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Tracking GPS Radio Occultation Signals in the Lower Troposphere: CHAMP Observations and Simulation Studies

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Atmospheric refractivity profiles observed by the georesearch satellite CHAMP reveal significant biases compared to ECMWF meteorological fields at altitudes below 5 km. The bias of the zonally averaged fractional refractivity deviation decreases down to -2% at altitudes below 2 km.
The longitude-latitude distribution at altitudes between 3 and 5 km, however, reveals a remarkable zonal and meridional structure with positive biases of up to +1% over South America and negative biases of -2% over the Eastern Tropical Pacific.

In the past end-to-end simulation studies were performed to separate bias contributions caused by critical refraction from contributions induced by deviations from spherical symmetry of the atmospheric refractivity field and the receiver's signal tracking algorithm. These simulations are based on radio sonde profiles obtained on the Atlantic ocean by research vessel "POLARSTERN". In about 40% of the observations between 60S to 60N vertical refractivity gradients below the threshold value of -157 km^{-1} are found. These critical refraction layers occur almost exclusively in the planetary boundary layer between 1 to 2.5 km altitude.

The focus of our contribution is on the free troposphere. At altitudes above 3 km biases are caused by deviations of the refractivity field from spherical symmetry and receiver-induced tracking errors. We discuss results from simulations studies including closed-loop, fly-wheeling and open-loop signal tracking models. The results indicate that four quadrant carrier phase extraction outperforms the two quadrant method currently implemented on CHAMP. Within regions of low signal-to-noise ratios a promising signal detection technique is bandwidth reduction of the receiver's carrier tracking loop.

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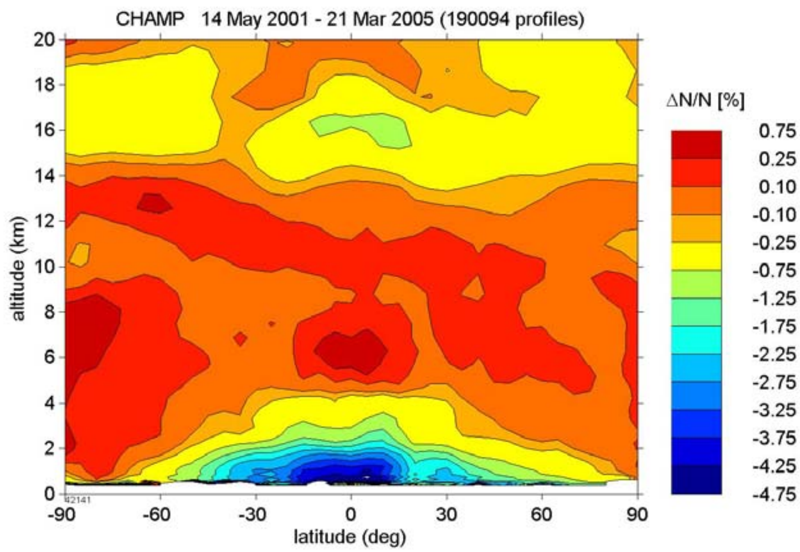
Status of CHAMP observations
- refractivity bias & standard deviation
- Amazon basin / Atlantic ocean

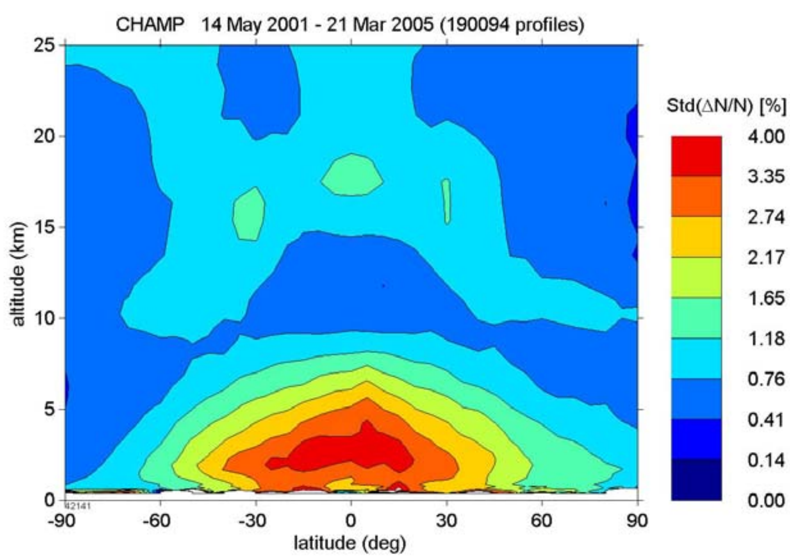
End-to-end simulations
- closed-loop („CHAMP“, „GPS/MET“)
- open-loop

Conclusion

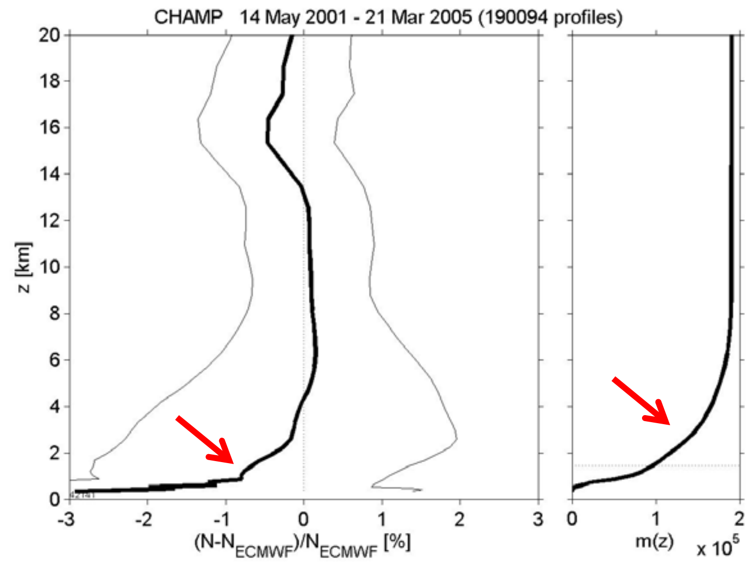
Refractivity bias



Standard deviation



Global mean



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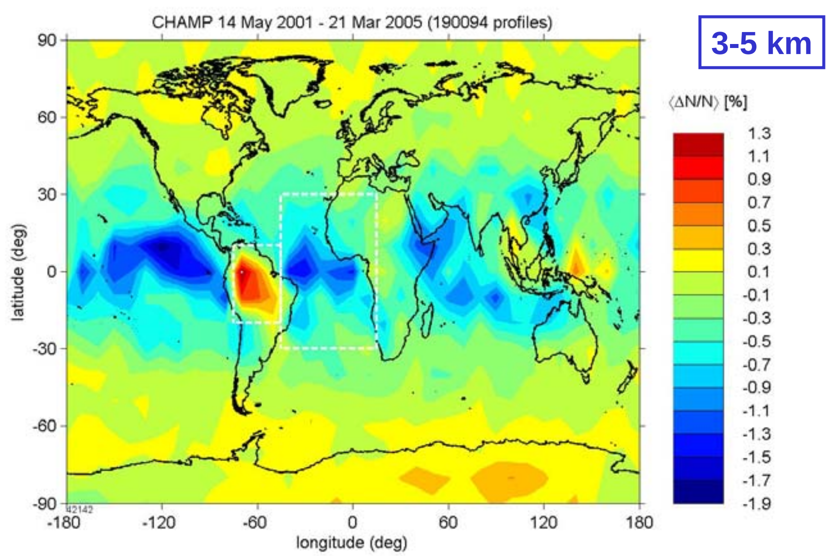
Refractivity bias



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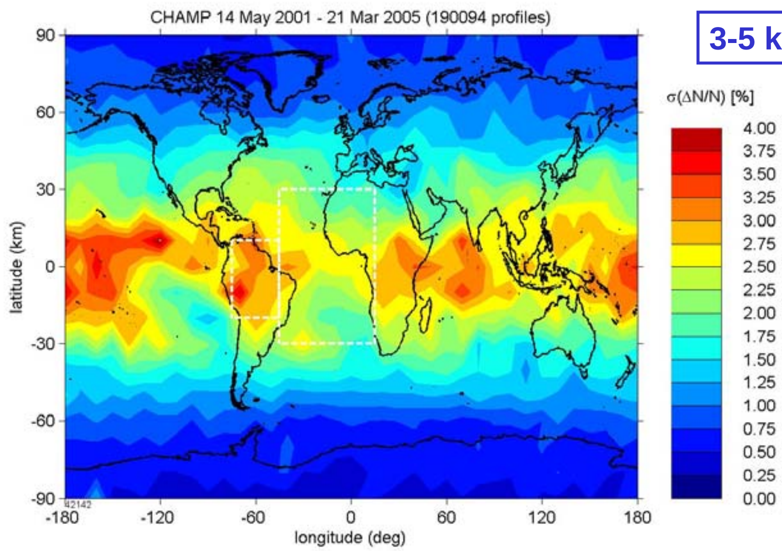
Standard deviation

3-5 km



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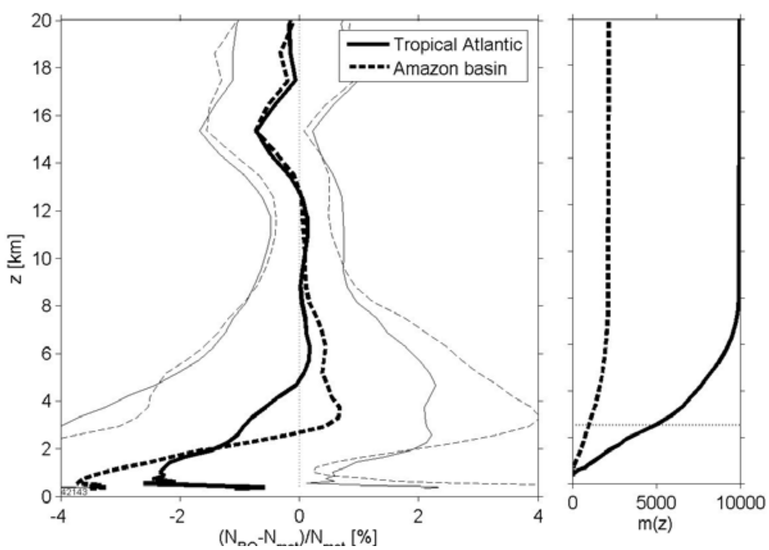
Bias: Atlantic / Amazon basin



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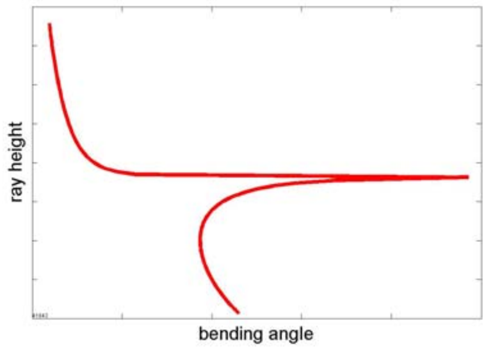
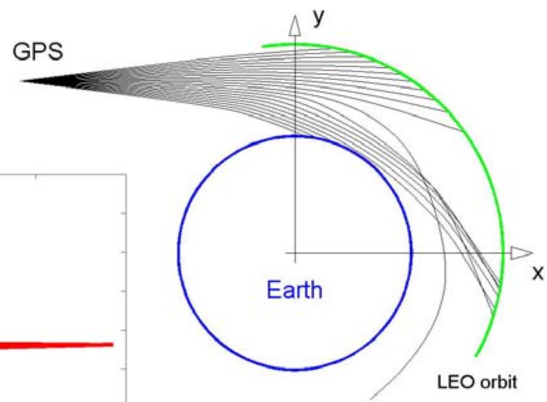
Critical refraction

threshold value for critical refraction

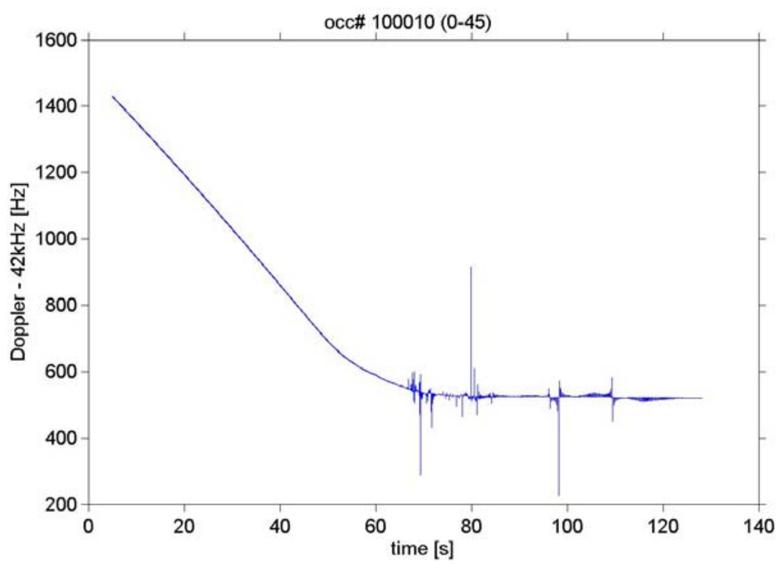
$dN/dz < -157\ km^{-1}$



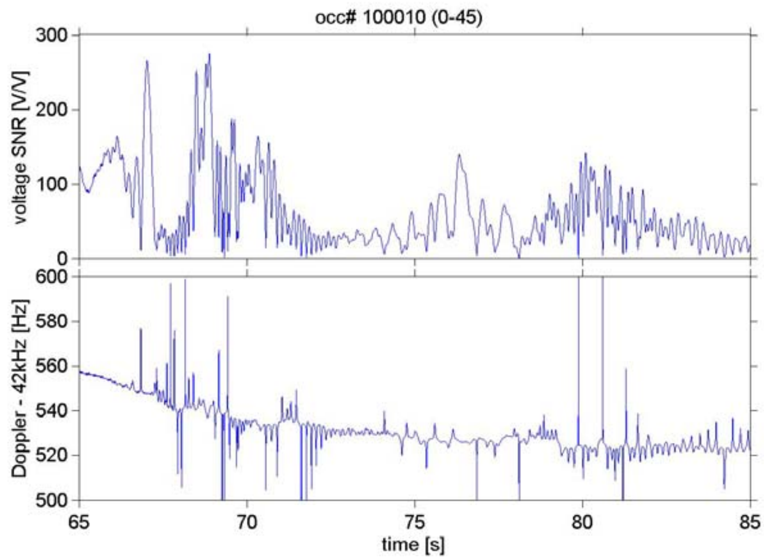


see e.g., S. Sokolovskiy, Radio Sci., 38 (3) 1058 doi:10.1029/2002RS002728, 2003

Simulated atmospheric profile (Doppler)



Simulated atmospheric profile (SNR & Doppler)



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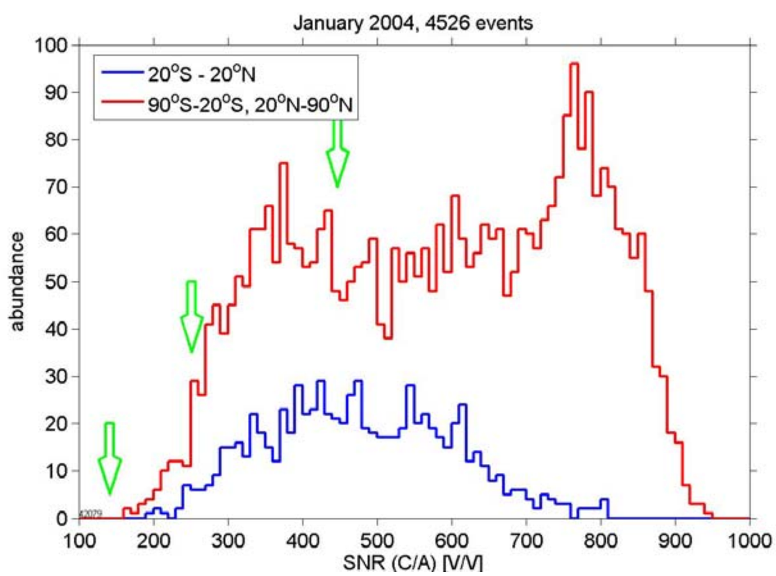
Voltage SNR



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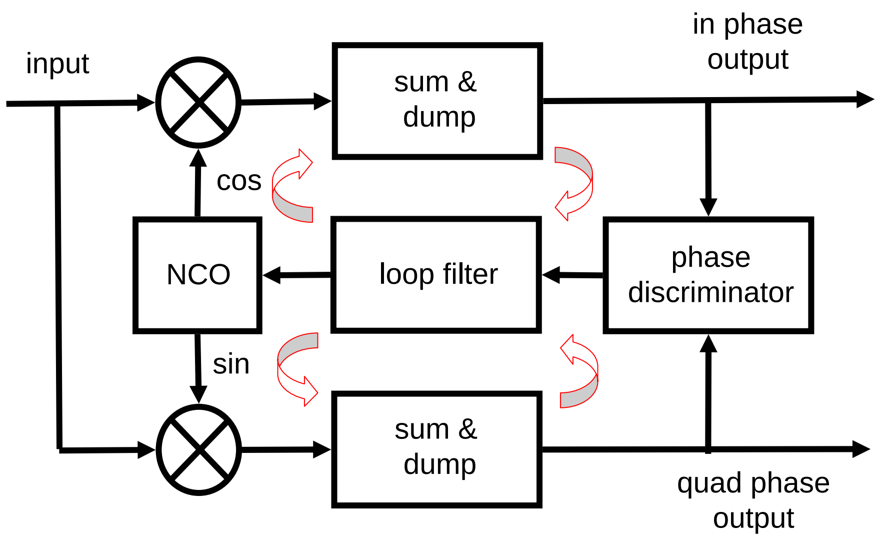
Closed-loop (carrier)



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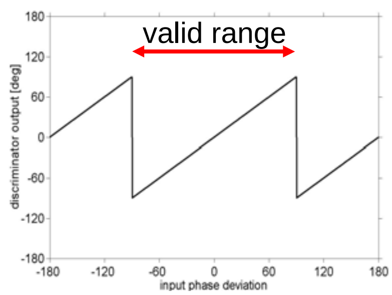
Residual phase extraction

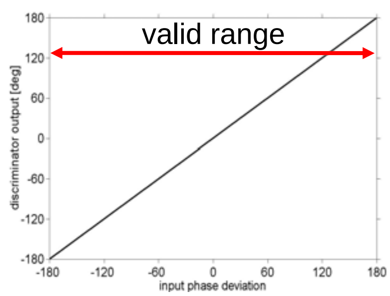
2-quadrant phase extraction

$\phi_R = atan(Q / I)$



4-quadrant phase extraction

$\phi_R = atan2(Q, I)$



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Loop filter parameter

2nd order loop, frequency update only

$$\delta f_{n+1}^{NCO} = \frac{1}{T}\left(\left(K_1 + K_2\right)\Phi_n^R - K_1\Phi_{n-1}^R\right)$$

3rd order loop, frequency update only

$$\delta f_{n+1}^{NCO} = \delta f_n^{NCO} + \frac{1}{T}\left(\left(K_1 + K_2 + K_3\right)\Phi_n^R + \left(-2K_1 - K_2\right)\Phi_{n-1}^R + K_1\Phi_{n-2}^R\right)$$

Φ_n^R residual phase [cycles]

T sampling time (1 ms)

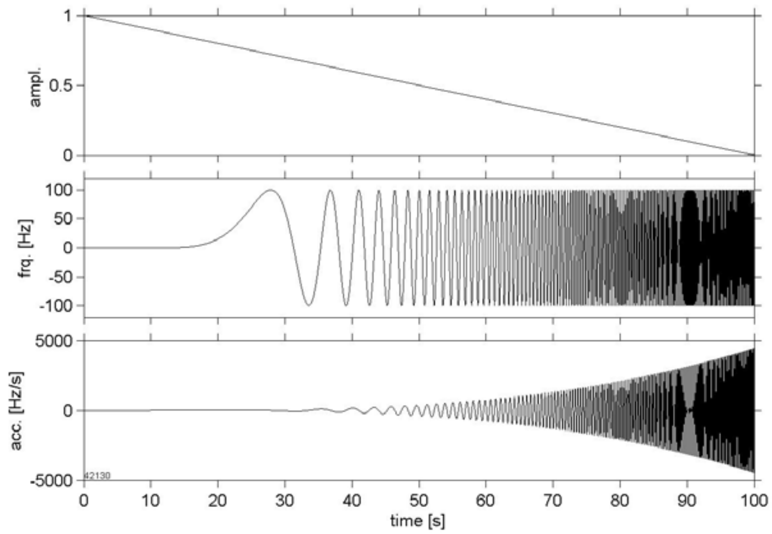
δf_n^{NCO} frequency change applied to NCO

Loop parameters

bandwidth [Hz]	K_1	K_2	K_3	comment
30	$7.358\ 10^{-2}$	$2.810\ 10^{-3}$		2nd order, standard under-damped
5	$1.283\ 10^{-2}$	$7.365\ 10^{-5}$	$1.590\ 10^{-7}$	3rd order, standard under-damped
30	$7.172\ 10^{-2}$	$2.383\ 10^{-3}$	$3.020\ 10^{-5}$	3rd order, standard under-damped
30	$8.003\ 10^{-2}$	$2.259\ 10^{-3}$	$2.172\ 10^{-5}$	3rd order, super-critically damped

S. A. Stephens and J. B. Thomas, Controlled-root formulation for digital phase-locked loops, *IEEE Transactions on Aerospace and Electronic Systems*, *31* (1), 78-95, 1995.

Test signal



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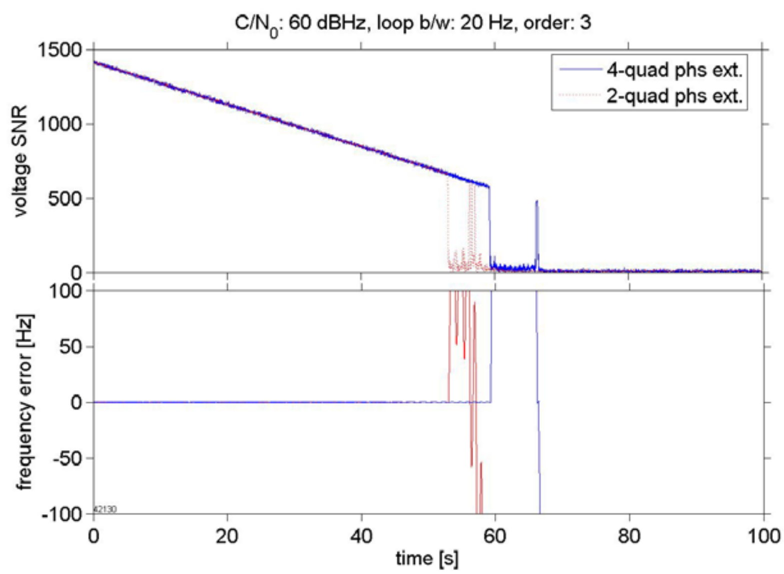
Loss of lock: phase acceleration



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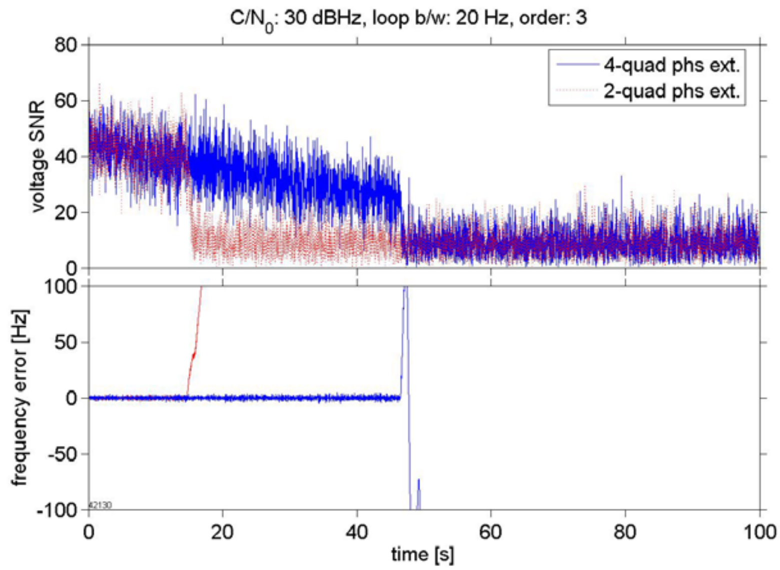
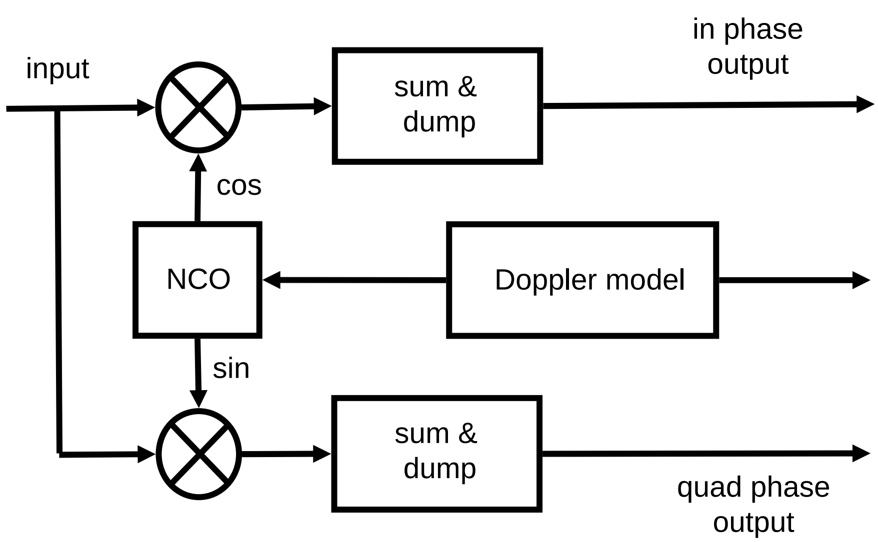
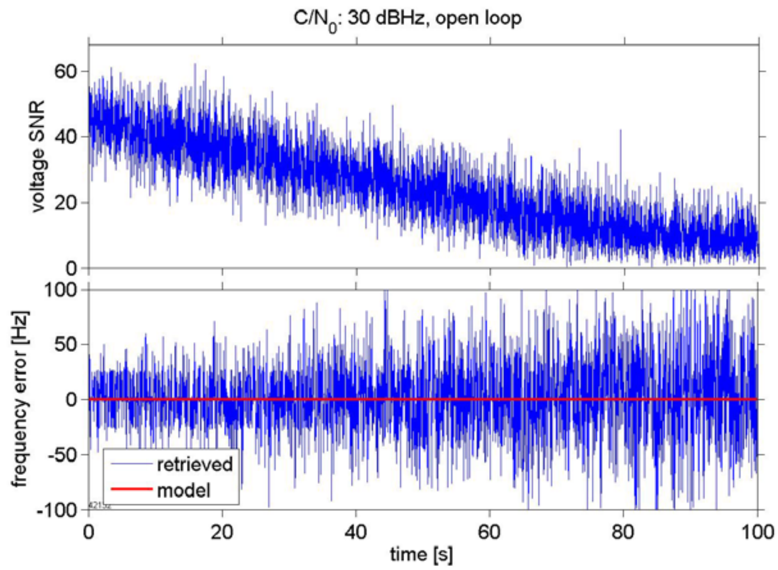
Loss of lock: low SNR



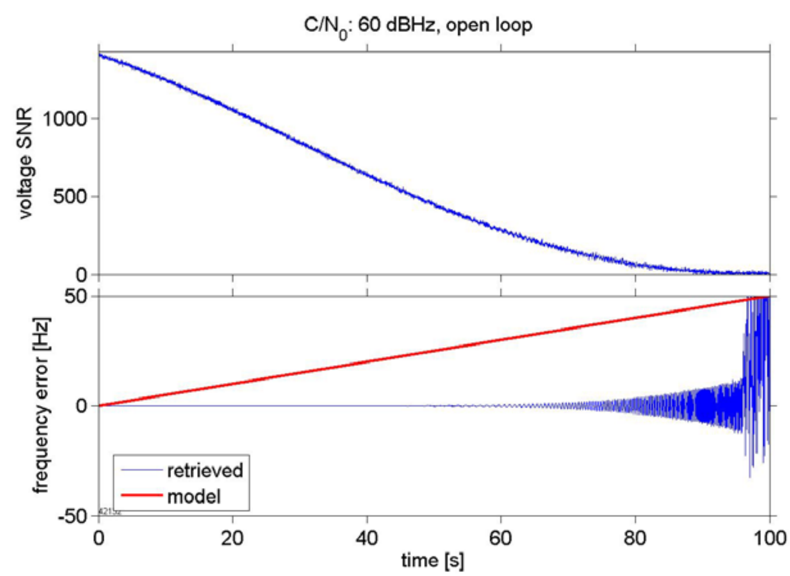
Open-loop



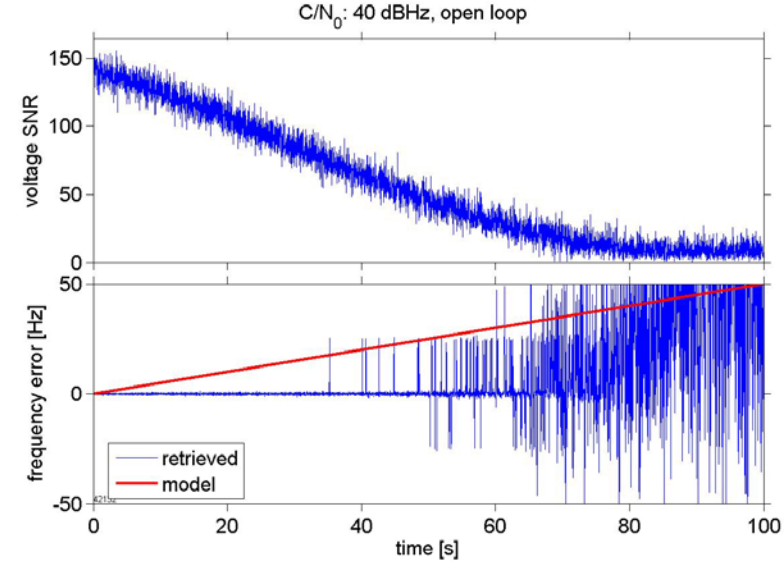
Open-loop: no model error



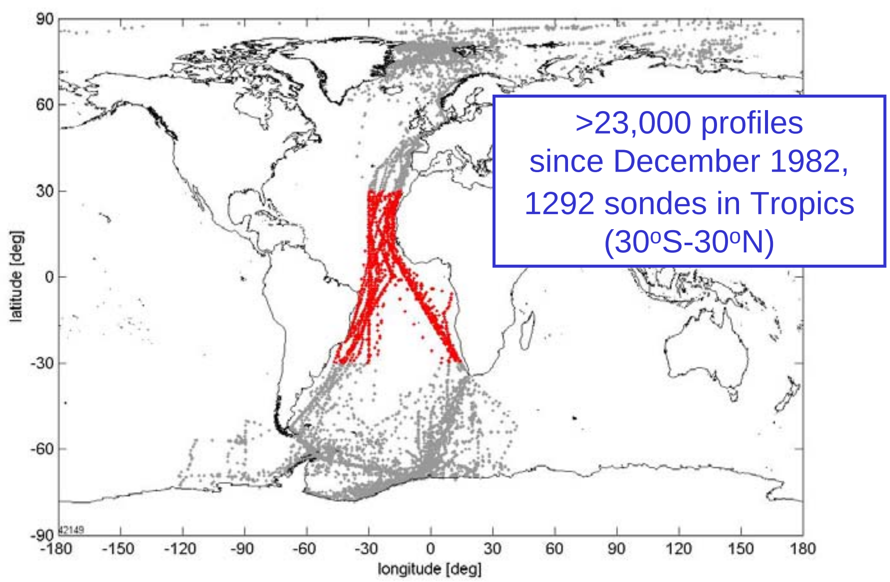
Open-loop: with model error



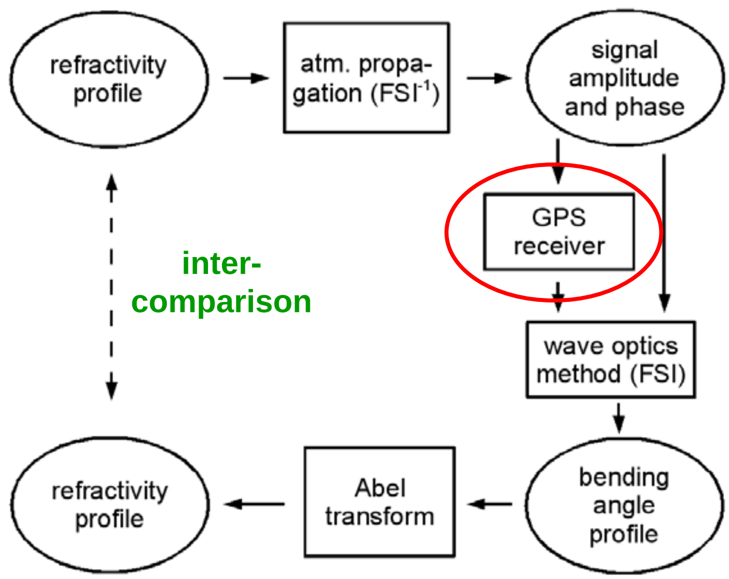
Open-loop: with model error



„POLARSTERN“ radio sonde data set



End-to-end simulation



Receiver model

inphase & quadphase correlation sums

$$I = \int dt\, u(t)\cos(2\pi f_{NCO} t) + N_I$$

$$Q = \int dt\, u(t)\sin(2\pi f_{NCO} t) + N_Q$$

u(t) : received signal
$N_{I,Q}$: noise
f_{NCO} : frequency of numerically-controlled oscillator, updated every C/A code period

receiver output

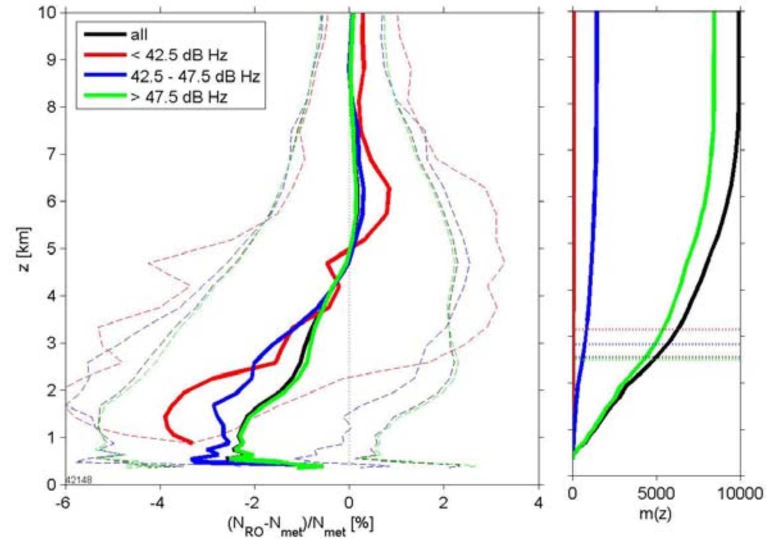
$$A = \sqrt{I^2 + Q^2}$$

$$\phi = \phi_{NCO} + \phi_R$$

A : signal amplitude
Φ_R : residual phase
Φ_{NCO} : NCO phase

C. O. Ao et al., JGR, 108 (D18) 4577 doi:10.1029/2002JD003216, 2003

CHAMP observation (Atlantic ocean)



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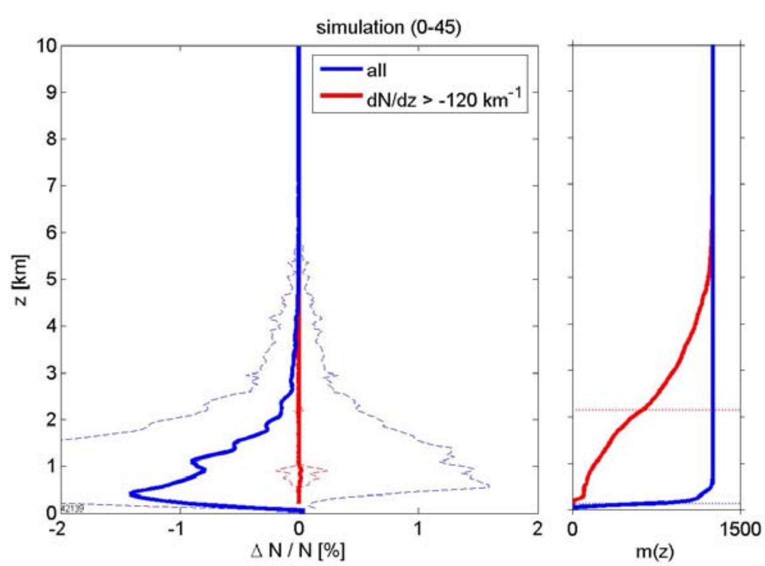
Ideal (no) receiver



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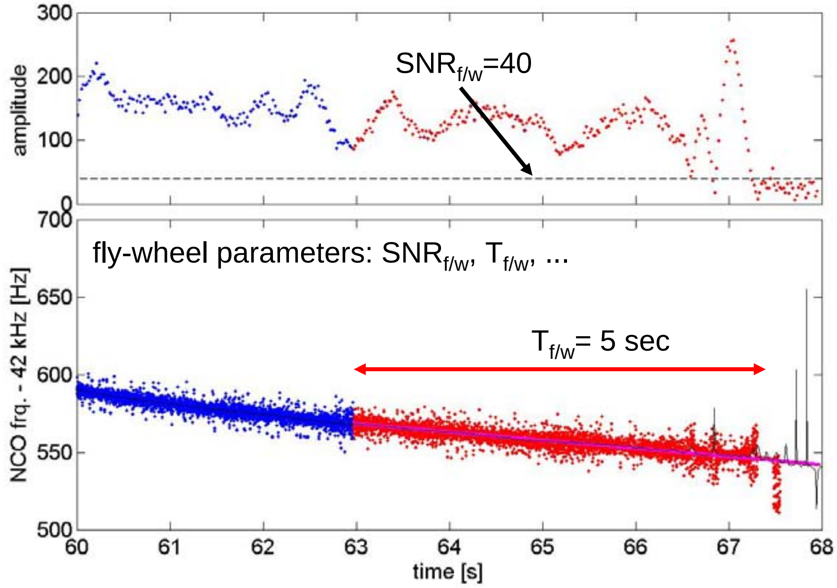
Fly-wheeling tracking mode



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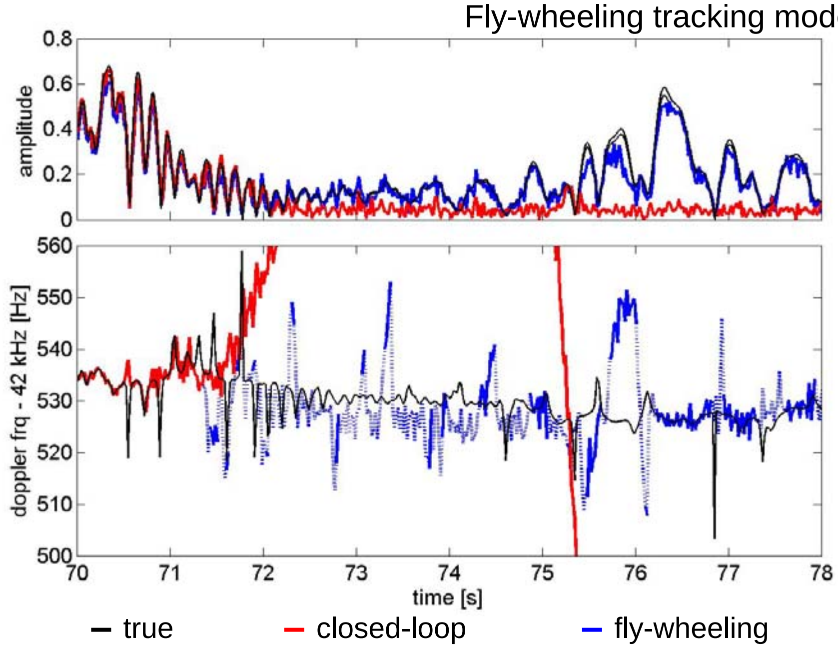
Fly-wheeling tracking mode (II)



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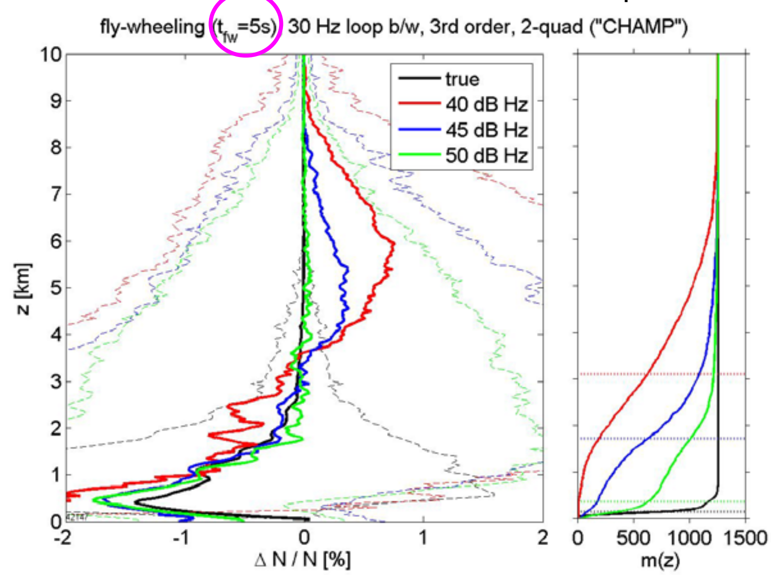
Simulation: „pseudo-CHAMP“



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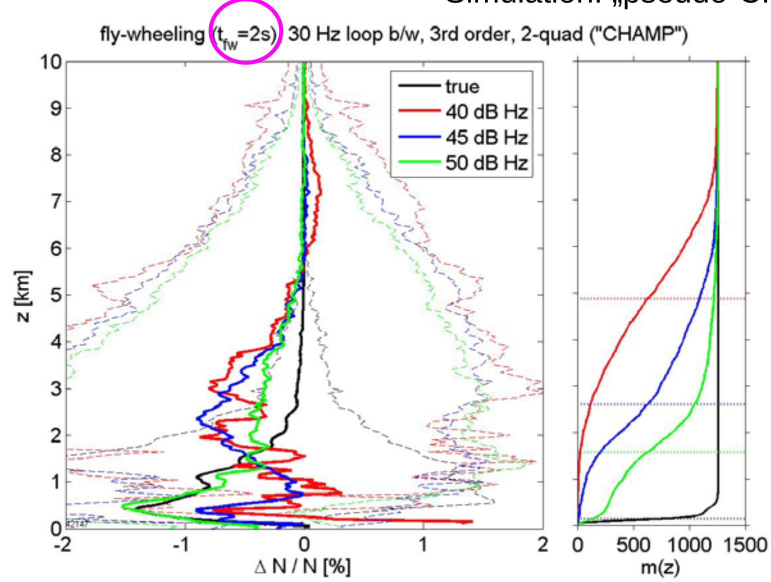
Simulation: „pseudo-CHAMP“



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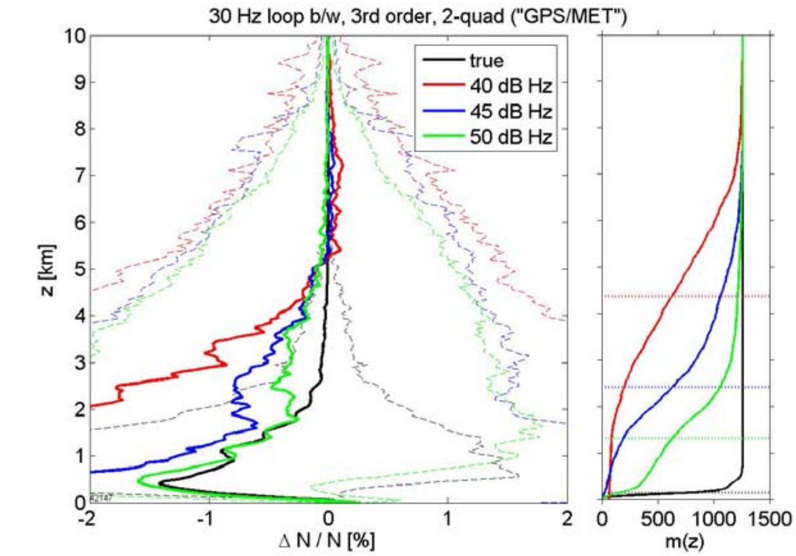
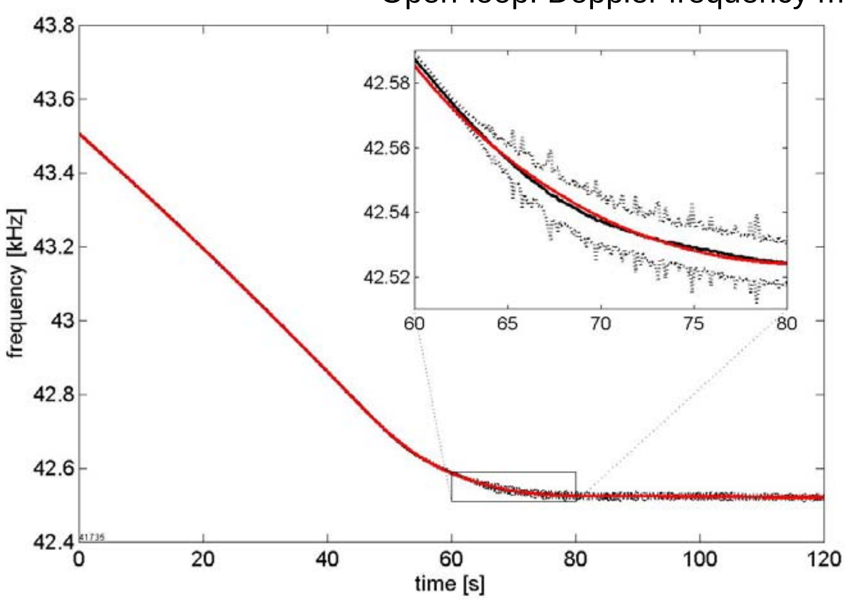
Simulation: „pseudo-GPS/MET“

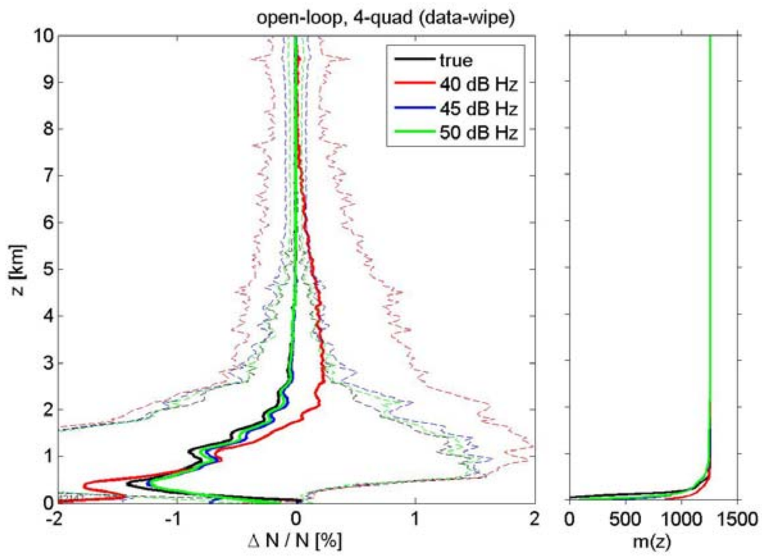


Open-loop: Doppler frequency model



— parameterization — mean profile ··· 1 σ std. deviation

Simulation: open-loop



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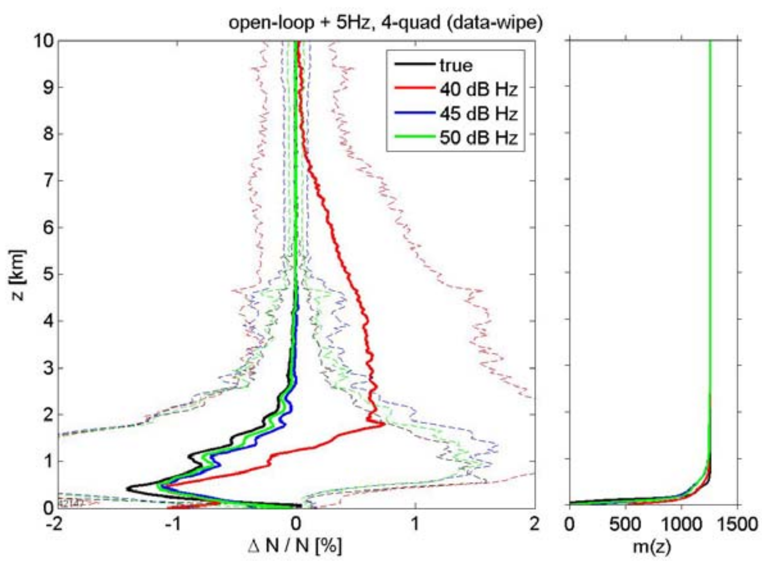
Simulation: open-loop, model biased by +5 Hz



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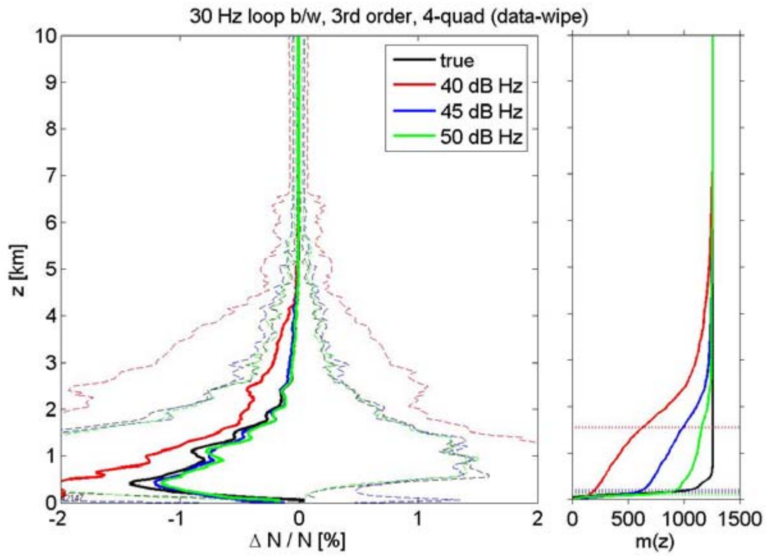
Simulation: „data-wipe“



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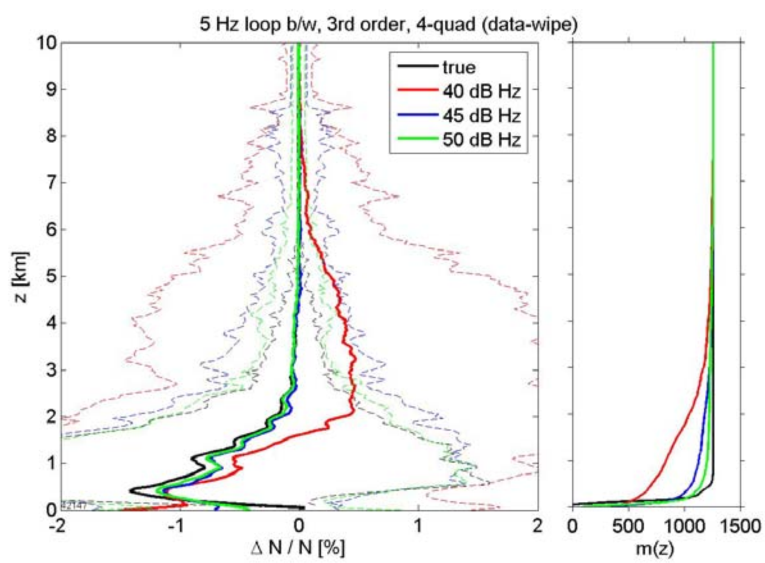
Simulation: reduced loop bandwidth



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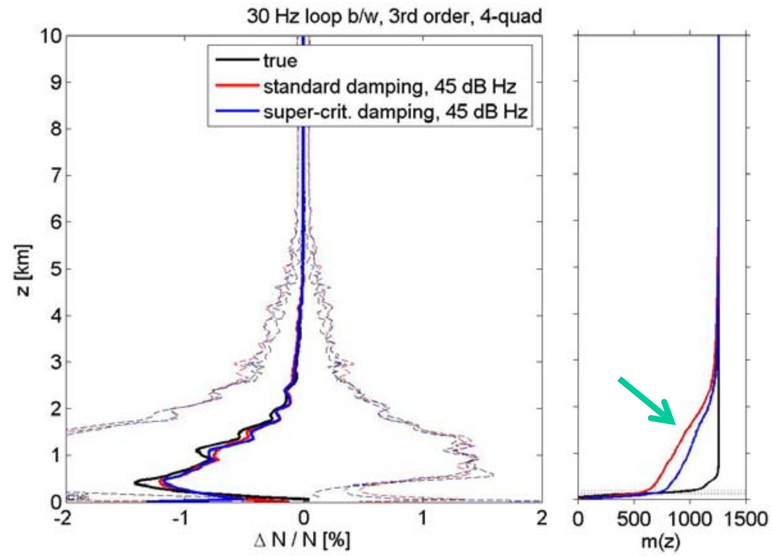
Simulation: effect of damping



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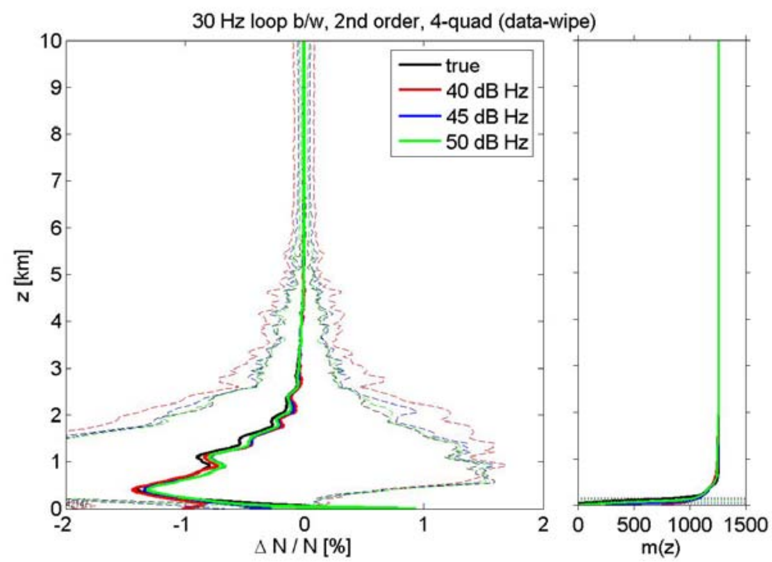
Simulation: reduced loop order



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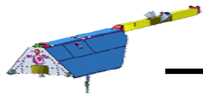

Conclusions

CHAMP observations

Negative bias on global scale (lower troposphere)

Positive bias in Amazon basin

Frequently loss of lock at PBL

Simulations

Data-wipe has positive impact

Open-loop: near-perfect retrieval w.r.t. N-bias, standard deviation and tracking within PBL, *but* possibly model-induced N-bias at low SNR (?)

Closed-loop: alternative options available (reduced loop bandwidth, lower loop order)

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