Beam Behavior Parameters in CryoSat Level1b products

CryoSat

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1 Document overview

1.1 Purpose

This document contains a detailed description of the Beam Behavior Parameter variables in CryoSat SAR/SARIn Level1b products. Moreover, the way these quantities are computed is here also described.

1.2 Acronyms

Aresys	Advanced Remote Sensing Systems
BBP	Beam Behaviour Parameters
IPF1	Instrument Processing Facility
SAR	Synthetic Aperture Radar
SARIn	Synthetic Aperture Radar Interferometric
SSS	Surface Sample Stack

1.3 Applicable documents

AD-01 Instrument Processing Facility L1b - CryoSat Ice netCDF L1B Product Format Specification, C2-RS-ACS-ESL-5364 issue 2.0,23th December 2020.

1.4 Reference documents

[AD1] Aresys, Quality improvements in SAR/SARIn BaselineC Level1b products, C2-TN-ARS-GS-5154 issue 1.0, 29th August 2014.

[AD2] Products Specification Format - Instrument Processing Facility L1b, C2-RS-ACS-GS-5106 issue 6.4, 30th April 2015.

[AD3] Pitch Estimation for CryoSat by Analysis of Stacks of Single-Look Echoes - M. Scagliola, M. Fornari and N. Tagliani - IEEE Geoscience and Remote Sensing Letters, vol. 12, no. 7, pp. 1561-1565, July 2015. doi: 10.1109/LGRS.2015.2413135

[AD4] Lead detection using Cryosat-2 delay-doppler processing and Sentinel-1 SAR images - M. Passaro, F. L. Müller, D. Dettmering - Advances in Space Research – 2017

[AD5] Aresys, CryoSat Characterization for FBR Users, C2-TN-ARS-GS-5179, issue 2.0, 13th June 2016

2 Beam Behaviour Parameter variables

As described in [AD-01], in CryoSat Level1b product there is a set of variables which characterize the surface sample stack. These variables were part of the Beam Beahaviour Parameters field in Waveform Group in the old EE file format used until BaselineC [AD2].

Variable Name	Long Name	Type
stack_std_20_ku	gaussian power fitting: std dev wrt beam number	short
stack_centre_20_ku	gaussian power fitting: center wrt beam number	short
stack_scaled_amplitude_20_ku	gaussian power fitting: amplitude	short
stack_skewness_20_ku	gaussian power fitting: skewness wrt beam number	short
stack_kurtosis_20_ku	gaussian power fitting: kurtosis wrt beam number	short
stack_std_angle_20_ku	gaussian power fitting: std dev wrt boresight angle	short
stack_centre_angle_20_ku	gaussian power fitting: center wrt boresight angle	short
dop_angle_start_20_ku	doppler angle start	int
dop_angle_stop_20_ku	doppler angle stop	int
look_angle_start_20_ku	look angle start	int
look_angle_stop_20_ku	look angle stop	int
stack_number_after_weighting_20_ku	number of contributing beams in the stack after weighting	short
stack_number_before_weighting_20_ku	number of contributing beams in the stack before weighting	short
stack_peakiness_20_ku	stack peakiness	short
stack_centre_look_angle_20_ku	gaussian power fitting: centre wrt look angle	short
stack_gaussian_fitting_residuals_20_ku	gaussian power fitting: residuals fitting	short

Tab.1 Beam Behaviour Parameter variables.

The Beam Behavior Parameter variables contain information about the stack of single look echoes that have been gathered for the surface sample located on Earth surface. It has to be underlined that the Beam Behavior Parameters (BBPs) contain the information related only to the single look echoes that the Specialized SAR/SARIn IPF1 averages together to obtain the multilooked 20Hz waveform. It is worth underlining that these variables are applicable to SAR/SARIn modes only. As a consequence, if it is applied the Surface Sample Stack Weighting [AD1] which avoids considering in the multilooking the single look echoes coming from the furthest bursts according to a threshold on the look angle, the BBPs are referred to the stack after stack weighting.

Following the definitions given in [AD-01], a description of each field annotated in the BBPs variables is here given

1) *stack_std_20_ku*: standard deviation of Gaussian that fits the range integrated power of the single look echoes within a stack. Standard deviation as function of stack beam number.
2) *stack_centre_20_ku*: position of the centre of Gaussian that fits the range integrated power of the single look echoes within a stack. Stack centre as function of stack beam number.
3) *stack_scaled_amplitude_20_ku*: amplitude of Gaussian that fits the range integrated power of the single look echoes within a stack.
4) *stack_skewness_20_ku*: 3rd central moment computed on the range integrated power of the single look echoes within a stack. Skewness as function of stack beam number.

5) *stack_kurtosis_20_ku*: 4th central moment computed on the range integrated power of the single look echoes within a stack. Kurtosis as function of stack beam number.
6) *stack_std_angle_20_ku*: standard deviation of Gaussian that fits the range integrated power of the single look echoes within a stack. Standard deviation as function of the boresight angle, that is the angle between: (a) antenna boresight direction, (b) direction from satellite to surface location. The boresight angle depends on geometry and attitude (roll and pitch).
7) *stack_centre_angle_20_ku*: position of the centre of Gaussian that fits the range integrated power of the single look echoes within a stack. Centre as function of the boresight angle, that is the angle between: (a) antenna boresight direction, (b) direction from satellite to surface location. The pointing angle depends on geometry and attitude (roll and pitch).
8) *dop_angle_start_20_ku*: value of Doppler Angle for the first single look echo in the stack. It is the angle between: (a) direction perpendicular to the velocity vector, (b) direction from satellite to surface location. The Doppler angle depends on velocity vector and on geometry.
9) *dop_angle_stop_20_ku*: value of Doppler Angle for the last single look echo in the stack. It is the angle between: (a) direction perpendicular to the velocity vector, (b) direction from satellite to surface location. The Doppler angle depends on velocity vector and on geometry.
10) *look_angle_start_20_ku*: value of Look Angle for the first single look echo in the stack. It is the angle between: (a) nadir direction from the satellite CoM to the surface, (b) direction from satellite to surface location. The look angle depends purely on geometry.
11) *look_angle_stop_20_ku*: value of Look Angle for the last single look echo in the stack. It is the angle between: (a) nadir direction from the satellite CoM to the surface, (b) direction from satellite to surface location. The look angle depends purely on geometry.
12) *stack_number_after_weighting_20_ku*: number of contributing beams in the stack after weighting: number of single look echoes in the stack after the Surface Sample Stack weighting is applied.
13) *stack_number_before_weighting_20_ku*: number of contributing beams in the stack before weighting: number of single look echoes in the stack before the Surface Sample Stack weighting is applied.
14) *stack_peakiness_20_ku*: stack peakiness computed from the range integrated power of the single look echoes within a stack according to [AD4]. Stack peakiness is defined as the inverse of the average of the range integrated power normalized for the power at zero look angle.
15) *stack_centre_look_angle_20_ku*: position of the centre of Gaussian function that fits the range integrated power of the single look echoes within a stack, according to [AD3]. Centre as function of the look angle, that is the angle between: (a) nadir direction from the satellite CoM to the surface, (b) direction from satellite to surface location.
16) *stack_gaussian_fitting_residuals_20_ku*: residuals of Gaussian function that fits the range integrated power of the single look echoes within a stack. It is the root mean squared error between the Gaussian fitting and the range integrated power of the single look echoes within a stack.

3 Evaluation of Beam Behaviour Parameter variables from Surface Sample Stack

It is worth recalling here that the SAR/SARIn Specialized IPF1 generates 20Hz waveforms in correspondence of an approximately equally spaced set of ground locations on the Earth surface, i.e. surface samples, and that a surface sample gathers a stack of single look echoes coming from the processed bursts during the time of visibility. Thus, for a given surface sample the Surface Sample Stack (SSS) can be defined as the collection of all the single looks echoes that are referred to the current surface sample. An example of Surface Sample Stack is shown in Fig.2, where it is possible to notice that the leading edge of the single look echoes in the stack are aligned, being the single look echoes in the stack aligned with respect to the window delay and to the slant range correction.

As the altimeter moves along the orbit, the instrument acquires the echo of a burst that is then processed to obtain the single look echoes so that, as function of the position of the Surface Sample with respect to the satellite, different angles can be defined and associated to the single look echoes. As described in Fig.1, the CryoSat Specialized SAR/SARIn IPF1 computes the following angles for each single look echo:

- Boresight angle (ϑ_{bore}): the angle at which the surfaces sample is seen with respect to the direction of the antenna boresight $\vec{x}_s$.
- Doppler angle (ϑ_{dop}): the angle at which the surfaces sample is seen with respect to the normal to the velocity vector $\vec{v}$.
- Look angle (ϑ_{look}): the angle at which the surfaces sample is seen with respect to the nadir direction of the satellite $\overrightarrow{CC_N}$.

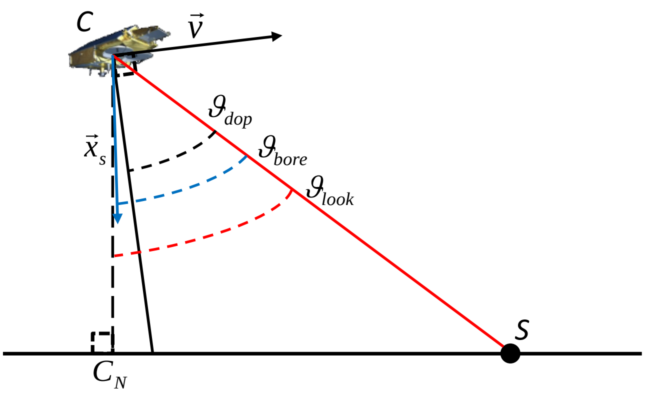
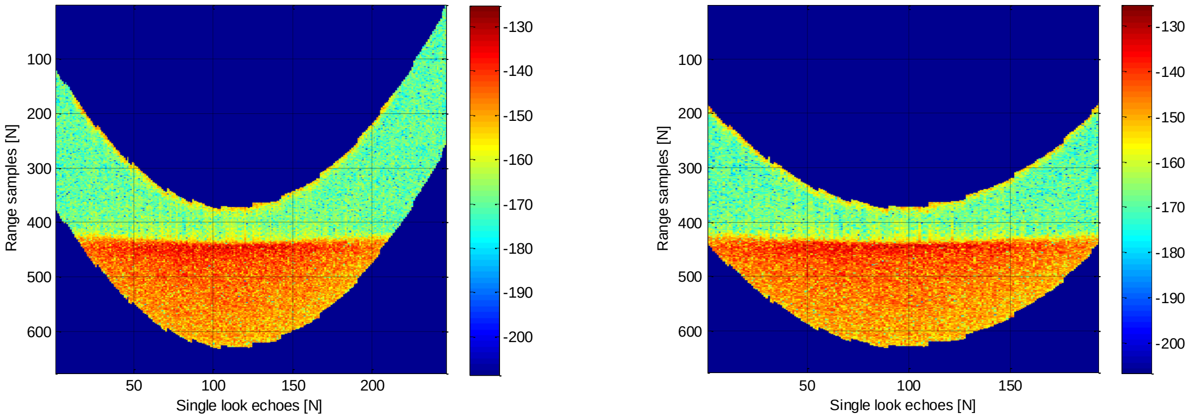


Fig.1 Boresight angle, Doppler angle and Look angle.

In the following figures, a sample Surface Sample Stack and the related measurements that contribute to the BBPs are discussed in two cases: before that the Surface Sample Stack Weighting is applied and after that the Surface Sample Stack Weighting is applied. In case that the Surface Sample Stack Weighting is not applied, the Surface Sample Stack coincides with the Surface Sample Stack before that the weighting is applied. It is worth recalling here that the Surface Sample Stack Weighting is aimed at filtering out the single look echoes originated by the furthest acquired bursts with respect to the surface sample. For more details on the Surface Sample Stack Weighting, please refer to [AD1].

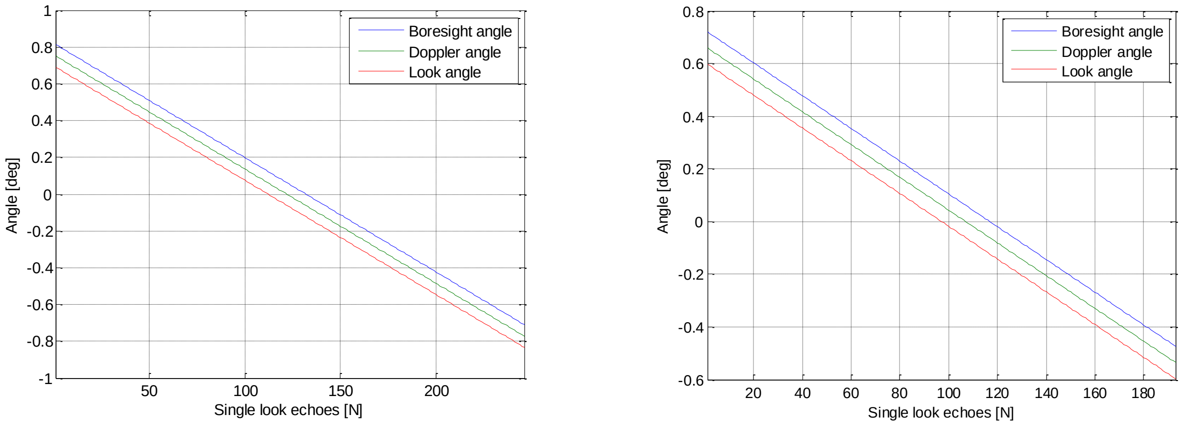
In Fig.2, an example of Surface Sample Stack power (in dB) acquired over ocean is shown. The stack is constructed by aligning the single look echoes with respect to the window delay of each burst with respect to the surface sample. Since the receiving acquisition window of the instrument is limited, the single look echoes from different bursts cannot cover the same interval of delays and when there are no data the samples of the stack matrix are set to zero (the blue background in the following figure). In Fig.2(b), the effect of the Surface Sample Stack Weighting can be noticed: the number of single look echoes is less.



(a) (b)

Fig.2 Surface Sample Stack power in dB: before Surface Sample Stack Weighting (a) and after Surface Sample Stack Weighting (b).

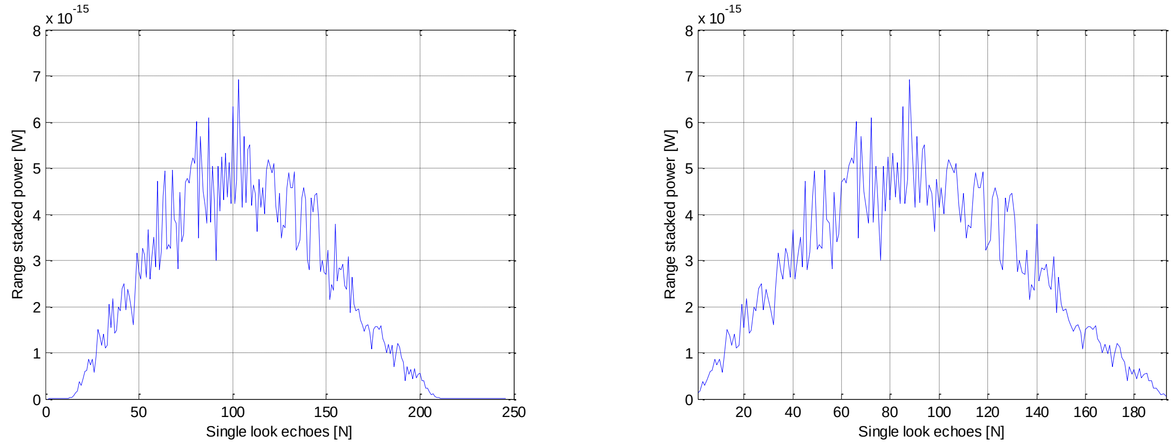
In Fig.3, the Boresight angle, the Doppler angle and the Look angle for each single look echo in the Surface Sample Stack are represented. In case that the Surface Sample Stack Weighting, the single look echoes having Look angle between -0.6 deg and 0.6 deg are selected according to [AD1].



(a) (b)

Fig.3 Boresight, Doppler and Look angle: before Surface Sample Stack Weighting (a) and after Surface Sample Stack Weighting (b).

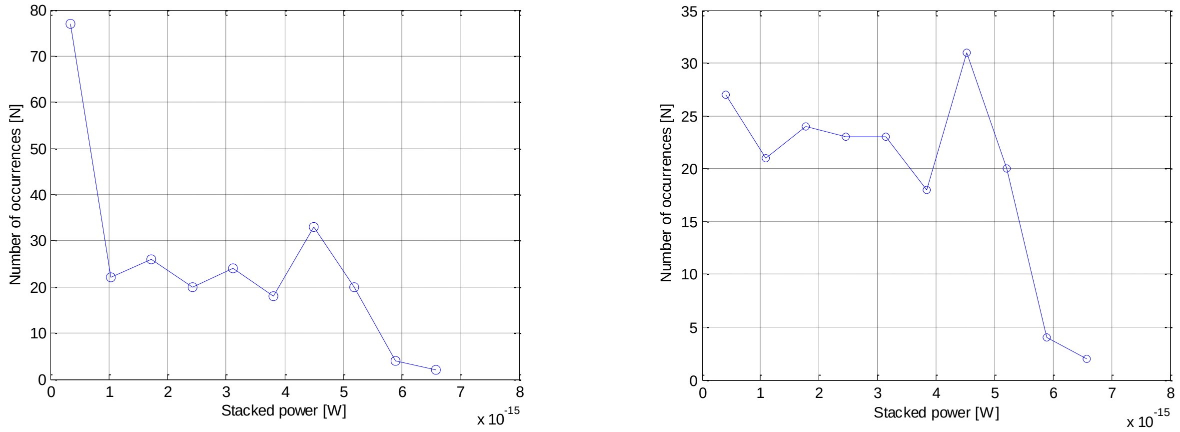
In Fig.4 the range integrated stacked power for the Surface Sample Stack shown in Fig.2 is reported. The range integrated stacked power is defined as the summation of the power for each single look echo so that the power profile as function of the single look index is obtained. In the following the range integrated stacked power is denoted by $P(i)$ with $i=1,\ldots,N$ being the N the number of single look echoes in the stack.



(a) (b)

Fig.4 Range integrated stack power: before Surface Sample Stack Weighting (a) and after Surface Sample Stack Weighting (b).

In Fig.5 the histogram of the range integrated stacked power shown in Fig.4 is represented.



(a) (b)

Fig.5 Histogram of range integrated stack power: before Surface Sample Stack Weighting (a) and after Surface Sample Stack Weighting (b).

In the following subsections the computation of each of the Beam Behaviour Parameters is detailed, referring to the figures above when it is needed.

3.1 Number of contributing beams

The number of contributing beams in the in the stack before weighting, here denoted as N_0, is written in the stack_number_before_weighting_20_ku variable.

The number of contributing beams in the in the stack after weighting, here denoted as N, is written in the stack_number_after_weighting_20_ku. In case that the Surface Stack Weighting is not applied we have that $N_0 = N$.

3.2 Doppler angle

Denoting by $\vartheta_{dop}(i)$ with $i = 1,\ldots,N$ the Doppler angle as function of the beam index in the stack, we have that

- dop_angle_start_20_ku results in $\vartheta_{dop}(1)$
- dop_angle_stop_20_ku results in $\vartheta_{dop}(N)$

From the information above, it can be reconstructed with some approximation the Doppler angle associated to each contributing beam in the Surface Sample Stack that has been multilooked to obtain the 20Hz Level1b waveform. In fact, in case of SAR, it can be generally assumed regular angular step between successive beams in the range going from $\vartheta_{dop}(1)$ to $\vartheta_{dop}(N)$. In case of SARIn, it can be generally assumed regular angular step between successive beams in the range going from $\vartheta_{dop}(1)$ to $\vartheta_{dop}(N)$, with the exception of one double step every one second due to the interleaved CAL4 bursts.

3.3 Look angle

Denoting by $\vartheta_{look}(i)$, with $i = 1,\ldots,N$, the Look angle as function of the beam index in the stack, we have that

- look_angle_start_20_ku results in $\vartheta_{look}(1)$
- look_angle_stop_20_ku results in $\vartheta_{look}(N)$

From the information above, it can be reconstructed with some approximation the Look angle associated to each contributing beam in the Surface Sample Stack that has been multilooked to obtain the 20Hz Level1b waveform. In fact, in case of SAR, it can be generally assumed regular angular step between successive beams in the range going from $\vartheta_{look}(1)$ to $\vartheta_{look}(N)$. In case of SARIn, it can be generally assumed regular angular step between successive beams in the range going from $\vartheta_{look}(1)$ to $\vartheta_{look}(N)$, with the exception of one double step every one second due to the interleaved CAL4 bursts.

3.4 Stack Centre of Gaussian fit

The mean of Gaussian fit of the range integrated stack power as function of stack beam number (stack_centre_20_ku) is computed according to the following formula starting from the range integrated stacked power $P(i)$ with $i = 1, \ldots, N$

$$C_{og} = \frac{\sum_{i=1}^{N} \left(P^2(i) \cdot i \right)}{\sum_{i=1}^{N} P^2(i)}$$

It can be noticed that C_{og} is computed as the Center of Gravity of the range integrated stack power. Then, the stack centre angle, which is the mean of Gaussian fit of the range integrated stack power as function of boresight angle (stack_centre_angle_20_ku), is computed as the boresight angle corresponding to the stack beam number C_{og}, i.e $\vartheta_{bore}(C_{og})$.

3.5 Standard Deviation of Gaussian fit

The standard deviation standard deviation of Gaussian fit of the range integrated stack power as function of stack beam number (stack_std_20_ku) is computed according to the following formula starting from the range integrated stacked power $P(i)$ with $i = 1, \ldots, N$

$$\sigma = \frac{1}{2} \frac{\sum_{i=1}^{N} P^2(i) \sum_{i=1}^{N} P^2(i)}{\sum_{i=1}^{N} P^4(i)}$$

Then, the standard deviation angle, which is the standard deviation of Gaussian fit of the range integrated stack power as function of boresight angle (stack_std_angle_20_ku), is computed as the boresight angle corresponding to $\vartheta_{bore}(C_{og} + \sigma) - \vartheta_{bore}(C_{og})$.

3.6 Stack Scaled Amplitude

The amplitude of Gaussian fit of the range integrated stack power (stack_scaled_amplitude_20_ku) is computed according to the following formula starting from the range integrated stacked power $P(i)$ with $i = 1, \ldots, N$

$$Amp = \sqrt{\frac{\sum_{i=1}^{N} P^4(i)}{\sum_{i=1}^{N} P^2(i)}}$$

3.7 Stack Skewness

The stack skewness (stack_skewness_20_ku) is computed according to the following formula starting from the range integrated stacked power $P(i)$ with $i=1,\dots,N$

$$\gamma_1 = \frac{\frac{1}{N}\sum_{i=1}^{N}\left(P(i)-\mu\right)^3}{\left[\frac{1}{N-1}\sum_{i=1}^{N}\left(P(i)-\mu\right)^2\right]^{3/2}} \text{, with } \mu = \frac{1}{N}\sum_{i=1}^{N}P(i)$$

It is worth noticing that following the formula above, γ_1 represents an estimate of the skewness of the random variable of the range integrated stacked power. As a consequence, γ_1 gives a measure of the symmetry of the sample histogram of $P(i)$, i.e. the empirical probability density function, shown as an example in Fig.5.

3.8 Stack Kurtosis

The stack kurtosis (stack_skewness_20_ku) is computed according to the following formula starting from the range integrated stacked power $P(i)$ with $i=1,\dots,N$

$$\gamma_2 = \frac{\frac{1}{N}\sum_{i=1}^{N}\left(P(i)-\mu\right)^4}{\left[\frac{1}{N-1}\sum_{i=1}^{N}\left(P(i)-\mu\right)^2\right]^{2}} - 3 \text{, with } \mu = \frac{1}{N}\sum_{i=1}^{N}P(i)$$

It is worth noticing that following the formula above, γ_2 represents an estimate of the kurtosis of the random variable of the range integrated stacked power. As a consequence, γ_2 gives a measure of the peakedness of the sample histogram of $P(i)$, i.e. the empirical probability density function, shown as an example in Fig.5.

3.9 Stack Peakiness

The stack peakiness (stack_peakiness_20_ku) is computed according to the following formula starting from the range integrated stacked power $P(i)$ with $i = 1, \dots, N$

$$\gamma_3 = \frac{1}{\frac{1}{N-1}\sum_{\substack{i=1 \\ i\neq\hat{i}}}^{N}\frac{P(i)}{P(\hat{i})}}, with\ \hat{i} = \min_{i}\left\{\left|\vartheta_{look}(i)\right|\right\}$$

It is worth noticing that following the formula above, γ_3 represents an estimate of the peakiness of the random variable of the range integrated stacked power. As a consequence, γ_3 gives a measure of the symmetry of the sample histogram of $P(i)$, i.e. the empirical probability density function, shown as an example in Fig.5. Refer to [AD4] for further details.

3.10 Stack Centre Look Angle

The stack centre look angle (stack_centre_look_angle_20_ku) is computed starting from the range integrated stacked power $P(i)$ with $i = 1, \dots, N$ and according to the following Gaussian function that models the along-track antenna pattern

$$G_{az}(\vartheta_{look}(i), \mu) = G_0 \cdot exp\left(-\frac{(\vartheta_{look}(i) - \mu)^2}{\gamma^2}\right)$$

Where $G_{az}(\vartheta_{look}(i), \mu)$ is the fitted antenna pattern as function of the look angle $\vartheta_{look}(i)$, γ is the along track antenna beam width at -3dB, μ is the stack centre to be estimated and G_0 is the maximum antenna gain according to [AD5]. The along-track antenna fitting is achieved by means of the Levenberg-Marquardt algorithm, which is a non-linear least square fitting method

$$\hat{\mu} \quad t.c. \quad \min_{\mu}\left\{\sum_{i=1}^{N}\left(P(i) - G_{az}(\vartheta_{look}(i), \mu)\right)^2\right\}$$

It is worth noticing that following the algorithm above, μ represents an estimate of the stack centre look angle [AD3]. As a consequence, $\hat{\mu}$ gives a measure of centre of symmetry of $P(i)$.

3.11 Stack Gaussian Fitting Residuals

The stack gaussian fitting residuals (stack_gaussian_fitting_residuals_20_ku) are computed as the difference between the range integrated stacked power and the fitted model for each look angle.

$$\varepsilon = \sqrt{\frac{\sum_{i=1}^{N}\left(P(i) - G_{az}(\vartheta_{look}(i), \hat{\mu})\right)^2}{N}}$$