Performance simulation of a spaceborne infrared coherent lidar for measuring tropospheric wind profiles.

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Outline

- Context/motivation
- IR coherent wind lidar
- Sensitivity study
- Preliminary results from simulations with a 3-D wind clouds and aerosols models
- Future works

Context

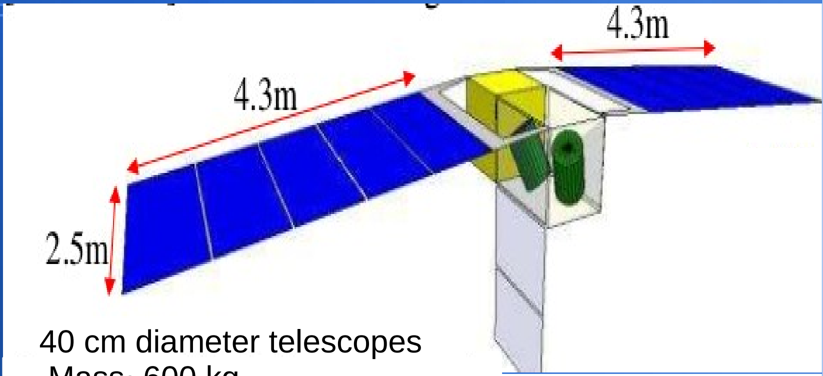
- Strong demands for tropospheric wind observation on **a global scale** for improving weather/climate models.
- ESA is going to lunch ADM-Aeolus (2015): a UV lidar using direct detection in order to measure line-of-sight wind profiles below 30 km with a precision of ~2 m/s
- NASA is studying a project with two lidars:

  i) UV direct detection for free troposphere and lower stratosphere

  ii) IR coherent (heterodyne) detection for the lower troposphere.

- The Japanese scientific community is studying the definition of a low orbital mission equipped a IR coherent lidar.

Instrument



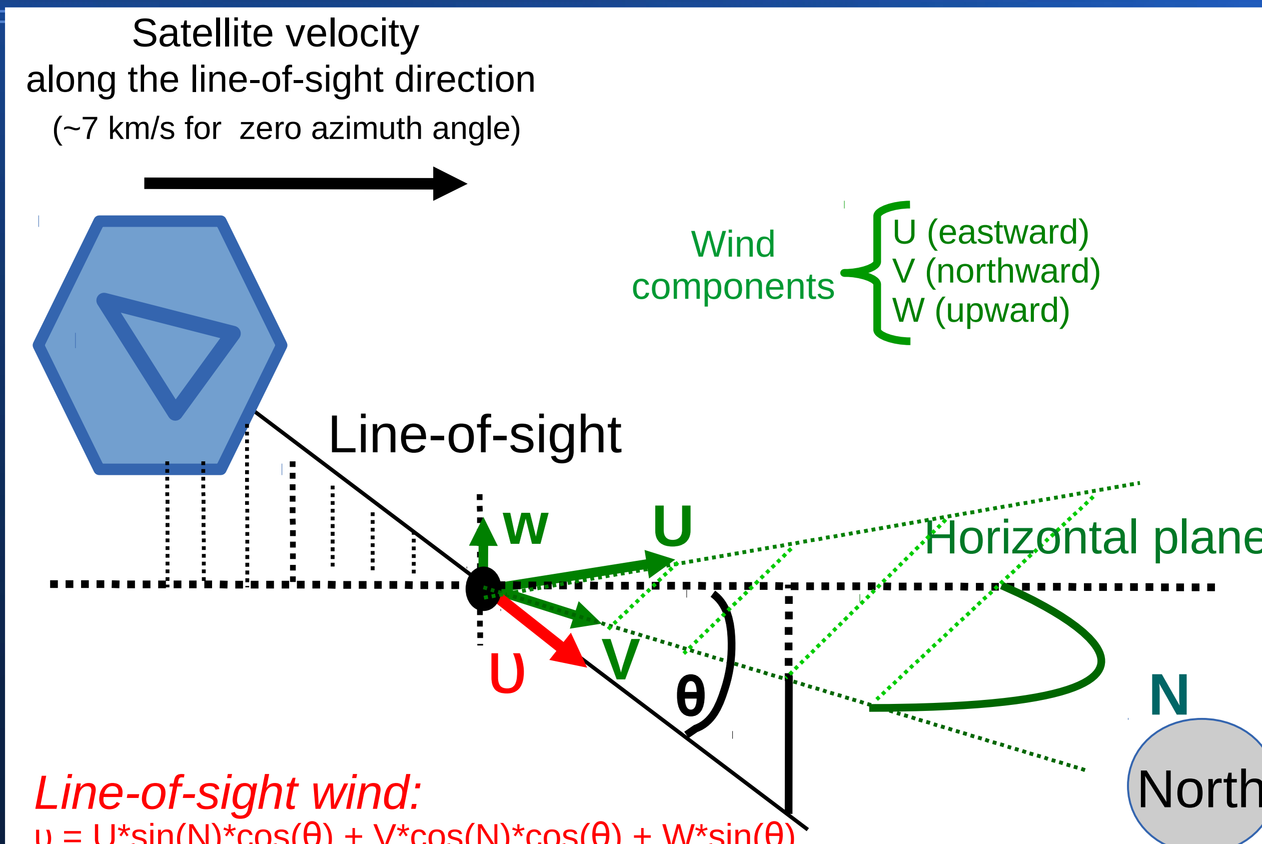
40 cm diameter telescopes
Mass~600 kg
Consumption ~ 675-730 W

- Two telescopes with orthogonal line-of-sights for retrieving both components of tropospheric horizontal wind (U,V).
- Horizontal wind precision: 1m/s in the boundary layer and 2 m/s in the free troposphere.
- Low orbit (200 km) with a downlooking nadir angle of 35 deg
- Orbit inclination TBD
- Two laser technologies are considered:

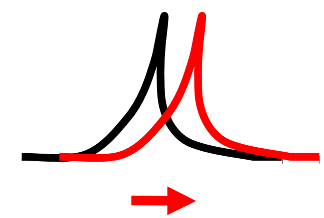
  Er:Fiber, 1570 nm, PRF=2500 Hz, pulse energy= 10 mJ

  Tm,Ho:YLF, 2.05 nm, cooled at 100 K, PRF=30 Hz, pulse energy= 125 mJ

Line-of-sight (LOS) wind



We measure the frequency shift due wind induced mean particles motion



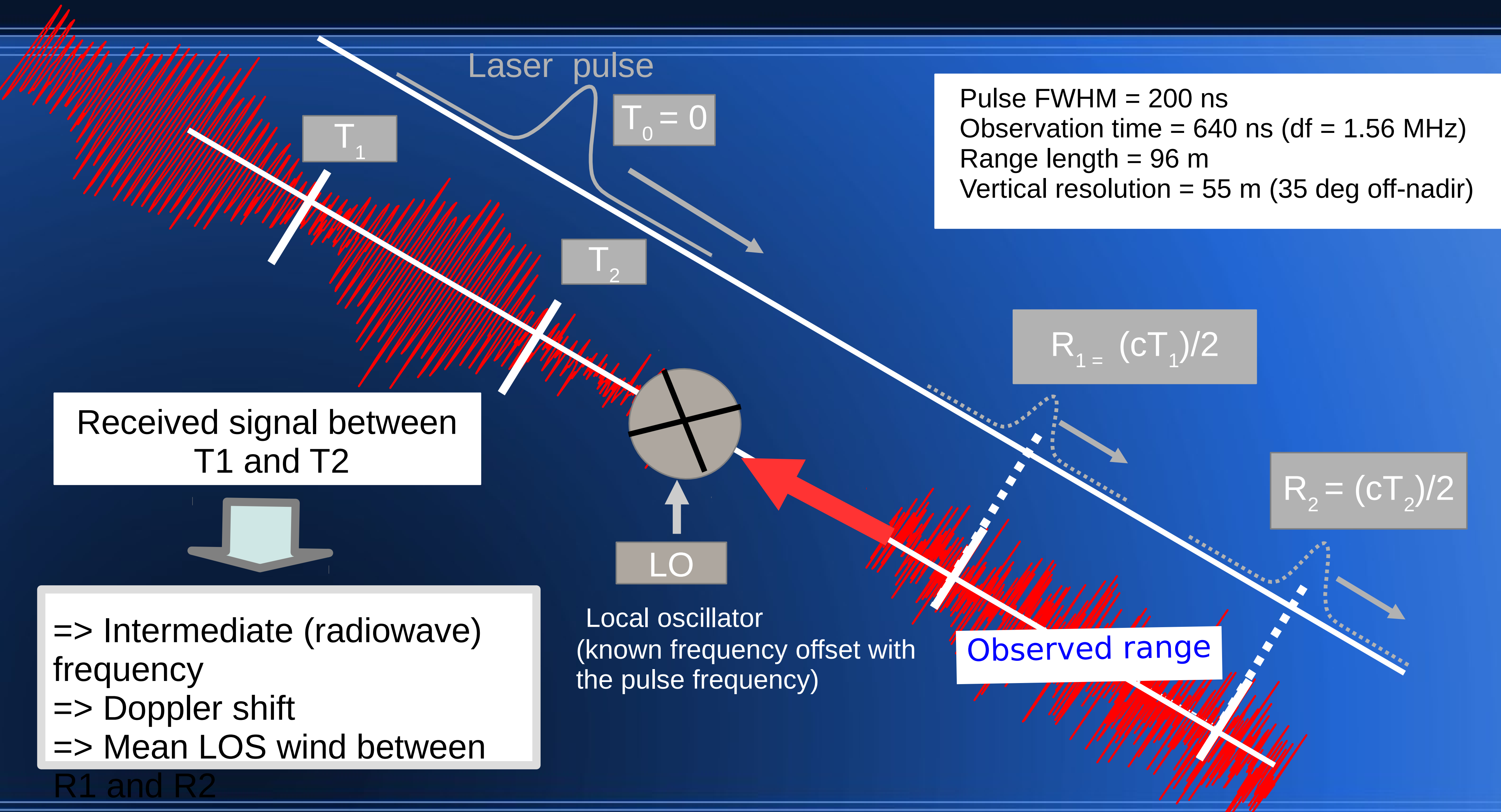
Doppler shift (Hz):

$DF = -2 \times \upsilon / \lambda$

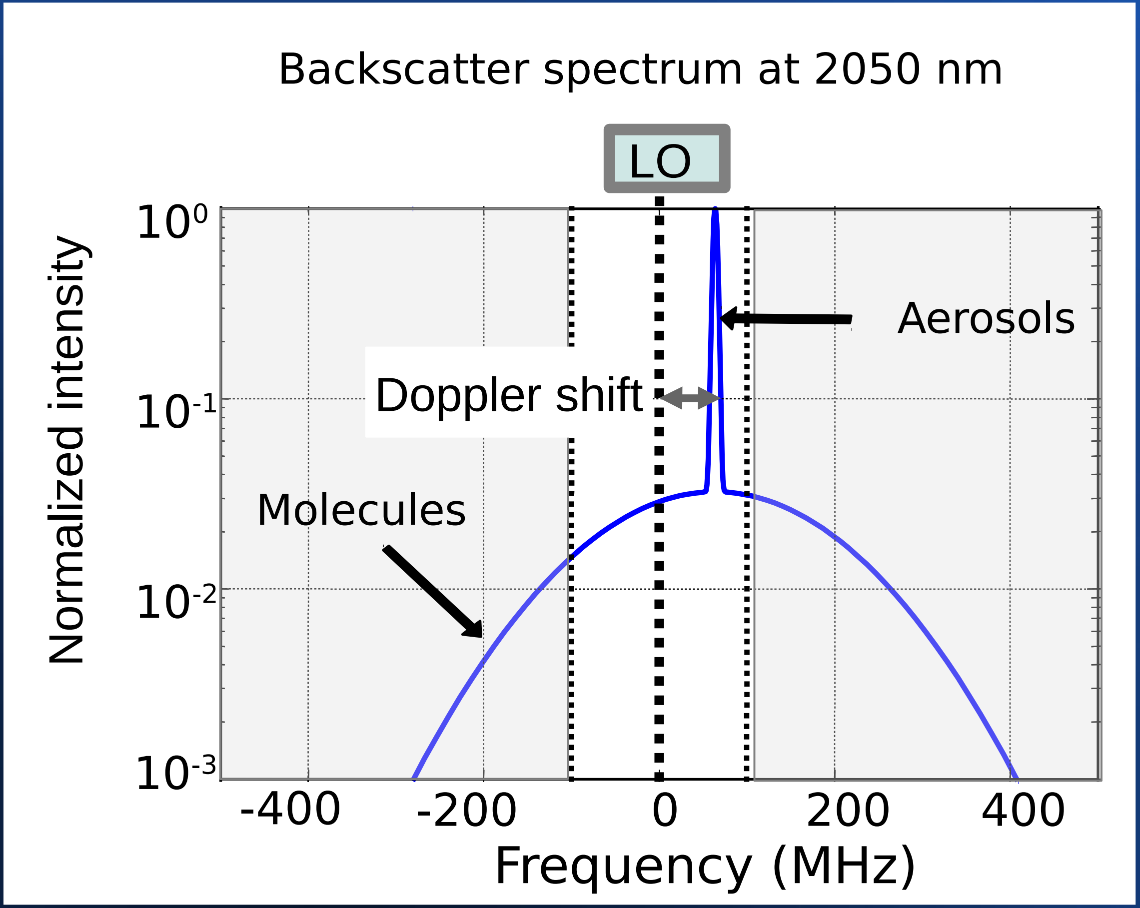
$\upsilon = 1$ m/s → $dF = -1$ MHz@ $\lambda = 2$ μm

Target: horizontal wind with 1 m/s precision in the boundary layer
=> LOS wind precision should be ~0.5 m/s.

Lidar heterodyne detection



Spectrum characteristics



* Heterodyne technique allows the resolution of the central line

* A bandwidth of 200 MHz is considered (**LOS-wind range of +/-100 m/s**)

* Spectral resolution of 1.56 MHz (256 spectral samples)

* Central peak width depends on the the laser pulse width, aerosol random motion, ...

* Molecular returns can be neglected (flat and low amplitude in the receiver bandwidth)

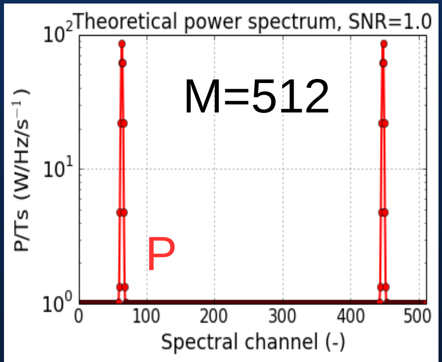
Signal simulation

Zrnic, D.: Estimation of Spectral Moments for Weather Echoes, Geoscience Electronics, IEEE Transactions, 17, 113–128, doi:10.1109/TGE.1979.294638, 1979.

Theoretical power spectrum

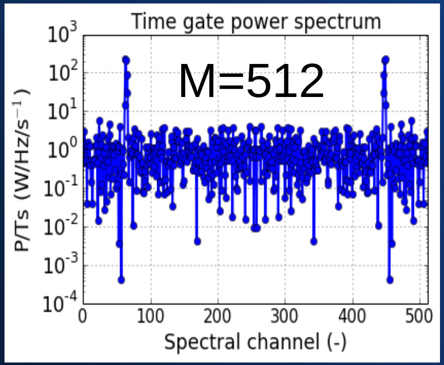
P

SNR = 1,
B = 200 MHz (Ts = 2.5 ns)
Pulse FWHM = 200 ns (1.5 MHz),
Doppler freq. = 50 MHz.



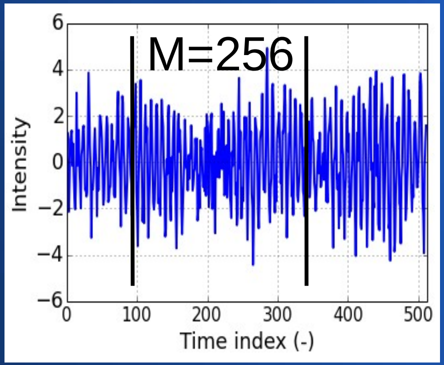
Time gate random coefficient spectrum (high resolution)

B = 200 MHz
df = 0.78 MHz



Simulated time domain signal

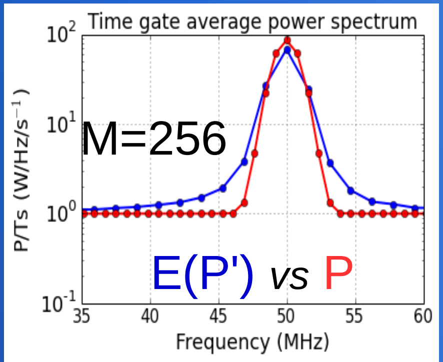
Ts = 2.5 ns
MTs = 640 ns



Simulated Power spectrum

P'

B = 200 MHz
df = 1.56 MHz



$E(eps) = 0$

$E(|eps|^2) = M/2Ts$ P

IFFT

eps' = FFT(s)

$P' = 2Ts/M\ |eps'|^2$

LOS-wind retrieval

Rye, B. and Hardesty, R.: Discrete spectral peak estimation in incoherent backscatter heterodyne lidar. I. Spectral accumulation and the Cramer-Rao lower bound, Geoscience and Remote Sensing, IEEE Transactions, 31, 16–27, doi:10.1109/36.210440, 1993

Frehlich, R. G. et Yadlowsky, M. J., Performance of mean-frequency estimators for Doppler radar/lidar, J. Atmos. Ocean. Technol, 11, 1217:1230, 1994

- Power spectrum is derived from Fourier analysis (resolution of 1.56 MHz in this analysis)
- The frequency of the line center is found using a standard Likelihood method Rye et al., (1993), Frehlich et al. (1994)

=> The spectrum amplitude is smoothed using a filter defined with the observational characteristics (SNR, laser pulse width)

=> The position of the maximum amplitude gives a first estimation of the line center

=> The estimate resolution is that of the spectrum (1.56 MHz for M=256)

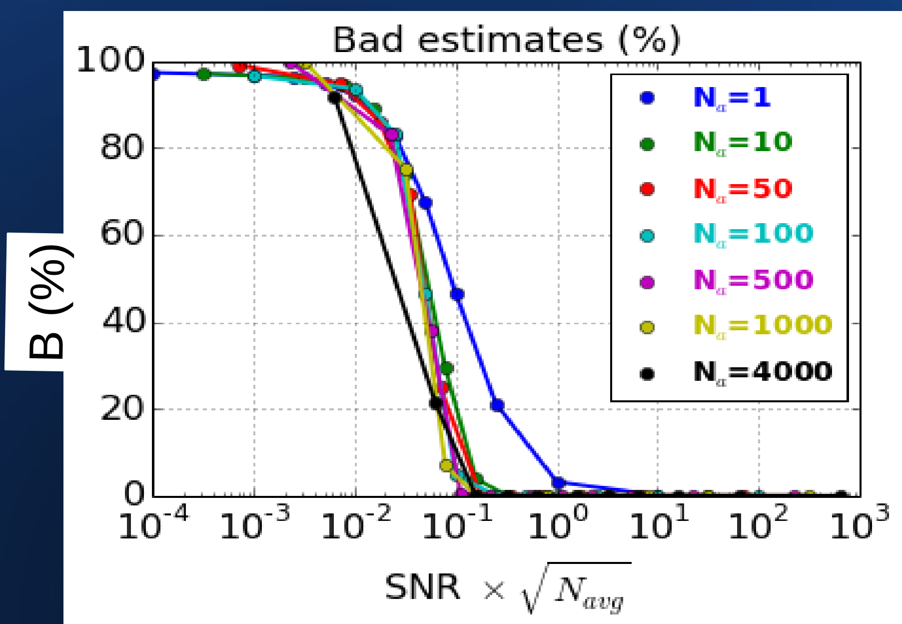
- In a second step, a spectrum sub-resolution is achieved using 2^{nd} order poly fit of the line amplitude at the selected frequency and the two closest ones.

Bad estimates statistics:
definition of the suited SNR range.

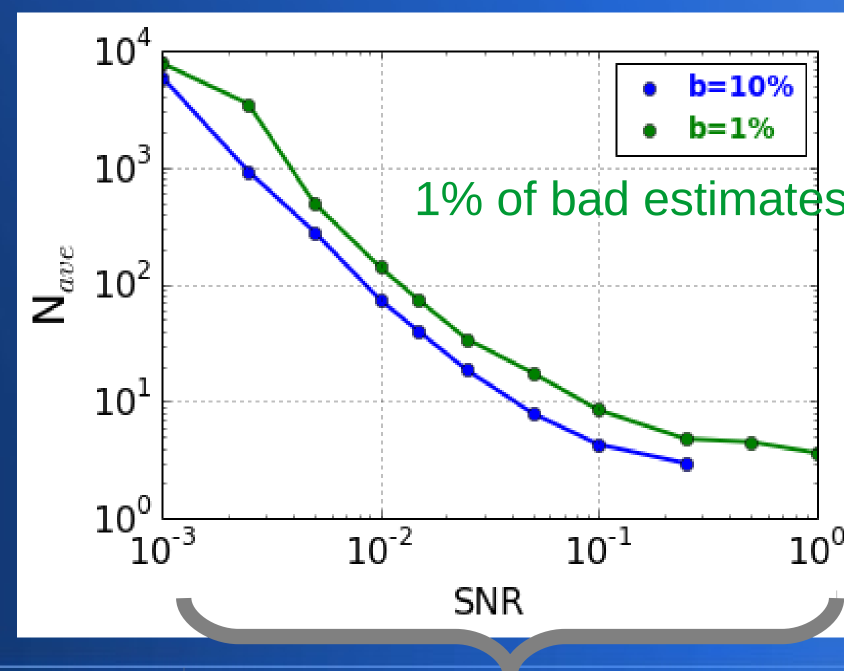
B = 200 MHz (Ts = 2.5 ns)
Spectrum resolution = 1.56 MHz (M=256)
Pulse FWHM = 200 ns (~0.96 MHz)
Random line frequency = 50 +/- 5 MHz

PRF = 30 Hz, range vertical resolution = 50 m (T=640 ns)
=> 100 km horizontal resolution: N ~ 430 pulses
[(100 km) / (7 km/s) * (30 Hz)]
=> 1 km vertical resolution: N ~ 20 ranges
[(1 km)/(50 m)]

Max. number of averaged spectra is 8000



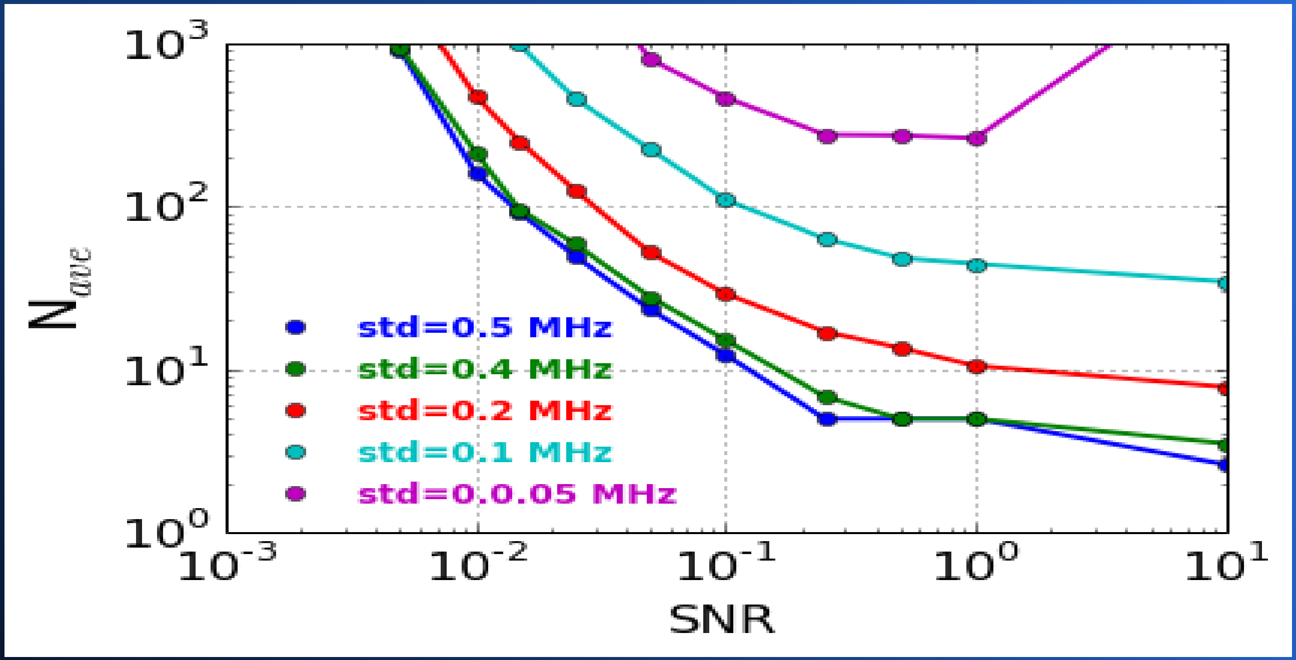
Na is the number of averaged spectra

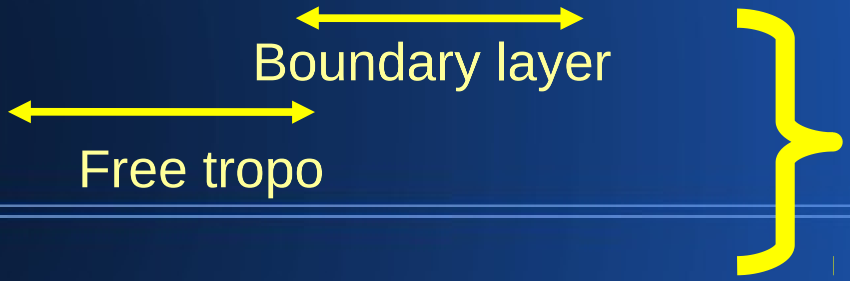


Suited single-range SNR

LOS-wind precision: SNR *vs* number of averaged spectra

M=256, target range = 96 m (640 ns)



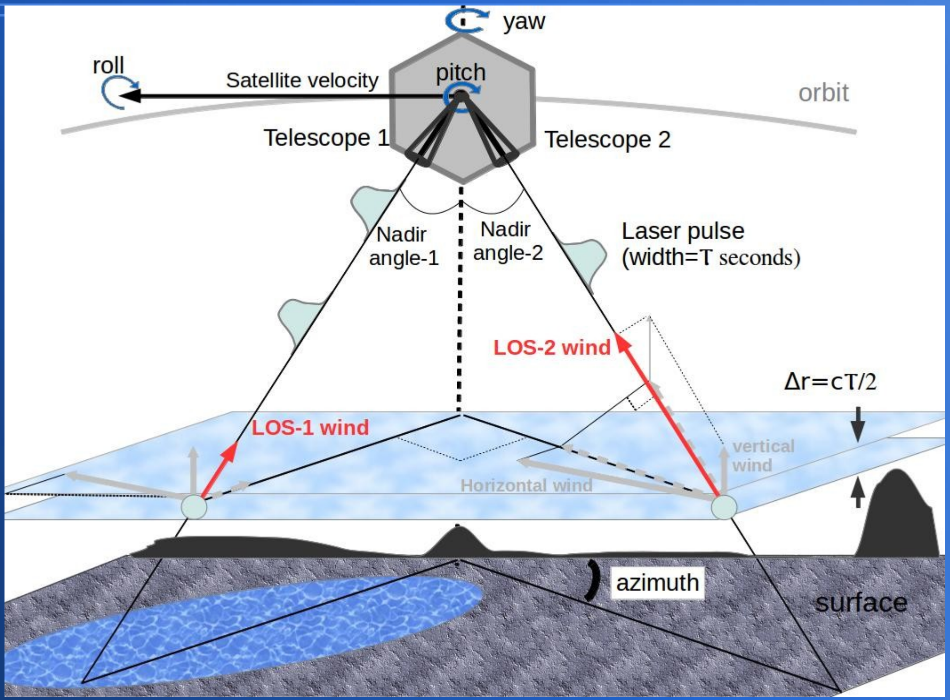


SNR range is estimated using the DWL simulator ISOSIM

ISOSIM-lidar

- End-to-end simulator developed in NICT:

1) Range gate signal power
2) Time domain signal
3) Power spectra
4) averaged spectra
5) Line-of-sight wind estimate



- 3-D atmosphere:
  - => Aerosols (dust, sea-salt, sulfate, black-carbon)
    - from the aerosol-chemistry Model of Aerosol Species in the Global Atmosphere (MASINGAR)

    horizontal grid of 1.125x1.125° and 48 verticals levels

  - => Winds (U,V), liquid water content, cloud coverage

    horizontal grid of 1.125x1.125° and 60 verticals levels

    => 2 types of cloud: stratus and cumulus

- Mie computation for extinction and backscatter coefficients
- surface model (SRTM30 elevation, water/land mask)
- Satellite displacement based on orbit TLE and 3-axis jitter

Atmopshere model references:

Tanaka, T. Y. et al.: MASINGAR, a global tropospheric aerosol chemical transport model coupled with MRI/JMA98 GCM: Model description, Meteorology and Geophysics, 53, 119–138, 2003.

Sekiyama, T.: Data assimilation of satellite-borne lidar aerosol observations and its validation with Asian Dust, PhD thesis from Department of Geophysics, Tohoku University, 2012.

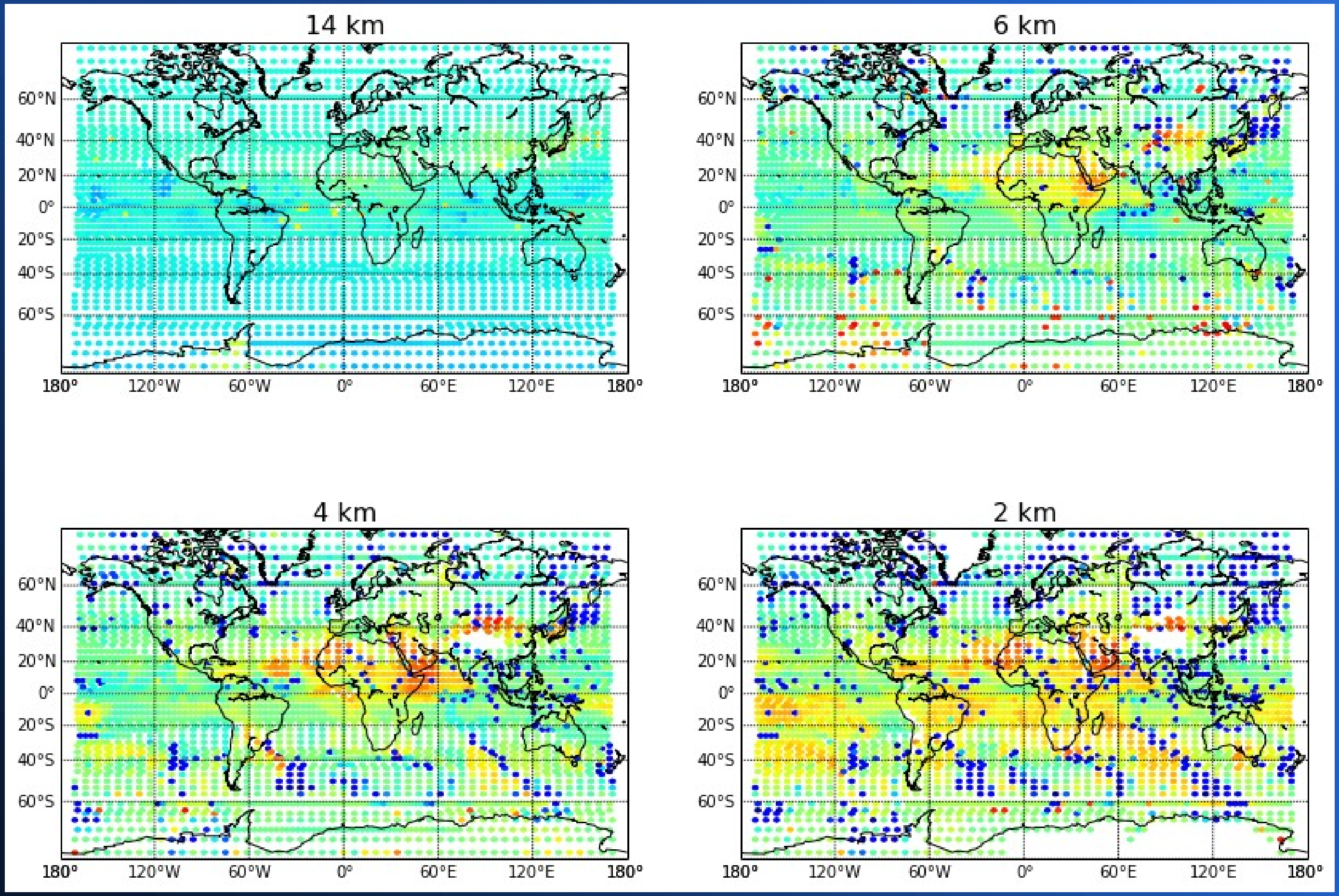
Model validation

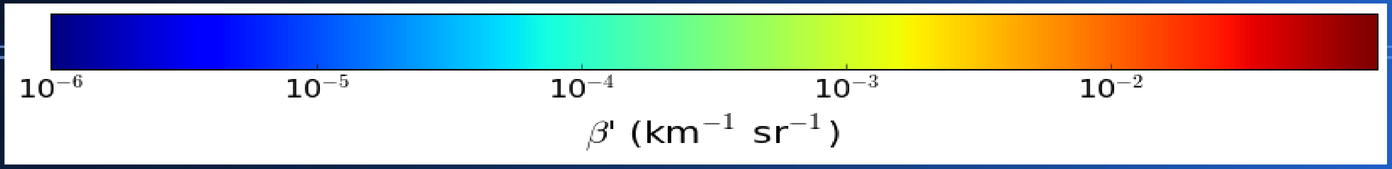
- The interactions between the atmosphere and the laser pulse are the critical part of the model
- They are described by the attenuated backscatter coefficent (β')
- ISOSIM calculations are performed at 1064 nm to be compared with Calipso **β'** (level 1b) at the same frequency
- Calispso data:

- 15 days from 1st August 2010

- Vertical average of 300 m

ISOSIM attenuated backscatter
at 1064 nm and Nadir direction





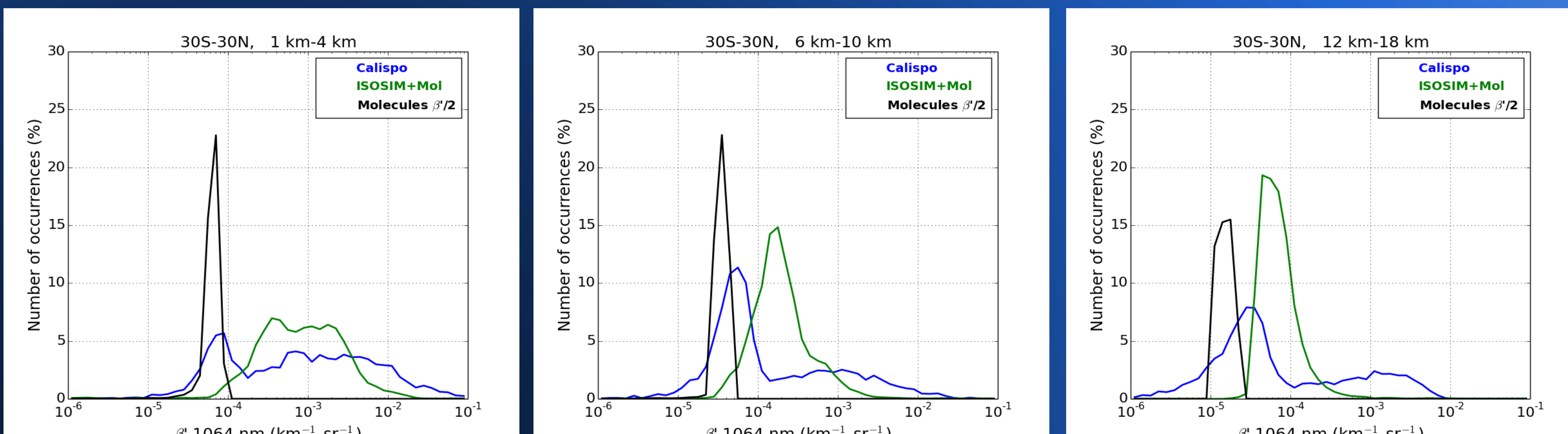
Preliminary results

Tropics

Calipso data have been horizontally averaged over 1000 km along the orbit track

- => reduce measurement noise and cloud impacts

Attenuated molecular backscattered is added to ISOSIM outputs



The Calipso data were obtained from the NASA Langley Research Center Atmospheric Science Data Center (ASDC).

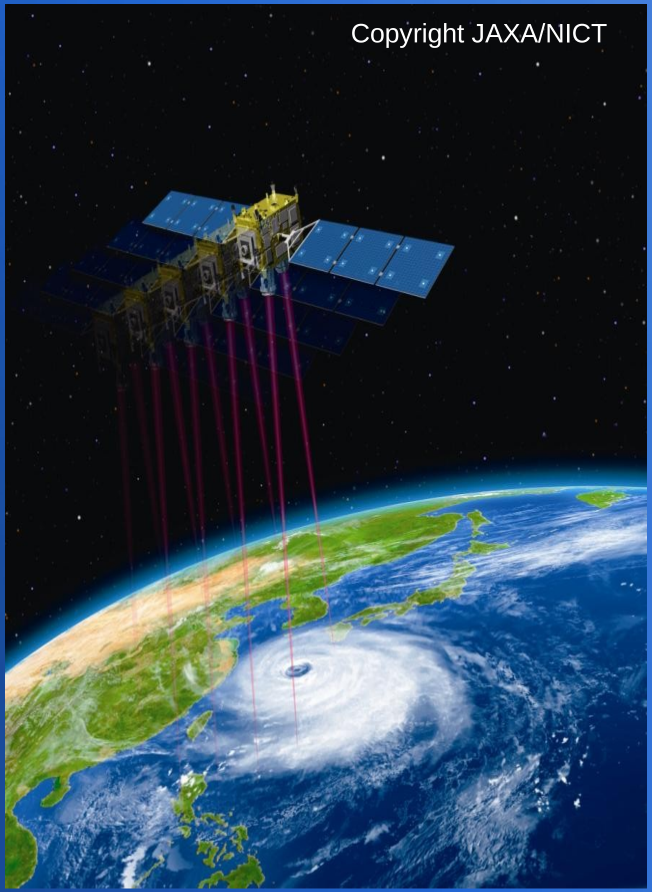
Conclusion

- Simulations to study the performances of a spaceborne IR DWL have been presented.
- This work is a part of a Japanese project for the definition of a future wind mission (launch after year 2020)
- Measurement characteristics and wind retrieval have been discussed and the suited SNR range for good measurements has been inferred.
- A simulator based on a 3-D atmospheric model has been developed for studying the atmospheric variability and instrumental parameters on the wind estimate errors.
- Preliminary results from the model have been shown.
- Works in progress:
  - Validation of the model using Calipso level 1b/level 2 measurements
  - In parallel, an OSSE is performed by the Meteorological Research Institute (Japan) using a full month of simulated data.
  - improvements: ice particles, turbulence, vertical winds.

More slides ….

Doppler Wind lidar (DWL) in Japan

- First proposition of a IR coherent lidar in 2001 for ISS
- Development of ground-based 2 µm coherent lidar (NICT) and 1.5 µm coherent airborne one (JAXA).
- A working group has started new studies for a spaceborne DWL to launched after 2020.
- A numerical simulator ISOSIM (Integrated Satellite Observation SIMulator for Coherent Doppler Lidar) is being developed in NICT for supporting and optimizing the definition of the instruments and of the wind retrieval algorithms.
- The impacts of the measurements on atmospheric model are investigated using ISOSIM simulations within an OSSE (Observing System Simulation Experiment).



S. Ishii et al., Future Doppler lidar wind measurement from space in Japan, Proc. of SPIE Vol. 8529, 2012

K. Okamoto et al., Simulation and impact study of future spaceborne Doppler wind lidar in Japan, 94th American Meteorological Society Annual Meeting, Feb. 2014.

Observational parameters:

Spectral bandwidth B (time sampling, Ts):

- 200 MHz (Ts=2.5 ns) to cover +/- 100 m/s LOS wind
- Increasing B: SNR^{-1} and number of bad estimates increases

Spectral resolution dF (Time gate):

- dF = B/2/M
- Estimate precision is better with low dF
- range gate length is proportional to dF^{-1}

=> M=256 (time gate = 640 ns) offer a good compromise between estimate precision and gate resolution (96 m)

=> M=128 is also considered (320 ns, 48 m)

Pulse FWHM width (DT) :

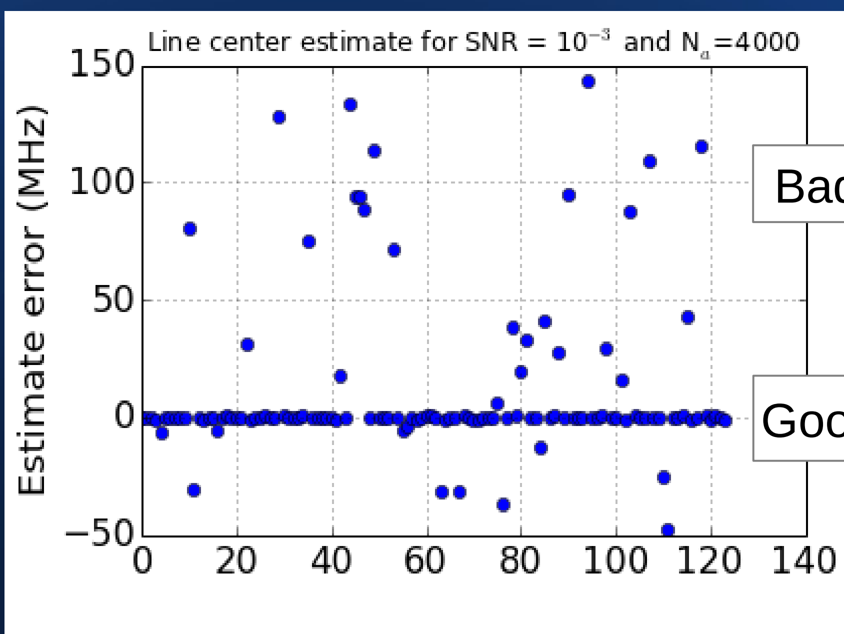
- Number of coherent cell in the time gate are proportional to DT^{-1}
- Wind estimate is better for small DT (spectral width =)
- DT=200 ns, Spectral width = 1.5 MHz
- DT between 200 and 700 ns is also considered.

Other parameters:

- PRF=30 Hz, Telescope diameter 40 cm, orbit height 200 km, nadir angle = 35 deg

Performance of the line center estimates algorithm based on repeated simulations

B = 200 MHz (Ts = 2.5 ns), Spectrum resolution = 1.56 MHz (M=256),
Pulse FWHM = 200 ns (1.5 MHz)
Random line frequency = 50 +/- 5 MHz



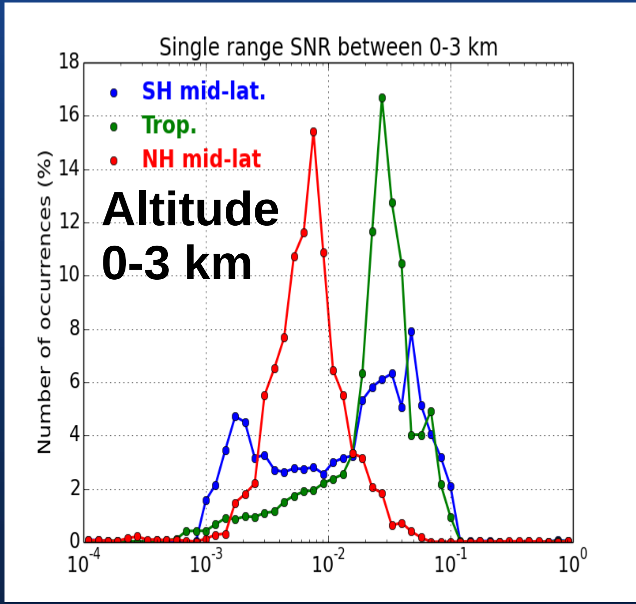
- LOS wind estimates are characterized by:
  => The number of bad estimates (noise peak selected instead of the atmospheric line)

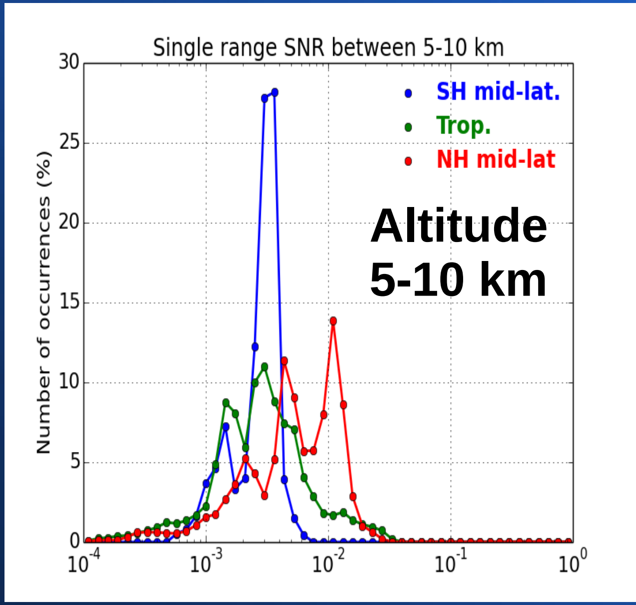
  => The spread of good estimates is related to the measurement precision

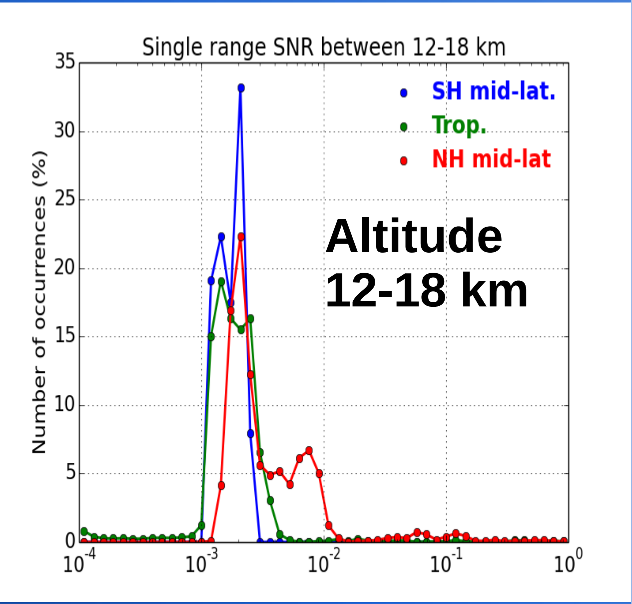
- Only observations with a small probability of bad estimations are used, typically < 10%.

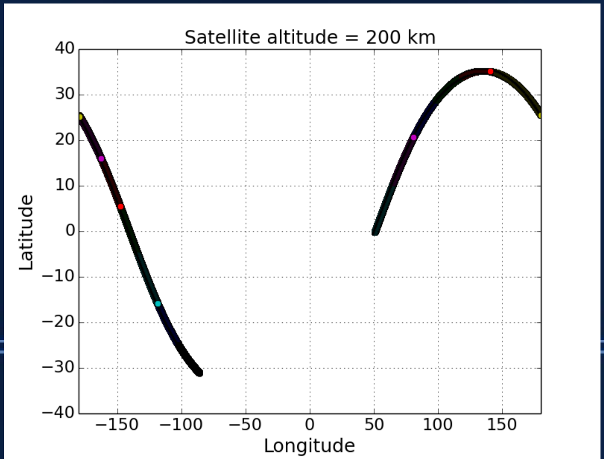
Calculated SNR using the simulator ISOSIM
(Atmospheric model for August 1st, 2010)

λ=2050 nm, Telescope diameter = 40 cm, Pulse energy = 125 mJ, Pulse FWHM = 200 ns, PRF = 30 Hz, B = 200 MHz (Ts = 2.5 ns), Spectrum resolution = 1.56 MHz (M=256, T=640 ns)
Orbit height =220 km, Nadir angle = 35 deg.









=> Most of the observations lie in the suited SNR range (SNR>10^3 for bad estimates < 10%)

=> Need Na>4000 in the **free/upper troposphere** (horizontal resolution 50-100 km, vertical resolution 1 km)

=> **In the lower troposphere,** good observations can be achieved with Na<100 (e.g. vertical resolution 100 m and horizontal resolution 10 km)

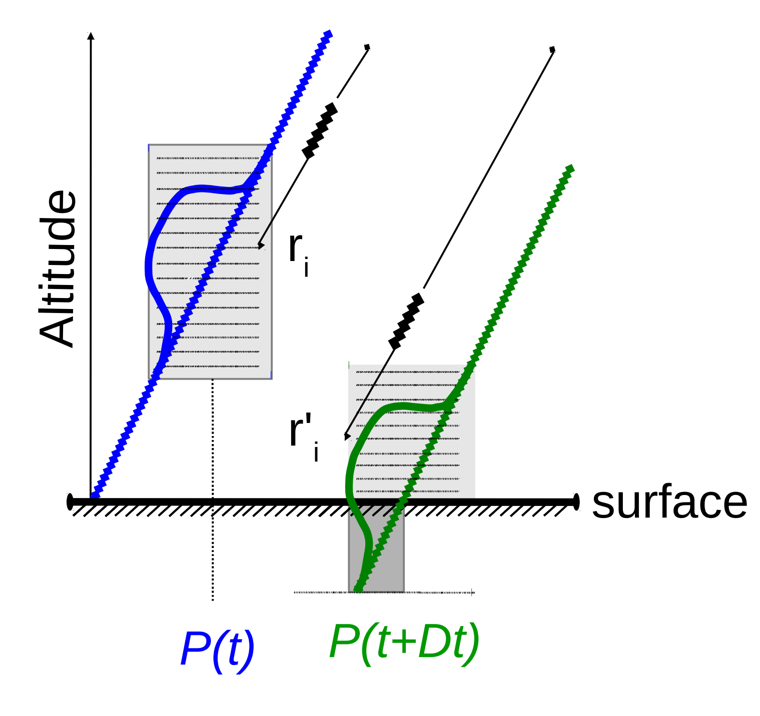
These results have to be taken with precautions because the model validation is still in-progress.

Signal power and SNR

- Instantaneous power:

$$P(t) = cA\delta r \sum_i \frac{\eta_i E(t - 2r_i/c)}{2r_i^2} \underbrace{\beta(r_i, \lambda) T^2(r_i, \lambda)}$$

Attenuated backscatter



- Noise is dominated by the LO shot noise:

$$SNR = \frac{\langle s^2 \rangle}{\langle n^2 \rangle} = \frac{\eta_H P}{h\nu B}$$

(SNR = signal to noise ratio)

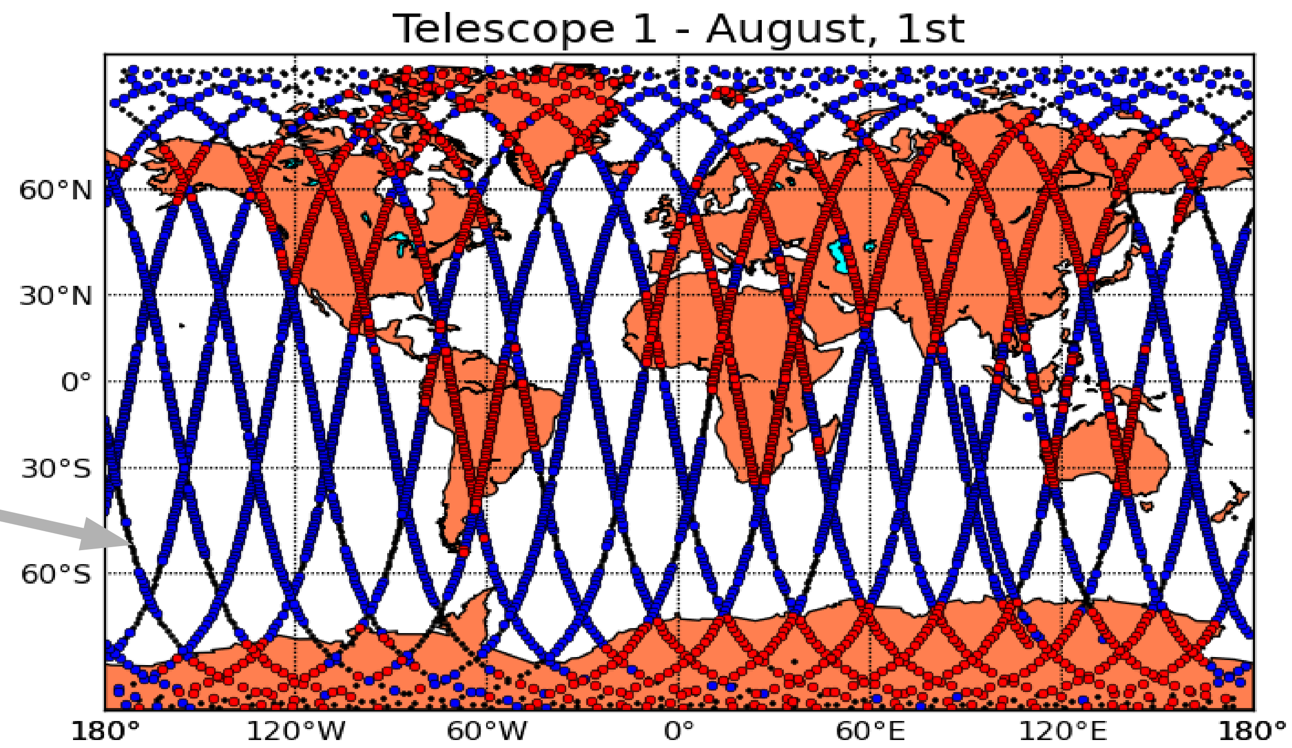
s is the noise-free signal intensity, P(t) is the noise free signal power, n is random with Gaussian distribution. E(t) is the pulse energy ; A=telescope area ; δr=scattering volume length ; r=distance between the receiver and the scattering volume ; β backscatter coefficient ; T= atmospheric transmission ; η detection efficiency (heterodyne and detector efficiencies, beams overlap, optical loss)

Example:
Surface return for 1-day simulation

(100-km horizontal average)

Red : SNR>10
Blue : SNR<10
Black : SNR<1

Black dots: Cloud signal attenuation

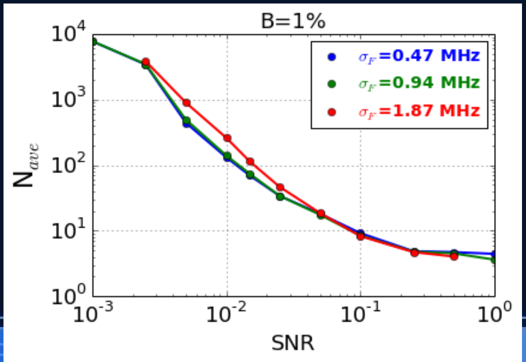


Laser power = 0.125 J, PRF=30 Hz, wavelength: 2050 nm, 100 km horizontal average

Purpose of ISOSIM

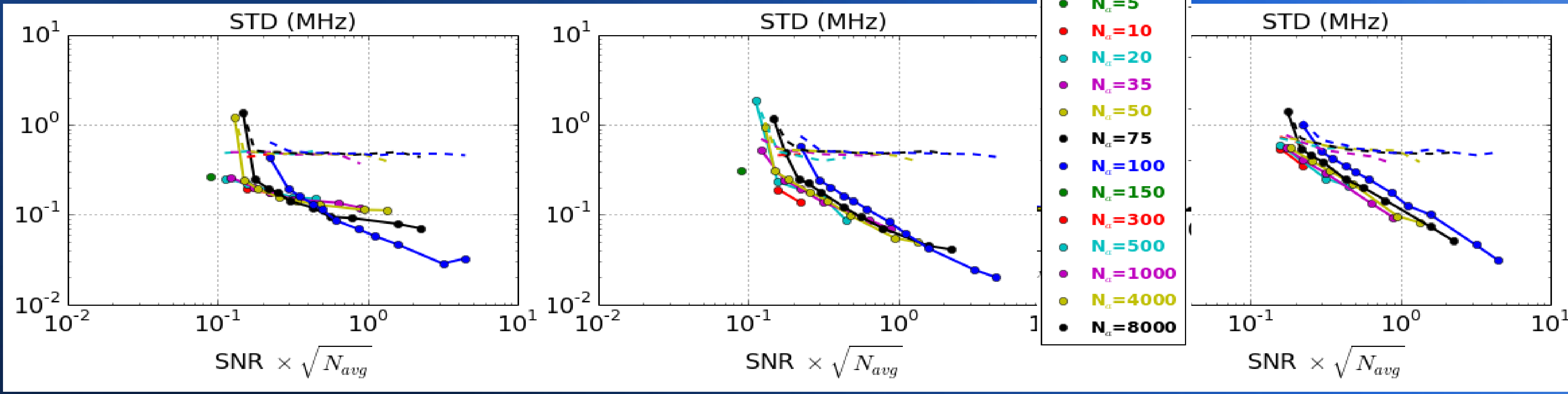
- Help at the definition of the instrument and of the observation strategy.
- Study the variability and the geographical distribution of the wind estimate errors
- Study of the impact of the instrumental parameters on the wind estimate errors
- Test the wind retrieval algorithms
- Signal average strategy and impact of the atmospheric inhomogeneities
- Generate simulated data for the OSSE and study the potential impact of the measurements on atmospheric models.

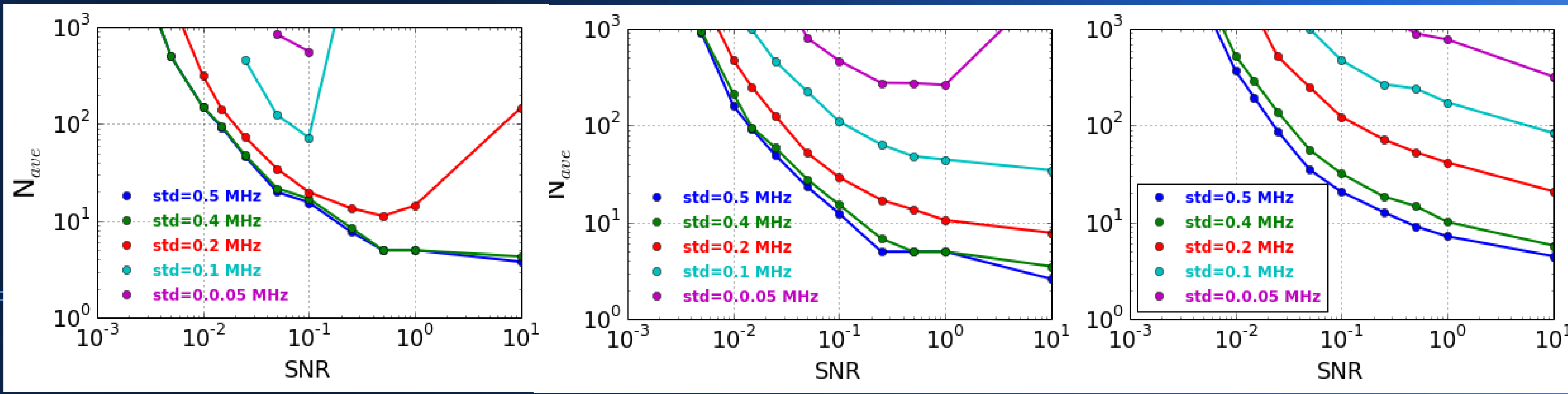
Pulse width sensitivity, M=256



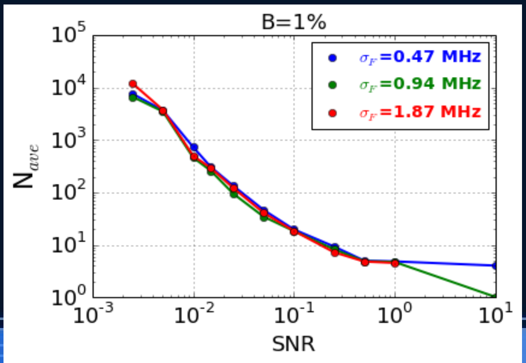
M=256, b=1%

0.47 MHz | 0.94 MHz | 1.88 MHz





Pulse width sensitivity, M=128

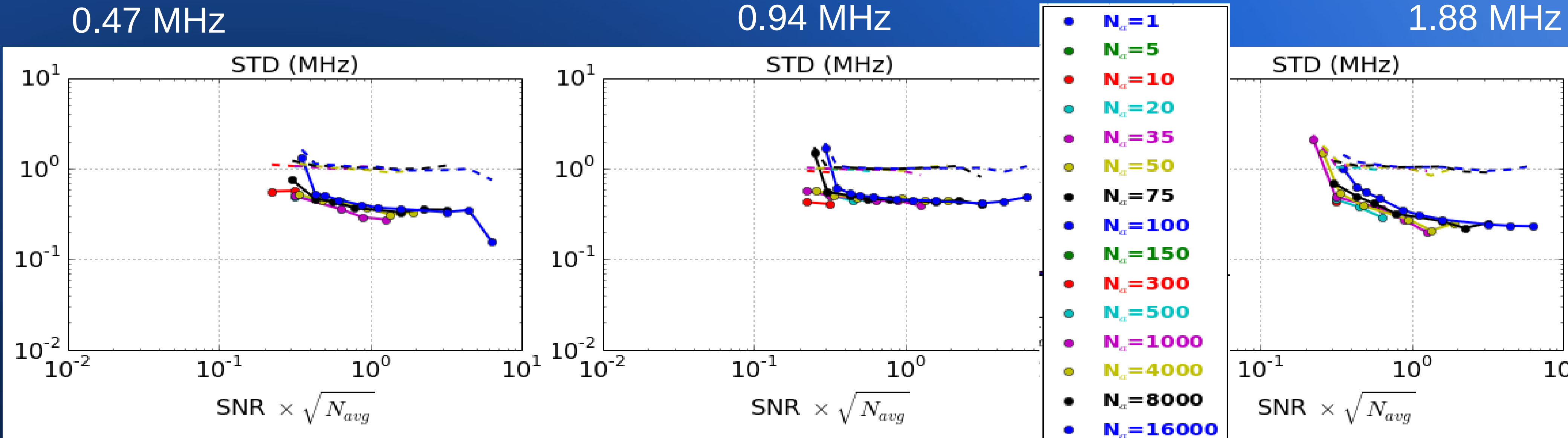


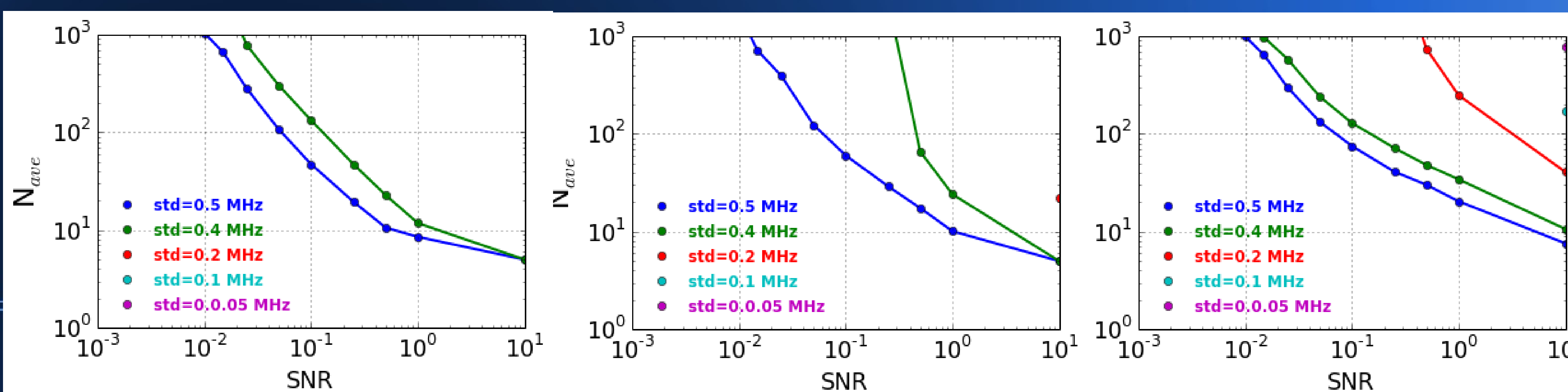
M=128, b=1%

0.47 MHz

0.94 MHz

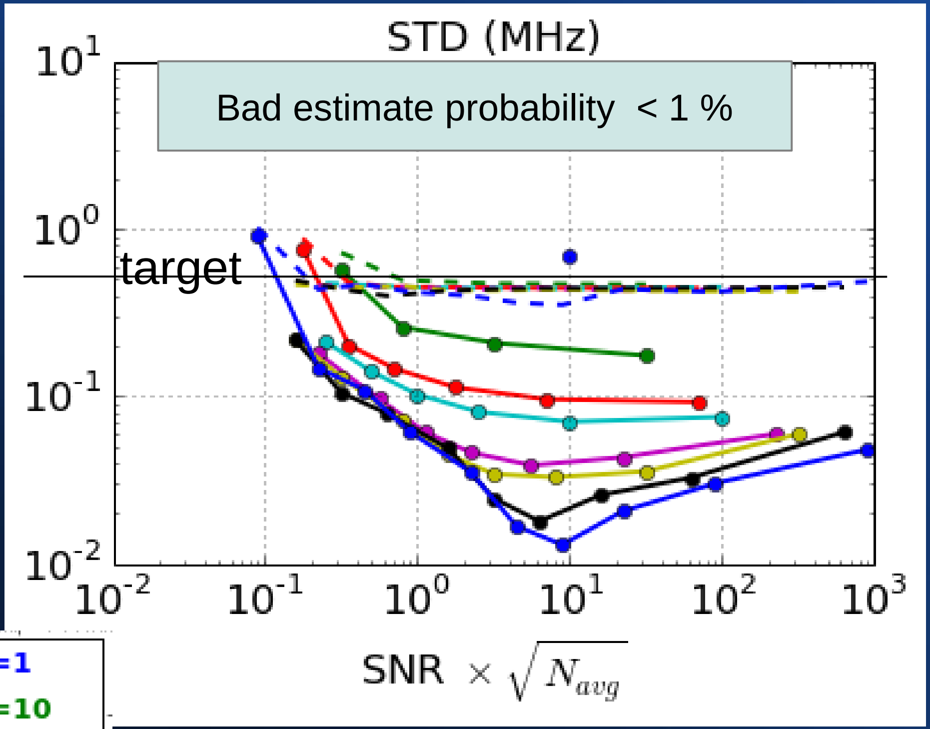
1.88 MHz

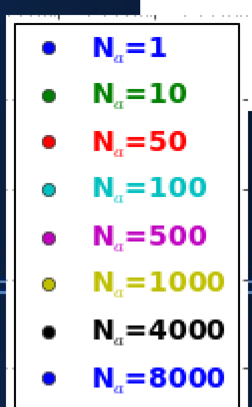




LOS-wind precision

RUN 1: different SNR and Na sampling





Dashed line: estimation without line-center fit
Full line: estimation with line center fit

Target: precision 0.5 m/s => STD = 0.5 MHz at λ=2050 nm

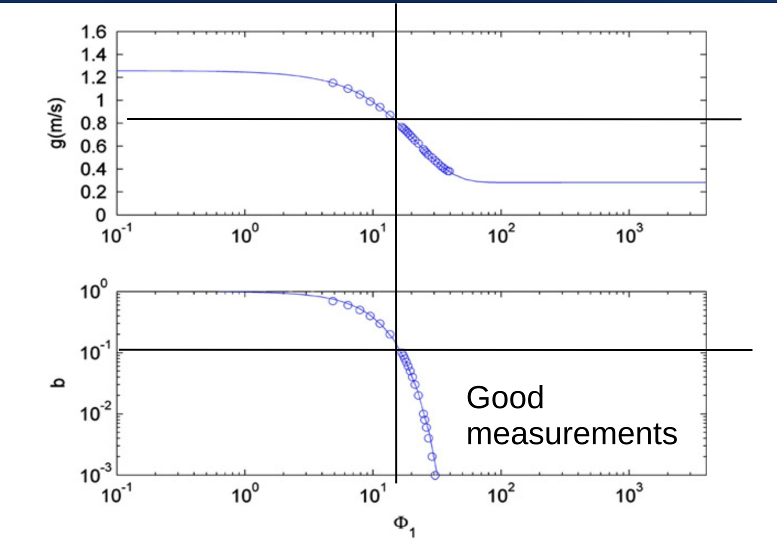
B = 200 MHz (Ts = 2.5 ns), Spectrum resolution = 1.56 MHz (M=256), Pulse FWHM = 200 ns (1.5 MHz)

Single shot analysis

Wu et al., JQSRT, 2013

Simulation of coherent Doppler wind lidar measurement from space based on CALIPSO lidar global aerosol observations

Platform height: 410 km
E = 250 mJ
Sampling: 0.05 micro-sec
Range interval = 7.5 micro-sec
Omega = 9.147
Vertical res. 0.795 km (nadir angle =)
Radius receiver lens: 50 cm



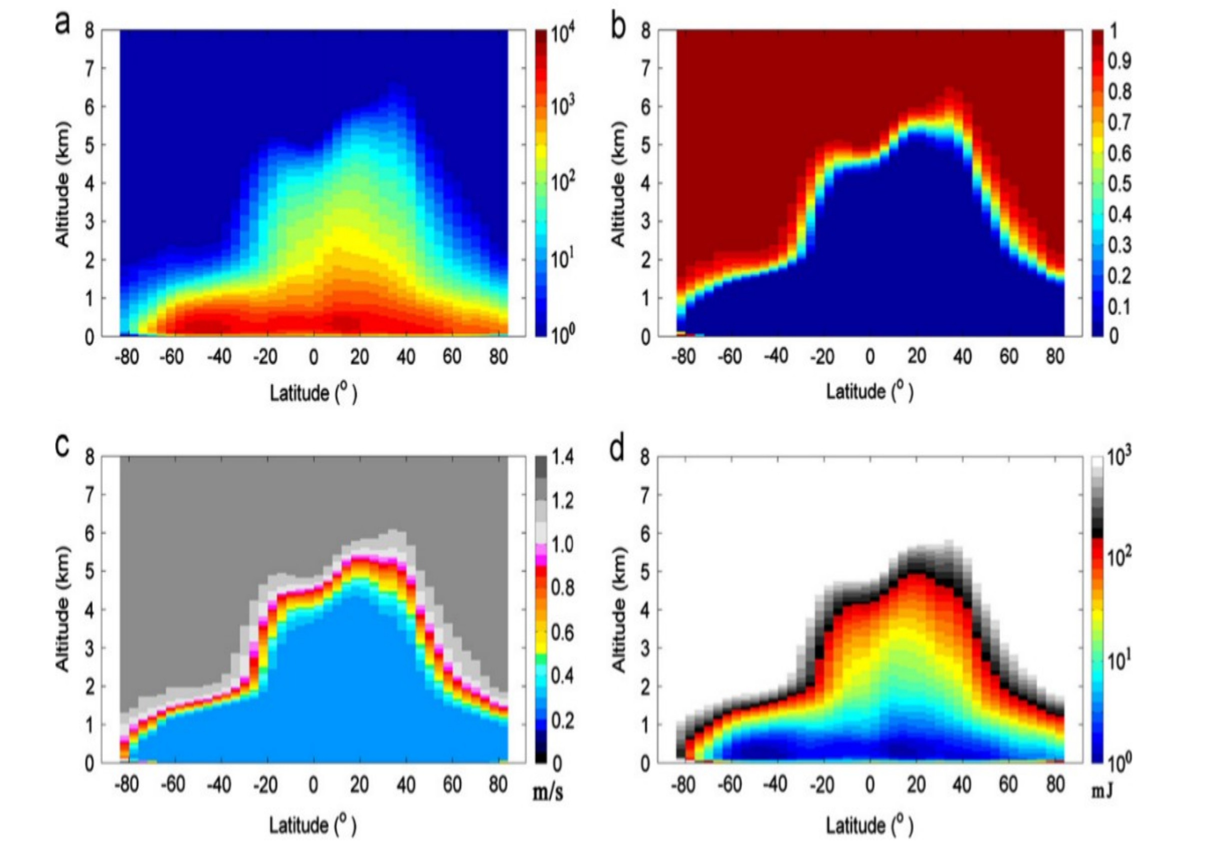
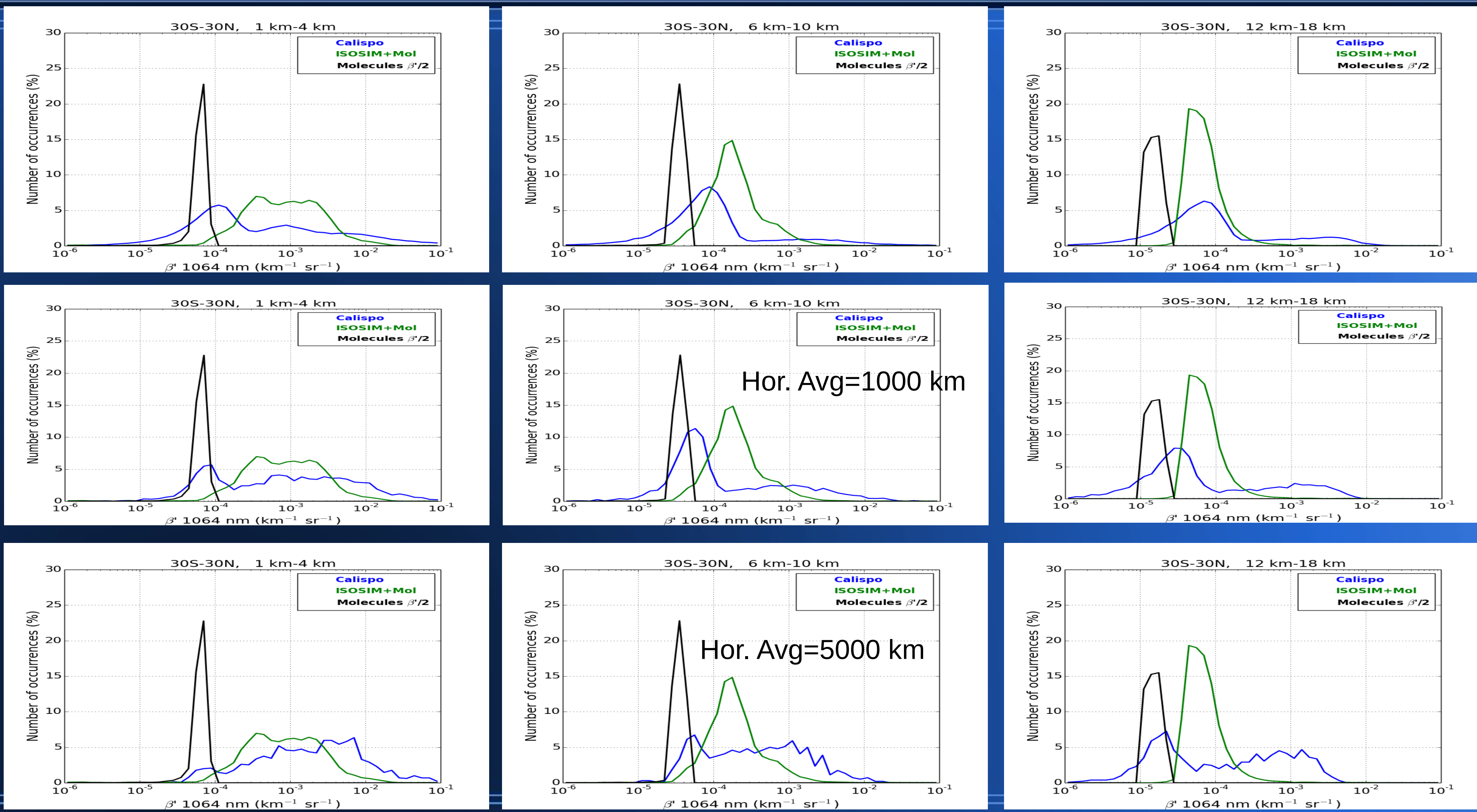
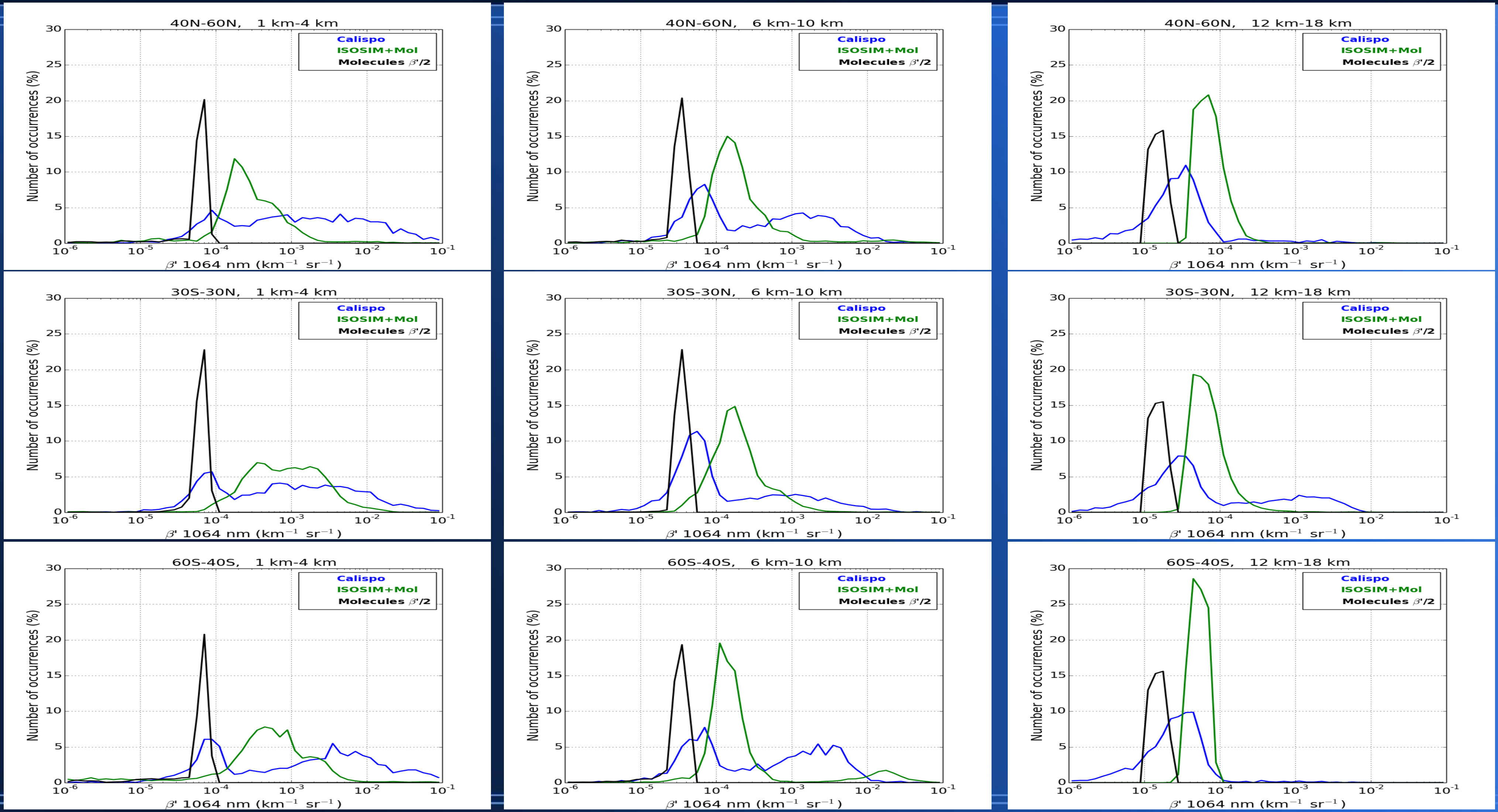


Fig. 5. Zonal-vertical distributions of (a) received number of coherent photoelectrons Φ_1, (b) fraction of bad estimates b, (c) radial velocity error in m s^{-1}, for a space-borne CDWL whose system parameters are given in Table 1, and (d) minimum laser pulse energy in mJ required to achieve a fraction of bad estimates of ~0.1, simulated for single laser shot.

ISOSIM vs Calipso
Tropics, horizontal average impact

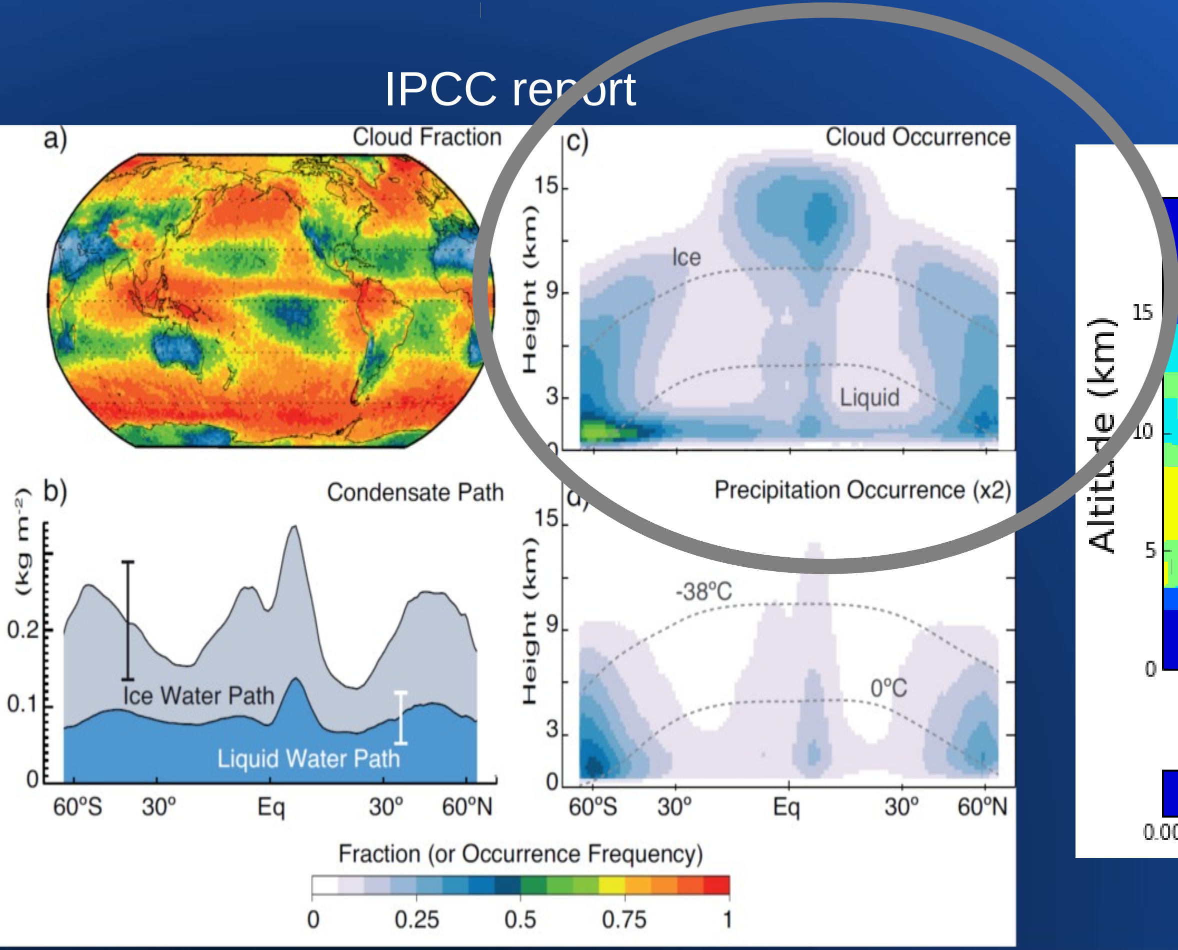


ISOSIM vs Calipso
(calipso hor. Average of 1000 km)

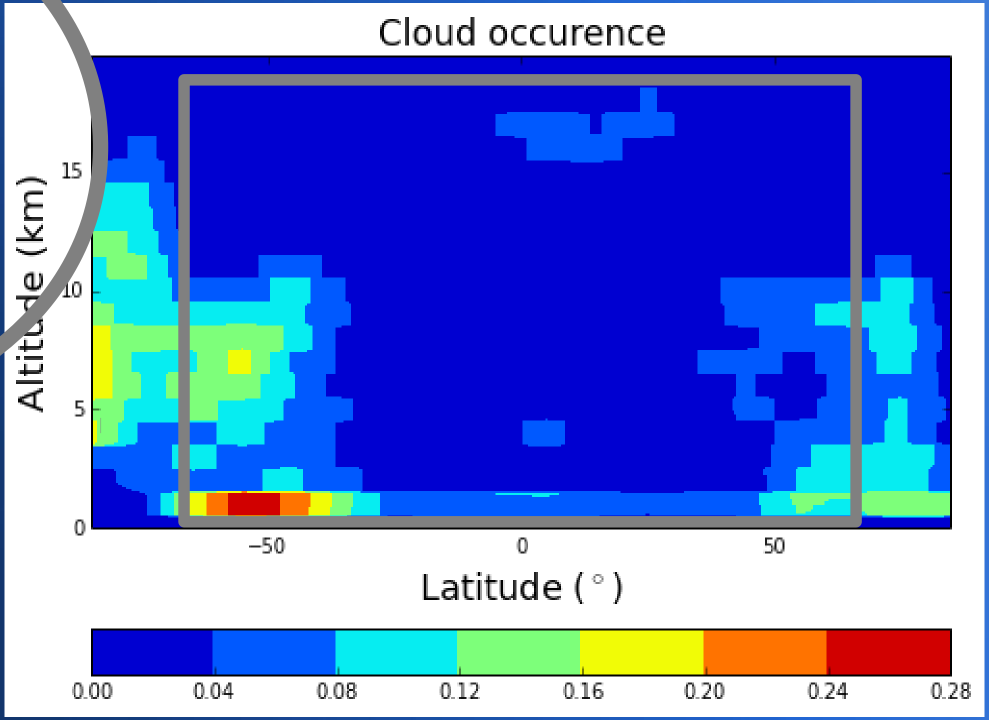


Clouds in ISOSIM

IPCC report



ISOSIM – August, 1st



Similar pattern but underestimation in ISOSIM by a factor ~2.