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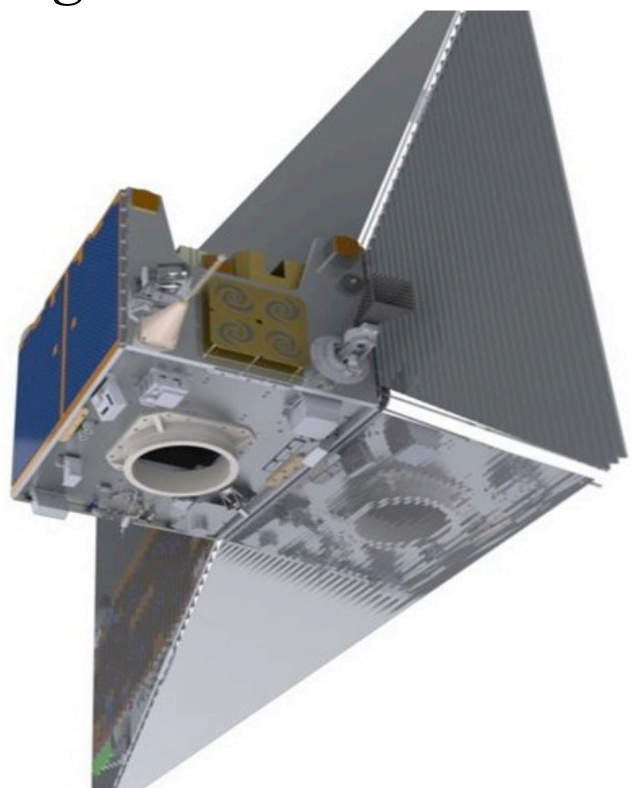
A wind geophysical model function for the TDS-1 GNSS-reflectometry observations

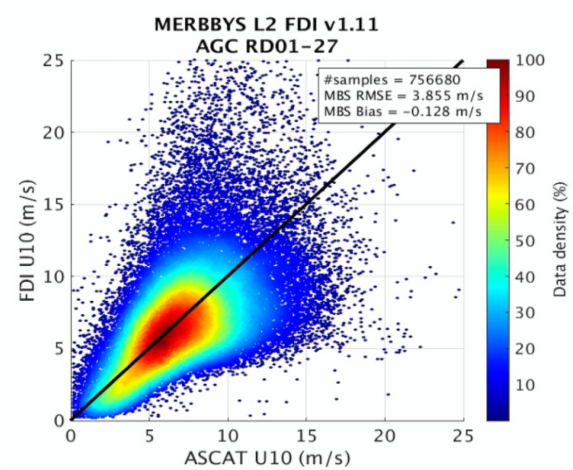
Wenming Lin, Marcos Portabella



$$\left\langle \left| Y(\Delta\tau, \Delta f) \right|^2 \right\rangle = \frac{p_t}{(4\pi)^3} \lambda^2 T_c^2 \int d\vec{\rho}\, \frac{G_T(\vec{\rho}) G_R(\vec{\rho}) \sigma^0(\vec{\rho}) \Lambda^2\left(\tau + \Delta\tau(\vec{\rho})\right) \left| S\left(\delta f(\vec{\rho})\right) \right|^2}{R_{T,\vec{\rho}}^2 R_{R,\vec{\rho}}^2}$$

TGSCATT

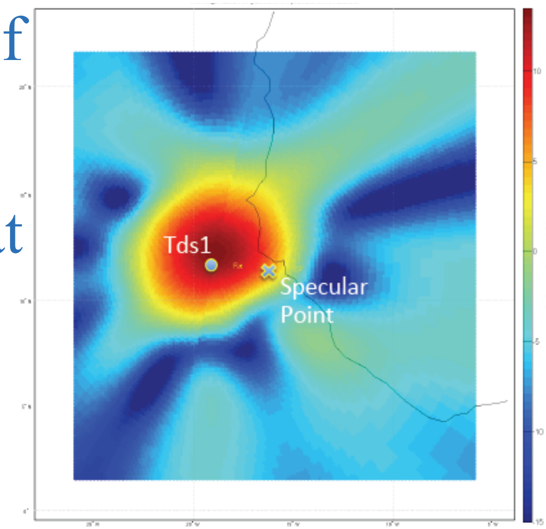
- ESA-funded TGSCATT study (May'16-Feb'18):
  - End to end scientific assessment of GNSS reflectometry scatterometric measurements from TDS-1 and data products
  - Seeks to establish the physical relation between GNSS-R signals and ocean wind and roughness properties
- Objectives/tasks
  - Revise and adapt simulation framework for TDS-1 (Wavpy)
  - Define GNSS-R observables using simulation framework
  - Develop/consolidate physical/empirical GMFs
  - Consolidation of L1 & L2 products (Merrbys)
  - Impact analysis on global NWP (O-B, preliminary OSEs & OSSEs)
- Partners: NOC, SSTL, MetOffice, SatOC (UK), ICM, IEEC (ES)
- Final workshop aims to present results Feb 2018
- http://www.satoc.eu/projects/tgscatt/



About TDS-1

- Launched in July 2014; predecessor of CYGNSS

- Most TDS-1 measurements are acquired at low antenna gain values



Foti et al., TDS-1 UCM, March 2015

- Operating in two gain modes:
  - Unmonitored automatic antenna gain (until April 2015)
    - Receiver absolute power levels are unknown
    - Automatically adjusts the GNSS receiver gain to make optimal use of the available dynamic range
  - Fixed gain control (since April 2015)
    - Better for calibration purposes
    - Lower "radiometric accuracy"

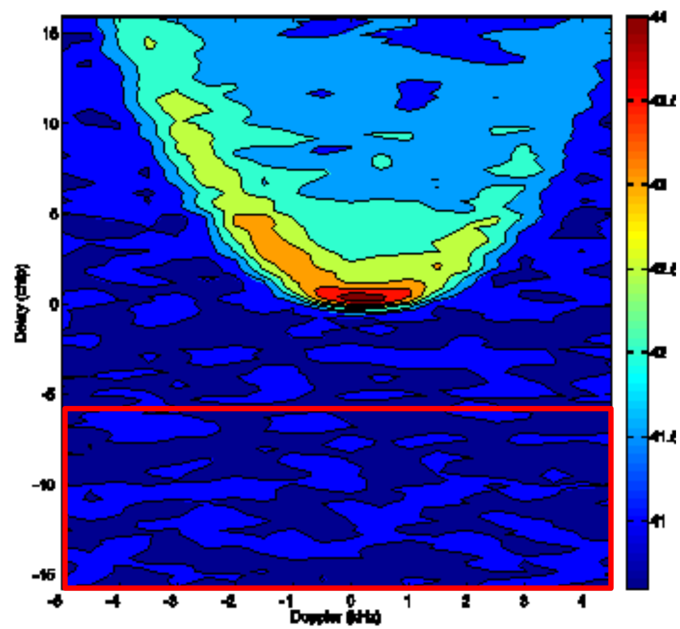
- In obs mode, transmitter power and antenna gain are unknown (no sigma0s provided)

1. Theoretical model – wavpy simulation

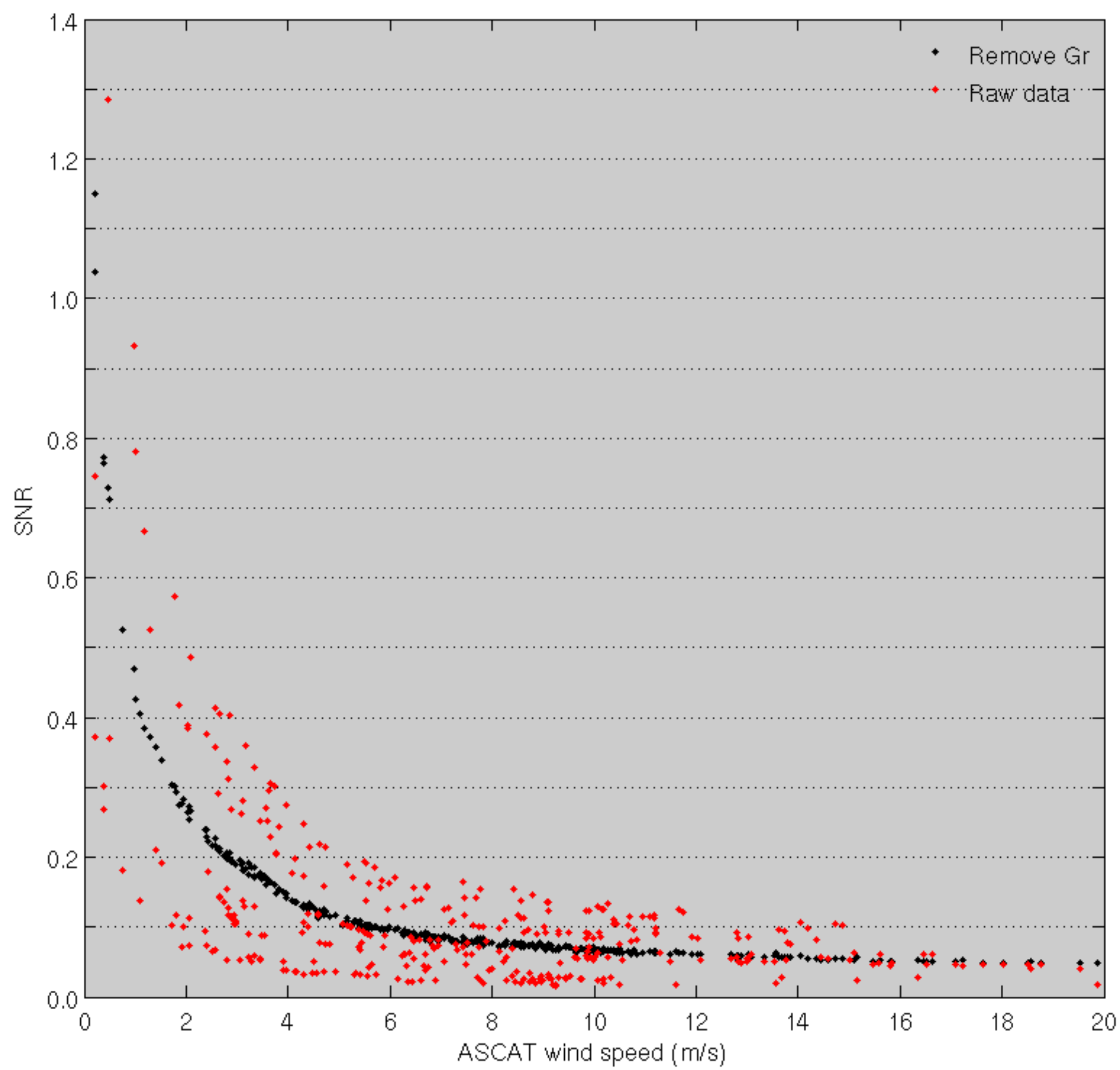
Benchmark:

- wavpy v4.2; (Elfouhaily et al., 1997;antenna T=200 K; noise figure=3 dB ...)
- TDS-1 geometry (position/velocity vectors of the receiver and the transmitter);
- Collocated ASCAT wind vectors and ECMWF forecast fields;

From the simulation point of view (ideal condition), the observables signal, signal-to-noise ration (SNR), peak, and peak-to-noise ratio (PNR) are equivalent to each other. However, it makes more sense to study SNR or PNR when comparing to the real TDS-1 data.



1. Theoretical model/simulation – **first-order effect**



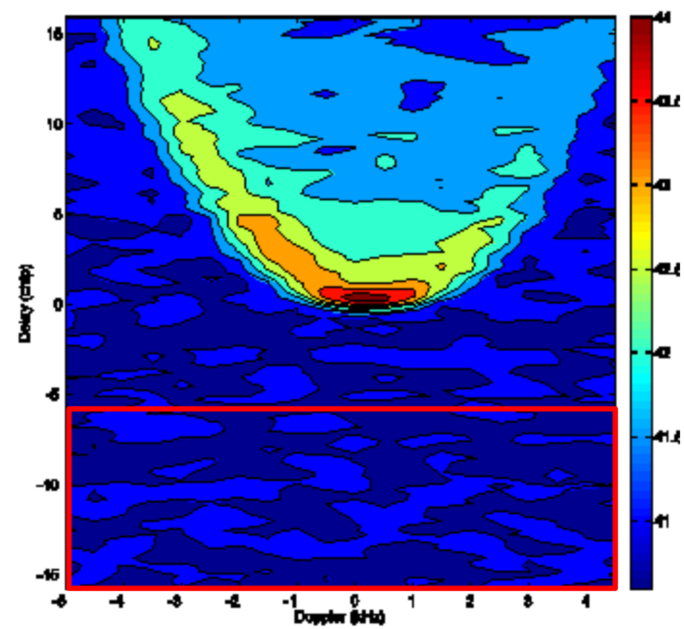
Incidence angle θ = 25° ± 0.5 °

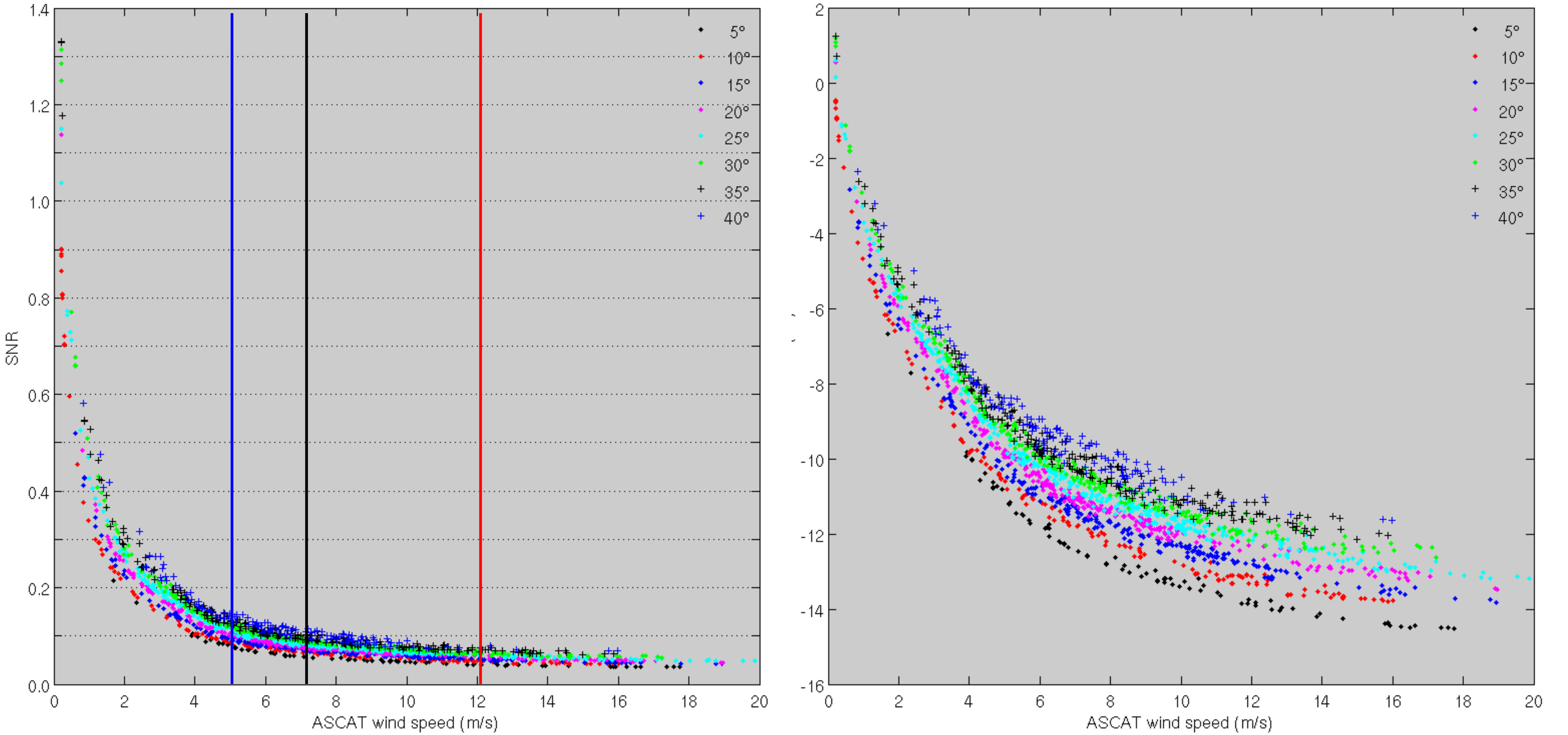
The primary issue of GMF development is to correct for the effect of **receiver antenna gain**.

$$SNR_1 = \frac{SNR_0}{G_r}$$

Red dots: raw SNR (wavpy)

Black dots: after decoupling the effect of receiver antenna gain Gr

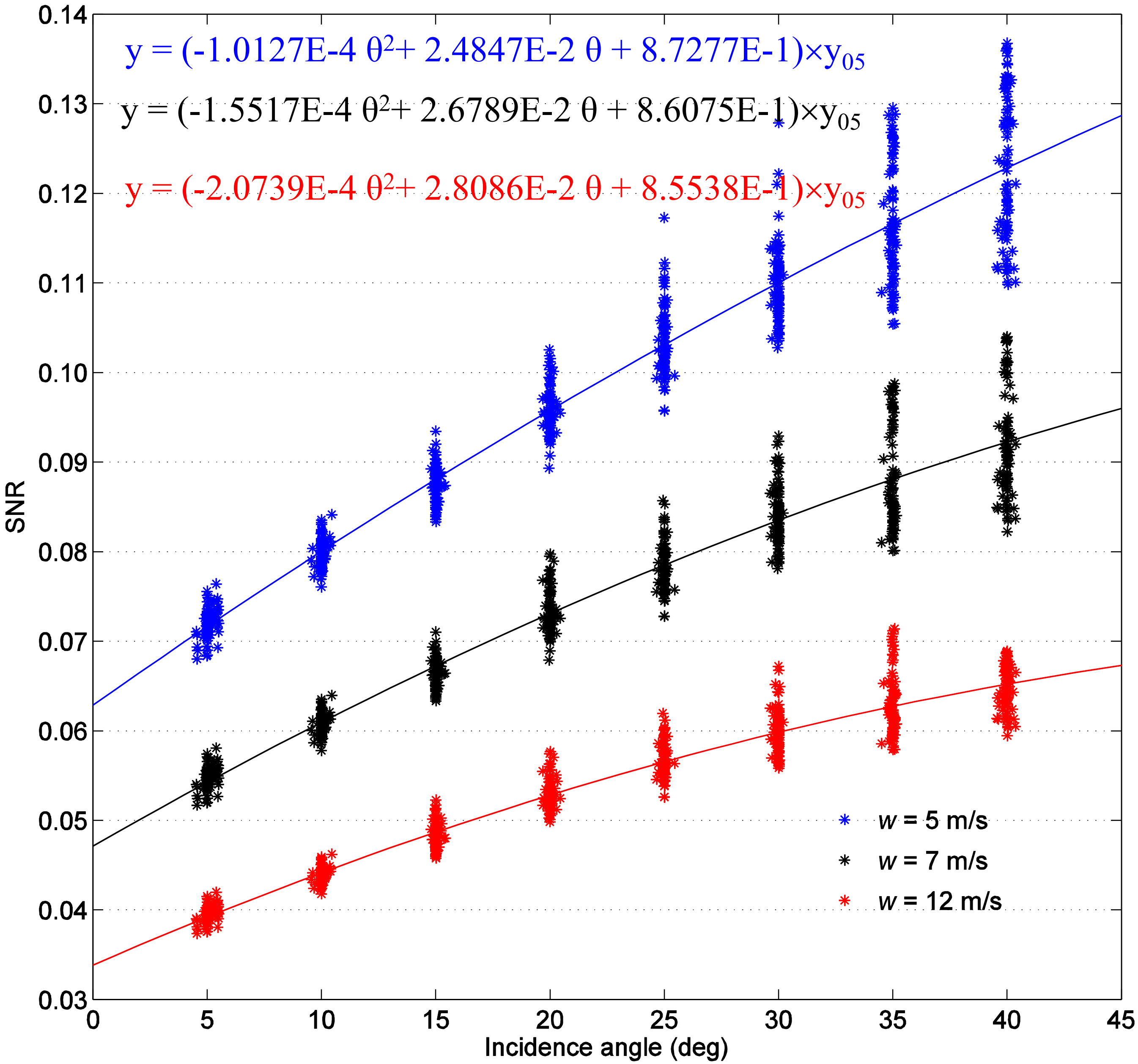




After decoupling the effects of receiver antenna gain Gr, SGR-ReSI SNR as a function of wind speed (x-axis) and incidence angle (colors). (left) linear space; (right) logarithmic space.

The residual dependence on incidence angle (and other factors, e.g., azimuth, latitude) is attributed to the effects of measurement area, transmitter and receiver geometry (distance from specular point to the transmitter and the receiver respectively).

The residual dependence ...



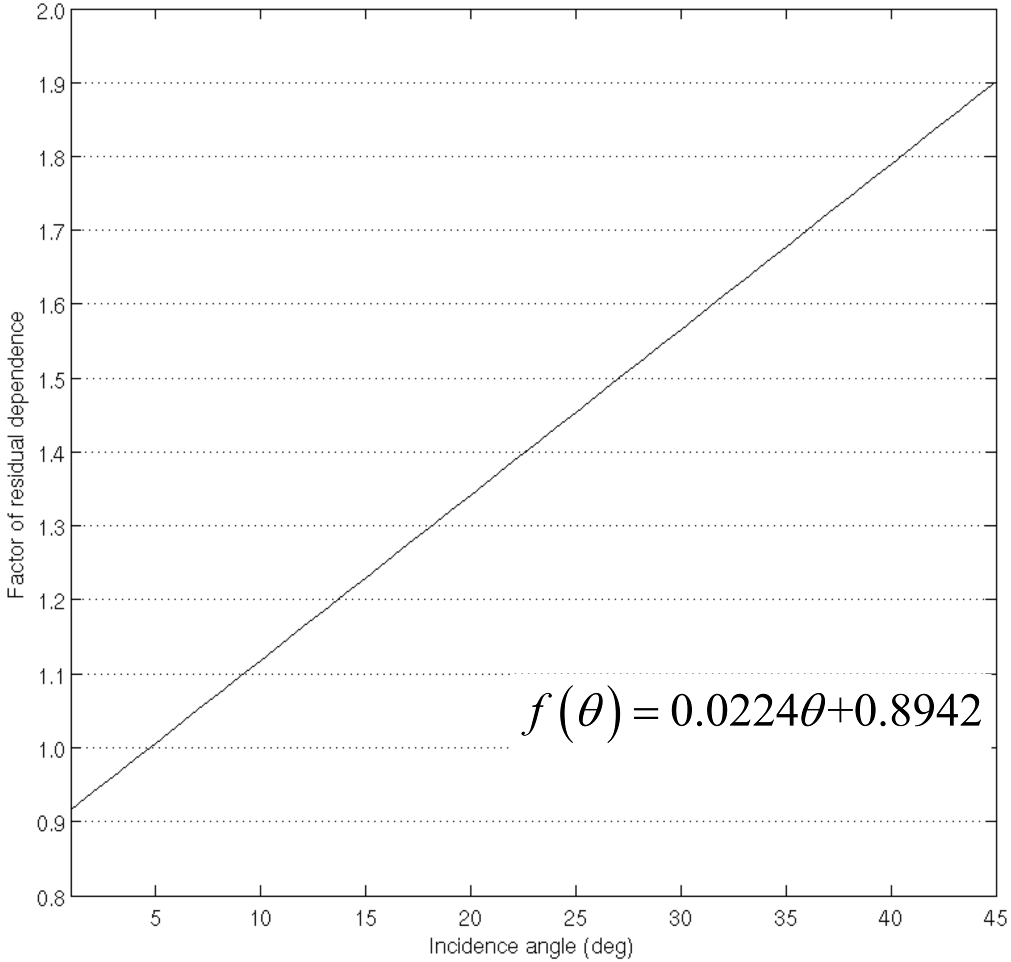
Second-order effect:

◆ Incidence angle
(surface area;distance to specular point)

Third order effects:
(variations at each θ)

◆ Relative motion?;
◆ Latitude?
◆ relative azimuth?
◆ *instrument snr?*

Linear approximation



The next step is to correct for the second-order effect induced by incidence angle

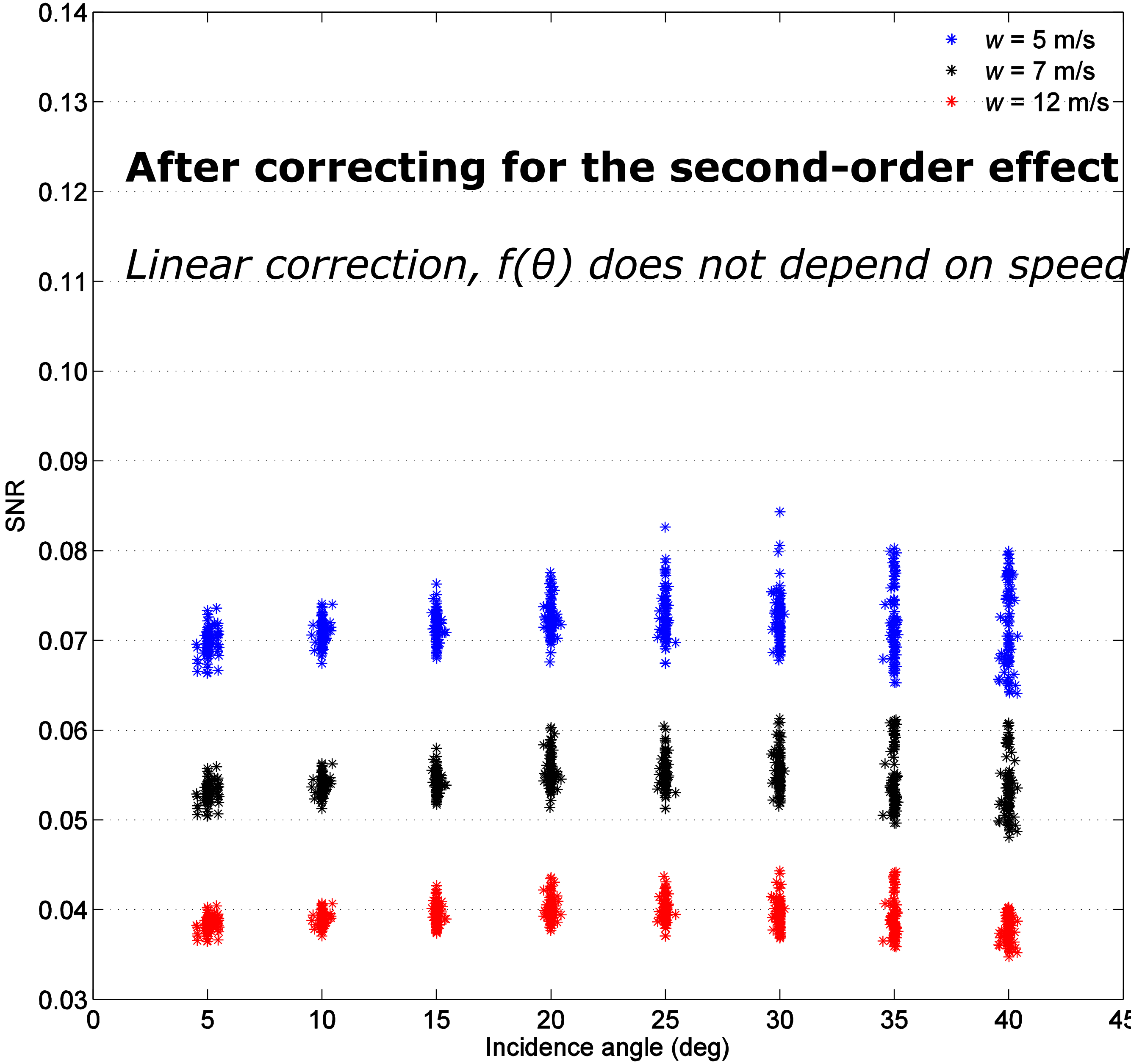
$$SNR_2 = \frac{SNR_1}{f(\theta)}$$

The residual dependence on incidence angle can be removed by applying a linear correction as above figure.

Here the SNR at θ = 5° is used as reference.

After correcting for the second-order effect …

Linear correction, f(θ) does not depend on speed



Variations

Third order effects:
(variations at each θ)

- Relative motion?;
- Latitude?
- relative azimuth?
- *instrument snr?*

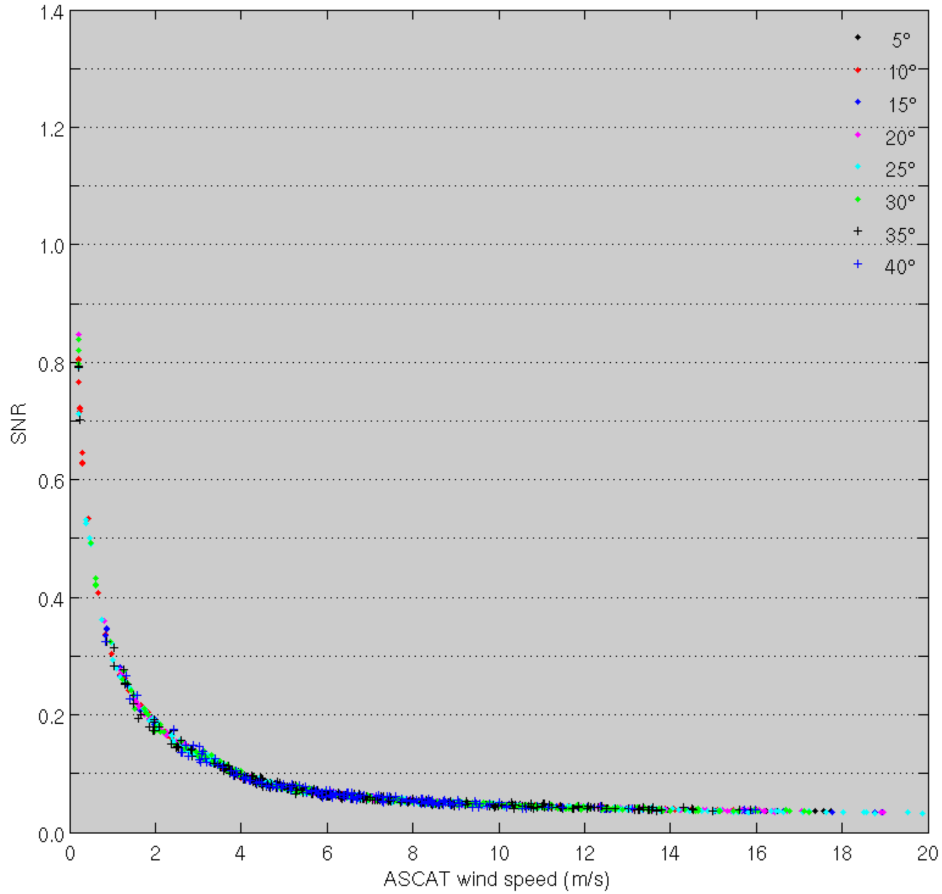
Relative motion

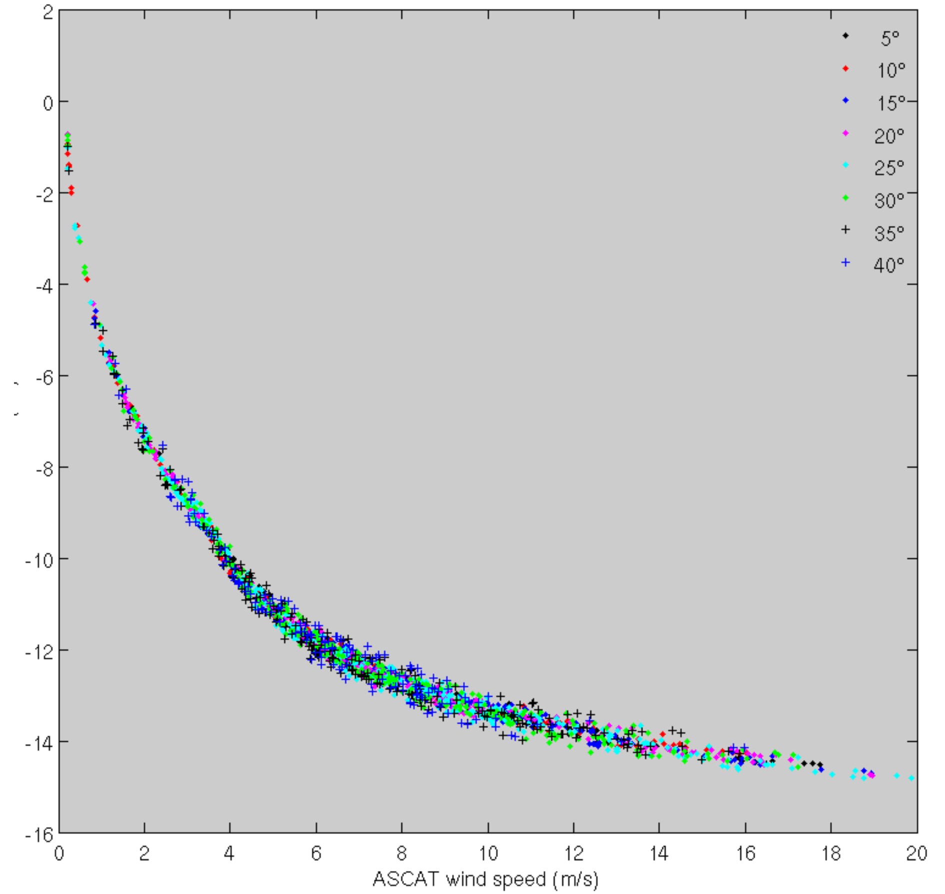
$$RM = \operatorname{acos}\left(\frac{\mathbf{v}_r \cdot \mathbf{v}_t}{\|\mathbf{v}_r\| \times \|\mathbf{v}_r\|}\right)$$

Relative azimuth

$$RA = \operatorname{mod}(\varphi - \phi, 360)$$

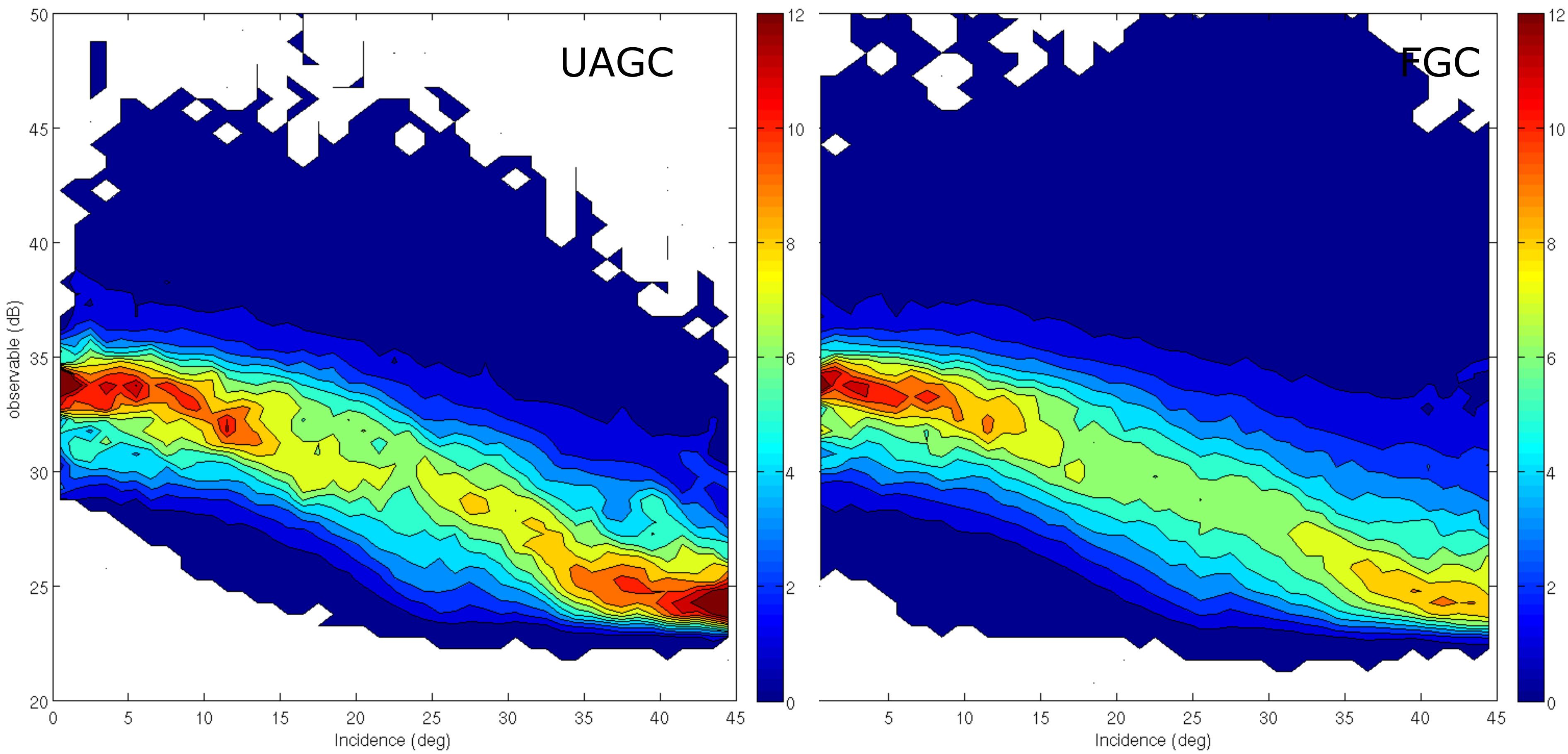
φ wind direction
ϕ observation azimuth





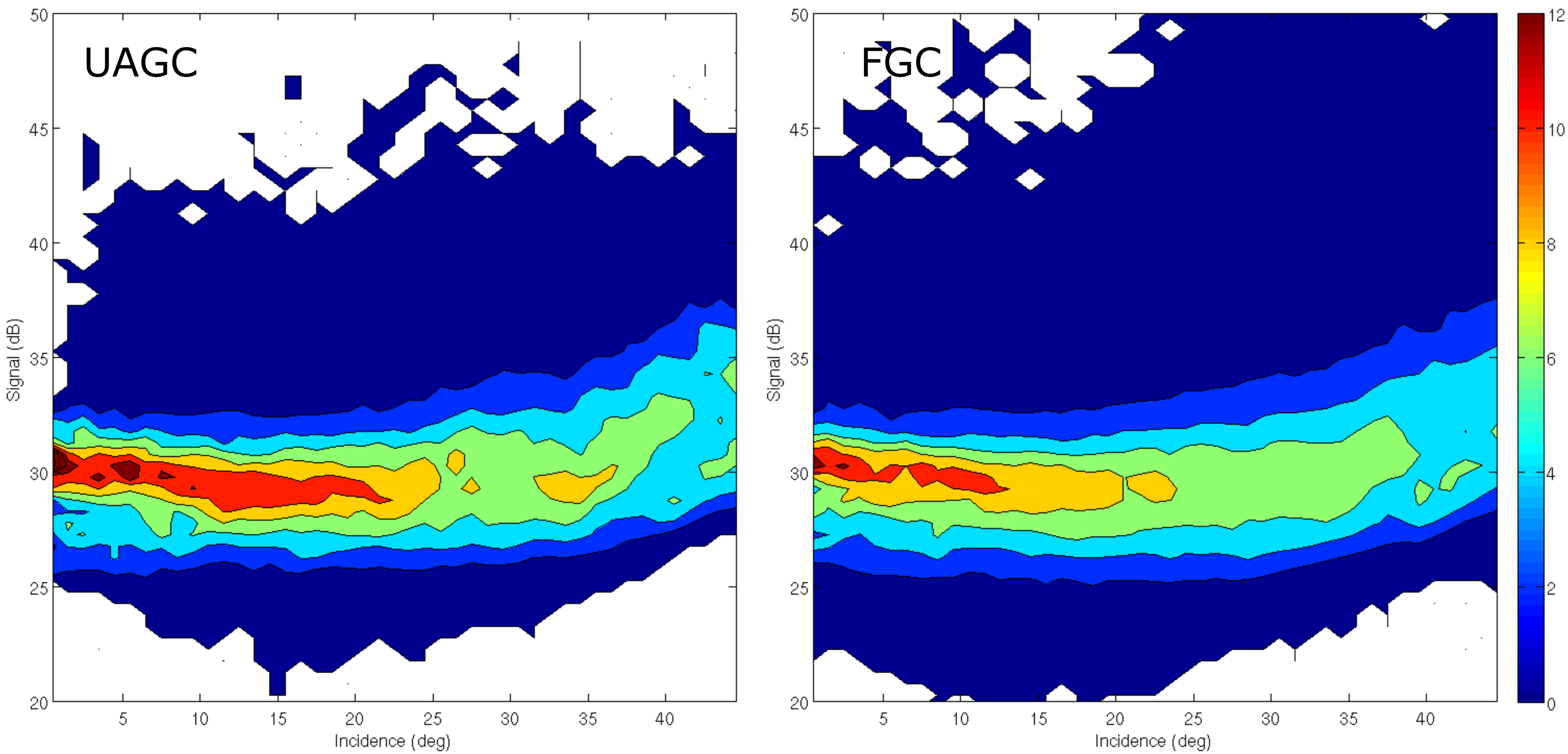
After further decoupling the effects of measurement area, transmitter and receiver geometry

Without wind speed PDF matching



2. Empirical model – real data

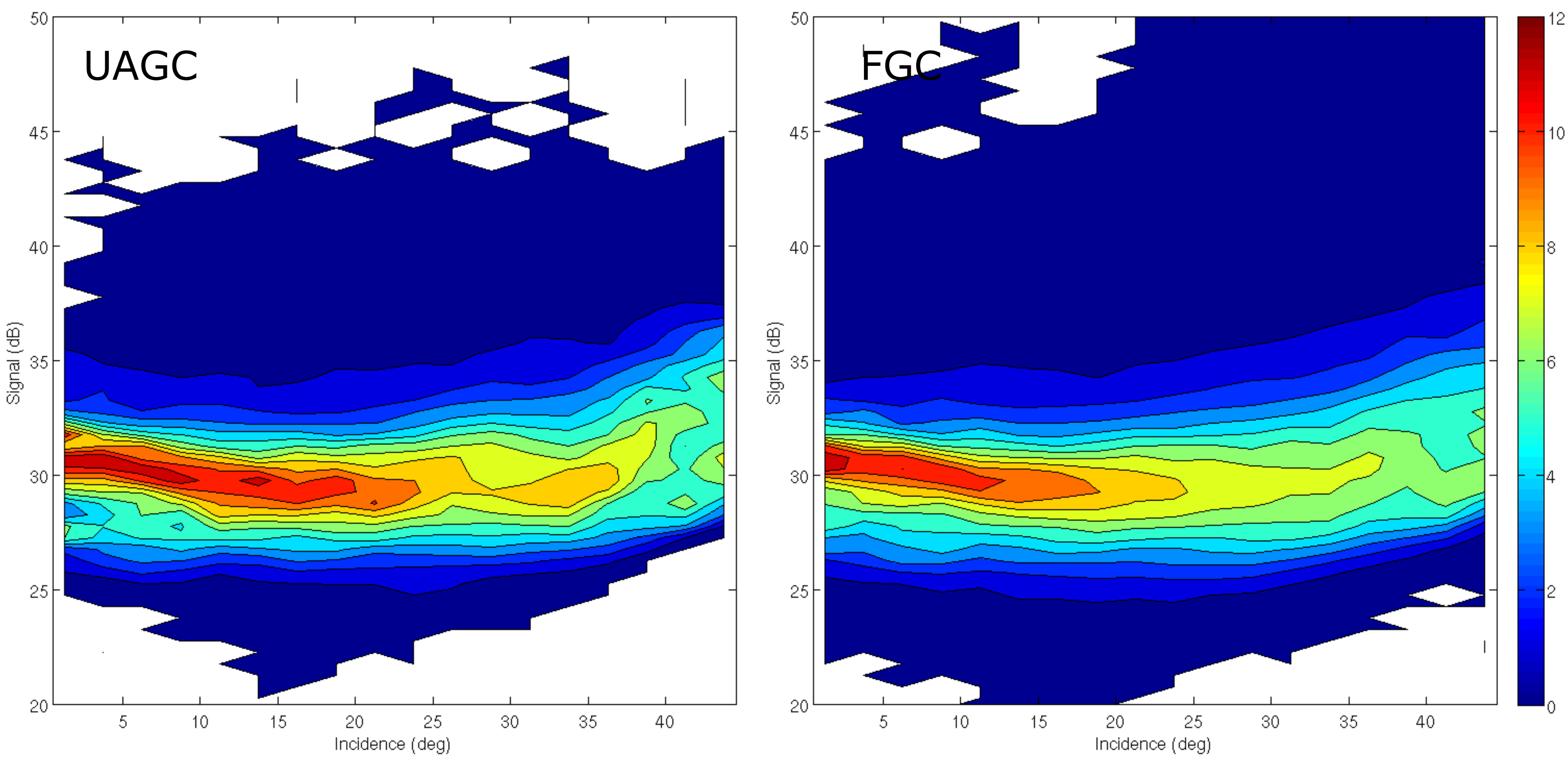
Preprocessing: Corrects for receiver antenna gain (first order) and incidence angle f(θ) (measurement area, and transmitter/receiver geometry) variations.



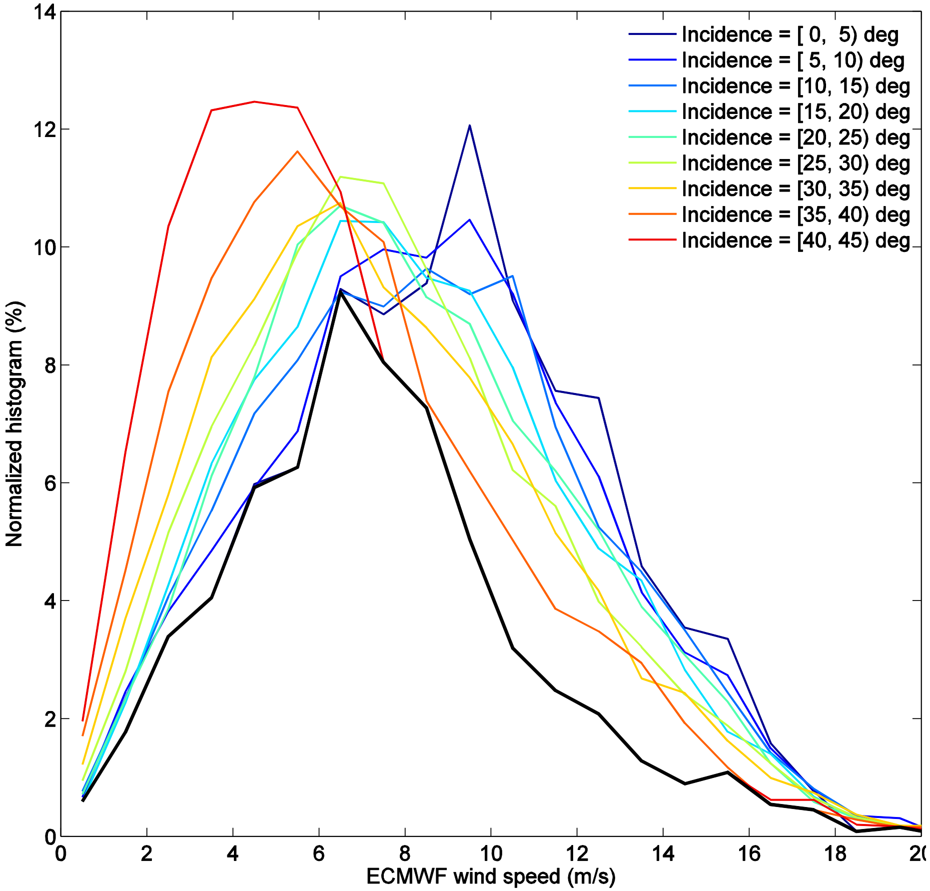
persistent dependecen on incidence angle

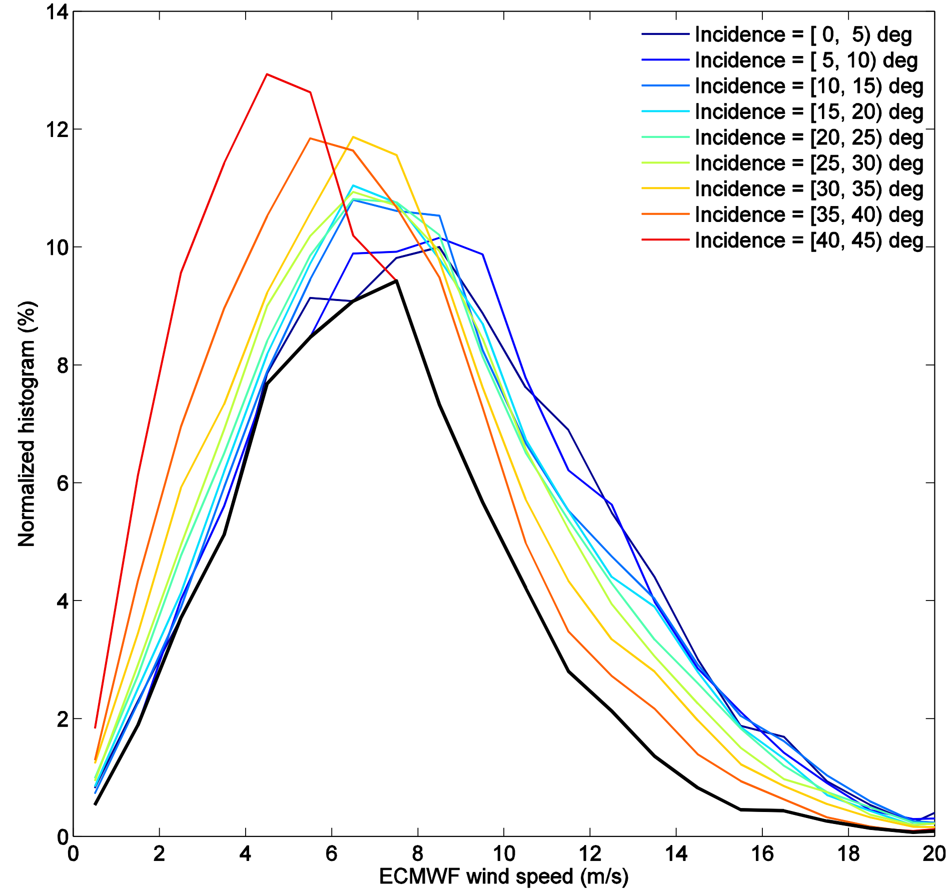
The same as previous slide, but with PDF matching

Persistent dependecen on incidence angle is attributed to the uncalibrated receiver antenna gain and the unknown transmitter antenna gain, which is modeled as $\Delta g(\theta,\varphi)$



Wind speed PDF for different incidence angles



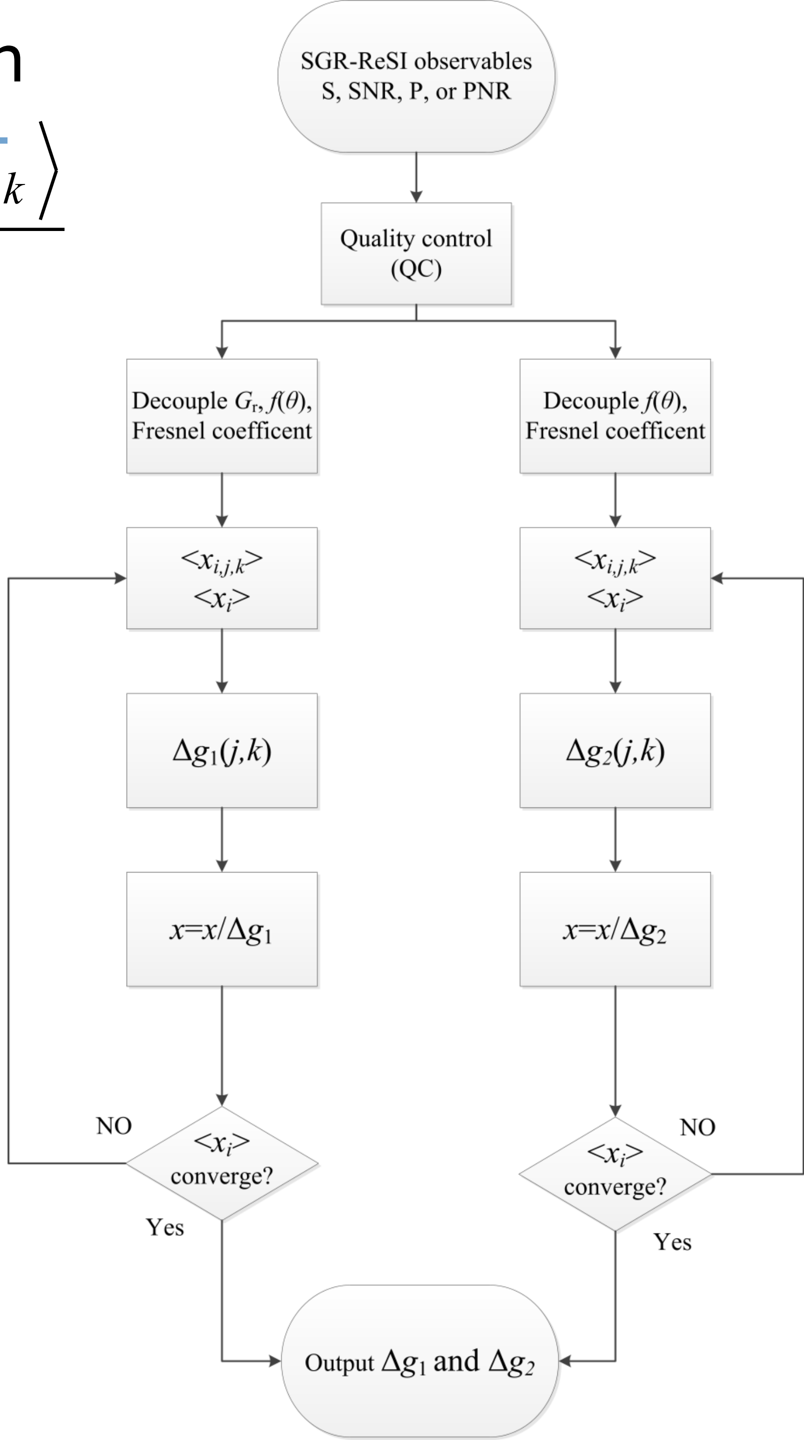


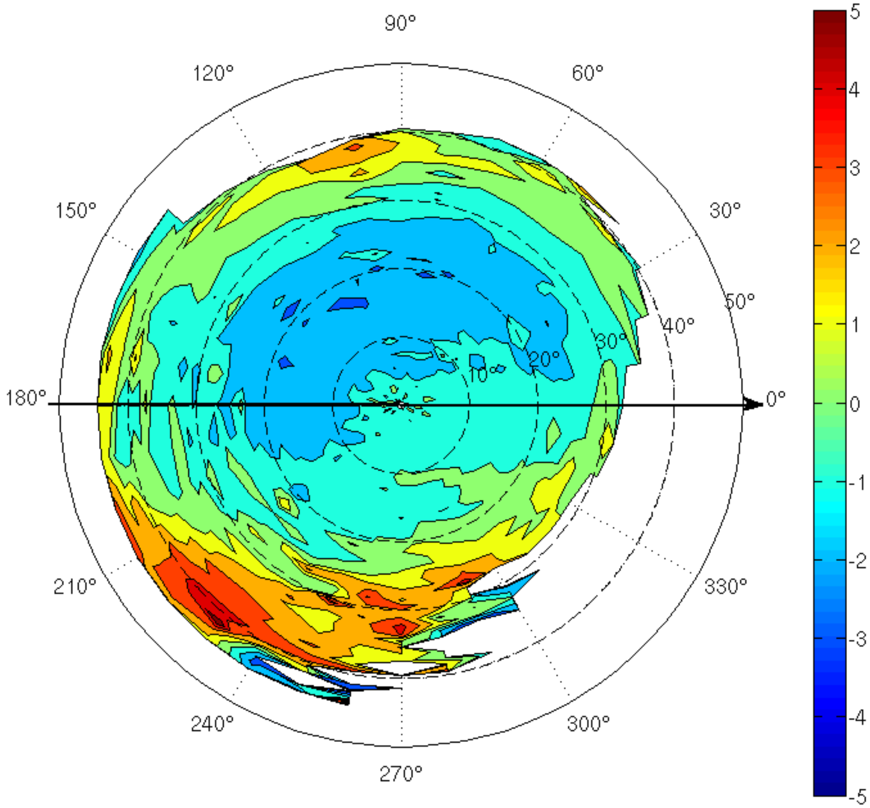
$\Delta g(\theta,\varphi)$ estimation

$$\Delta g_{j,k} = \frac{1}{N}\sum_i \frac{n_i \cdot \langle x_{i,j,k} \rangle}{\langle x_i \rangle}$$

Remarks:

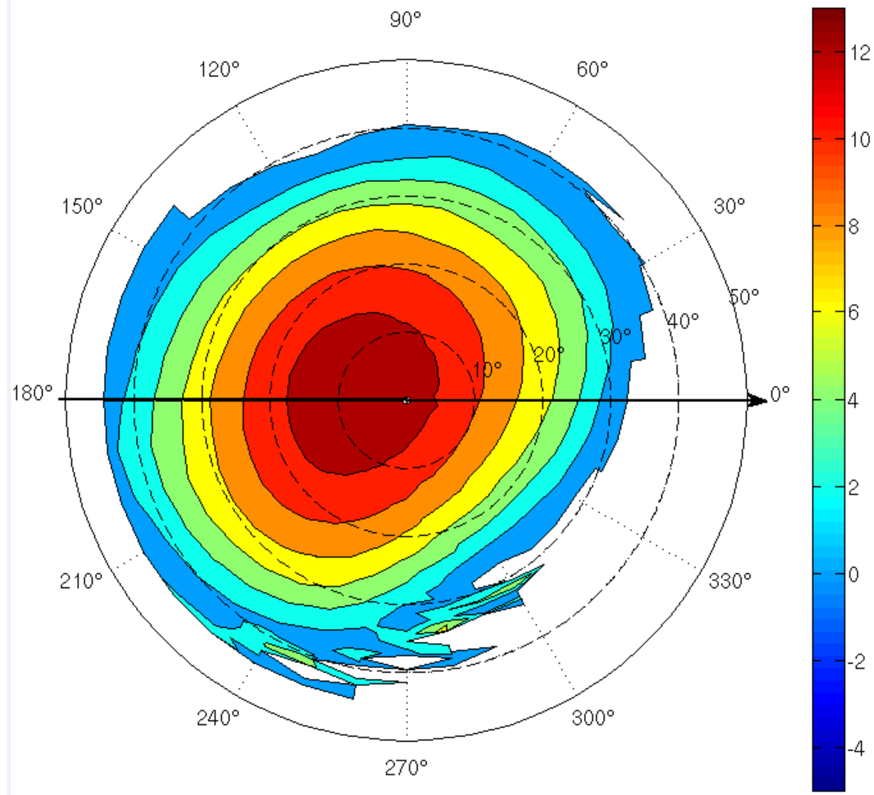
- *i,j,k* represent the bin number of wind speed, incidence angle, and azimuth angle (SP to Receiver vector in the receiver's antenna frame), respectively.
- bin size: 1 m/s for *i*, 1° for *j*, and 10 ° for *k*.
- Fresnel coefficient is calculated using the collocated ECMWF SST data ;
- The estimation of Δg generally converges after three iterations.
- Δg_1 consists of the contribution from transmitter antenna gain, and the unknown bias of receiver antenna gain.
- Δg_2 consists of Δg_1 and receiver antenna gain





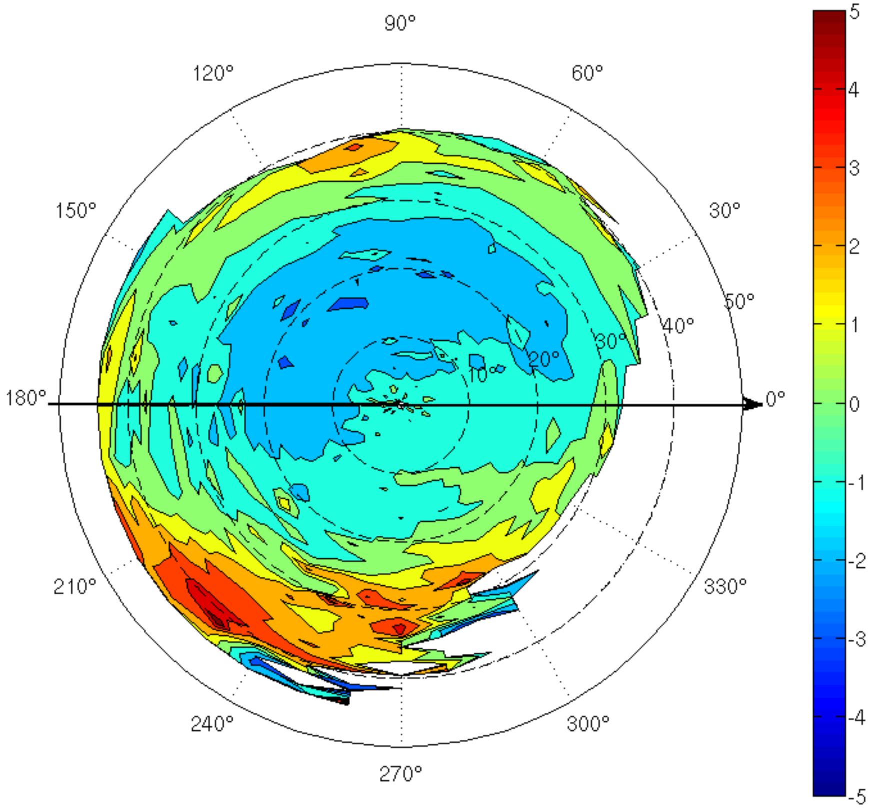
$$\Delta g_1(\theta,\varphi)$$

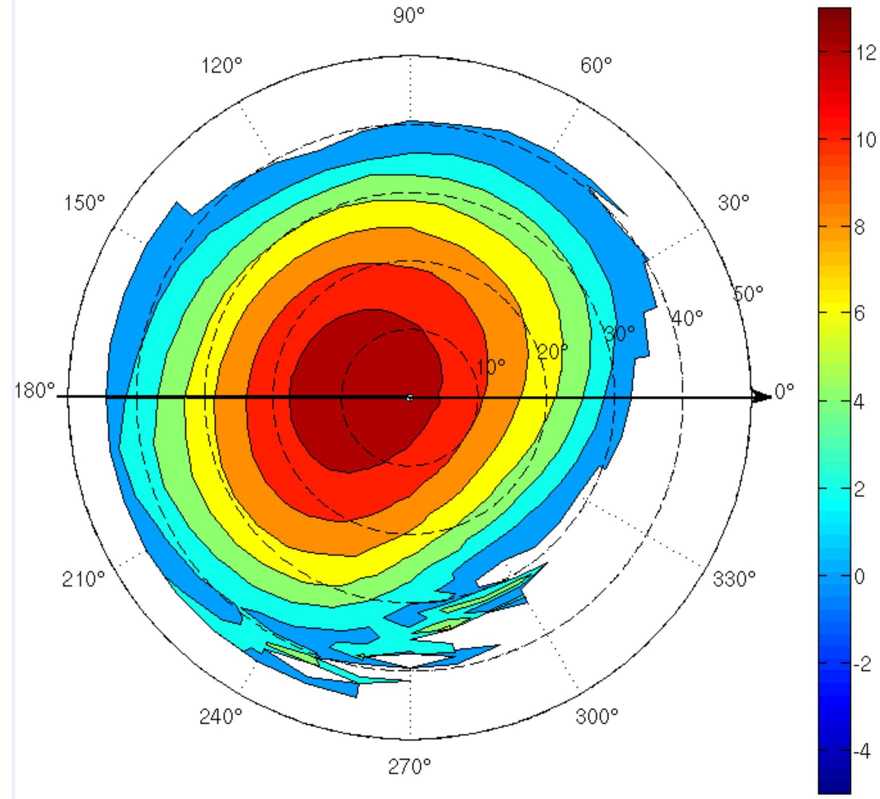
Further calibration factor
(combined receiver & transmitter G)



$$\Delta g_2 / \Delta g_1$$

Inferred receiver
antenna gain pattern





$$\Delta g_1(\theta,\varphi)$$

Further calibration factor
(combined receiver & transmitter G)

Estimated receiver
antenna gain pattern

Calibration factors may be estimated for every transmitter

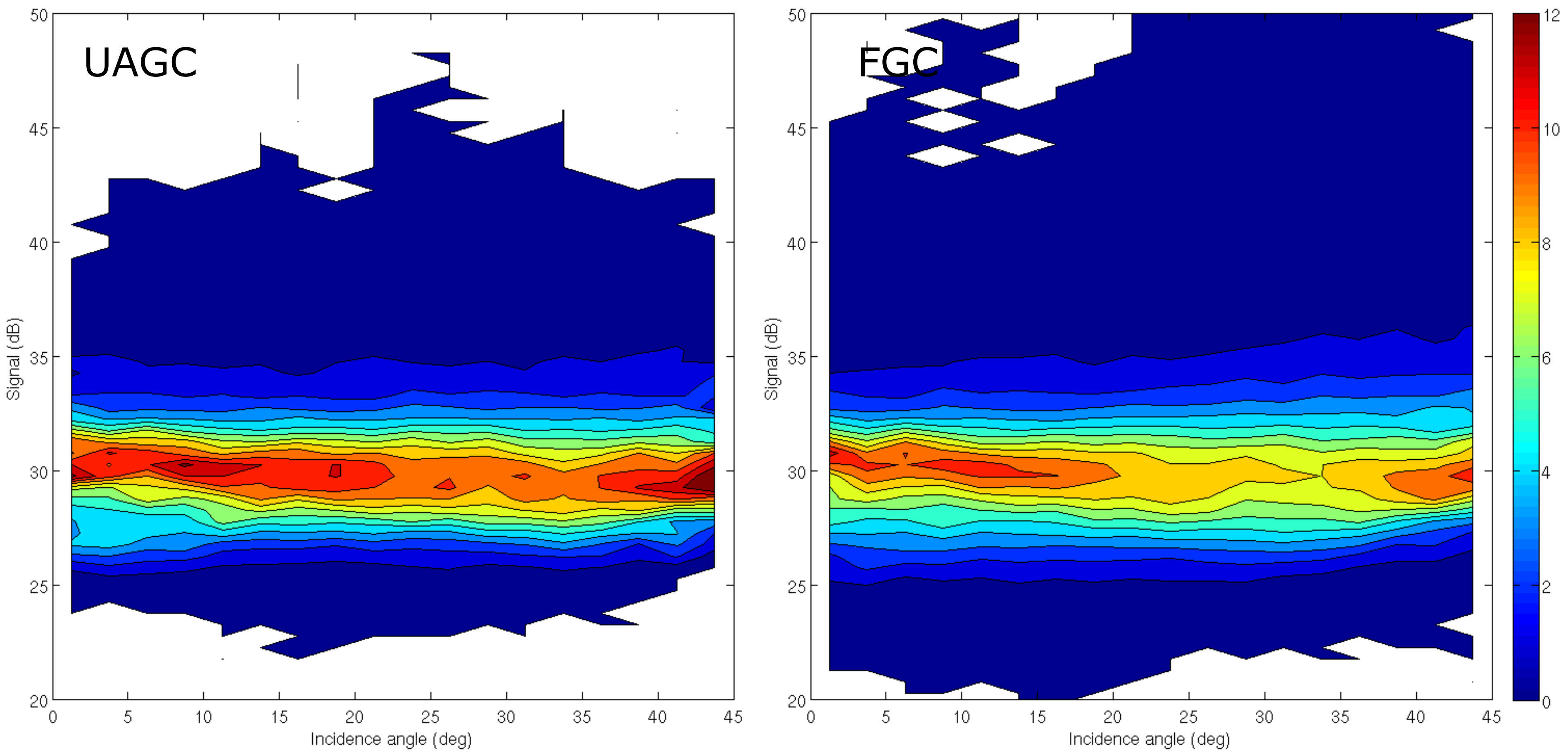
3. Analysis - after decoupling all the known/modeled dependences

No more dependence on the incidence angle

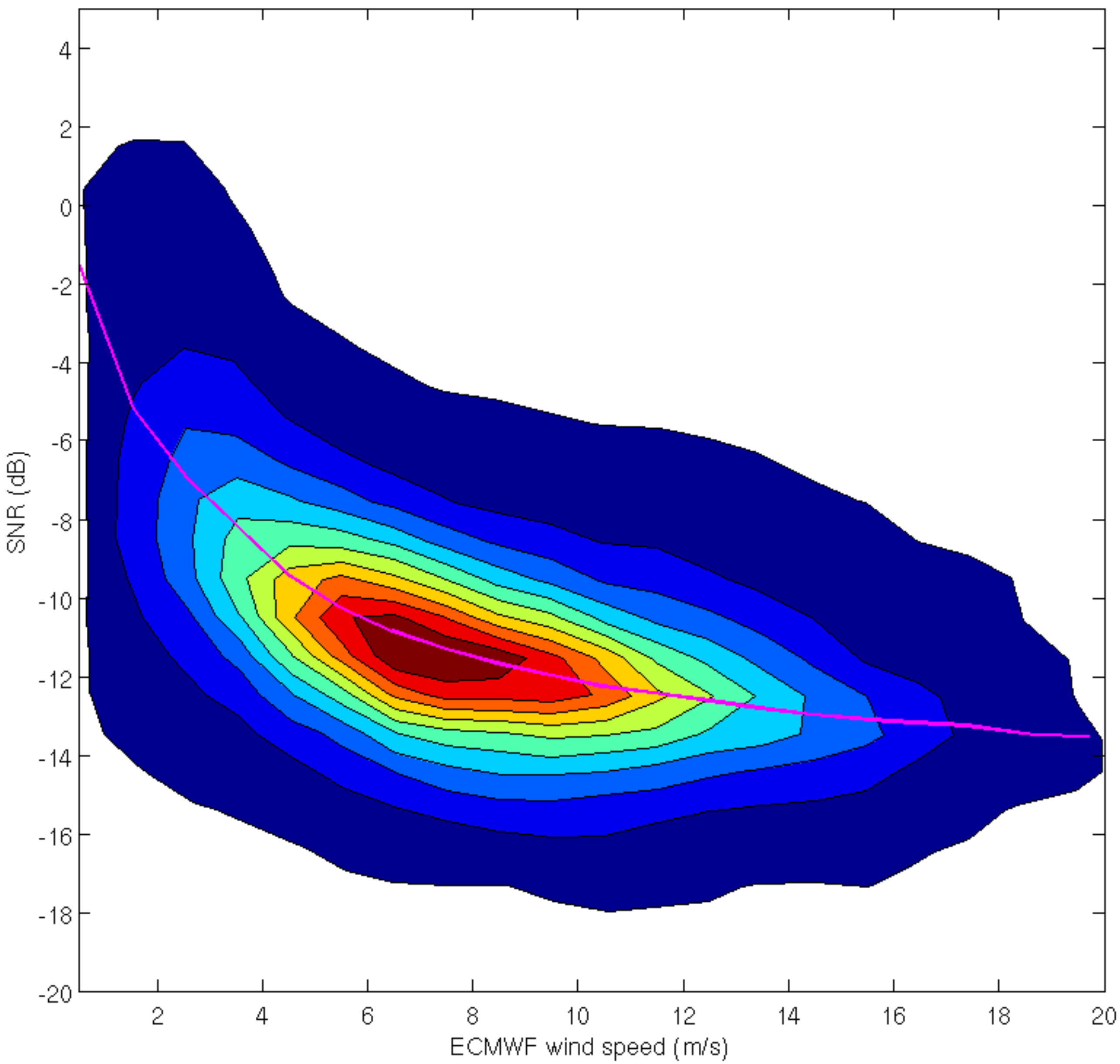
UAGC has much less uncertainty than FGC

$$SNR_1 = \frac{SNR_0}{G_r} \qquad SNR_2 = \frac{SNR_1}{f(\theta)}$$

$$SNR_3 = \frac{SNR_2}{\Delta g_1(\theta,\varphi)}$$



Global analysis - UAGC

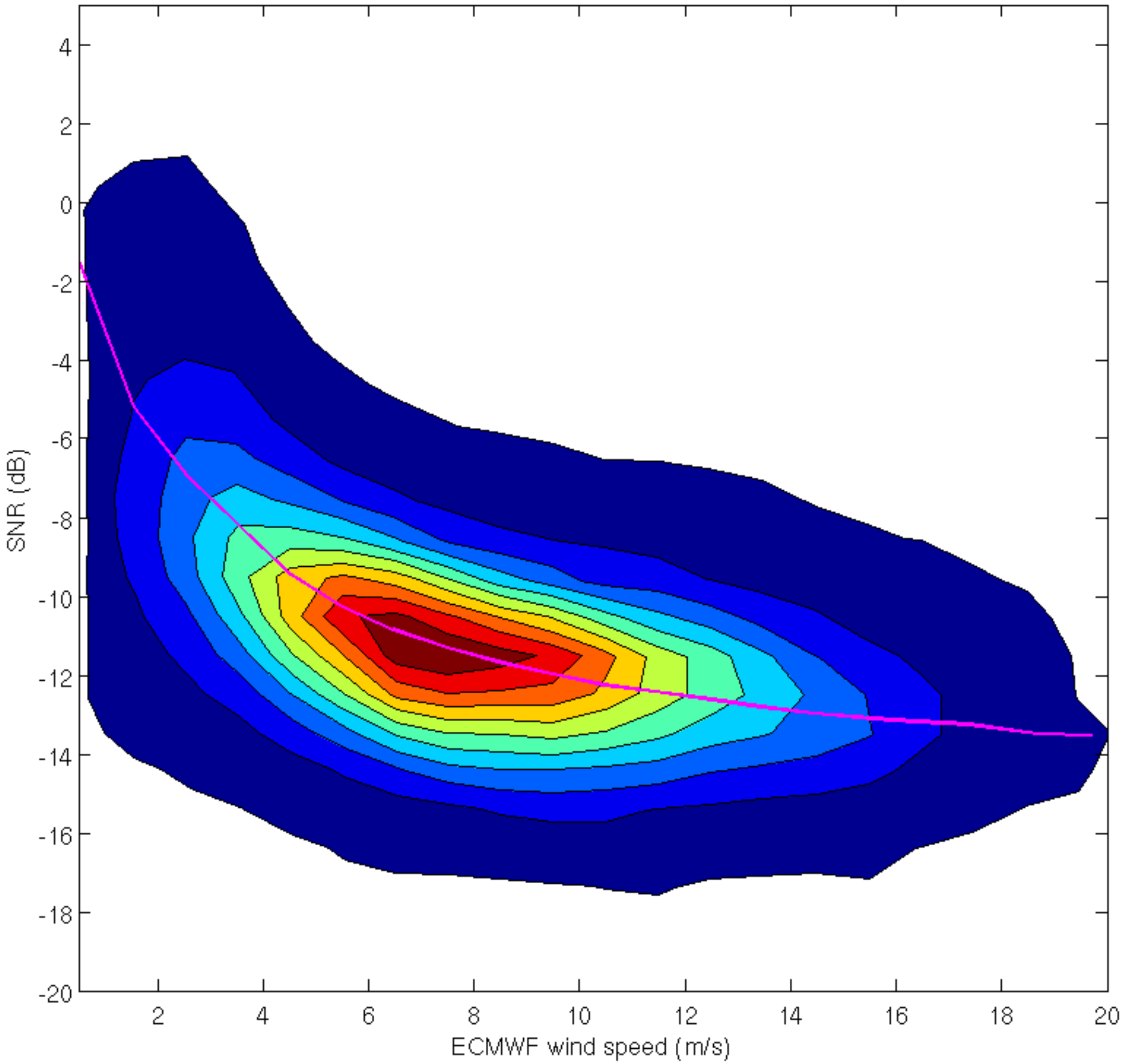


First-order correction

Correct for receiver antenna gain

$$SNR_1 = \frac{SNR_0}{G_r}$$

Global analysis - UAGC

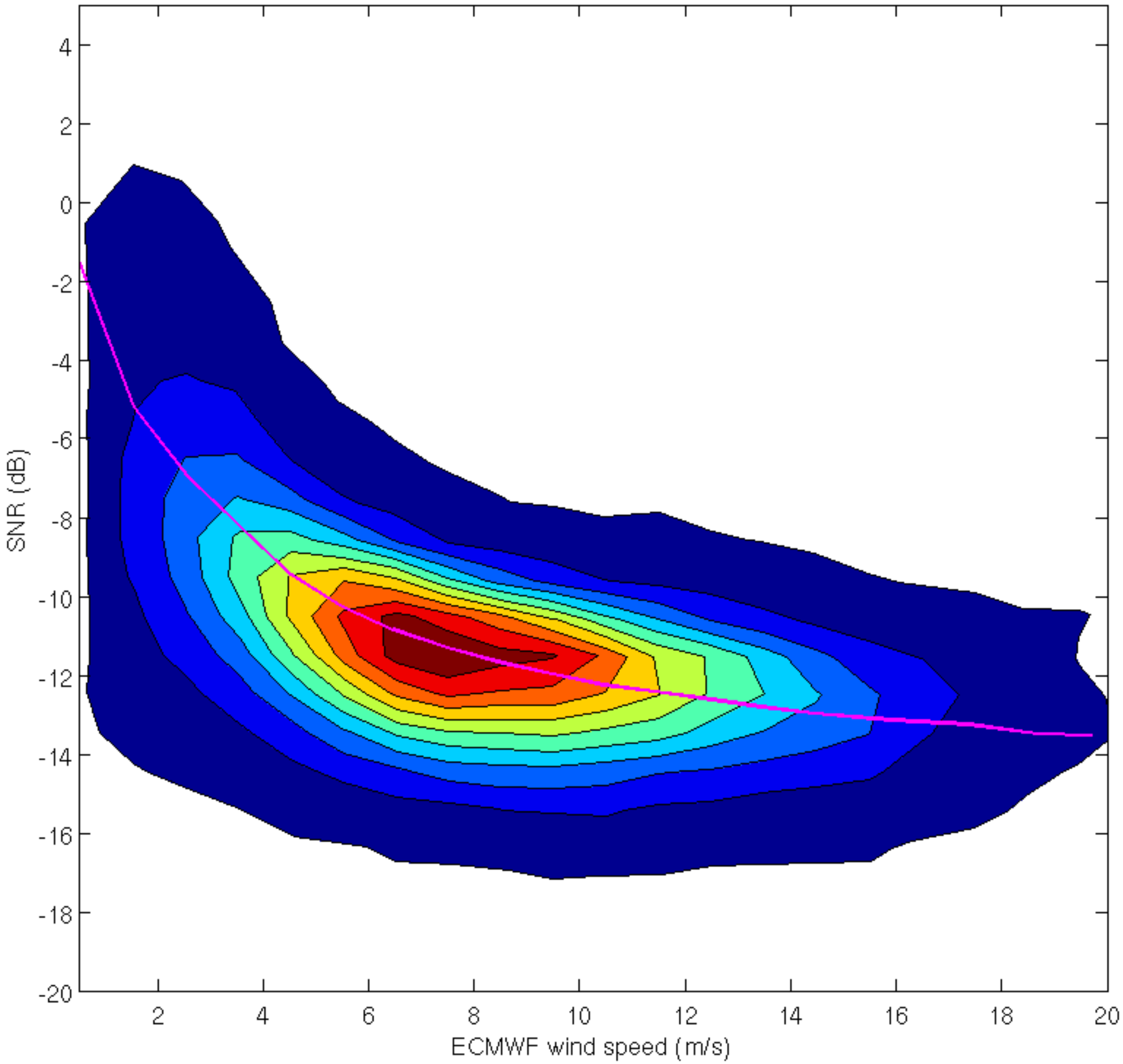


Second-order correction

Further correct for incidence angle

$$SNR_2 = \frac{SNR_1}{f(\theta)}$$

Global analysis - UAGC



Total correction

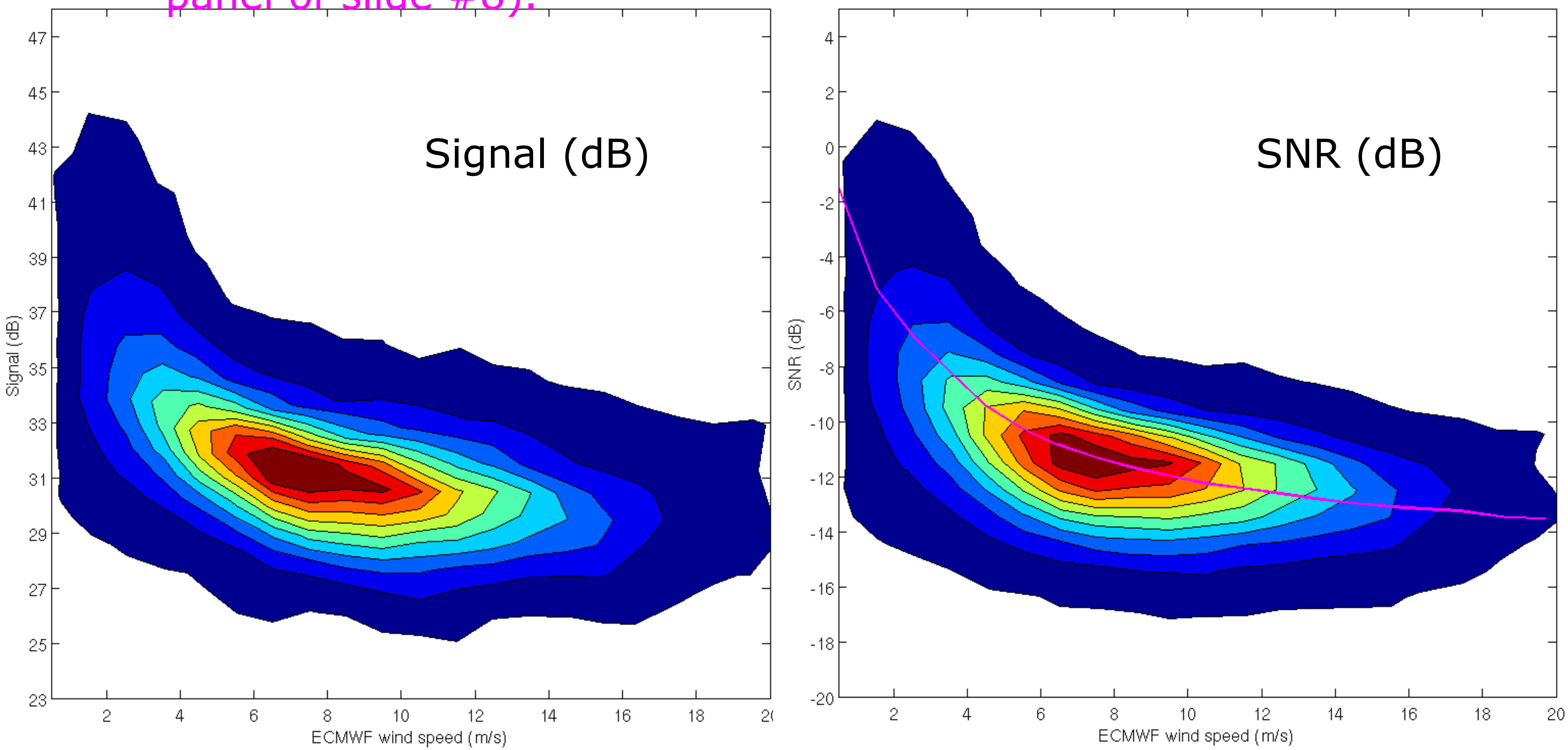
Further correct for gain pattern

$$SNR_3 = \frac{SNR_2}{\Delta g_1(\theta, \varphi)}$$

Global analysis

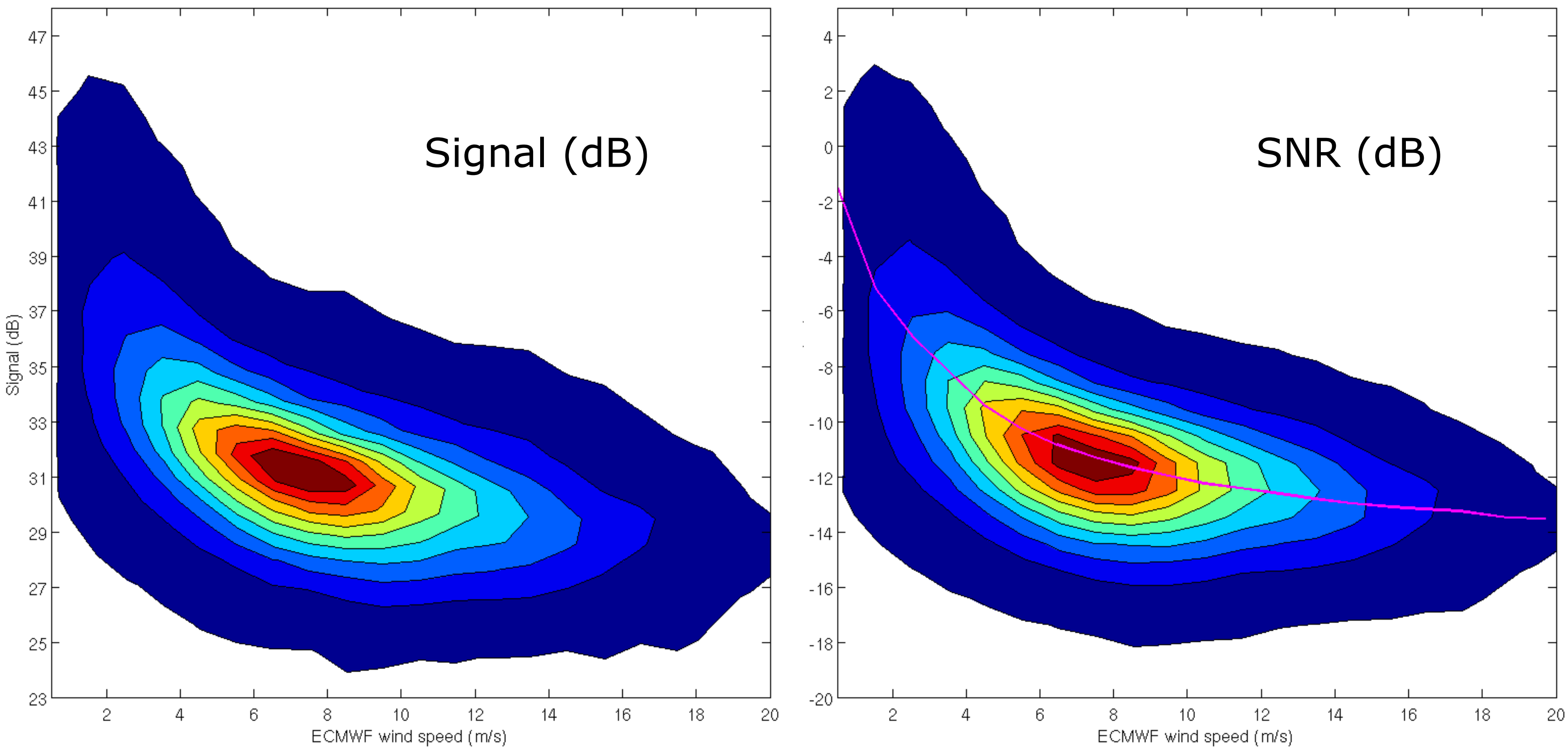
2D histogram of Signal (left) and SNR (right) versus wind speed @ **UAGC**

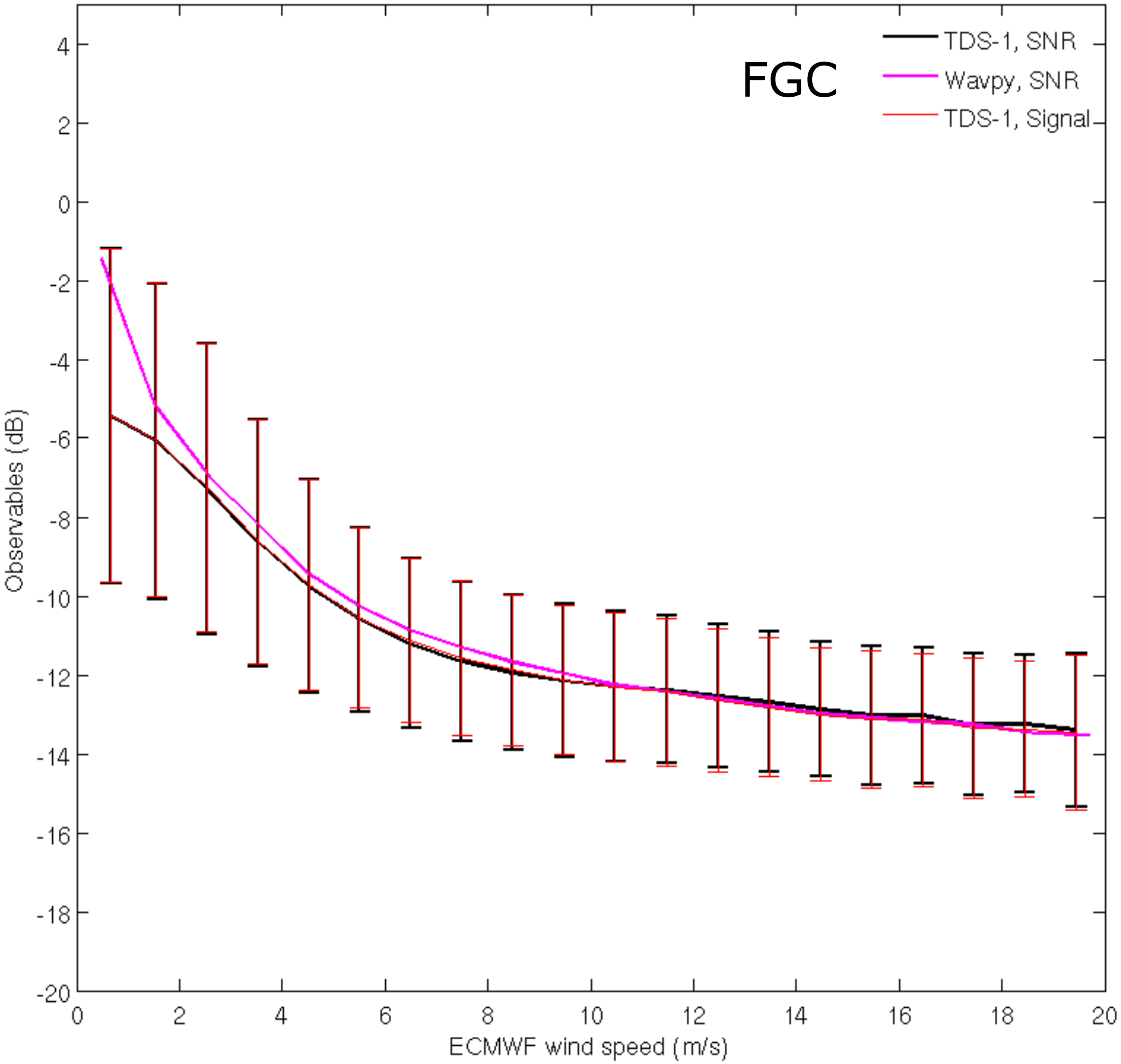
- Contour lines in linear space, i.e., 1%, 10%, 20% ...90% of the maximum bin
- Magenta curve is the theoretical model derived from wavpy. (right panel of slide #8).



2D histogram of Signal (left) and SNR (right) versus wind speed @ **FGC**

- Contour lines in linear space, i.e., 1%, 10%, 20% ...90% of the maximum bin
- Magenta curve is the theoretical model derived from wavpy.





Signal shows slightly smaller uncertainty than SNR

Note the large discrepancy at low winds.

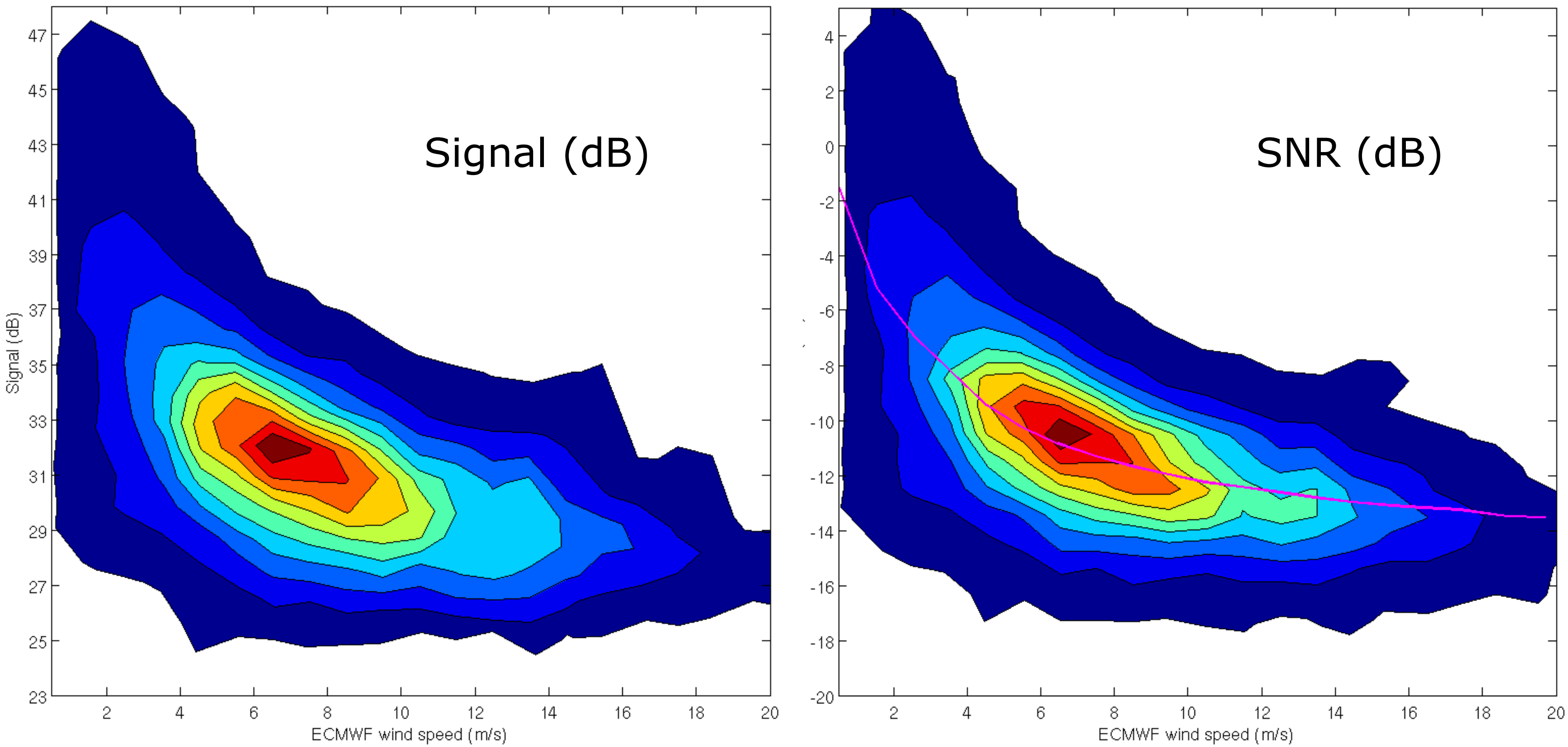
The mean SNR/Signal of SGR-ReSI as a function ECMWF wind speed. Errorbars indicate the SD values of the corresponding bins.

Signal is scaled for the sake of comparison.

ASCAT collocation analysis (high latitudes)

2D histogram of Signal (left) and SNR (right) versus ECMWF wind speed @ **FGC**

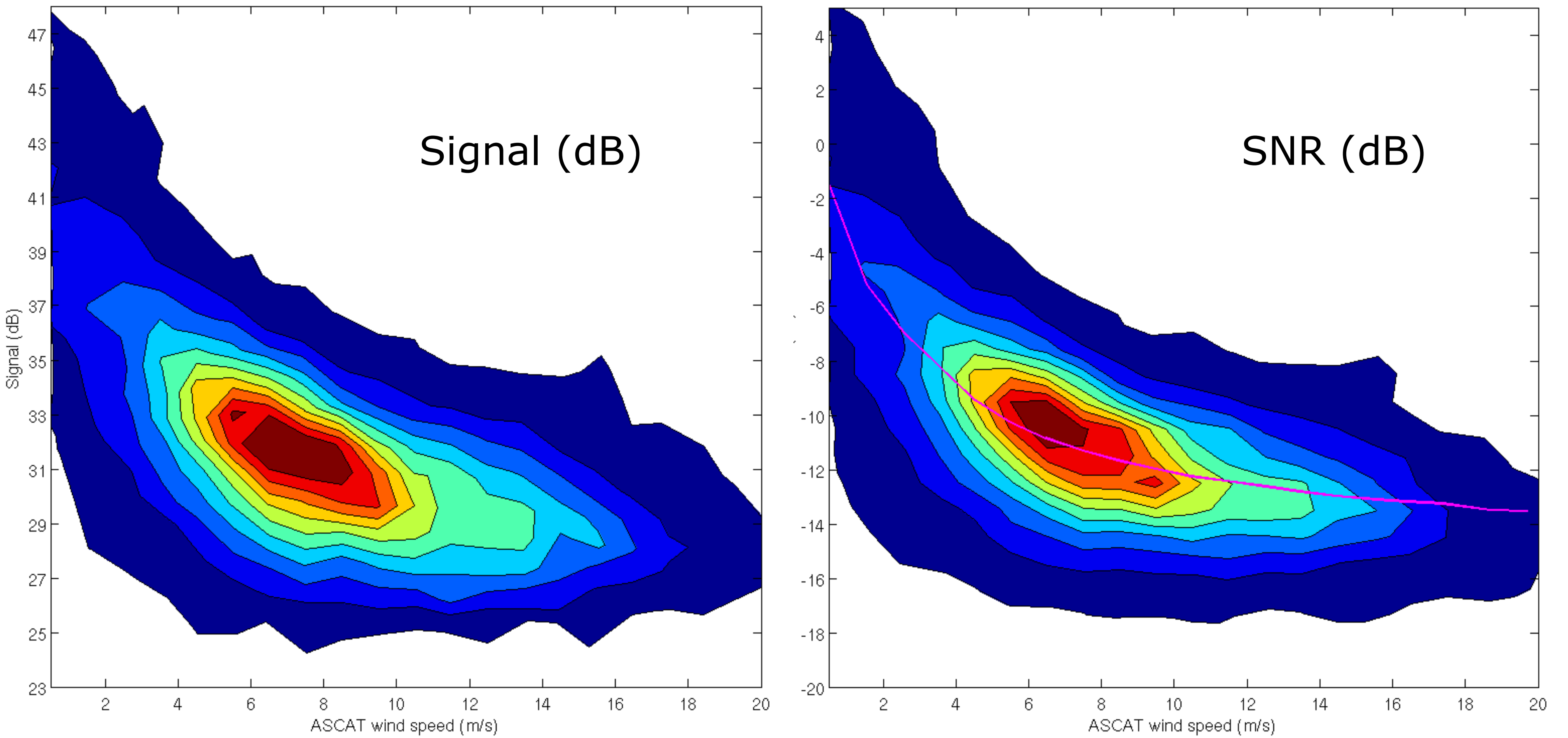
- Contour lines in linear space, i.e., 1%, 10%, 20% ...90% of the maximum bin
- Magenta curve is the theoretical model derived from wavpy.

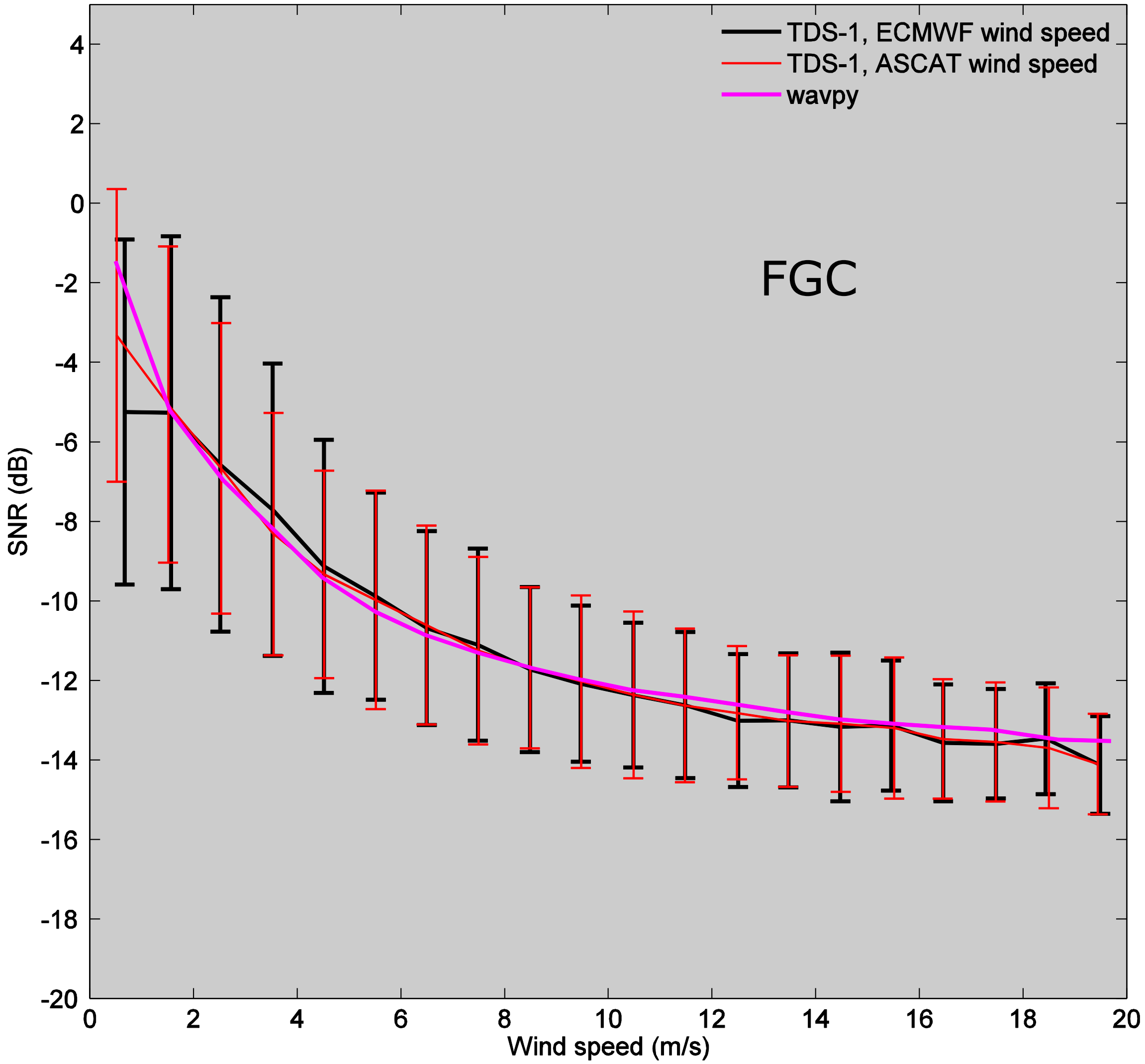


ASCAT collocation analysis (high latitudes)

2D histogram of Signal (left) and SNR (right) versus ASCAT wind speed @ **FGC**

- Contour lines in linear space, i.e., 1%, 10%, 20% ...90% of the maximum bin
- Magenta curve is the theoretical model derived from wavpy.





SNR fit with ASCAT wind speed (red curve) has less uncertainty & better fits theoretical sensitivity at low winds

Conclusions

- After decoupling all the mentioned effects, the globally measured observables (e.g., SNR) correspond well to the theoretical model derived from wavpy
- UAGC mode has less uncertainty than FGC mode
- FGC shows larger sensitivity to high winds; “effective sensitivity” needs to be verified
- For the SGR-ReSI measurements, ASCAT winds are more representative than ECMWF winds, particularly at low winds
- Near future work
  - Analyse simulated sensitivities to other observables (wind direction, mss, SWH)
  - Verify simulated sensitivities with real data
  - Consolidate empirical GMF & associated error model
- EUMETSAT Research Fellowship (GOODIE) – KNMI/ICM
  - 3-year post-doc fellowship (G. Grieco) – since March 2017
  - To develop an observation operator for GNSS-R
  - In collaboration with IEEC, NOC, Univ. Michigan

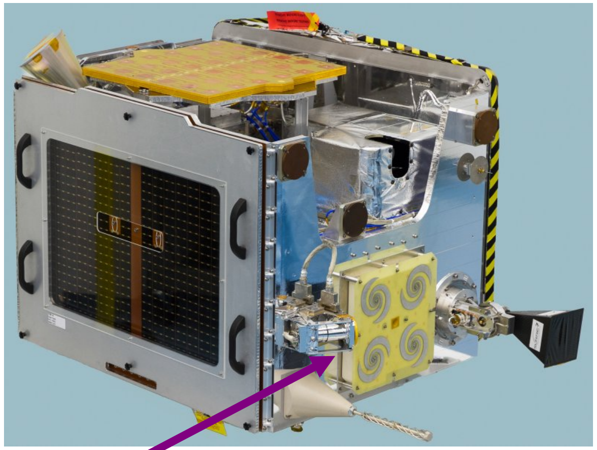
TDS-1 and SGR-ReSI

- TechDemoSat-1 Mission
  - 160 kg UK-funded Satellite Demonstrator
    - 8 UK payloads
  - Launched July 2014
- SGR-ReSI
  - COTS Based GNSS Receiver with GNSS reflectometry coprocessor
  - New low power instrument for measuring wind speed and mss over ocean
  - Instrument also used on **NASA CYGNSS** mission
- SSTL with NOC released TDS-1 data on www.merrbys.org

SGR-ReSI Unit

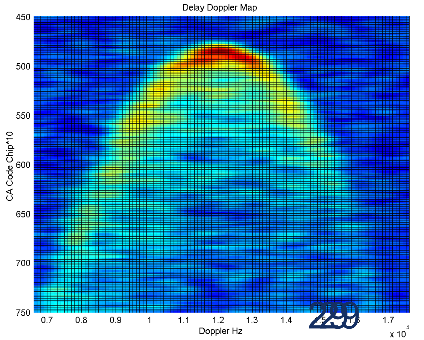
Zenith Antenna

5-10 watts, 1.5 kg

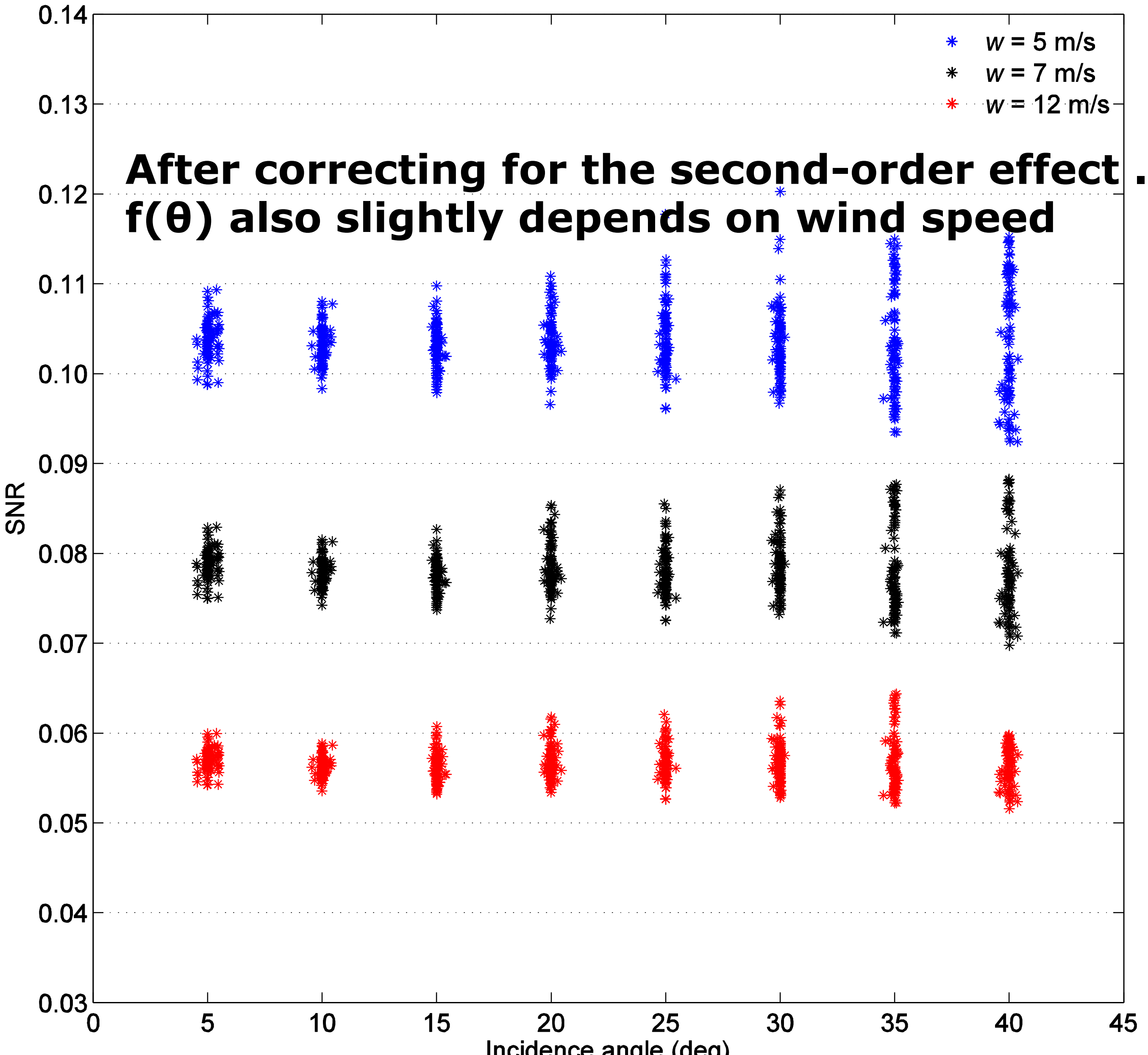


Nadir Antenna

Delay Doppler Map



After correcting for the second-order effect …
f(θ) also slightly depends on wind speed



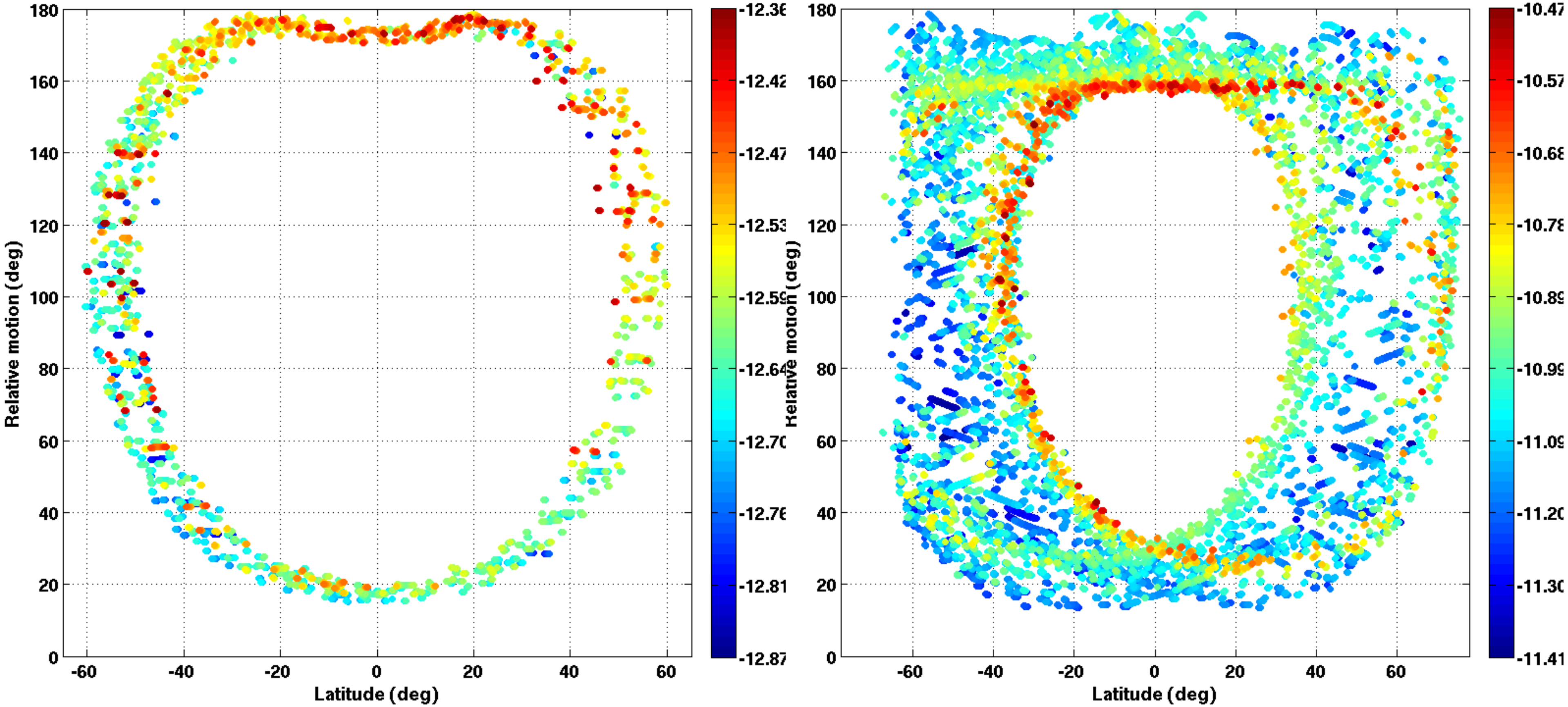
Relative motion

$$RM = \operatorname{acos}\left(\frac{\mathbf{v}_r \cdot \mathbf{v}_t}{\|\mathbf{v}_r\| \times \|\mathbf{v}_r\|}\right)$$

Relative azimuth

$$RA = \operatorname{mod}\left(\varphi - \phi, 360\right)$$

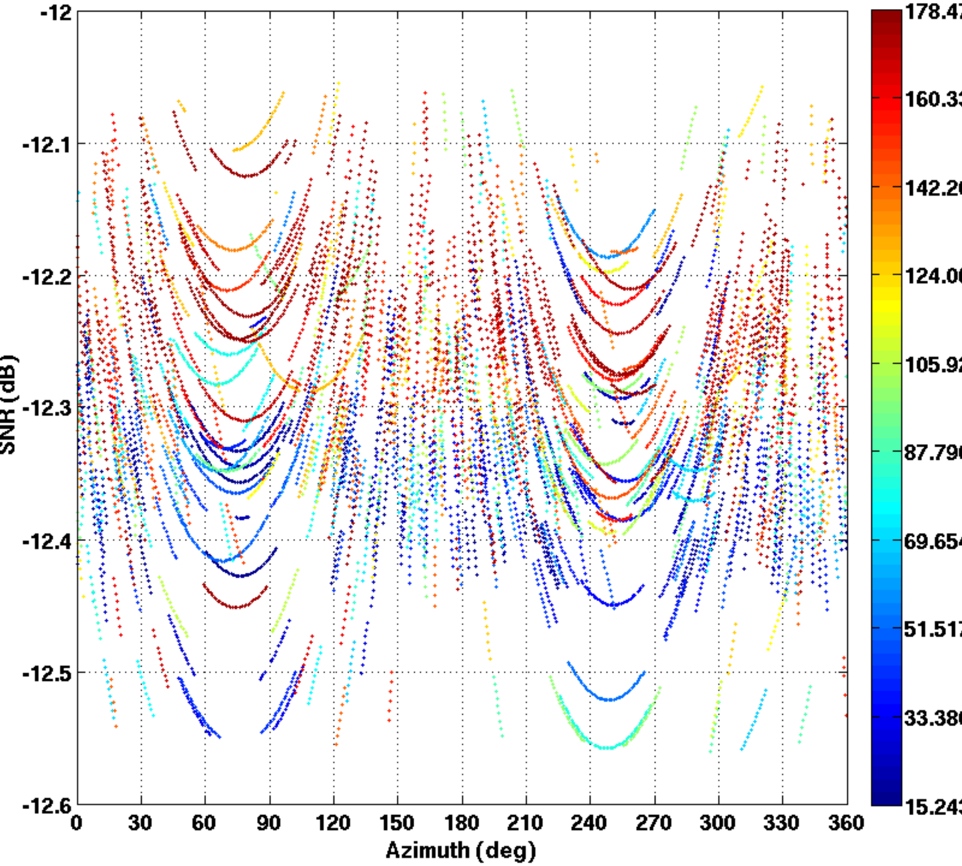
φ wind direction
ϕ observation azimuth

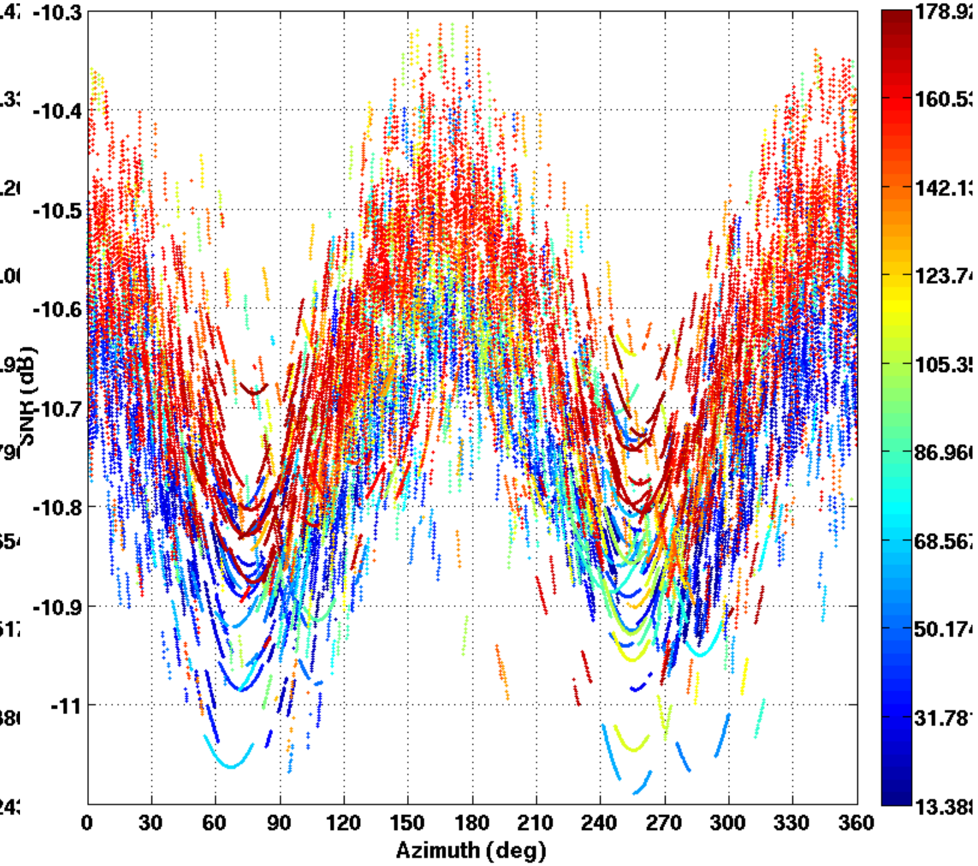


Incidence = 5°
wspd = 7 m/s

Incidence = 25°
wspd = 7 m/s

SNR (colorbar) as a function of **latitude (x-axis)** and **the relative motion (y-axis)** between the receiver and the transmitter





Incidence = 5°
wspd = 7 m/s

Incidence = 25°
wspd = 7 m/s

- *No wind direction skill at low incidence angle;*
- *Larger variations at higher incidence angles (slide 6) – because of the azimuth modulation*

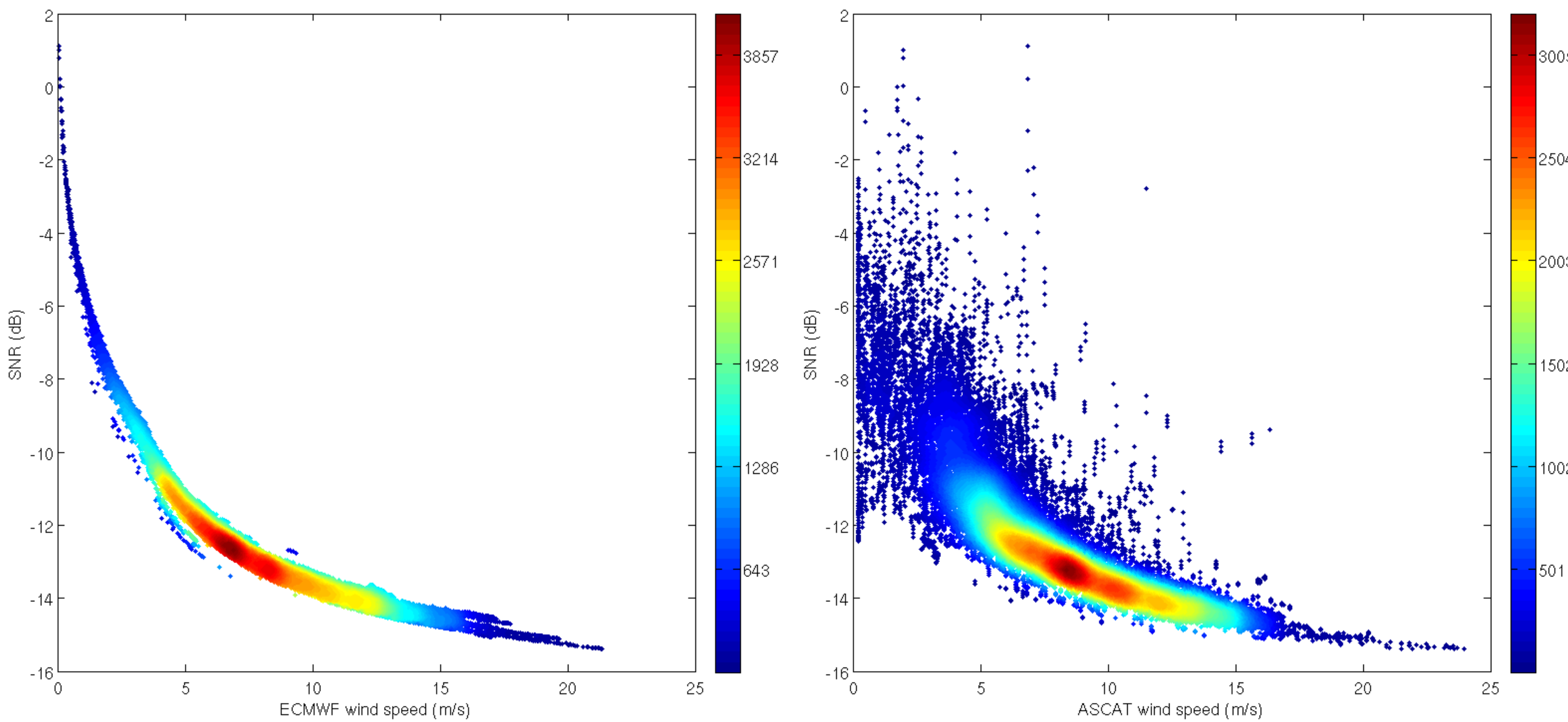
SNR (y-axis) as a function of **azimuth (x-axis)** and **the relative motion (colorbar)** between the receiver and the transmitter

How do we model the third-order effects? Negligible?

After decoupling the first&second order effects

4E4 real measurements
ECMWF wind as input
wavpy

4E4 real measurements
Simulated SNR versus
collocated ASCAT winds.



Larger measurement uncertainty at mid latitude