

Optimal noise filtering and ionospheric calibration of GPS radio occultation signals

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2nd FORMOSAT-3/COSMIC Data Users Workshop
Boulder, CO, October 22-24, 2007

Model-independent ionospheric calibration:

$$Y(X) = C_1 Y_1(X) - C_2 Y_2(X)$$

$$C_1 = f_1^2 / (f_1^2 - f_2^2); \quad C_2 = f_2^2 / (f_1^2 - f_2^2)$$

$$f_1 = 1.57542 \text{GHz}; \quad f_2 = 1.2276 \text{GHz}$$

Y and X can be:

excess phase and time;

or bending angle and impact parameter.

Assumption: ionospheric effects are additive and $\sim 1/f^2$

Additive noise on Y1 and Y2 is amplified by factors C1 and C2

Noise on Y2 is larger than on Y1 due to:

- less power of the GPS L2 signal;
- semi-codeless tracking of L2 signal.

Modified ionospheric calibration (to reduce the effect of L2 noise):

$$Y(X) = Y_1(X) + C_2 \langle Y_1(X) - Y_2(X) \rangle$$

where $\langle \rangle$ means extra smoothing compared to that on Y_1
Assumption: $\langle \rangle$ suppresses the noise by still preserving the ionospheric effects (larger scales) to calibrate Y_1

This approach was first time applied for processing GPS/MET “A/S on” data in 1995:

Rocken C. et al., JGR, 102, D25, 29,849-29,866, 1997

Smoothing Y_1 and $Y_1 - Y_2$ with different ad hoc fixed windows:

Schreiner W. et al. Proc. ION 2000, Long Beach, CA 103-112, 1998

Steiner A. et al., Ann. Geophys., 17, 122-138, 1999

Gorbunov M., Radio Sci., doi:10.1029/2000RS002370, 2002

Hajj G. et al., J. Atm. Solar-Terr. Phys., 64, 451-469, 2002

Wickert J. et al., JMSJ, 82, B1, 381-395, 2004

Kuo et al., JMSJ, 82, B1, 507-531, 2004

Beyerle G. et al., GRL, doi:10.1029/2005GL023109, 2005

It is clear that suppression of the Y2 noise by increasing of the smoothing window comes at the expense of the un-calibrated (small-scale) ionospheric effects on Y1

The magnitude of the Y2 noise and of the small-scale ionospheric effects are different for each occultation

Thus the optimal smoothing window for Y1-Y2 which minimizes the sum of the errors due to the Y2 noise and to the un-calibrated ionospheric effects is different for each occultation.

At COSMIC Data Analysis and Archive Center (CDAAC) an optimal smoothing window for Y1-Y2 is estimated individually for each occultation.

CDAAC uses FFT for low-pass filtering of the phase (concurrently with the calculation of derivatives)

$$y(k) = (2\pi)^{-1} \int y(x) \exp(-ikx) dx$$

$$\langle y(x) \rangle = \int y(k) w(k, k_0) \exp(ikx) dk$$

$$\langle y'(x) \rangle = -i \int y(k) w(k, k_0) \exp(ikx) k dk$$

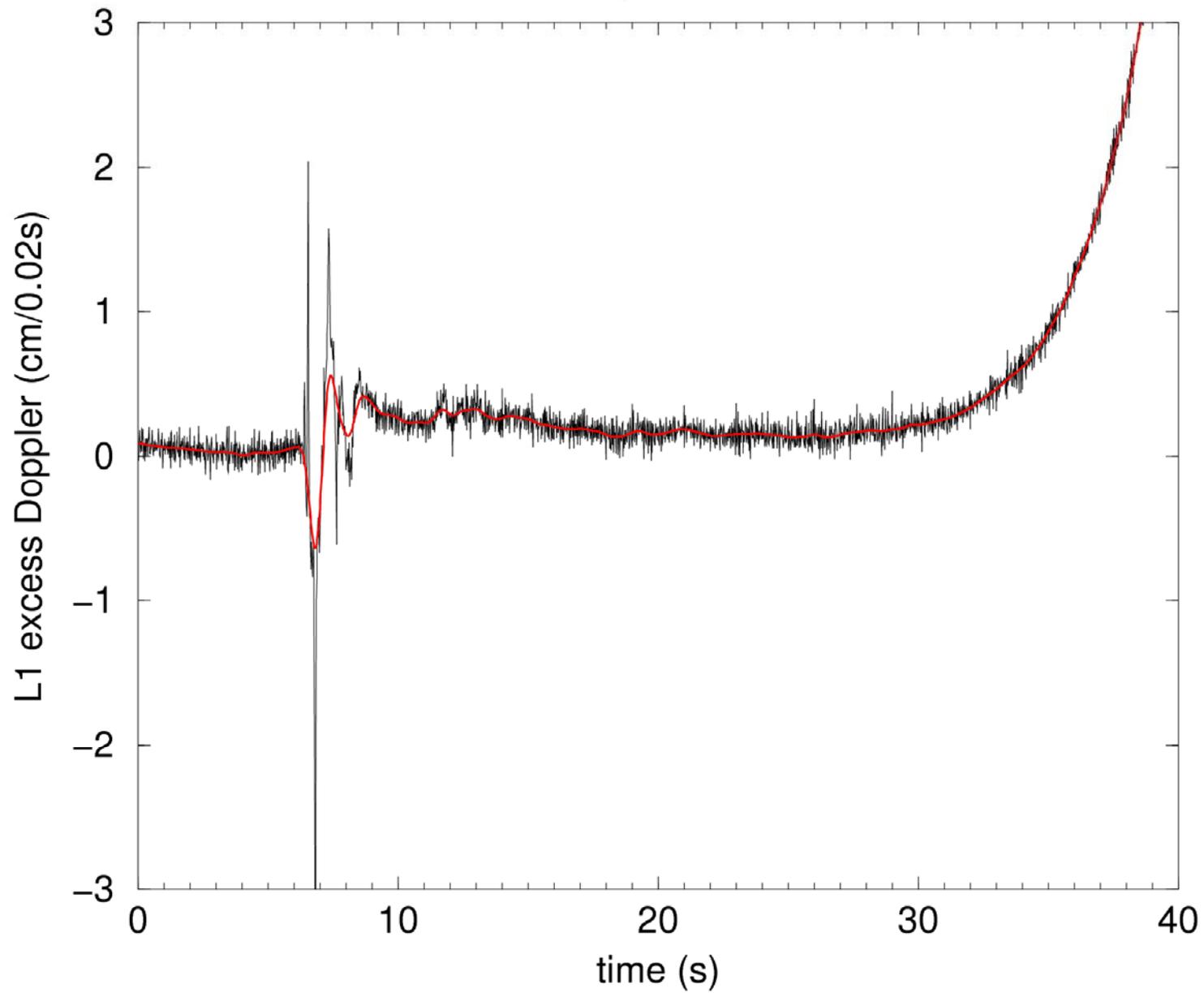
$$\langle y''(x) \rangle = \int y(k) w(k, k_0) \exp(ikx) k^2 dk$$

where $w(k, k_0) = \exp(-k^2 / k_0^2)$

the width of the filter response function (smoothing window) $\sim 1/k_0$

L1 phase is low-pass filtered with the window 0.5 s (25 samples)
- consistent with the size of the Fresnel zone for $v \sim 2-3$ km/s

COSMIC, occulted link



Finding optimal window for smoothing Y1-Y2

Use height interval 60-80 km:

- the noise and the uncalibrated ionospheric effects overshadow the neutral-atmospheric variations;
- effect of sporadic ionospheric layers is not significant for most occultations; thus the obtained estimate of the residual noise is applicable, in most cases, for the profile below.

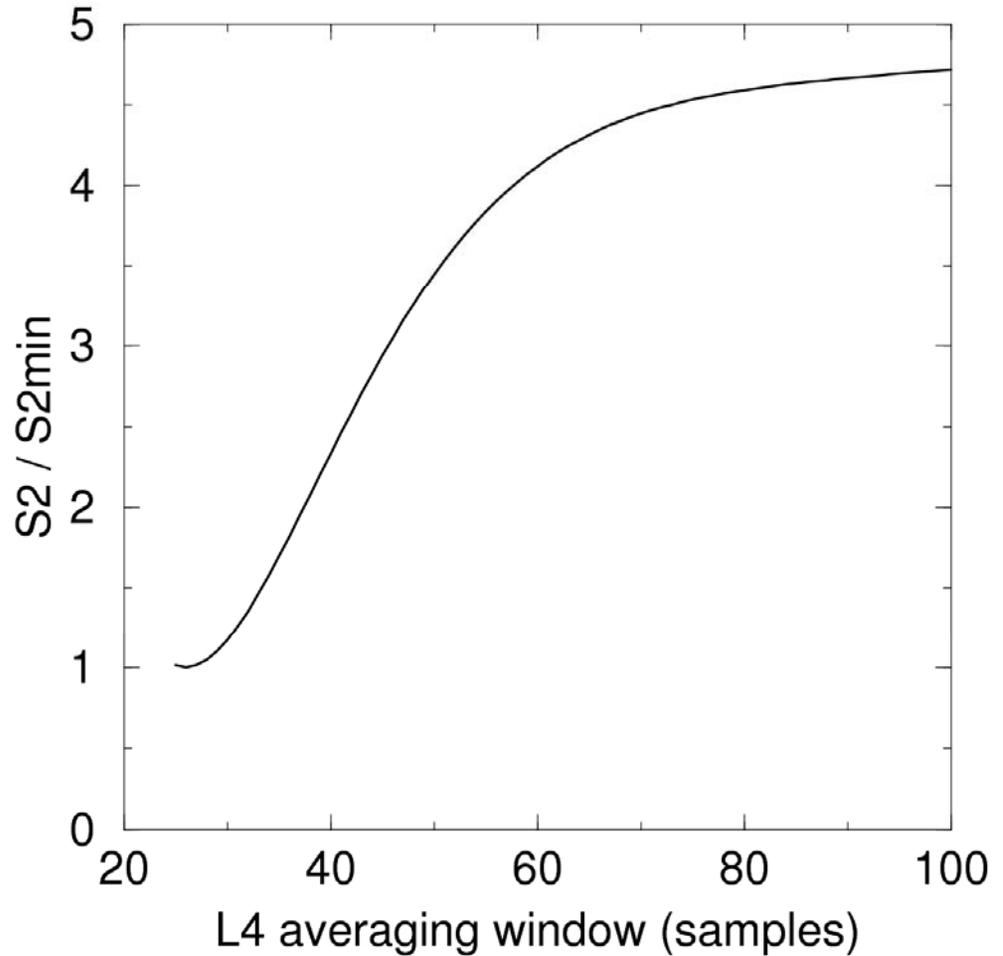
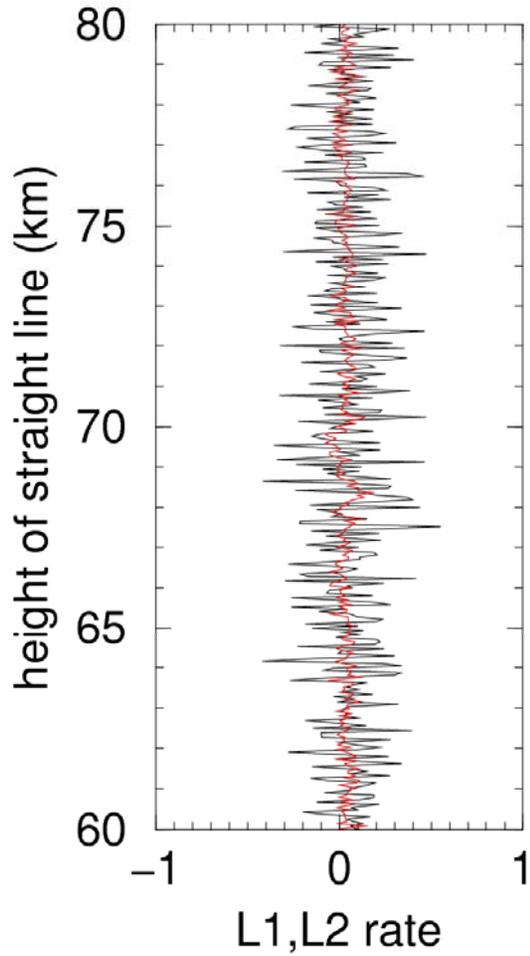
Simple criterion: minimizing fluctuation of the ionosphere-free Doppler (other criteria yield similar results):

$$S2 = \int_{60km}^{80km} |Y_1''(x) + C_2 < Y_1''(x) - Y_2''(x) >|^2 dx = \min$$

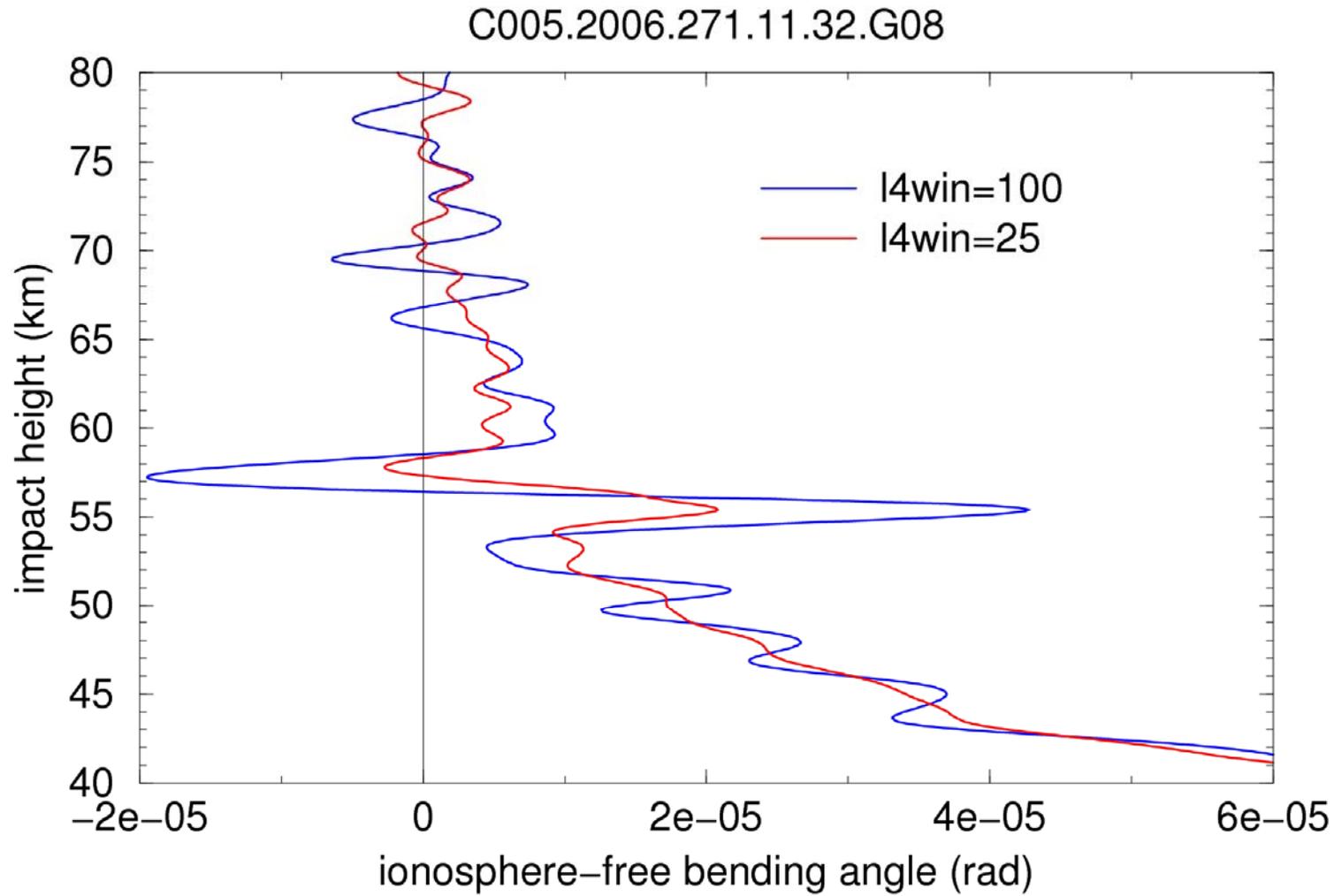
Occultations with different levels of the L2 noise and the ionospheric irregularities yield different optimal smoothing windows < >

Low (L2 noise / iono. irreg.) level; opt. window = 25 samples

C005.2006.271.11.32.G08

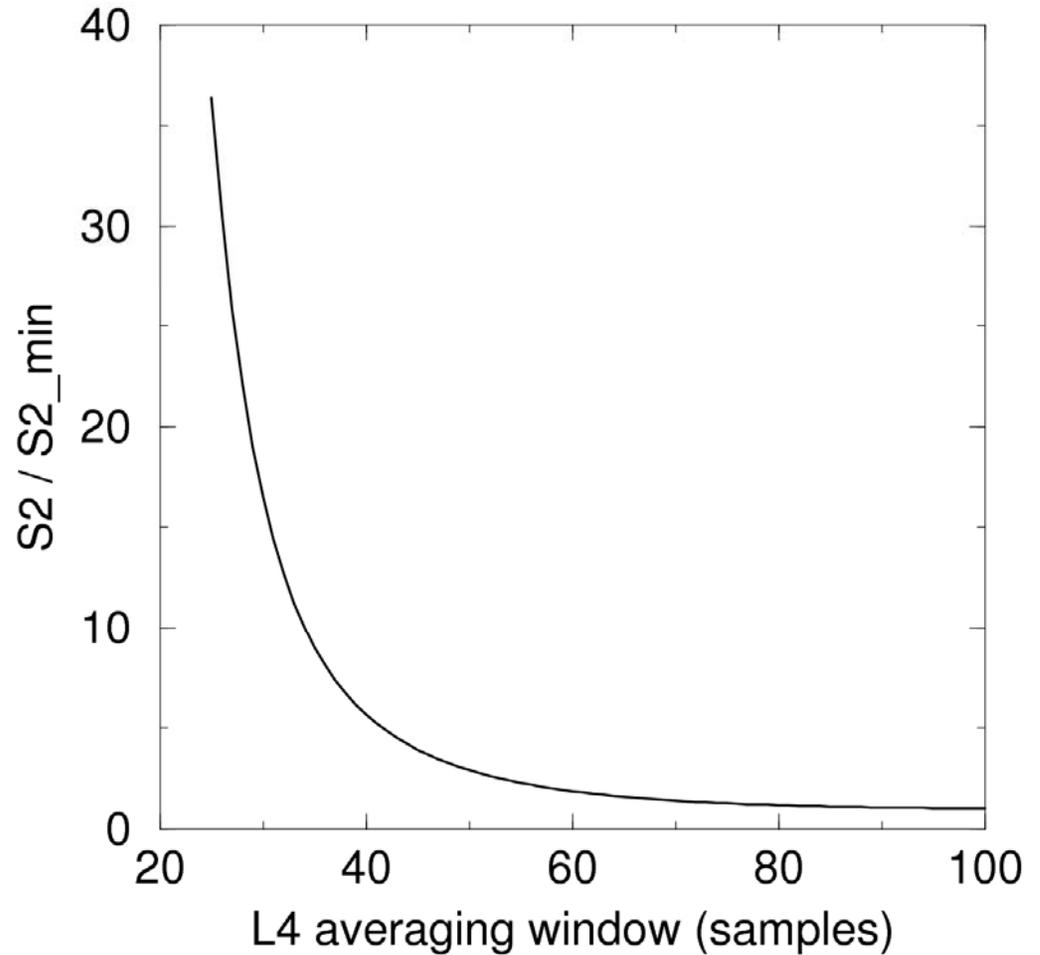
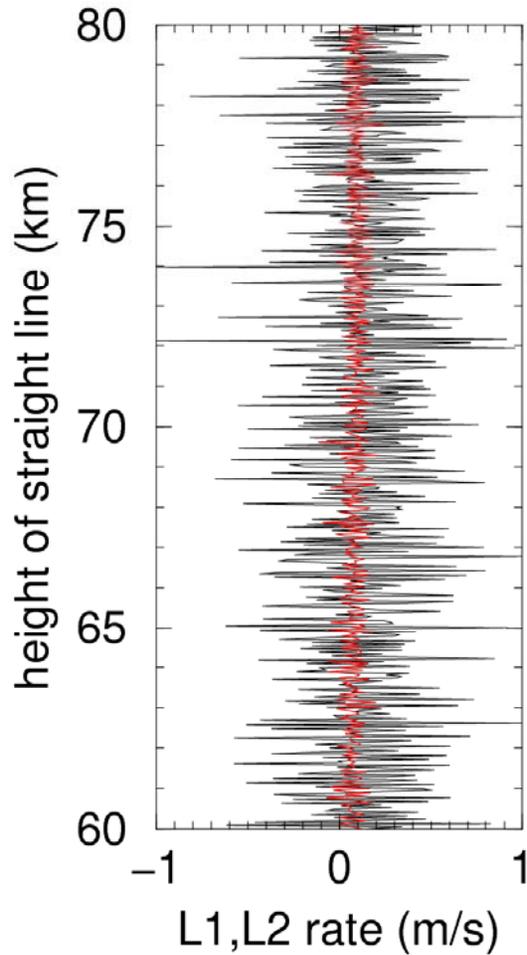


Low (L2 noise / iono. irreg.) level; opt. window = 25 samples

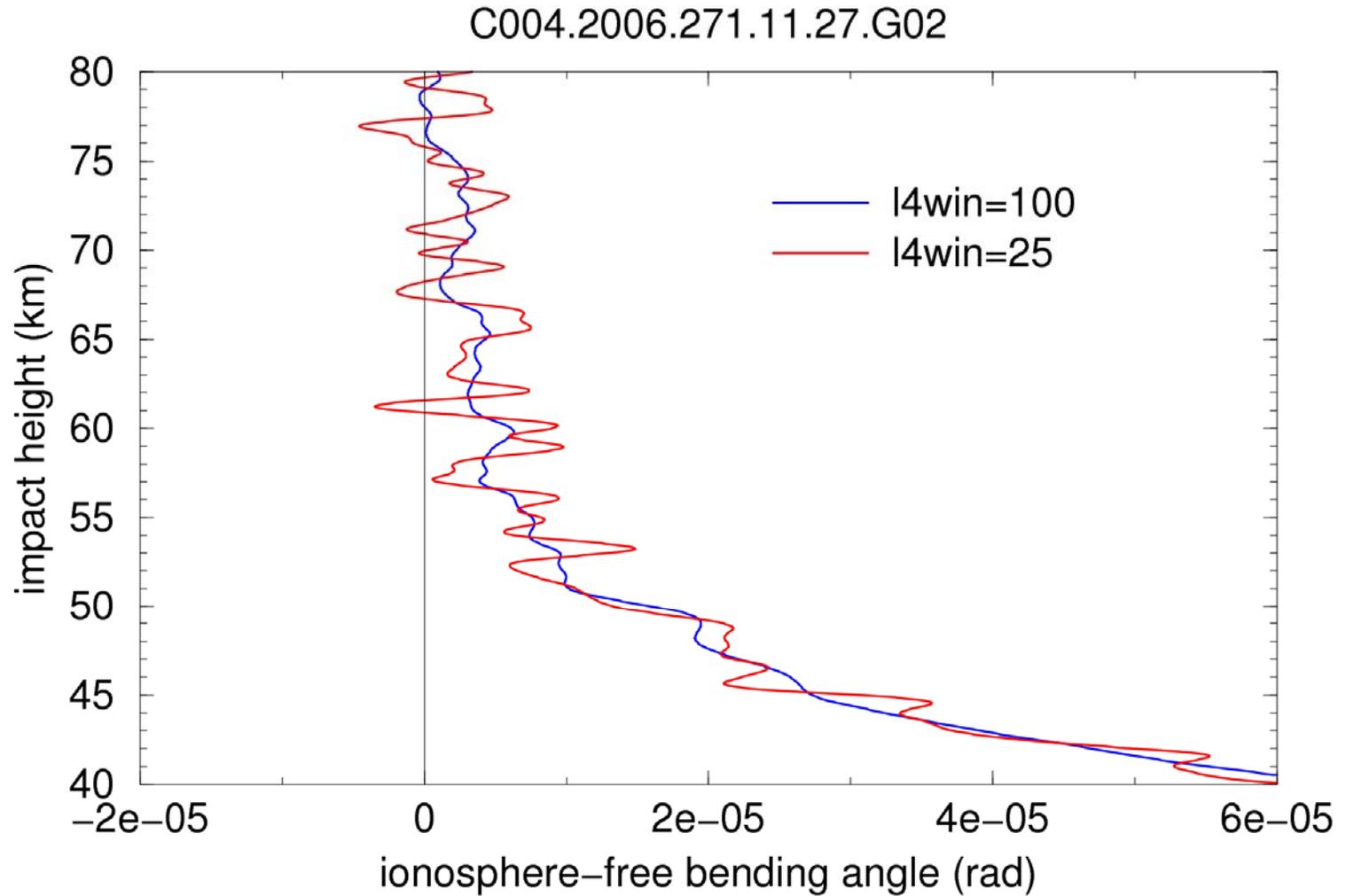


High (L2 noise / iono. irreg.) level; opt. window > 100 samples

C004.2006.271.11.27.G02

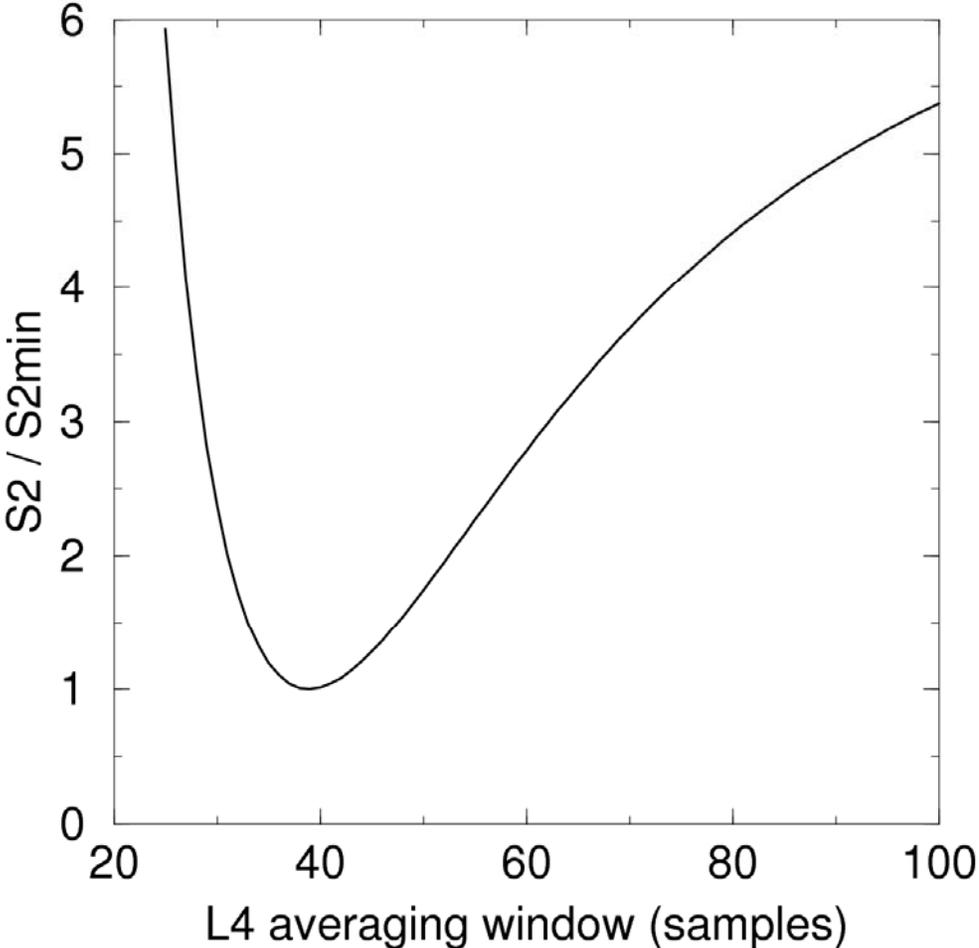
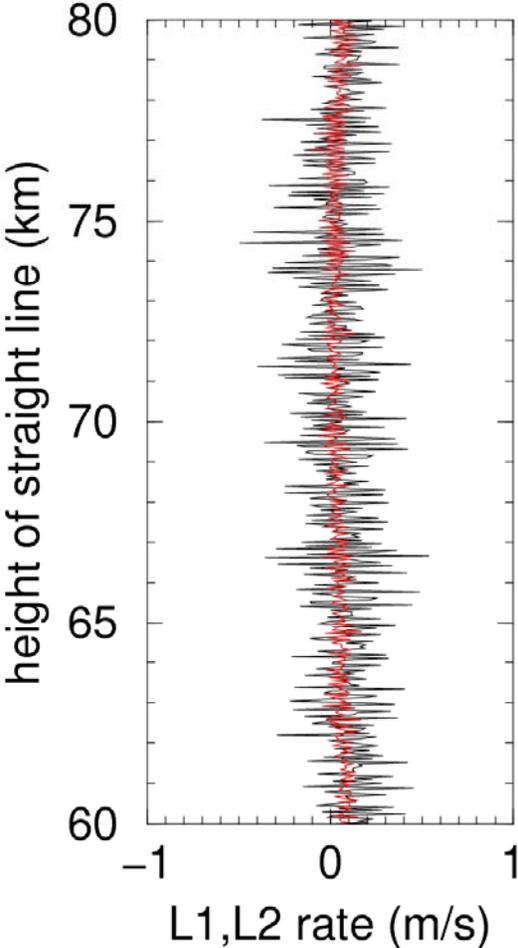


High (L2 noise / iono. irreg.) level; opt. window > 100 samples

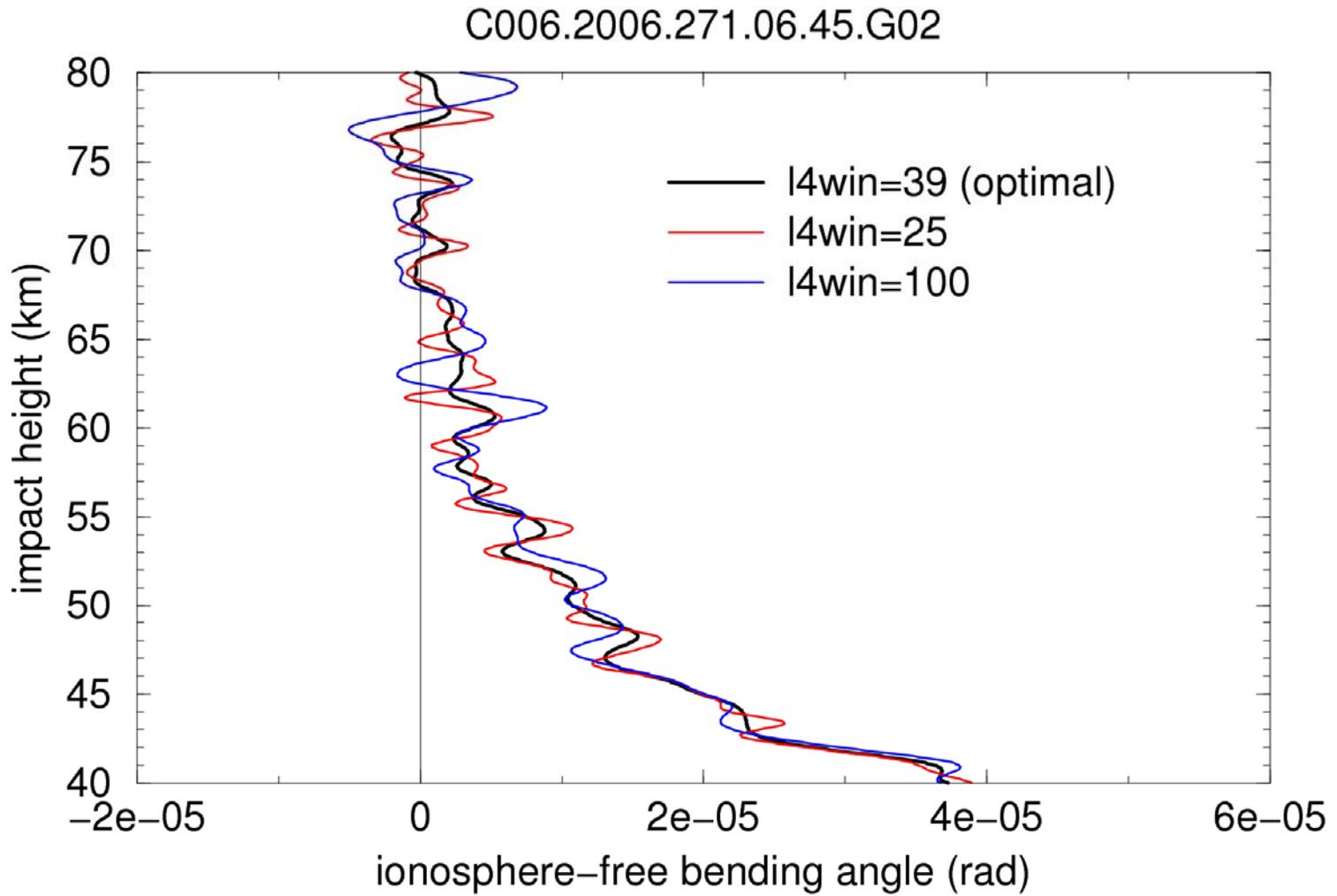


Medium (L2 noise / iono. irreg.) level; opt. window = 39 samples

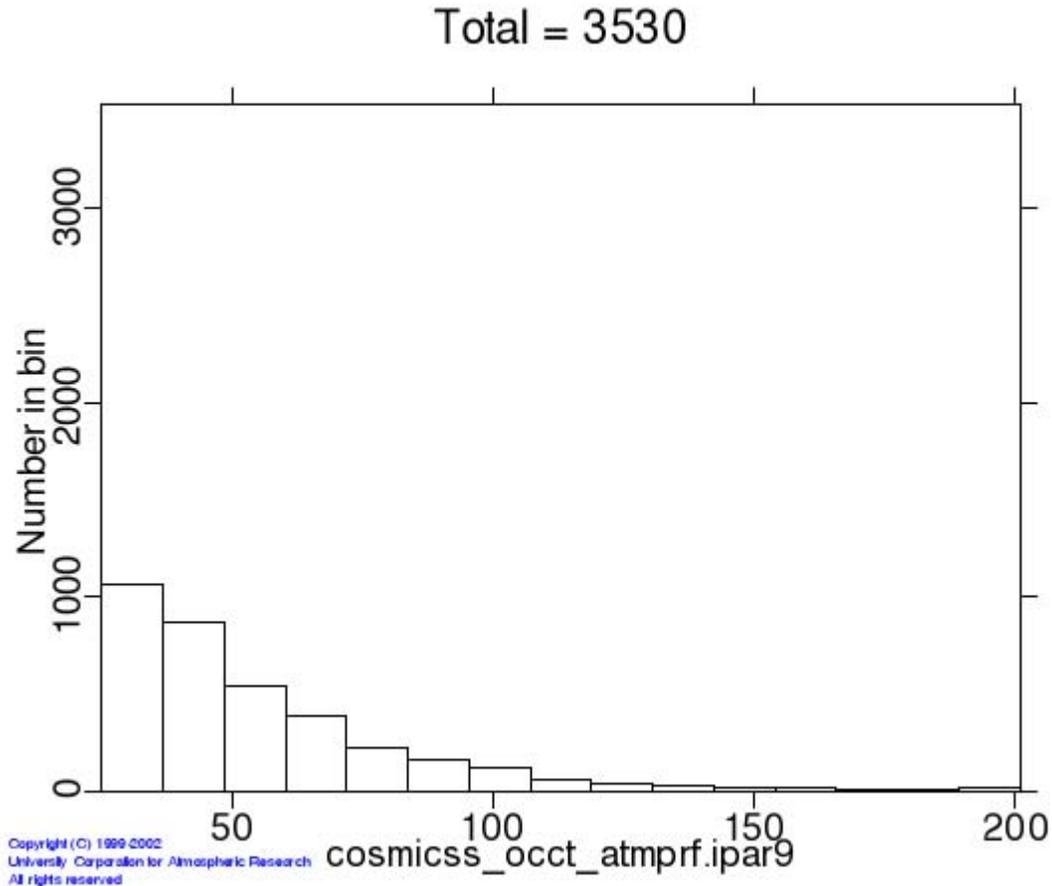
C006.2006.271.06.45.G02



Medium (L2 noise / iono. irreg.) level; opt. window = 39 samples

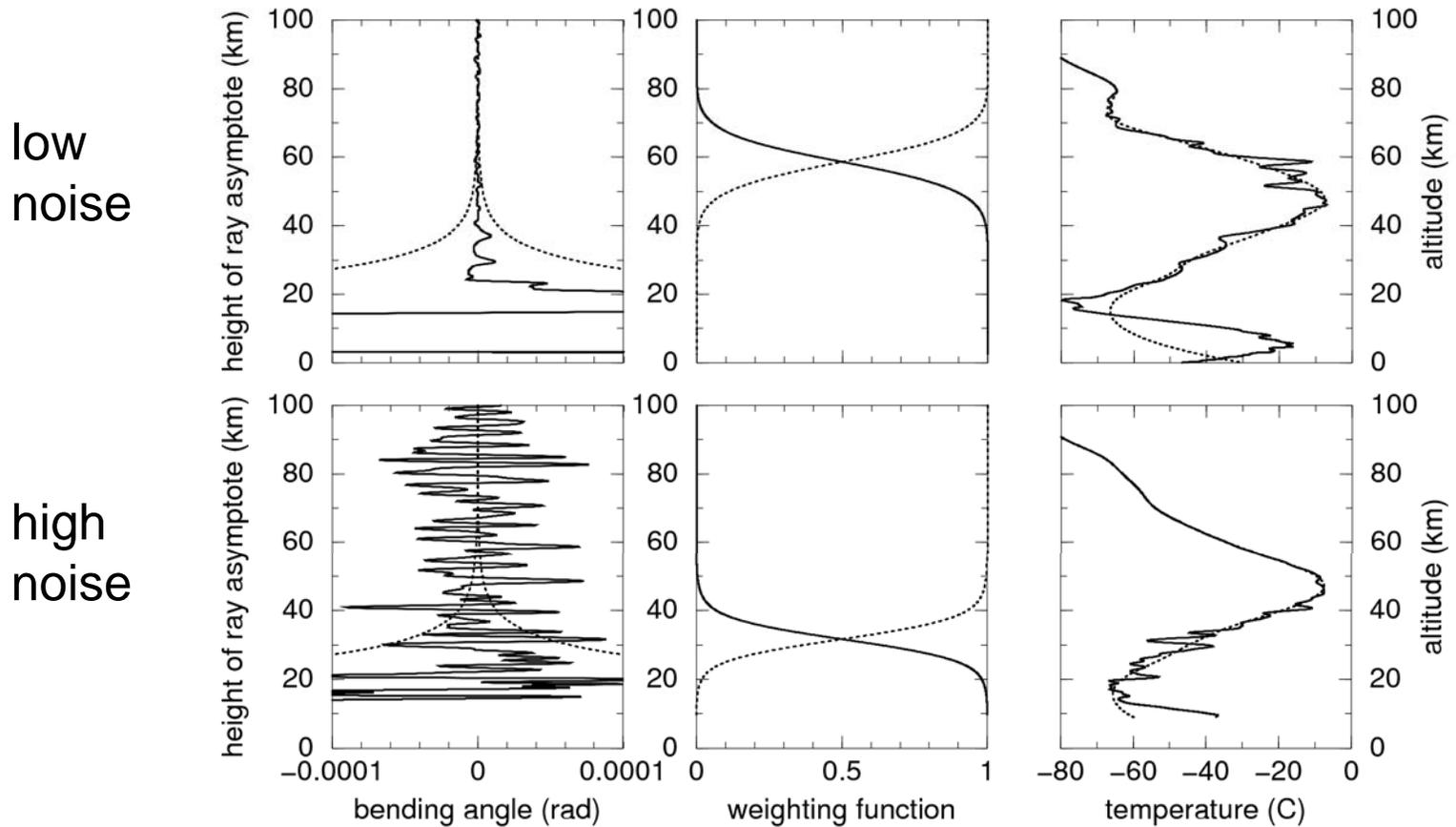


Statistical distribution of the optimal filtering window

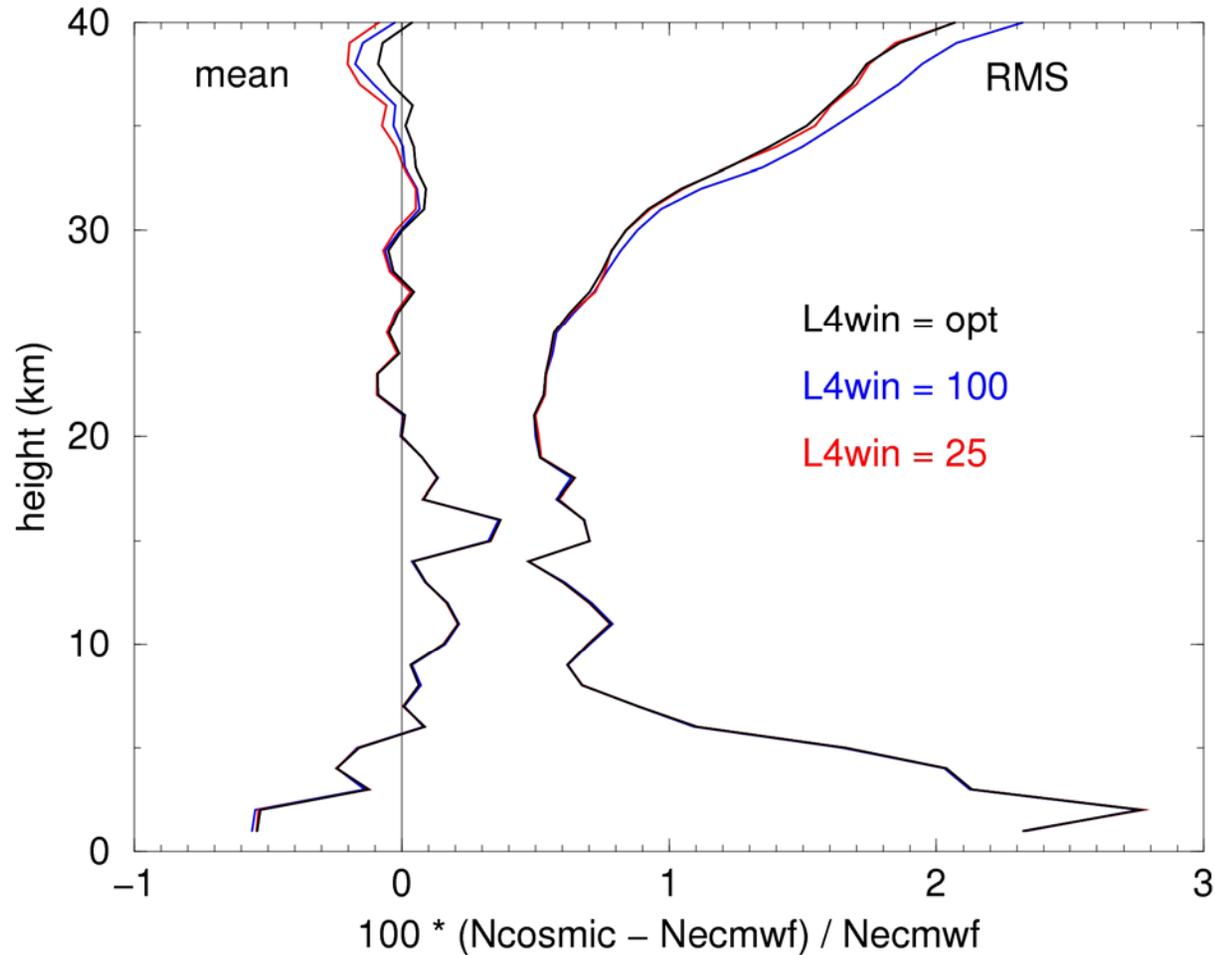


size of the optimal smoothing window (50 Hz samples)

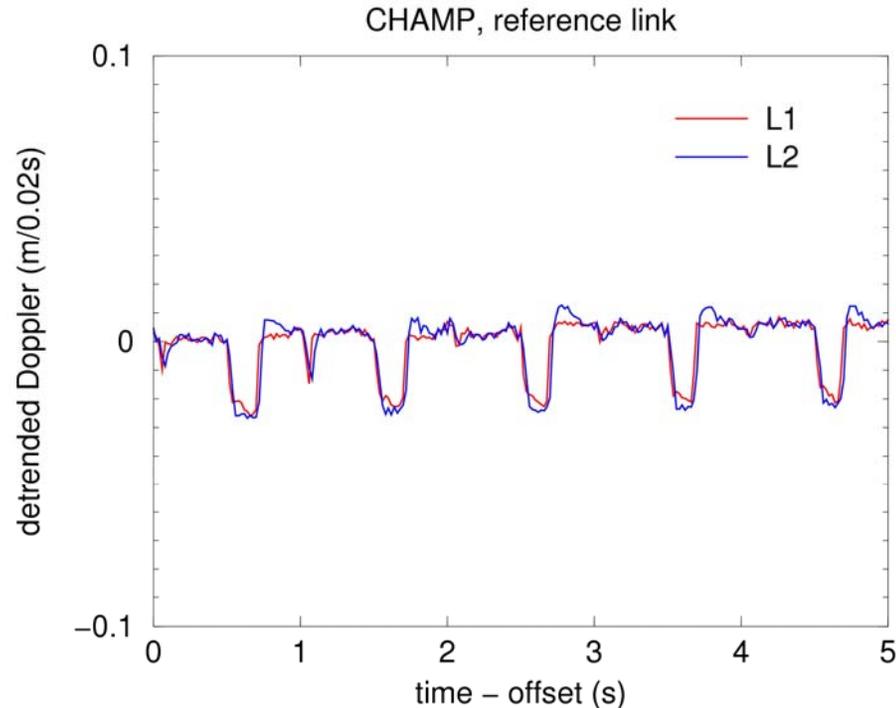
Smaller residual noise results in smaller weight of climate model in optimization (initialization) of the ionosphere-free bending angle for the Abel inversion. An example:



Statistical comparison of COSMIC retrieved refractivities to ECMWF global analysis (21 levels). The use of the optimal L4 filtering window individually for each occultation reduces the mean and the standard deviation at \Rightarrow 30 km.



Optimizing L4 filtering window for the reference link must be done concurrently with the differencing with the occulted link (solving for receiver clock).



An example: large clock distribution errors in CHAMP receiver, being smoothed on reference link will not be eliminated after differencing. Minimizing of S2 shall be applied separately for Y1 and Y2 on occulted link after differencing with reference link.

Finding optimal windows for L1-L2 filtering on reference link has to be done concurrently with differencing with L1 and L2 signals on occulted link

Ionosphere-free signal from reference link for differencing with L1 occulted signal:

$$Y(X) = Y_1(X) + C_2 < Y_1(X) - Y_2(X) >$$

Then minimizing S2 for differenced occulted Y1 (finding optimal window 1 for the reference link)

Ionosphere-free signal from reference link for differencing with L2 occulted signal:

$$Y(X) = Y_2(X) + C_1 < Y_1(X) - Y_2(X) >$$

Then minimizing S2 for differenced occulted Y2 (finding optimal window 2 for the reference link)

Summary

Ionospheric calibration by optimizing L1-L2 filtering window individually for each occultation reduces the noise of the ionosphere-free bending angle, increasing the accuracy of retrieved refractivity at \Rightarrow 30 km

Optimization of L1-L2 filtering window on occulted link (after differencing) can be done regardless of the way of data processing on the reference link.

Optimization of L1-L2 filtering window on reference link must be done concurrently with differencing of the reference and occulted link data for optimal removal of clock errors

CDAAC currently is processing all RO data with optimization of L1-L2 filtering window on occulted link after differencing.