Doppler correction algorithm for EarthCAER Cloud Profiling Radar

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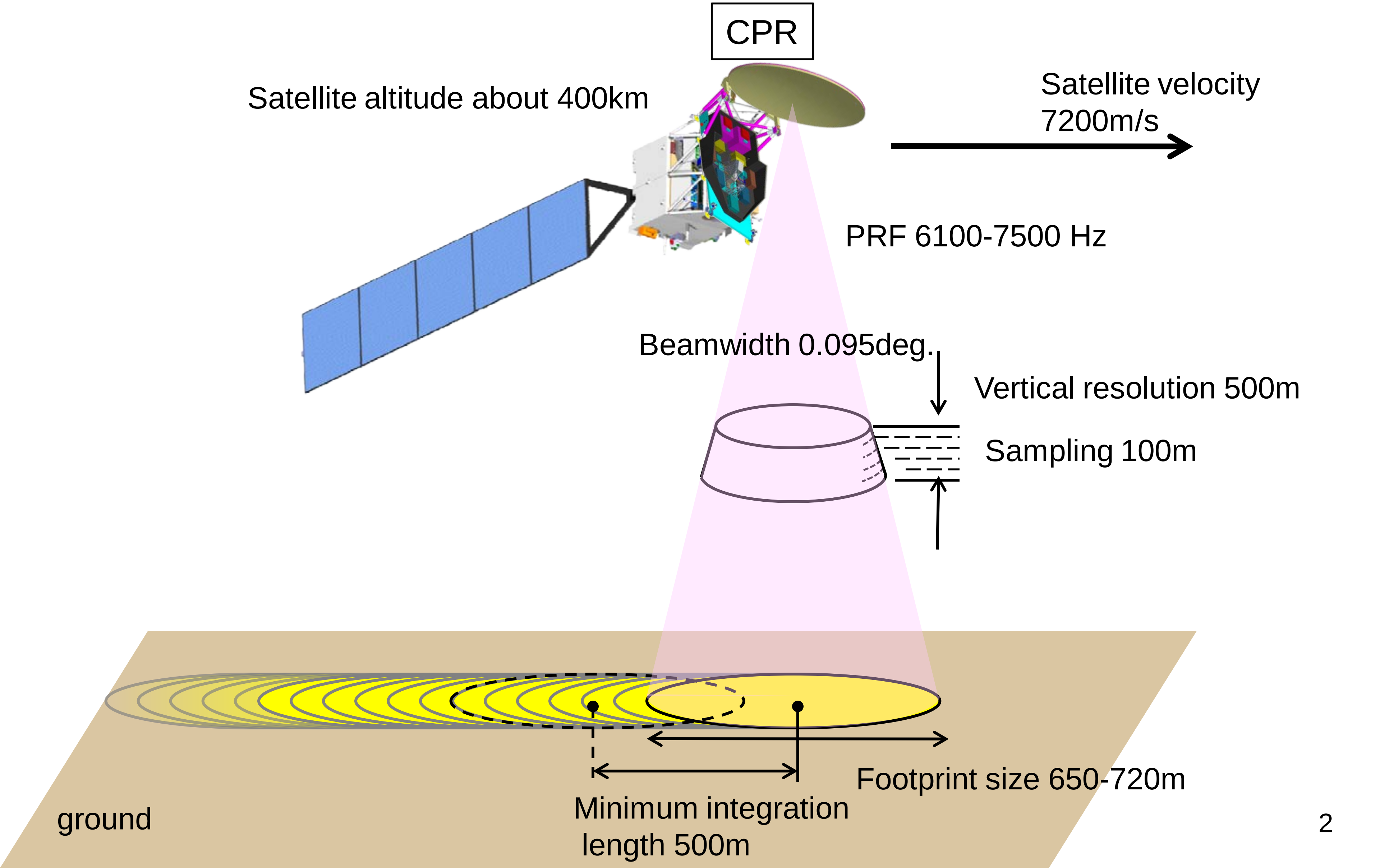
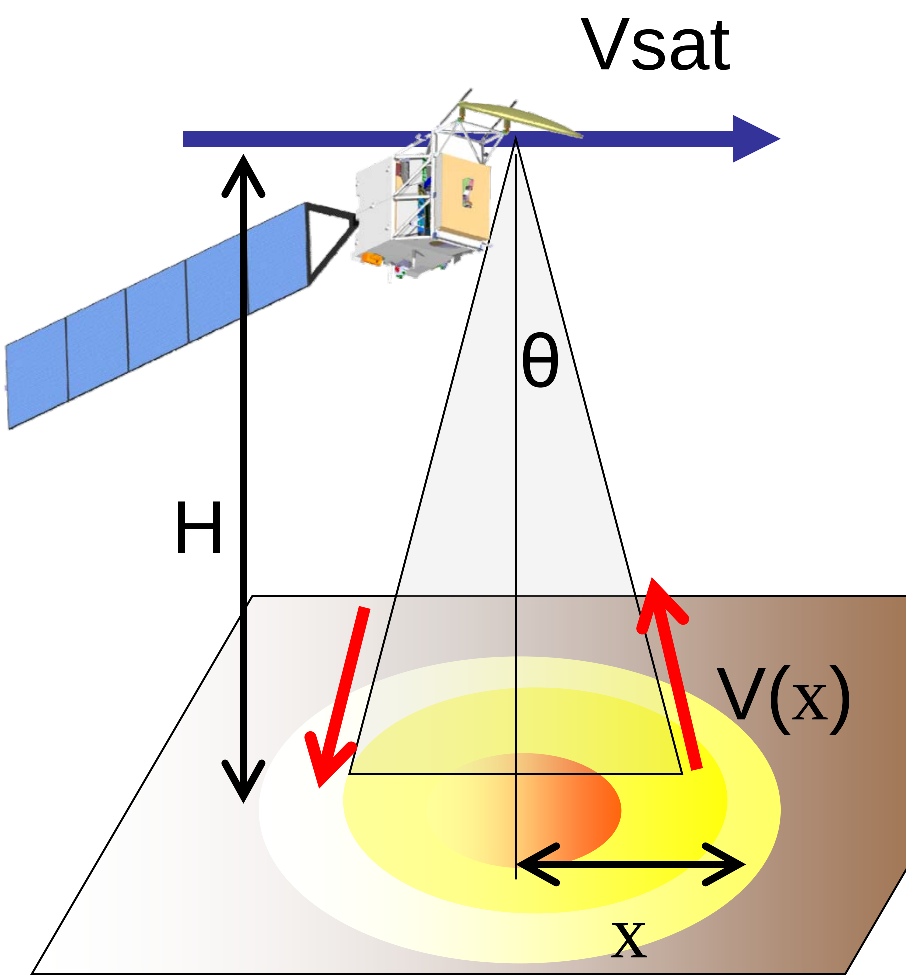
Schematic view of EarthCARE CPR observation



Doppler velocity error with non-uniform reflectivity



θ: angle from nadir
V(x)=Vsat*sinθ =Vsat*x/H

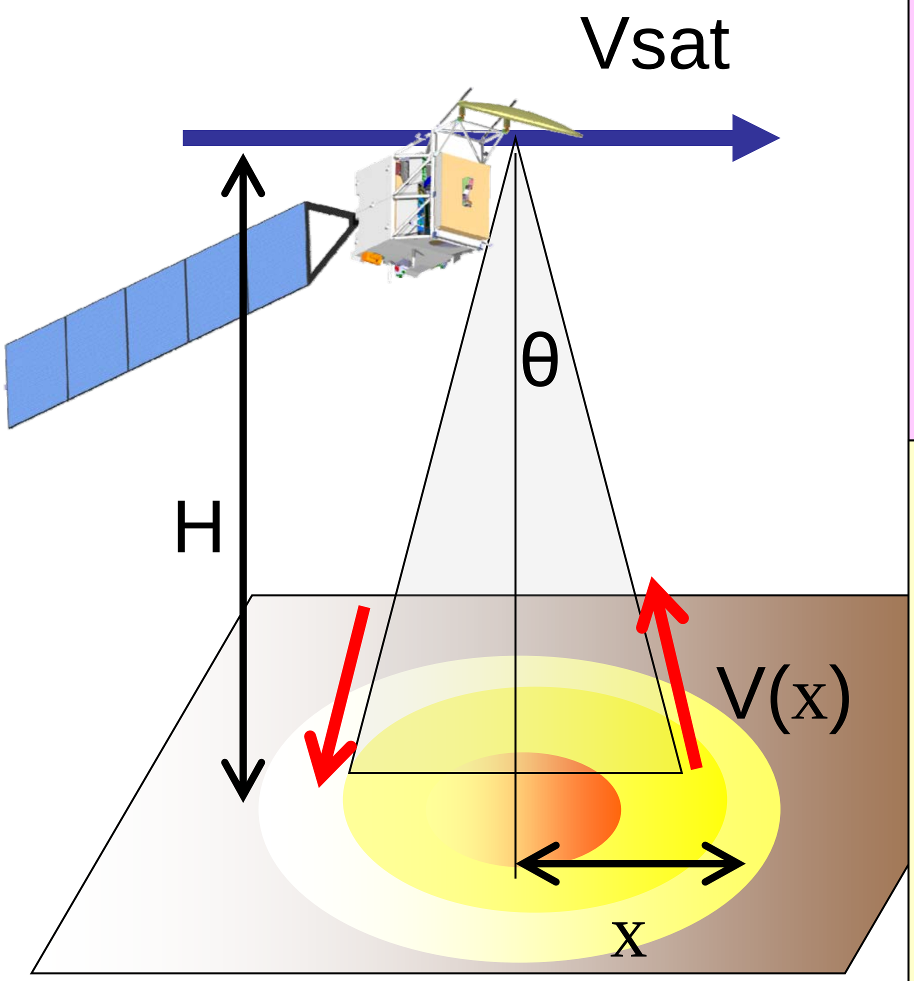
Ex. θ =beamwidth/ 2
Vbw=Vsat＊sin(beamwidth/2）
=5.97 m/s

Doppler measured by CPR is reflectivity weighted velocity i.e.

$$V_{CPR} = \frac{\int (V(x) + w(x)) \cdot f(x) z(x) dx}{\int f(x) z(x) dx}$$

z(x): reflectivity w(x):vertical wind
f(x): beam pattern

Doppler velocity error with non-uniform reflectivity



If non-uniform reflectivity

$$V_{CPR} \neq \int w(x)(z(x)/\bar{z})dx$$

$$V_{error} = V_{CPR} - \int w(x)(z(x)/\bar{z})dx$$

Doppler measured by CPR is reflectivity weighted velocity i.e.

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z(x): reflectivity w(x):vertical wind
f(x): beam pattern

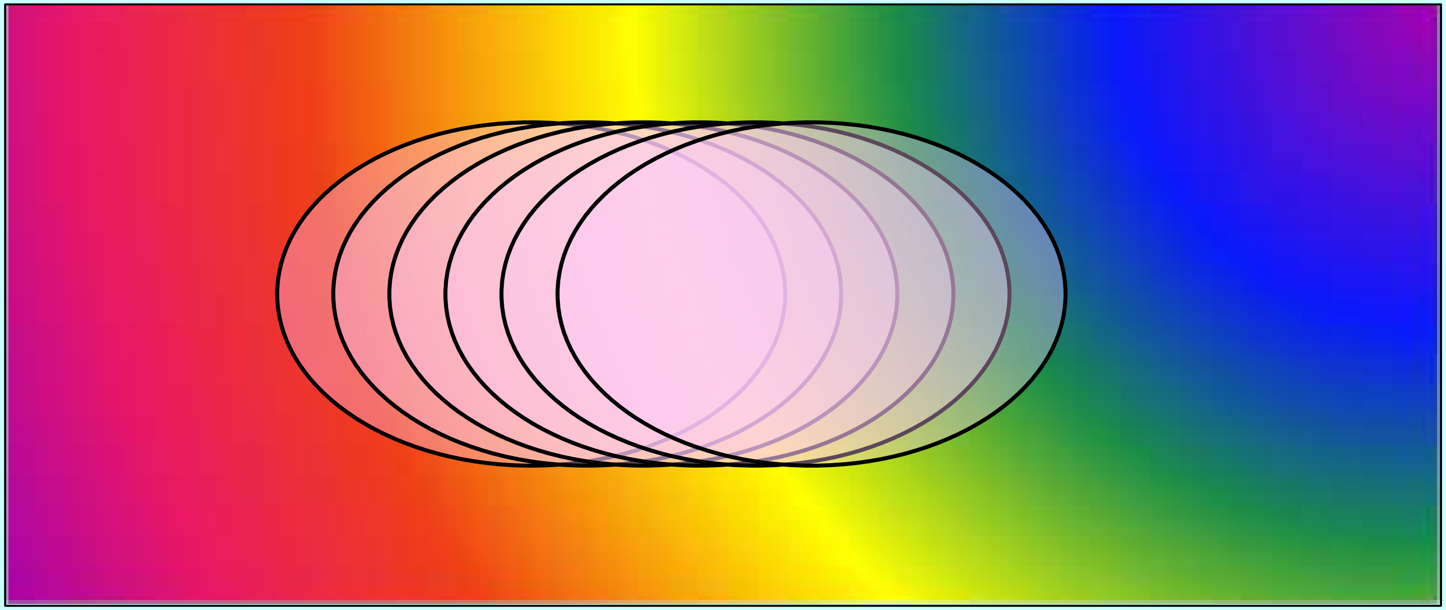
Topics

1. Reflectivity distribution & Doppler error after horizontal integration

2. Doppler folding consideration

3. Simulation of Doppler error using reflectivity data

1. Reflectivity distribution & Doppler error after horizontal integration



Doppler error formula after horizontal integration

$V_{error}(x_n)$: one pulse Doppler error

x_n: beam center location at n th pulse

$$V_{error}(x_n) = \frac{\int v(x - x_n) f(x - x_n) z(x) dx}{\int f(x - x_n) z(x) dx}$$

$\overline{V}_{error}(x_{00})$: Pulse-integrated Doppler error

x_{00}:Center of integration

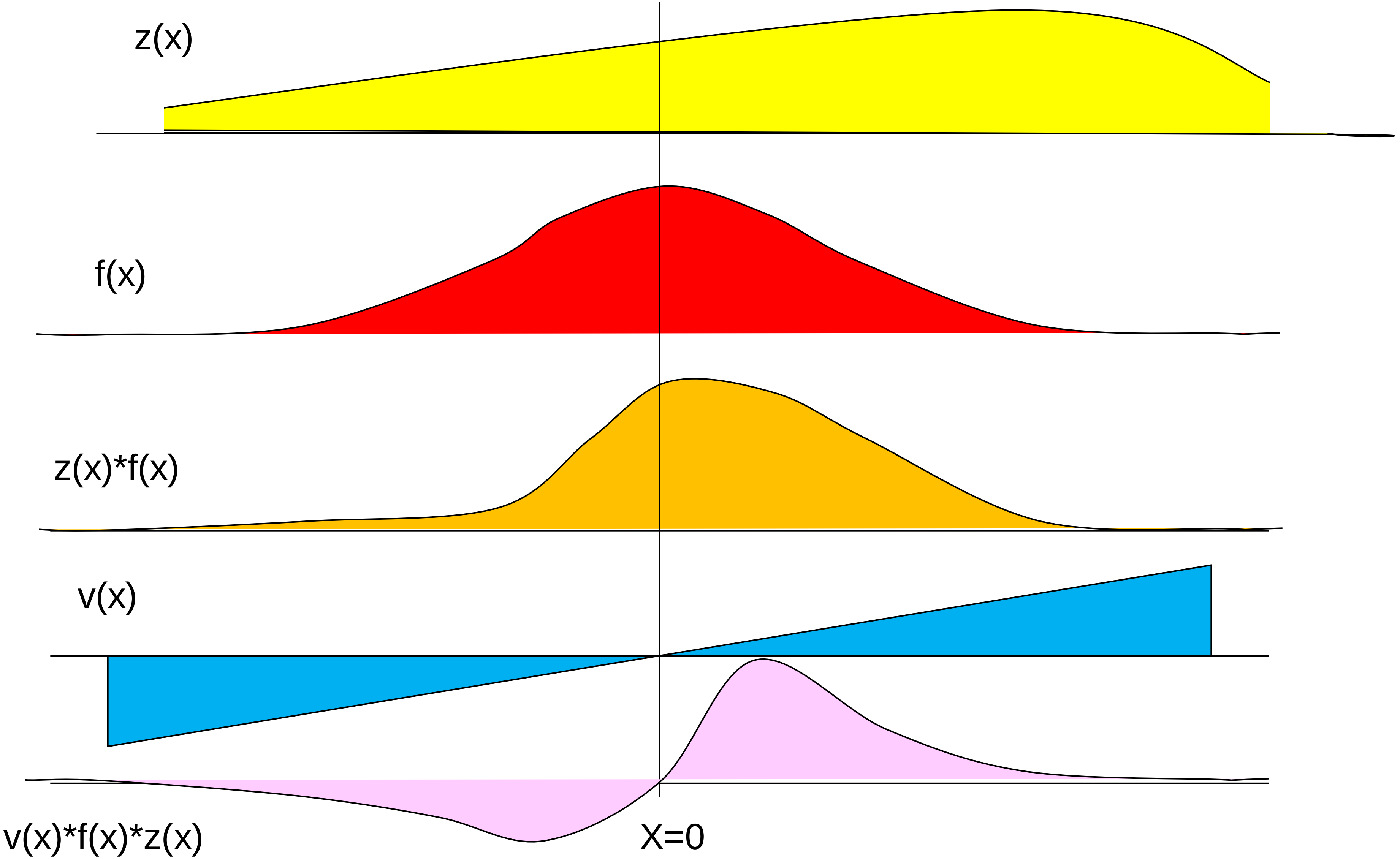
$$\overline{V_{error}}(x_{00}) = \sum_{-N/2}^{N/2} V(x_n) Z(x_n) \Big/ \sum_{-N/2}^{N/2} Z(x_n)$$

$$Z(x_n) = \int f(x - x_n) z(x) dx$$

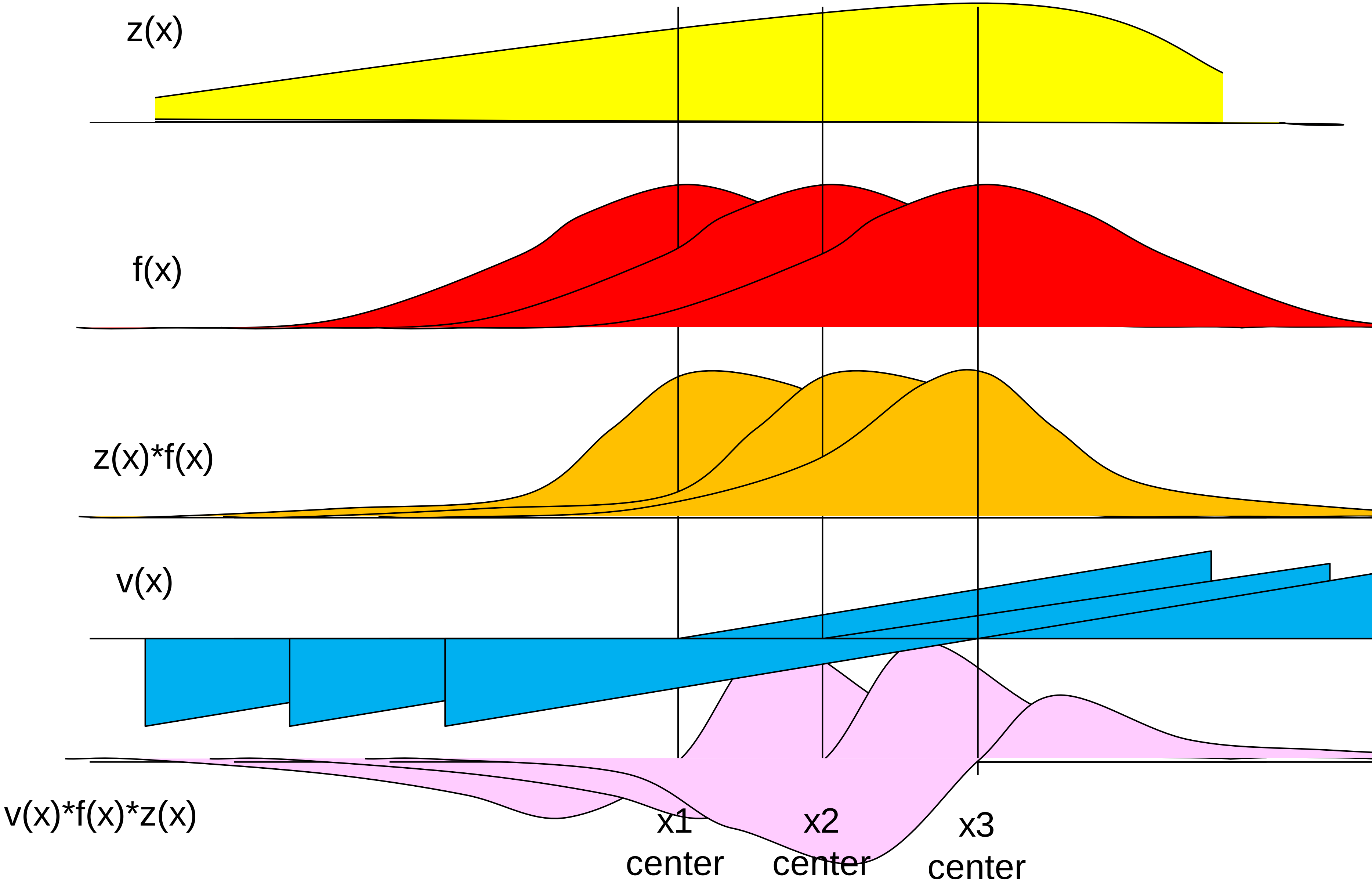
$$= \sum_{-N/2}^{N/2} \int v(x - x_n) f(x - x_n) z(x) dx \Big/ \sum_{-N/2}^{N/2} Z(x_n)$$

N: Pulse number with horizontal integration

Doppler error integration within footprint



Horizontal integration with satellite moving



Doppler error formula after horizontal integration

$V_{error}(x_n)$: one pulse Doppler error

$$V_{error}(x_n) = \frac{\int v(x-x_n) f(x-x_n) z(x) dx}{\int f(x-x_n) z(x) dx}$$

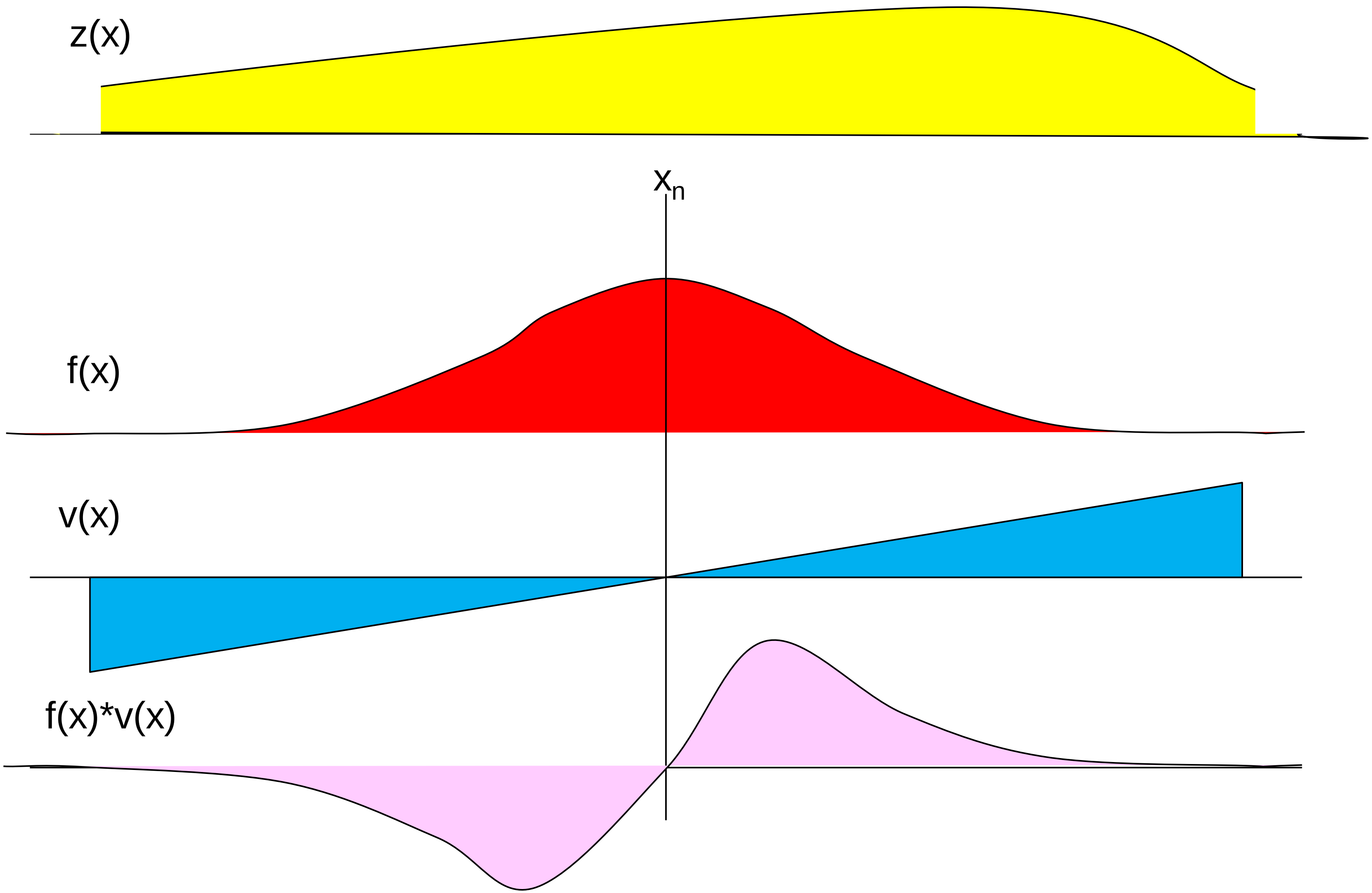
$\overline{V}_{error}(x_{00})$: Pulse-integrated Doppler error

$$\overline{V_{error}}(x_{00}) = \sum_{-N/2}^{N/2} V(x_n) Z(x_n) \Bigg/ \sum_{-N/2}^{N/2} Z(x_n)$$

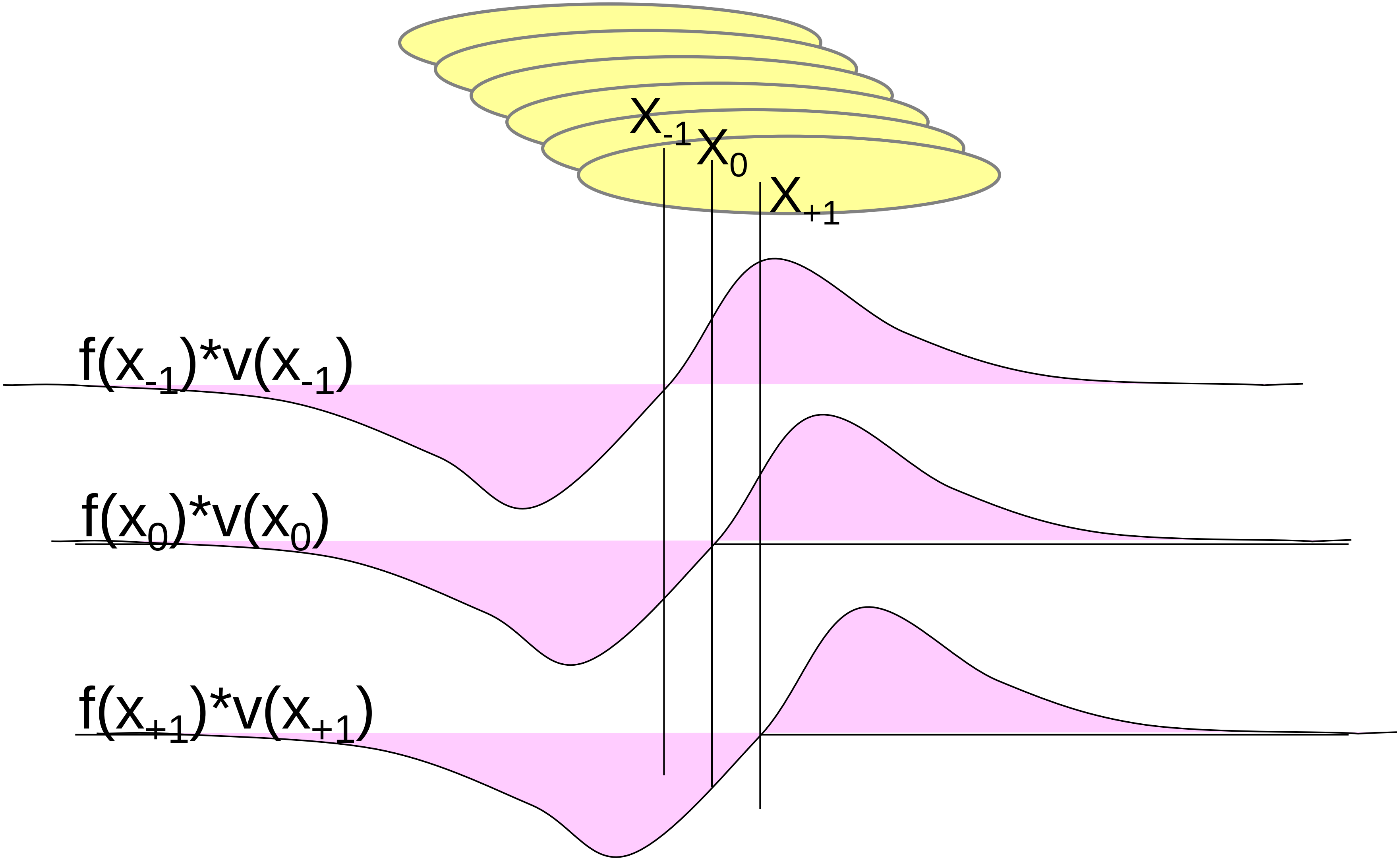
$$Z(x_n) = \int f(x-x_n) z(x) dx$$

$$= \sum_{-N/2}^{N/2} \int v(x-x_n) f(x-x_n) z(x) dx \Bigg/ \sum_{-N/2}^{N/2} Z(x_n)$$

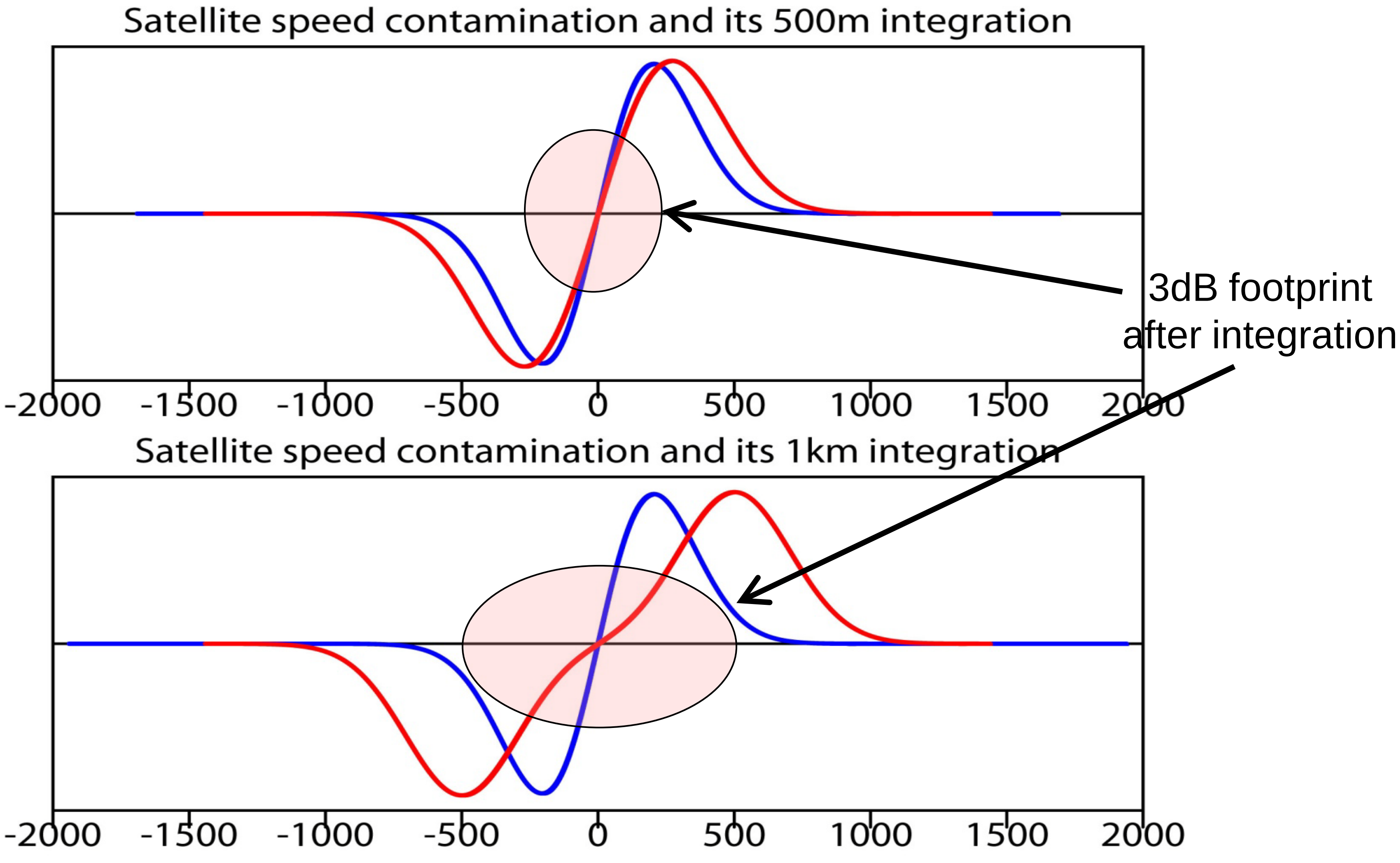
Change order of multiplication for Doppler error



f(x) *v(x) pattern shift with satellite moving

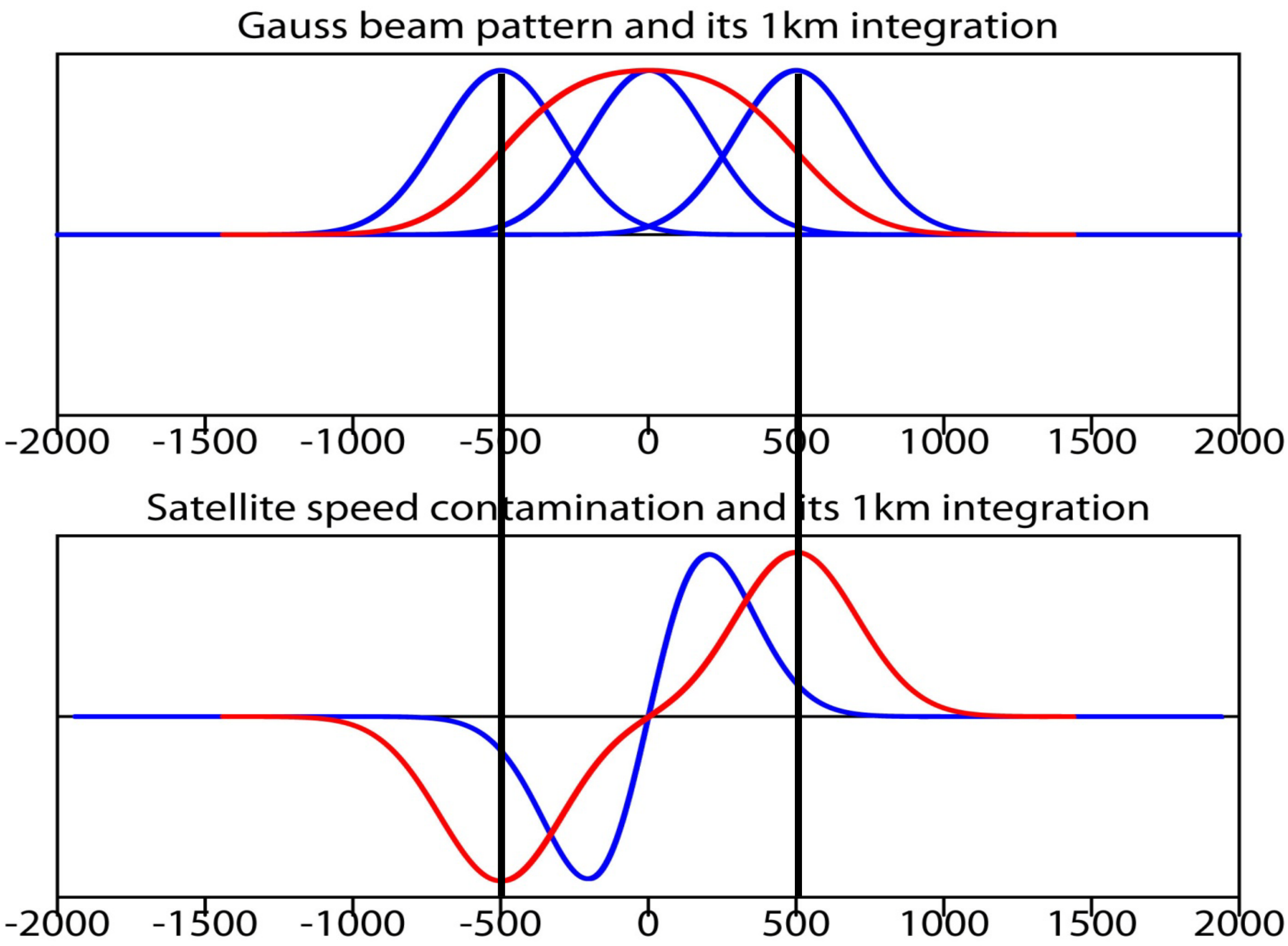


f(x) *v(x) pattern after 500m & 1km integration

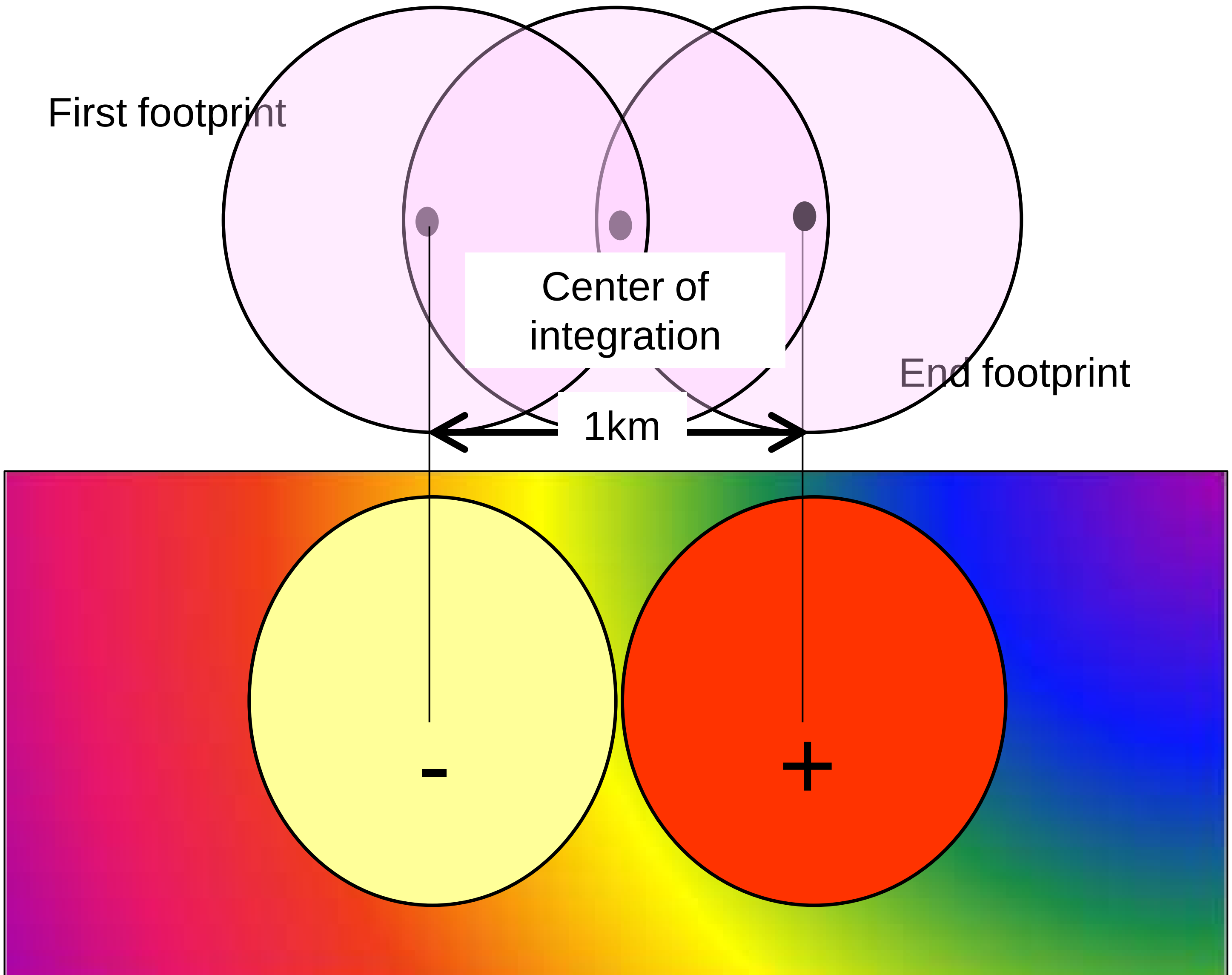


Red line: f(x)*v(x) after horizontal integration

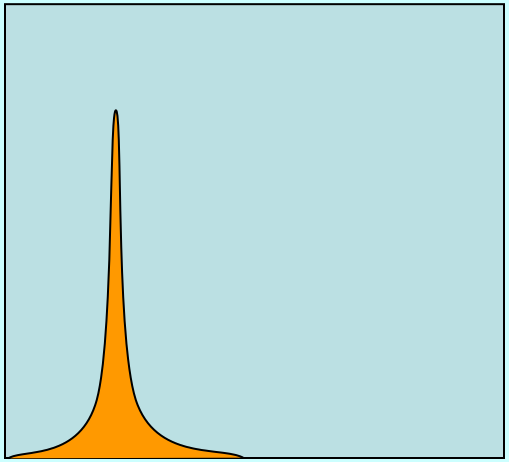
f(x) & f(x)*v(x) pattern after 1km integration

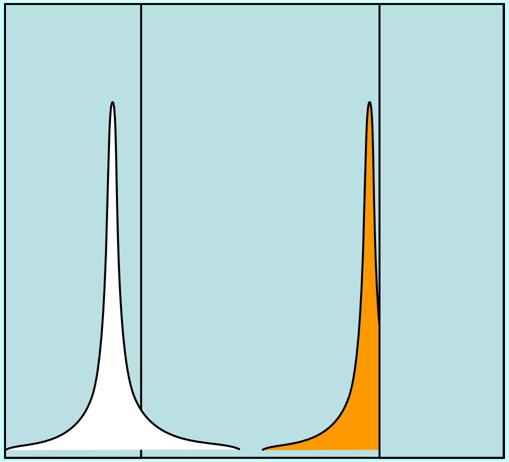


Footprint & f(x)*v(x) pattern in horizontal view



2. Doppler folding consideration





Doppler folding

$$V\max = \frac{\lambda \cdot PRF}{4}$$

PRF: Pulse Repetition Frequency

Vmax: Maximum velocity folding

$$V\max = Vsat * x_{fold} / H$$

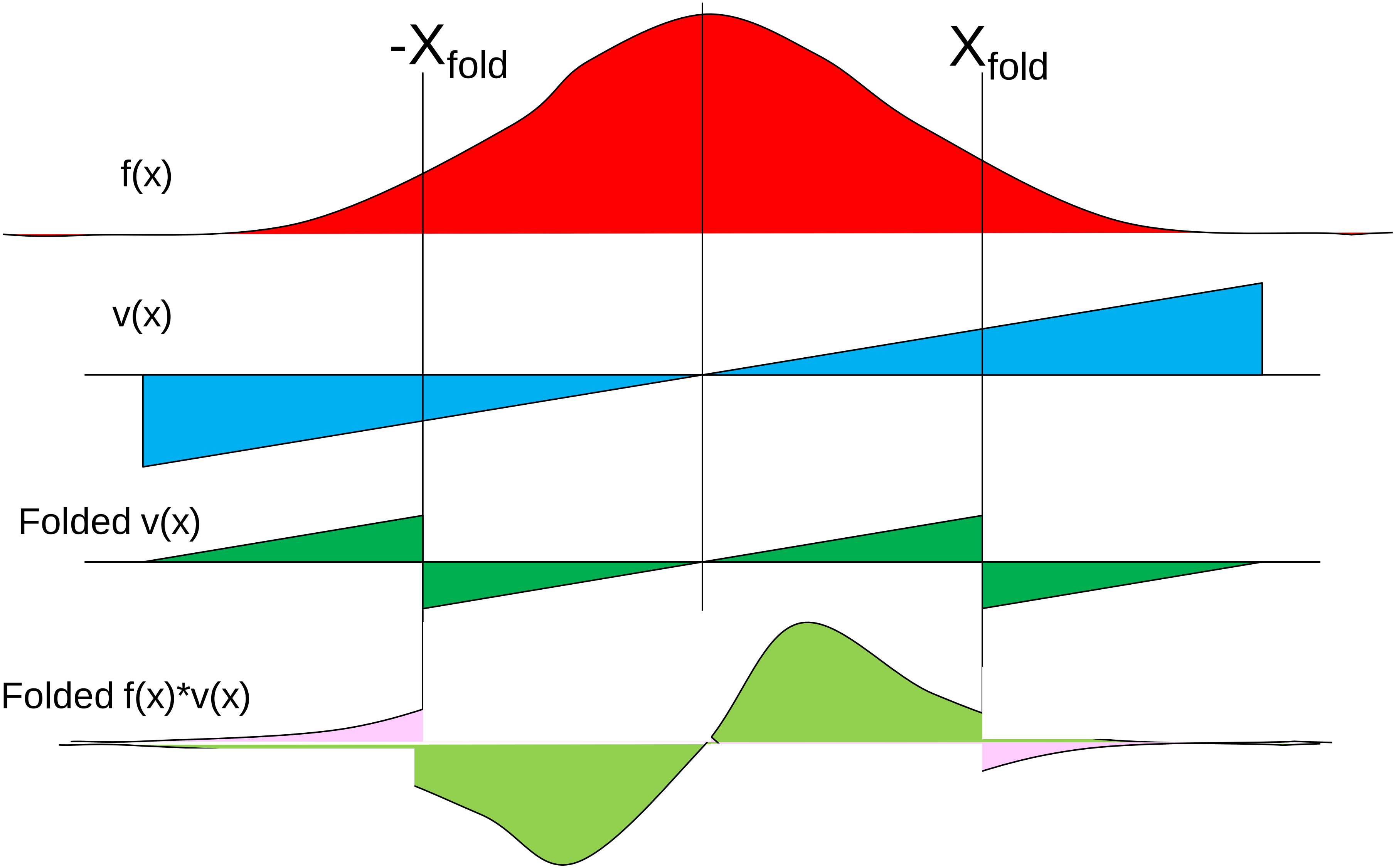
$$x_{fold} = \frac{\lambda \cdot PRF}{4} \bullet \frac{H}{Vsat}$$

$$= 332.3m(PRF\,7500Hz)$$

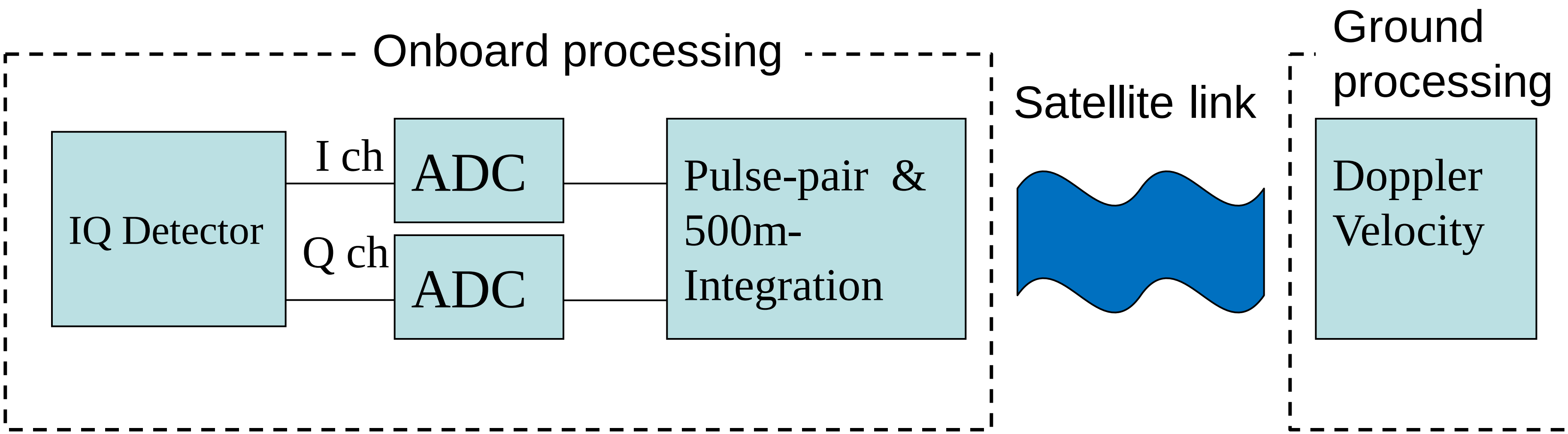
$$= 270.2m(PRF\,6100Hz)$$

x_{fold}: Doppler folding position from center

Change order of multiplication for Doppler error



Doppler processing using Pulse-pair (1)



$$w_k = I_k + iQ_k$$

I_k: I ch time series

Q_k : Q ch time series

k: pulse number

T: pulse interval

$$R(T) = \overline{w_k{}^* \cdot w_{k+1}}$$

$$= \mathrm{Re}\, R(T) + i\, \mathrm{Im}\, R(T)$$

$$\mathrm{Re}\, R(T) = \sum (I_k I_{k+1} + Q_k Q_{k+1})$$

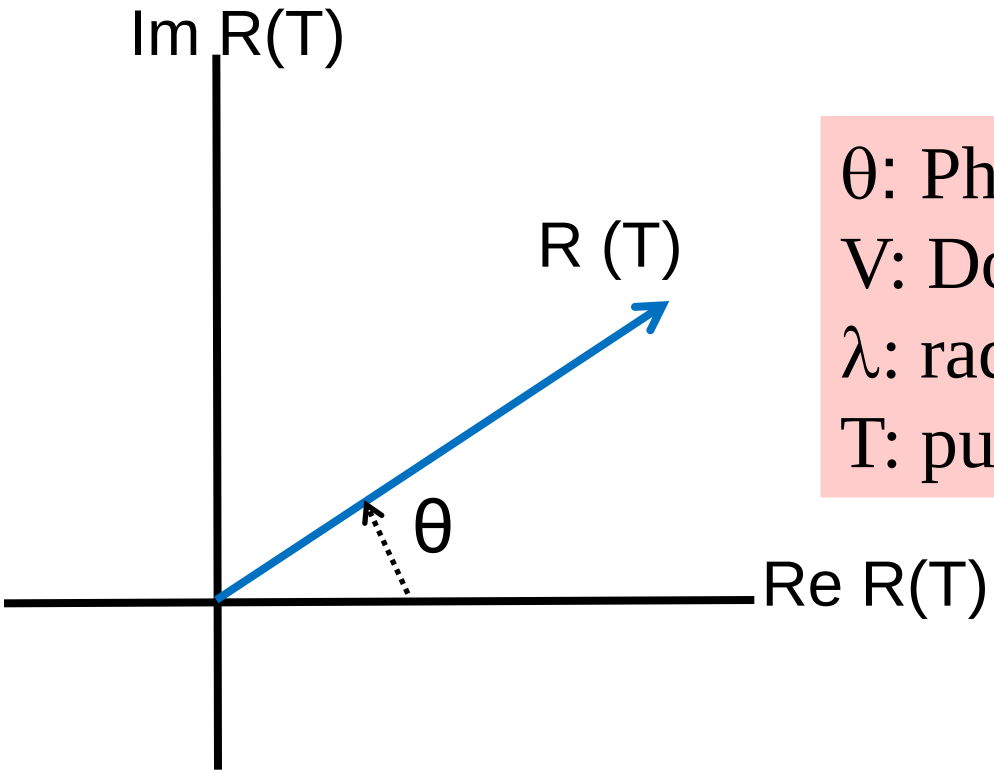
$$\mathrm{Im}\, R(T) = \sum (Q_k I_{k+1} - I_k Q_{k+1})$$

R(T): Complex cross correlation PP

Doppler processing using Pulse-pair (2)

$$\theta = 2\pi \frac{2TV}{\lambda}$$

$$V = \frac{\lambda}{4\pi T} \tan^{-1}\left(\frac{\operatorname{Im} R(T)}{\operatorname{Re} R(T)} \right)$$



θ: Phase change between pulses
V: Doppler velocity
λ: radio wave length
T: pulse interval

Formula of Doppler velocity error using PP

c(x),q(x): Real & imaginary part of R(T) function at x

$$c(x) = \mathrm{Re}\, R(T) = \cos(x / x_{\max} \cdot \pi)$$

$$q(x) = \mathrm{Im}\, R(T) = \sin(x / x_{\max} \cdot \pi)$$

x_{max}: Doppler folding position from beam center

C(x),Q(x): Real & imaginary part of R(T) function at x_n

$$C(x_n) = \int c(x - x_n) f(x - x_n) z(x) dx \Big/ Z(x_n)$$

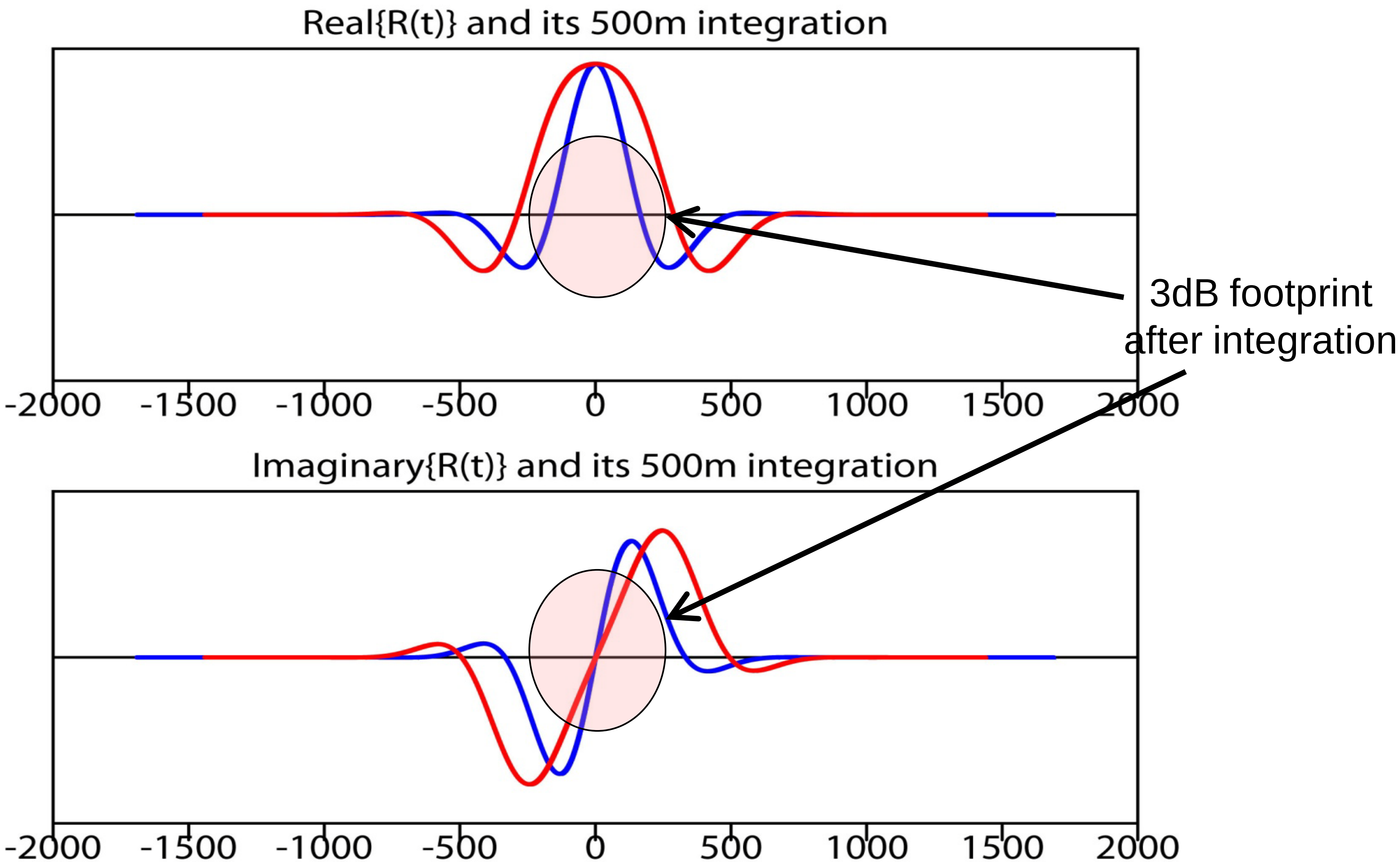
$$Q(x_n) = \int q(x - x_n) f(x - x_n) z(x) dx \Big/ Z(x_n)$$

$$Z(x_n) = \int f(x - x_n) z(x) dx$$

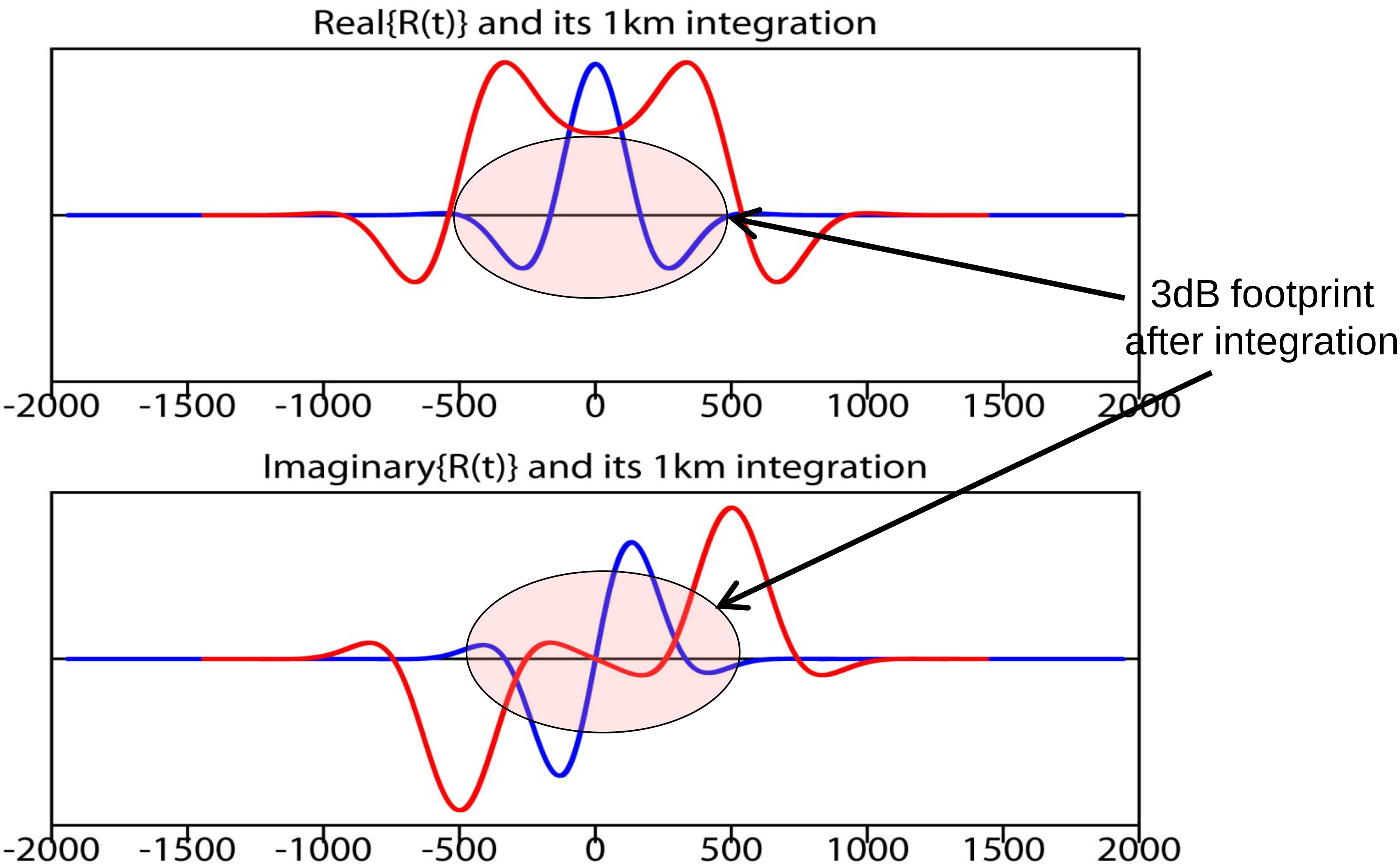
$\overline{V}(x_{00})$: Pulse-integrated Doppler error

$$\overline{V_{error}}(x_{00}) = \frac{\lambda \cdot PRF}{4\pi} \arctan\left(\sum_{-N/2}^{N/2} Q(x_n) Z(x_n) \Big/ \sum_{-N/2}^{N/2} C(x_n) Z(x_n) \right)$$

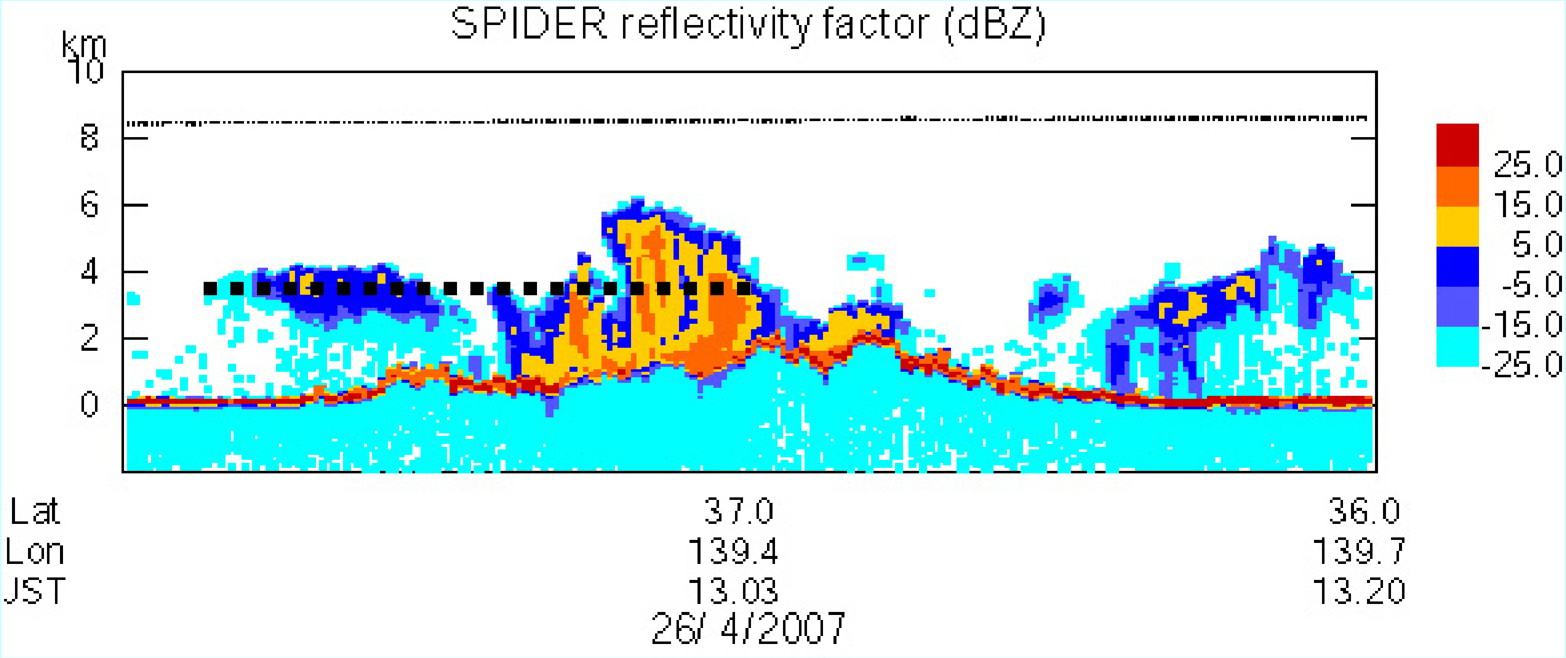
f(x) *c(x) & f(x)*q(x) pattern with 500m integration

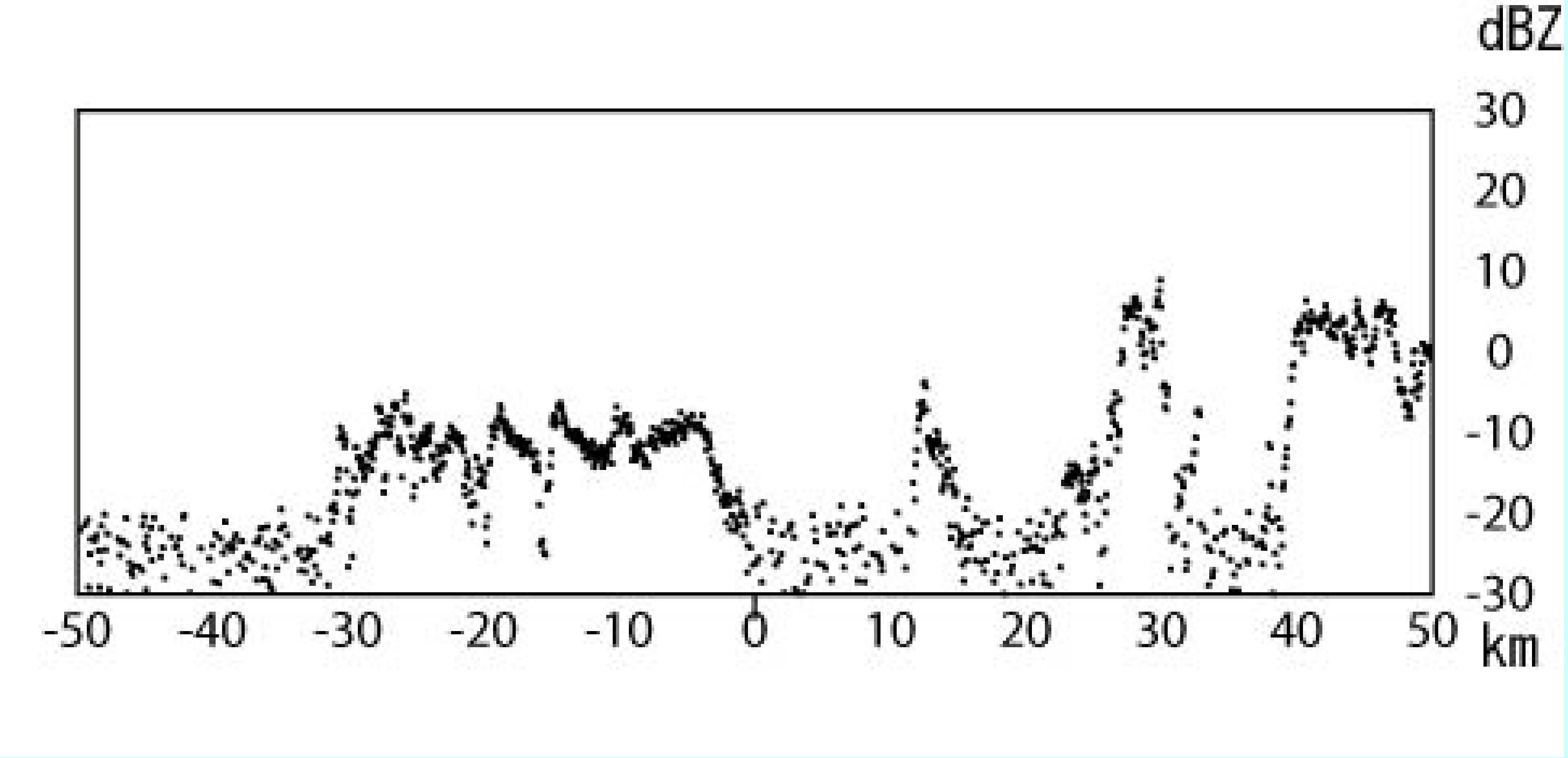


f(x) *c(x) & f(x)*q(x) pattern with 1km integration



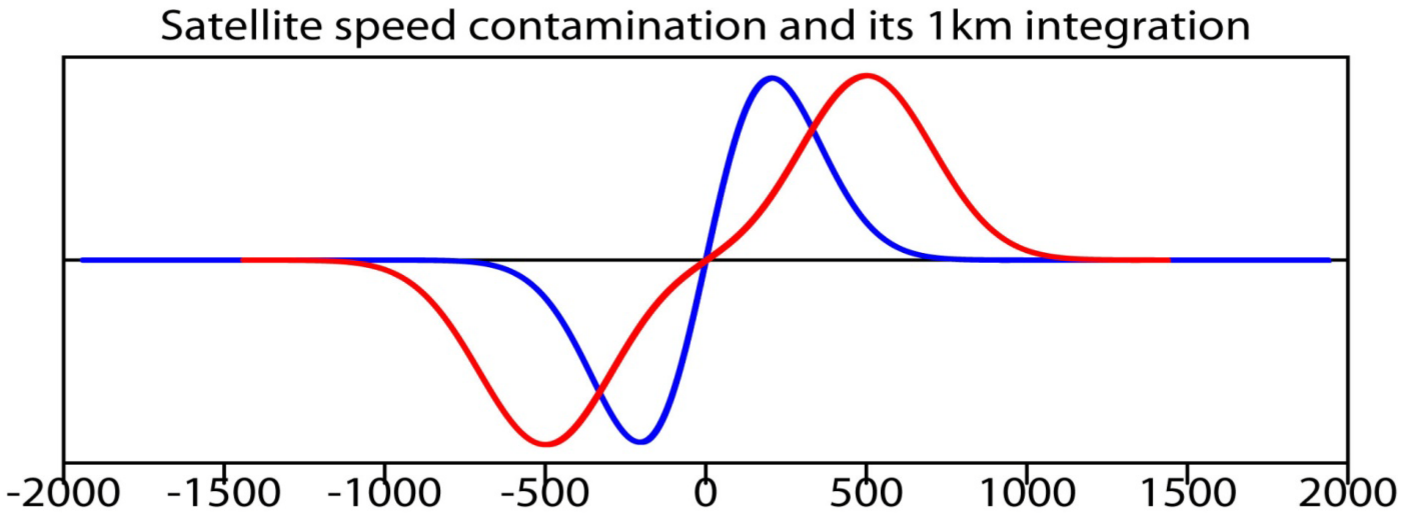
3. Simulation of Doppler error using real observation

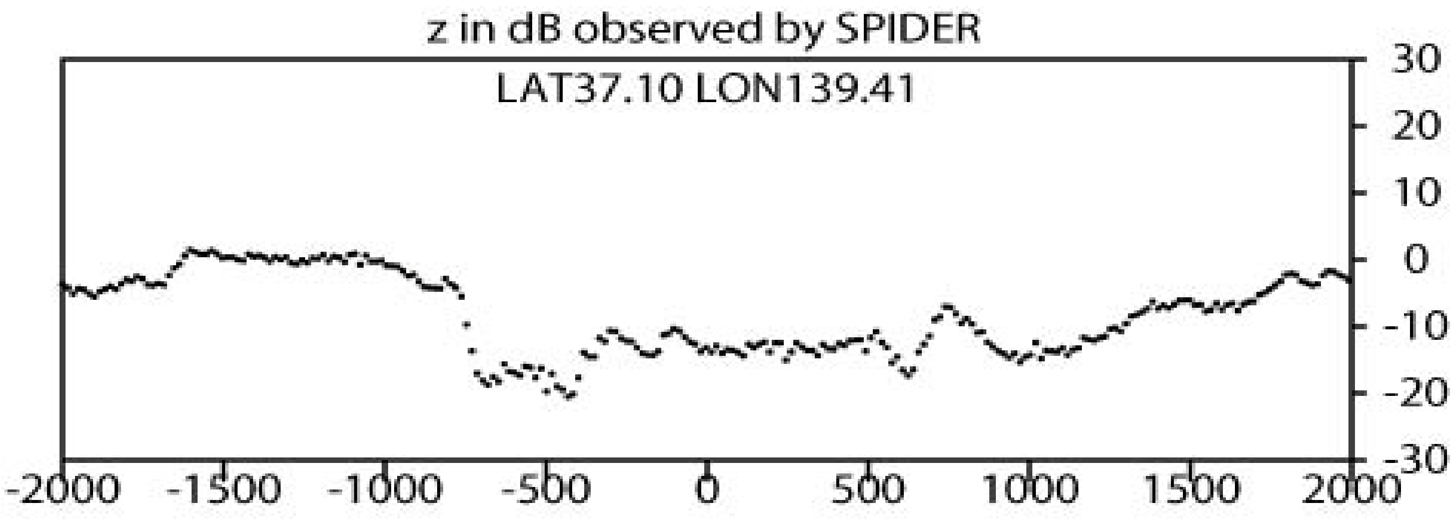




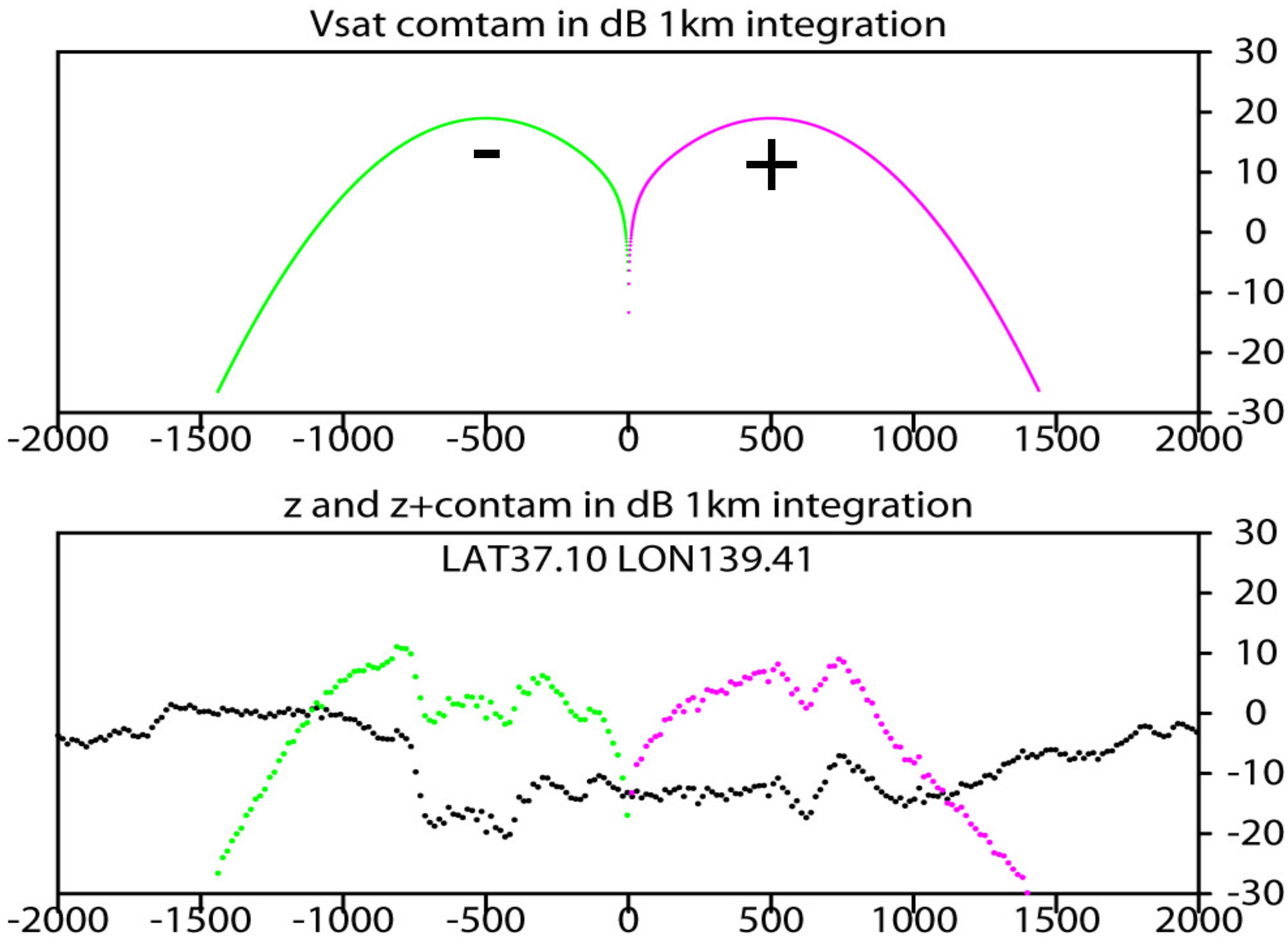
dBZ
30
20
10
0
-10
-20
-30
-50
-40
-30
-20
-10
0
10
20
30
40
50
km

z(x) & f(x)*v(x) pattern in dB



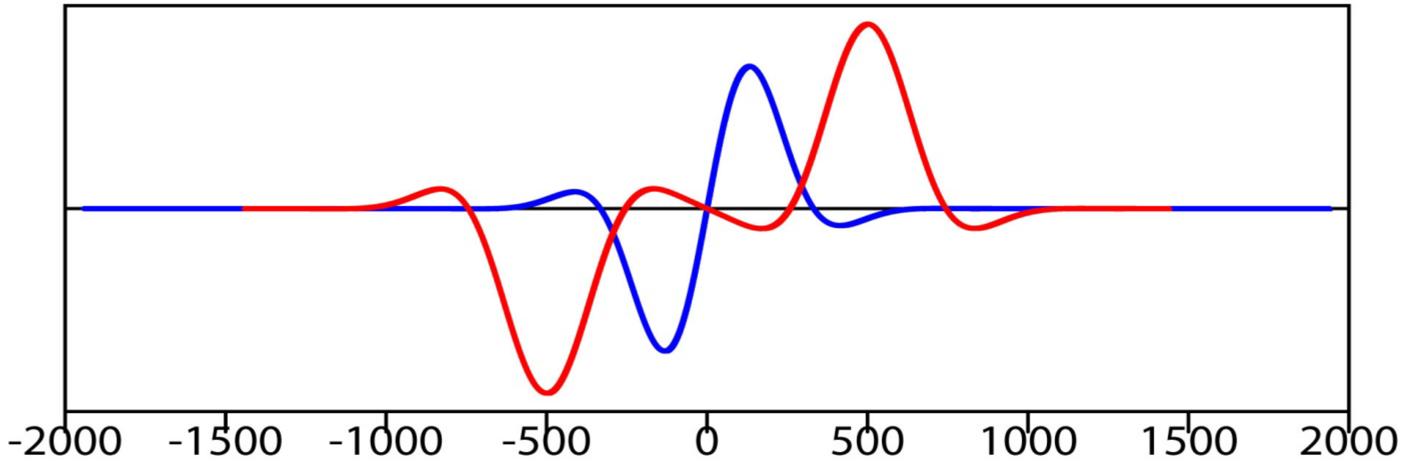


z(x) & f(x)*v(x) pattern in dB

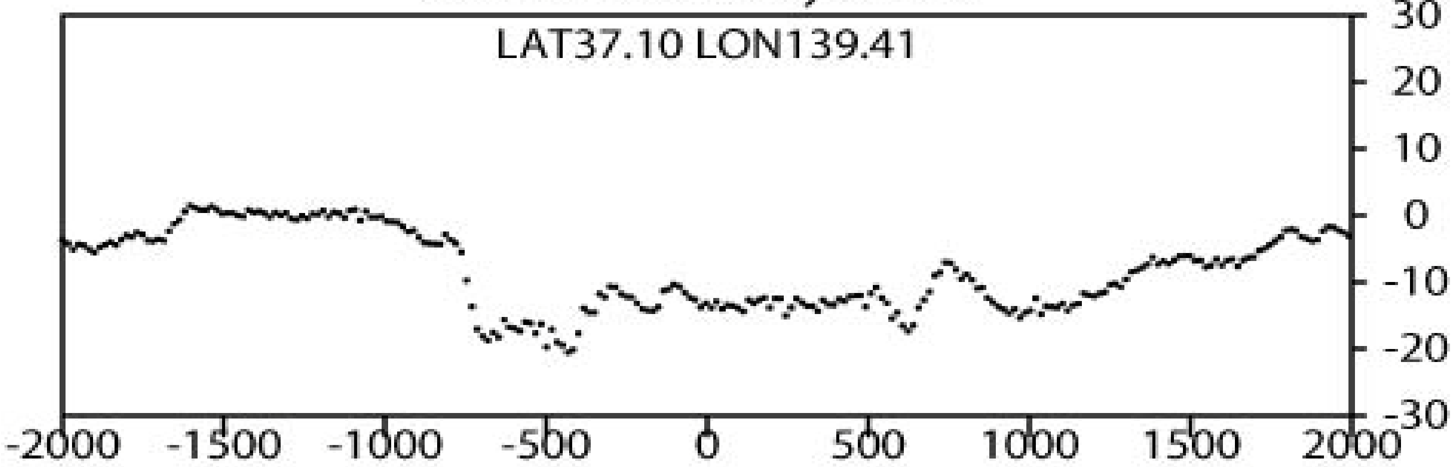


z(x) & Q(x) pattern in dB

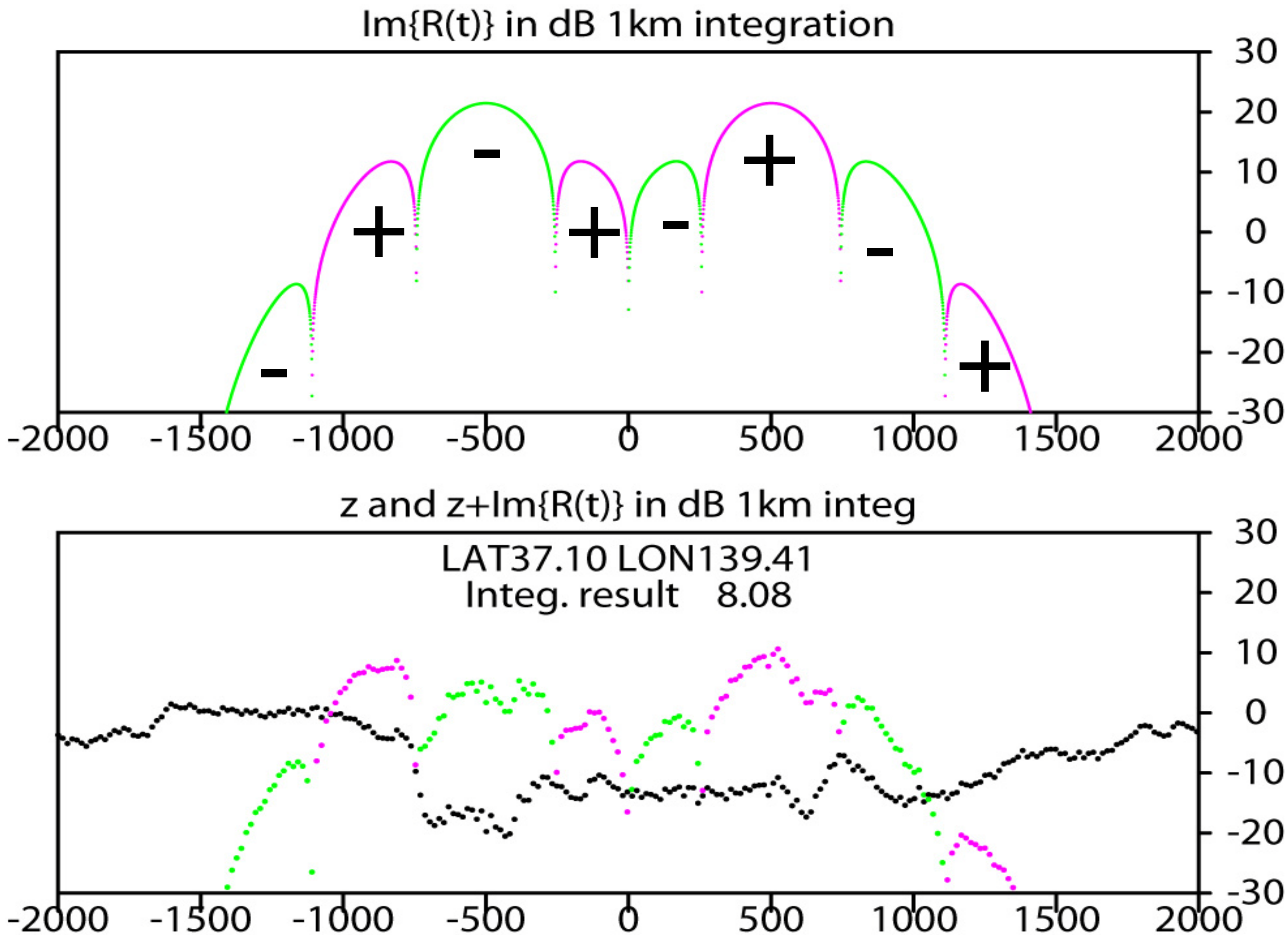
Imaginary{R(t)} and its 1km integration



z in dB observed by SPIDER

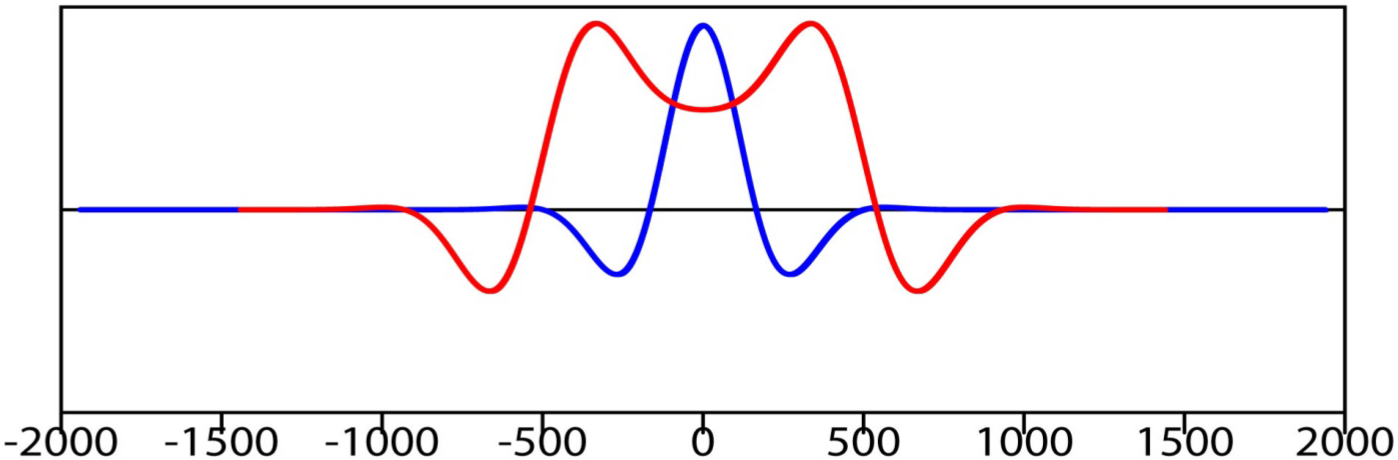


z(x) & Q(x) pattern in dB

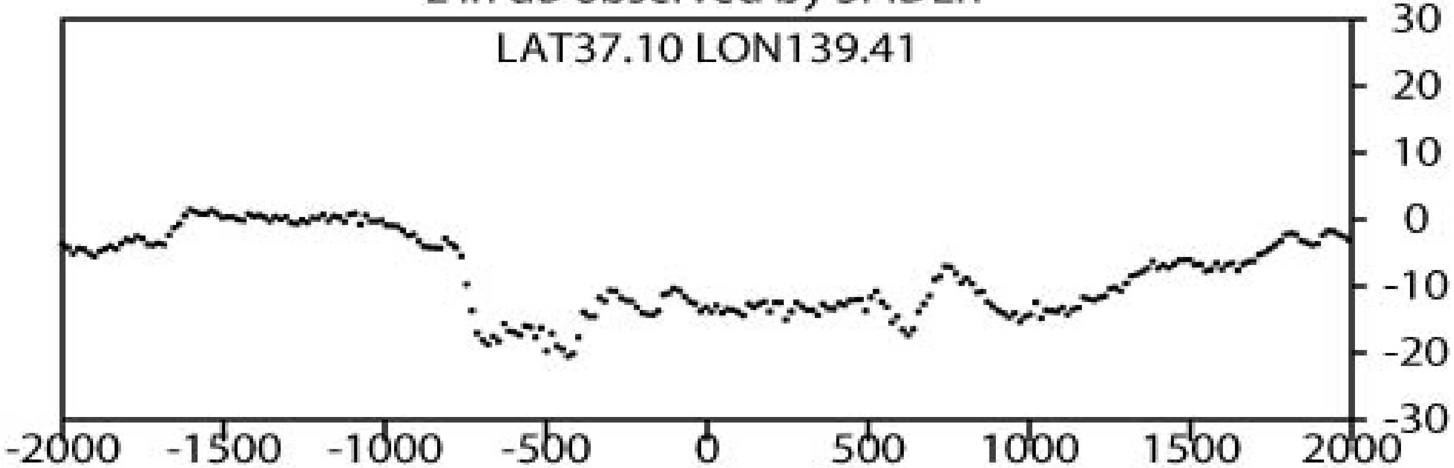


z(x) & C(x) pattern in dB

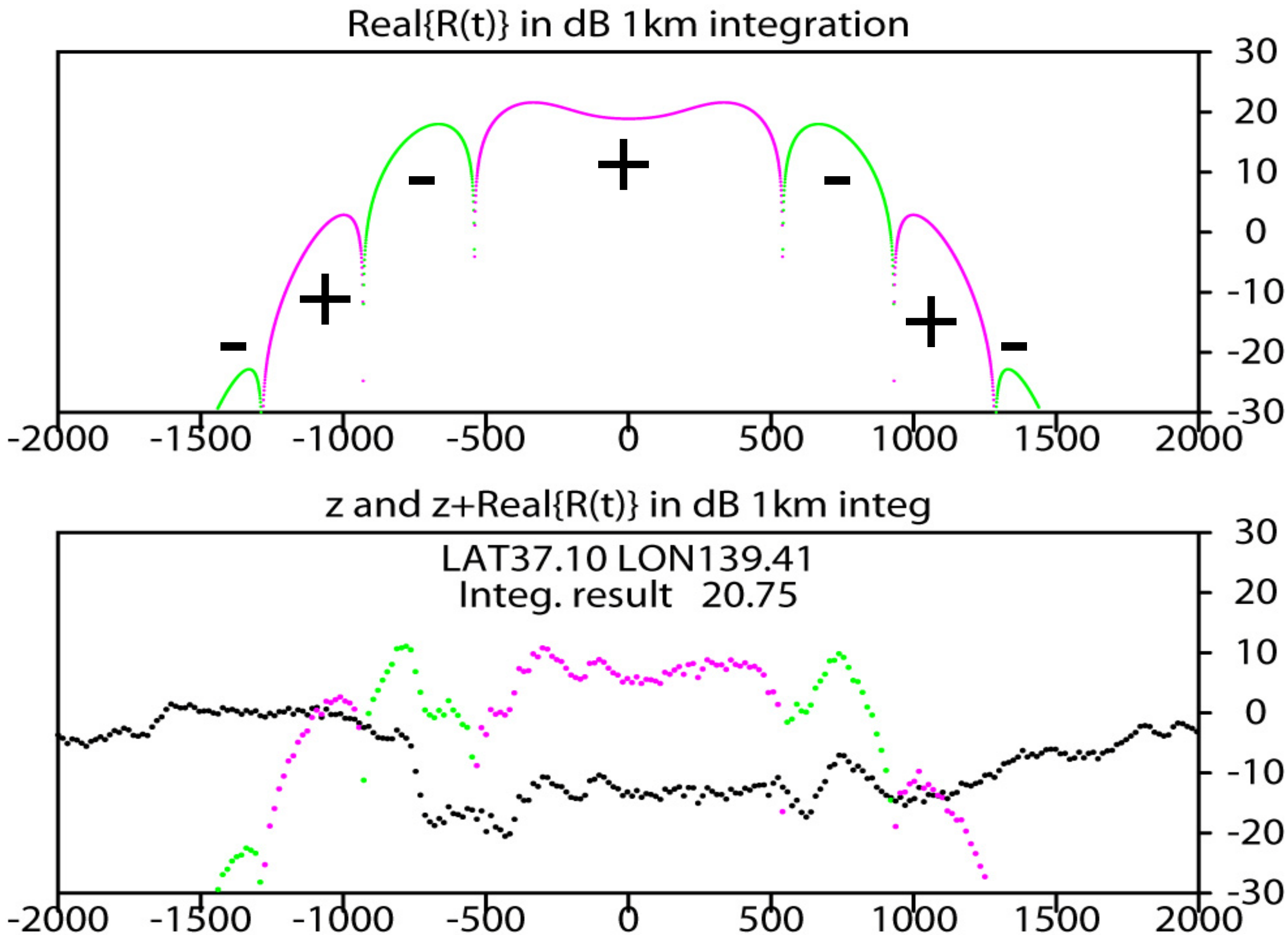
Real{R(t)} and its 1km integration



z in dB observed by SPIDER



z(x) & C(x) pattern in dB



Pulse-pair to Doppler error

$$\overline{V_{error}}(x_{00}) = \frac{\lambda \cdot PRF}{4} \arctan\left(\sum_{-N/2}^{N/2} Q(x_n) Z(x_n) \Big/ \sum_{-N/2}^{N/2} C(x_n) Z(x_n) \right)$$

$$= \frac{3.19E^{-3} \bullet 7500}{4\pi} \tan^{-1}\left(\frac{8.08}{20.75} \right)$$

$$= 0.70$$

Summary

1. Doppler error can be estimated from reflectivity referring first and end footprint

2. Integrated real and imaginary part of R(t) is useful to considering Doppler error with folding

3. Doppler error value is demonstrated using SPIDER observation