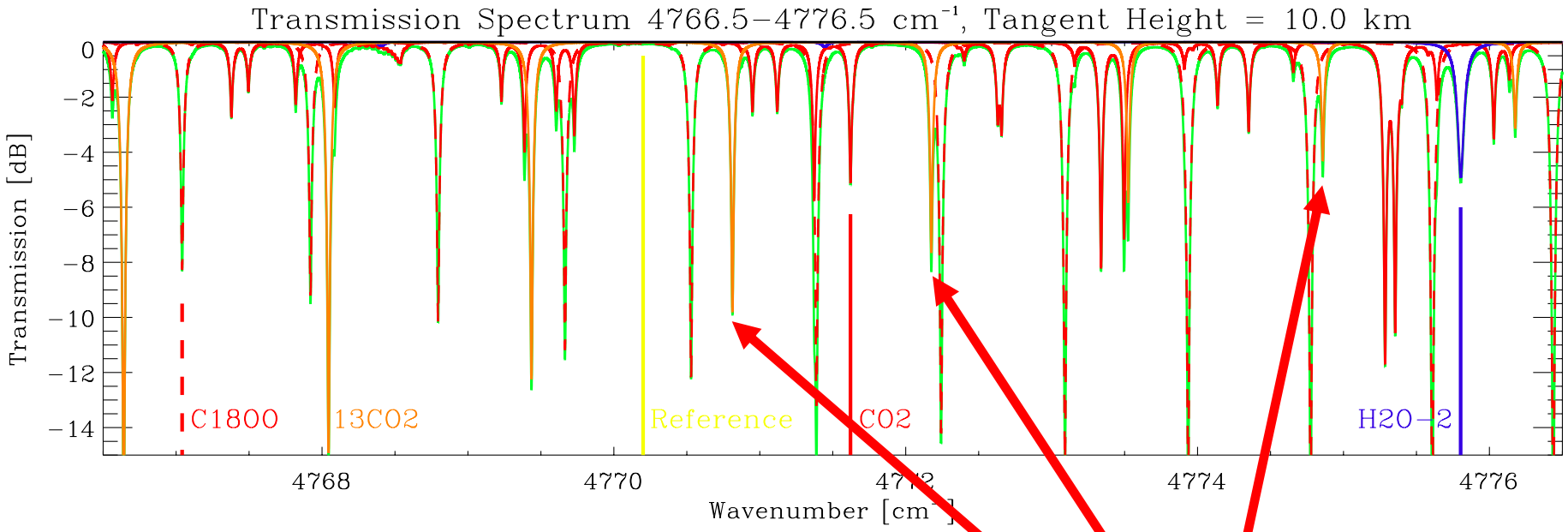
CO_2-H_2O-Wind 2.1µm LIO demo breadboard (2)

also allows to probe $^{13}CO_2$ in addition to $C^{18}OO$

the mode-hop free tuning range of near-2.1µm DFB laser diodes is > 10 cm^{-1}, i.e., three DFB diodes (manufactured for near 4769.0 cm^{-1} and 4773.0 cm^{-1} @ T_0,i_0) can basically do the job for all diff-transmission pairs of the demo breadboard



Candidate lines for $^{13}CO_2$ isotope measurements, in addition to $C^{18}OO$ and CO_2 (whether included will depend on LIO Rx demux and filter layout)

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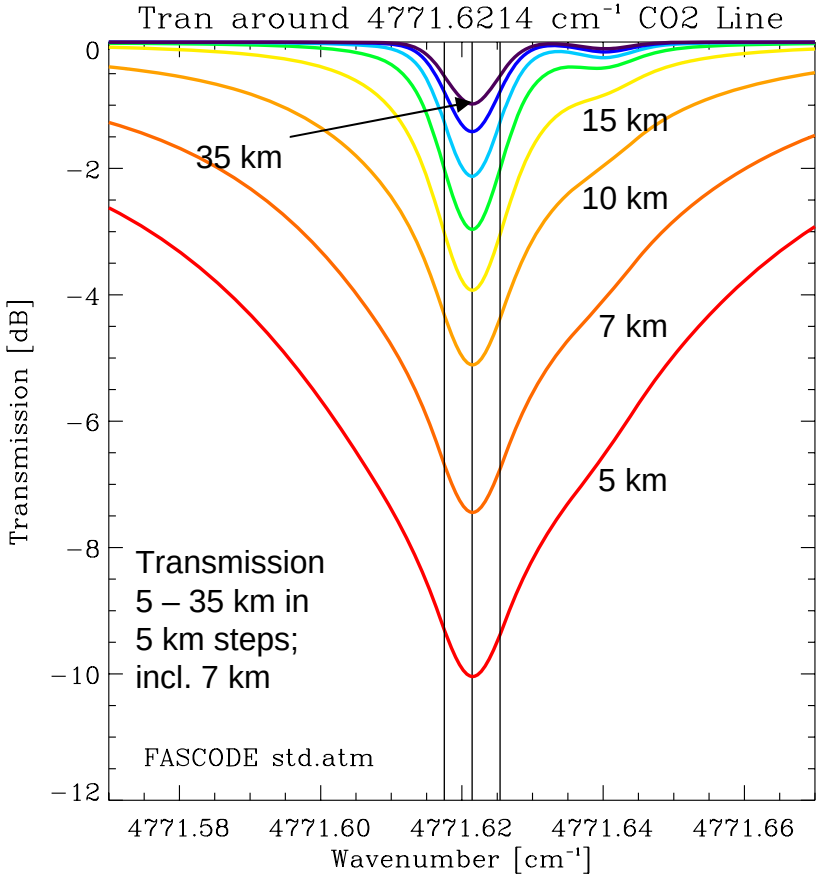
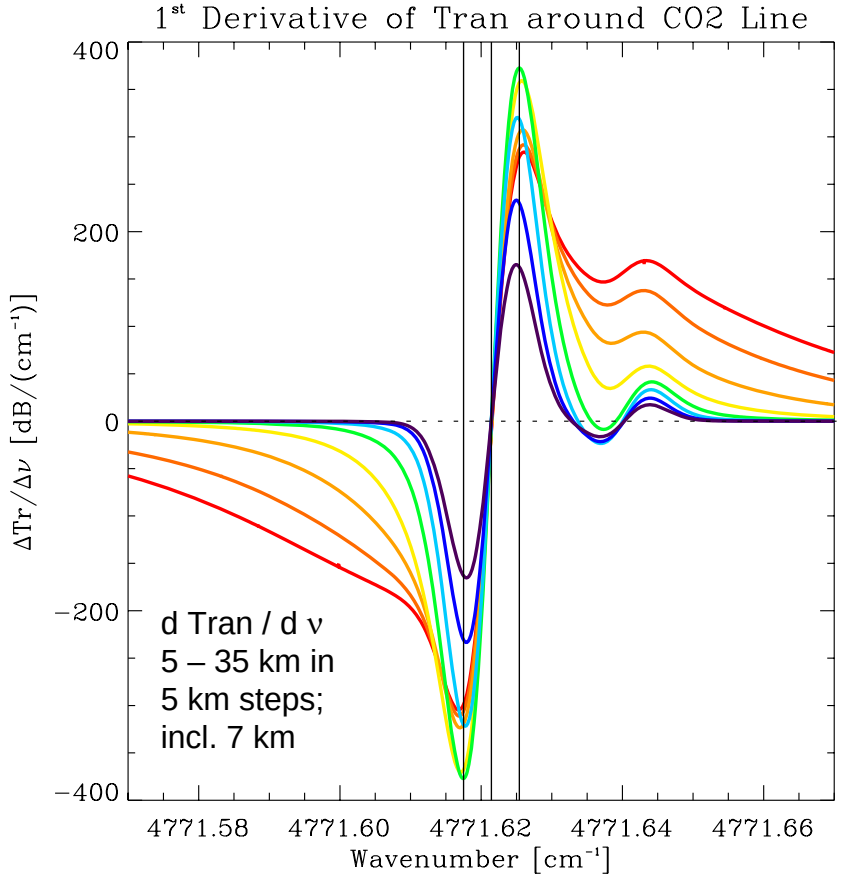
CO_2-H_2O-Wind 2.1μm LIO demo breadboard (3)

wind measurement in practice as double-diff

transmission dTran ($\propto V_{los}$) = [wind(1) – ref] – [wind(2) – ref] is exploited in practice since the CO_2-wind signals share one LIO Rx filter and are thus transmitted in temporal sequence (within 10 ms); the demo breadboard has one (tunable) signal for CO_2-wind





wind line spacing: df/f ~ +/-0.9 x 10^{-6} about CO_2 line center frequency (~ Doppler FWHM);
near-2.1μm DFB diode FWHM ~ 2 x 10^{-8}, freq. stability ~ 1 x 10^{-8}, intensity stability < 0.1%

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CO_2-H_2O-Wind 2.1μm LIO demo breadboard (4)

freq.stability df/f_0 ~ 1 x 10^{-8} or better: fs-laser frequency comb stabilized target frequencies of the DFB diodes

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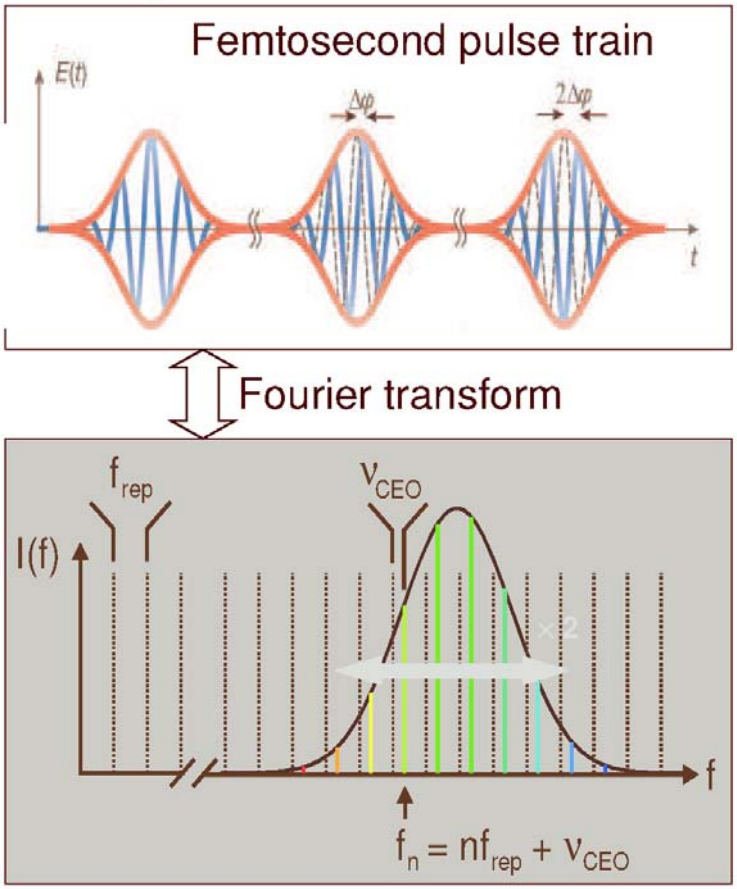
Frequency Metrology (1)
What is a Frequency Comb ?

Pulse-to-Pulse phase slip

- The spectrum of a femtosecond laser contains hundreds of thousands of lines seperated by the repetition frequency
- The frequency comb is offset from the origin by ν_{CEO},due to the phase slip of the carrier envelope, $\Delta\varphi$



(Toptica, 2006)

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what's next? – via ACCUDEMO to ACCURATE
towards a demonstration mission

- perform and complete detailed LRO+LIO scientific performance analyses for all parameters, thermodynamic, wind, greenhouse gases and isotopes; as well as for the complementary aerosol, cloud, and turbulence information
- produce a breadboard of the LIO transmitter-receiver system (for CO_2, H_2O, and Wind near 2.1 μm as representative system)
- start implementation of ACCURATE as space mission:
  1st: ACCUDEMO LIO proof-of-concept mission (baseline: Tx space to Rx mountain top/airplane); in coordination with ATOMMS LRO proof-of-concept (baseline: Tx-Rx stratospheric aircraft); …
  2nd: full 4-8 satellites demo mission (e.g., Europe, U.S., Joint mission,…)