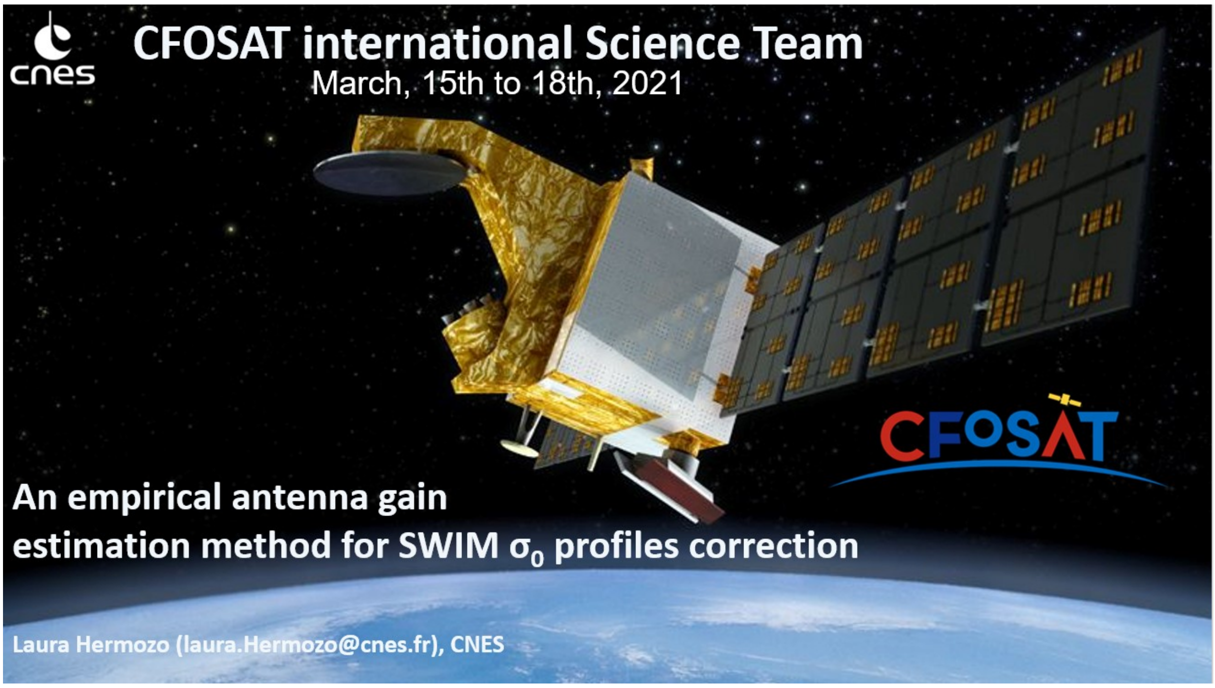


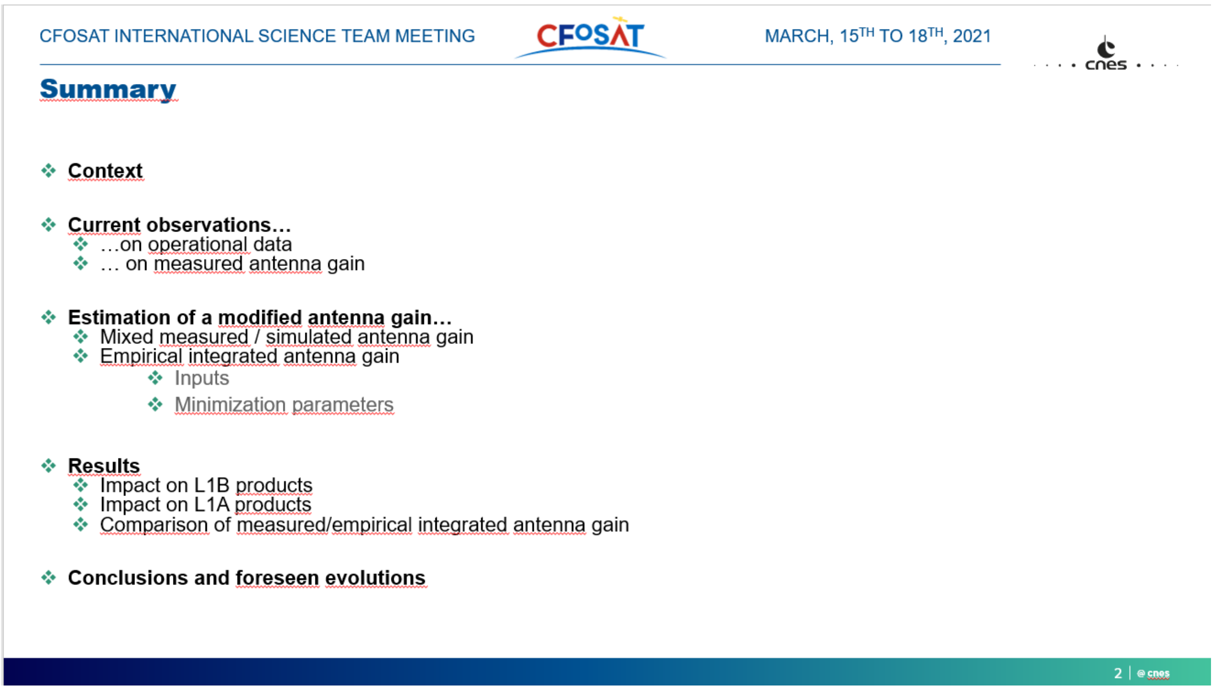
CFOSAT international Science Team

March, 15th to 18th, 2021

An empirical antenna gain estimation method for SWIM σ_0 profiles correction

Laura Hermozo (laura.Hermozo@cnes.fr), CNES

This presentation focuses on the recent improvements of the SWIM antenna gain correction of the received power to retreive sigma0 profiles in the level 1A processing.
These improvements impact the level 2 sigma 0 mini-profiles, and the number of sigma0 profiles used to compute the 2-directional wave spectra.
They are not yet implemented in the current operational products and will be in the next version of operationnal SWIM data.



Summary

- **Context**
- **Current observations…**
  - …on operational data
  - … on measured antenna gain
- **Estimation of a modified antenna gain…**
  - Mixed measured / simulated antenna gain
  - Empirical integrated antenna gain
    - Inputs
    - Minimization parameters
- **Results**
  - Impact on L1B products
  - Impact on L1A products
  - Comparison of measured/empirical integrated antenna gain
- **Conclusions and foreseen evolutions**

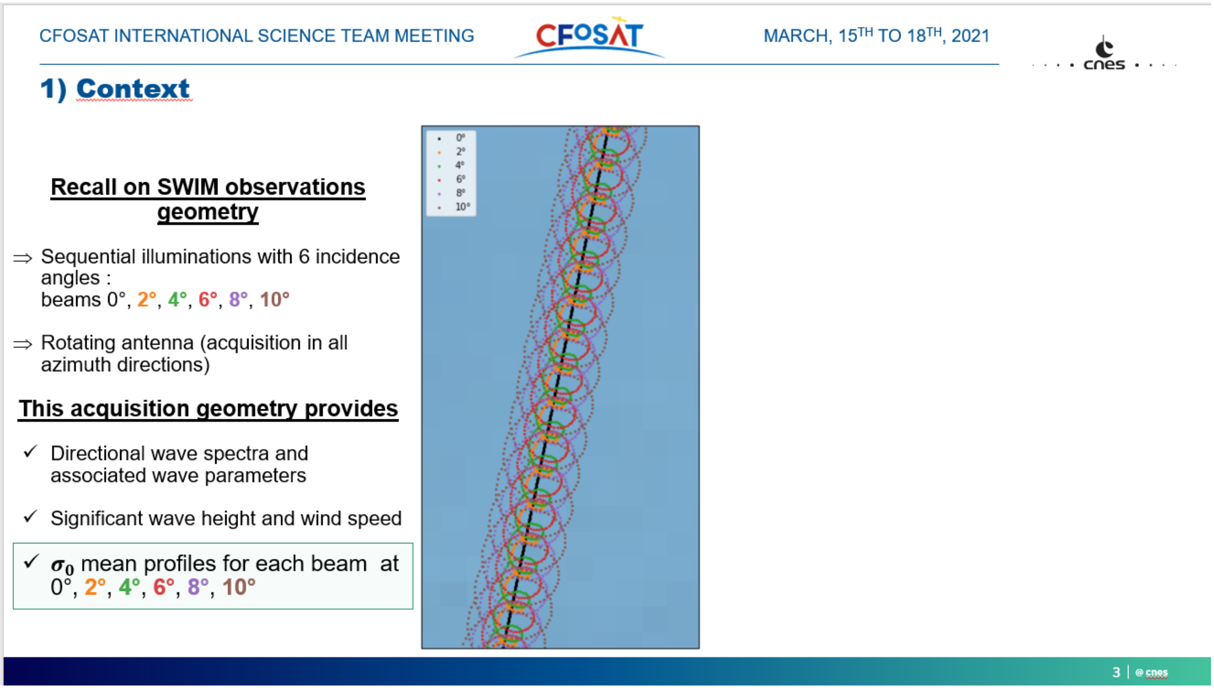
I will first introduce the **context** of SWIM observation geometry and data that it provides thanks to this geometry.
I will then recall **what we observe** :

- on the trend of operational (current and versions of SWIM products) **sigma0 profiles** with respect to elevation.
- and on the **antenna gain** used to correct the signal from the antenna contribution and to compute sigma0 profiles.

I will then focus on the evolutions of the **integrated antenna gain estimation** using two different methods :

- The first temporary evolution being the one currently implemented in the operational products,
- and the second evolution corresponding to the estimation of an **empirical** integrated antenna gain.

The **impact of the empirical integrated antenna gain** will then be shown and compared to both the measured and mixed ones.
I will finally end with the **conclusions and foreseen evolutions** in the following version of operational SWIM products



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1) Context

Recall on SWIM observations geometry

⇒ Sequential illuminations with 6 incidence angles :
beams 0°, 2°, 4°, 6°, 8°, 10°

⇒ Rotating antenna (acquisition in all azimuth directions)

This acquisition geometry provides

- ✓ Directional wave spectra and associated wave parameters
- ✓ Significant wave height and wind speed
- ✓ σ_0 mean profiles for each beam at 0°, 2°, 4°, 6°, 8°, 10°

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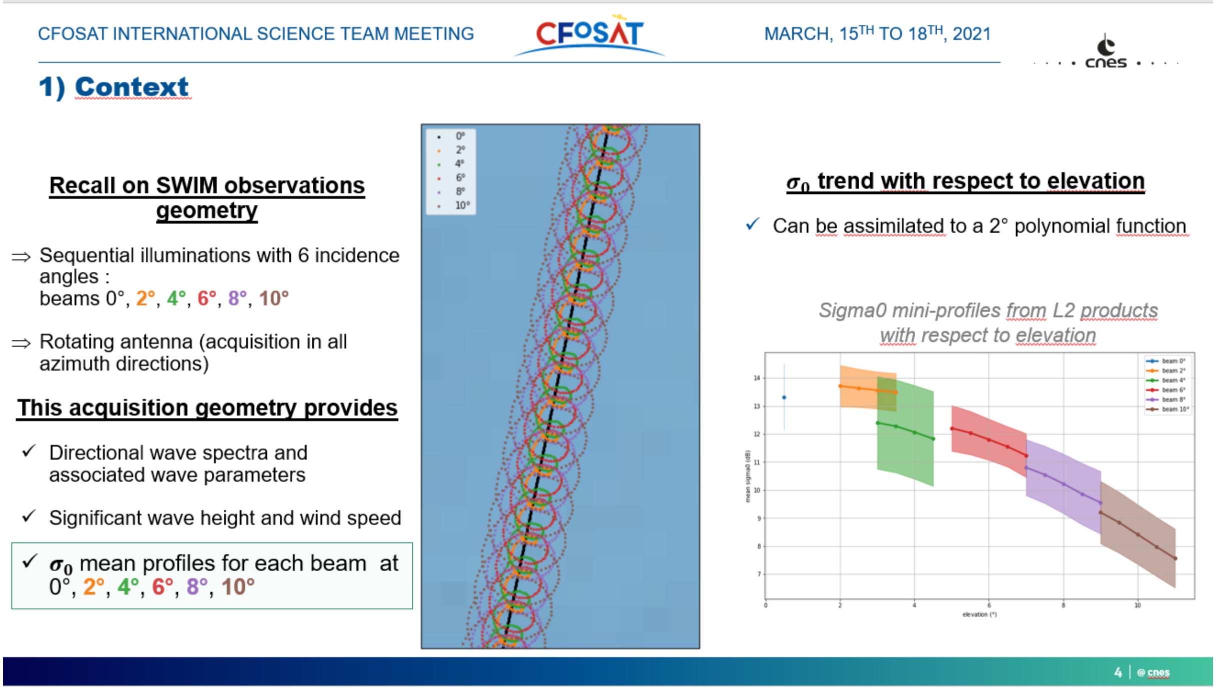
SWIM is a real aperture radar which operates in Ku band.
It illuminates scenes sequentially with 6 incidence angles, from nadir to 10°, and has a rotating antenna, thus providing information in all azimuth directions (see the example of SWIM track for the different beams).
SWIM can thus provide **mean sigma0 profiles for incidences from 0 to 10°, in all azimuth directions**.
It has been shown that for incidence around 8°, for Ku band, the radar cross-section variations are quite insensitive to wind speed, and radar cross-section modulation spectrum is proportional to wave slope spectrum.
This allows to provide directional wave slope spectra from beams 6,8 and 10° (called spectrum beams).
As SWIM has a nadir beam, it also delivers significant wave height and wind speed, as conventional altimeters do.



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1) Context

Recall on SWIM observations geometry

⇒ Sequential illuminations with 6 incidence angles :
beams 0°, **2°**, **4°**, **6°**, **8°**, **10°**

⇒ Rotating antenna (acquisition in all azimuth directions)

This acquisition geometry provides

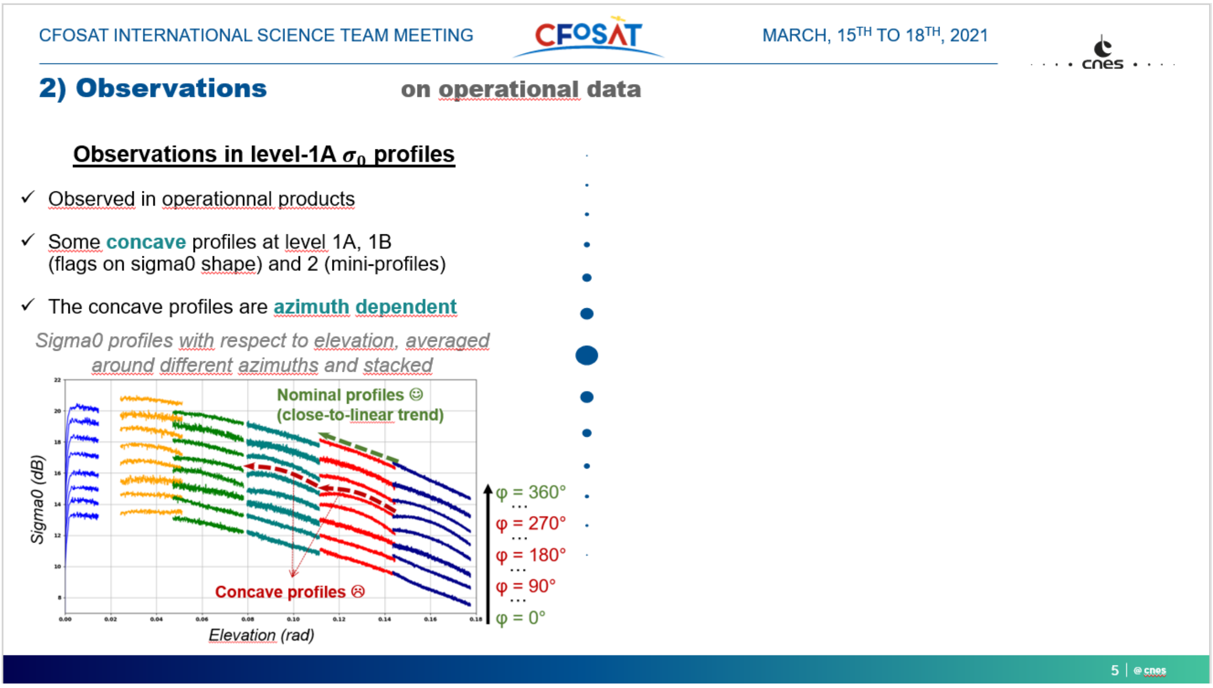
- ✓ Directional wave spectra and associated wave parameters
- ✓ Significant wave height and wind speed
- ✓ σ_0 mean profiles for each beam at 0°, **2°**, **4°**, **6°**, **8°**, **10°**

σ_0 trend with respect to elevation

- ✓ Can be assimilated to a 2° polynomial function

Sigma0 mini-profiles from L2 products with respect to elevation

We will focus on the **mean sigma0 profiles** provided in both the level 1A and level 2 (averaged mini-profiles per boxes and azimuth sector) processing.
At the low incidence angles over which SWIM operates, the geometric optics assumptions can be applied : thus sigma0 profiles **decrease with respect to elevation**, with a **trend close to a 2° polynomial function**, as you can see on the right hand side figure.



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2) Observations on operational data

Observations in level-1A σ_0 profiles

- ✓ Observed in operationnal products
- ✓ Some **concave** profiles at level 1A, 1B (flags on sigma0 shape) and 2 (mini-profiles)
- ✓ The concave profiles are **azimuth dependent**

Sigma0 profiles with respect to elevation, averaged around different azimuths and stacked

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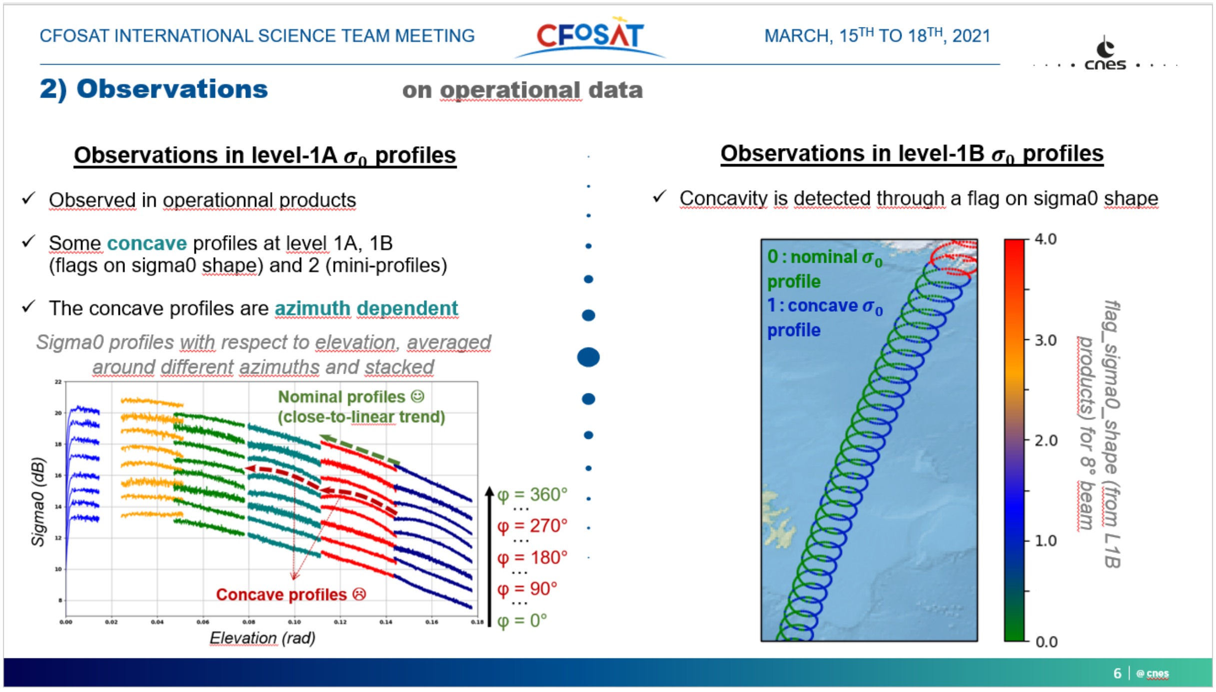
Meanwhile, the CALVAL analysis underlined some anomalies in the trend of sigma0 profiles with respect to elevation : in the v.4.3.1 and previous versions of operational SWIM products, we noticed some **concave-shaped sigma0 profiles**.

These concave profiles appear periodically **according to the rotating antenna azimuth**.

On this figure, L1A-sigma0 profiles with respect to elevation were averaged around various azimuth directions and stacked one on top of each other. We can see that around 0° azimuth angles, the shape of sigma0 profiles looks nominal. But around the 180° azimuth sector, mean sigma0 profiles tend to look more and more concave with respect to elevation.



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2) Observations on operational data

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Sigma0 profiles with respect to elevation, averaged around different azimuths and stacked

Observations in level-1B σ_0 profiles

- ✓ Concavity is detected through a flag on sigma0 shape

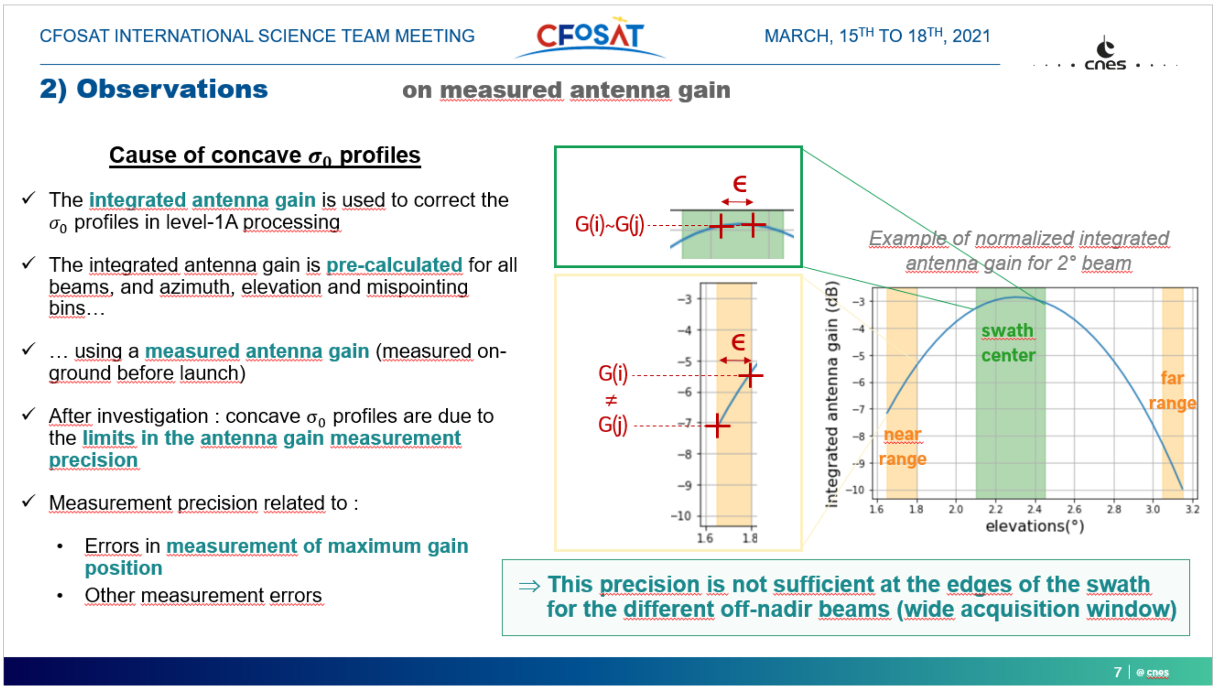
This is also seen in the **L1B products** with the flag called *flag_sigma0_shape.*
This flag is computed by comparing the 2° polynomial fit parameters on the shape of the sigma0 profile with respect to elevation

- on SWIM measured sigma0 profiles
- and on TRMM sigma0 profiles

This flag is set to :

- 0 when the shape parameters of the measured SWIM sigma0 fit are within TRMM's range,
- 1 when they are out of a given threshold.

We cleary see on the right hand side figure a symmetric pattern in the flag's values along an ascending track, for the 8° beam, over ocean.
A similar behaviour is also seen for beams 6° and 10° (this flag is only computed for spectrum beams)



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2) Observations on measured antenna gain

Cause of concave σ_0 profiles

- ✓ The **integrated antenna gain** is used to correct the σ_0 profiles in level-1A processing
- ✓ The integrated antenna gain is **pre-calculated** for all beams, and azimuth, elevation and mispointing bins…
- ✓ … using a **measured antenna gain** (measured on-ground before launch)
- ✓ After investigation : concave σ_0 profiles are due to the **limits in the antenna gain measurement precision**
- ✓ Measurement precision related to :
  - Errors in **measurement of maximum gain position**
  - Other measurement errors

⇒ **This precision is not sufficient at the edges of the swath for the different off-nadir beams (wide acquisition window)**

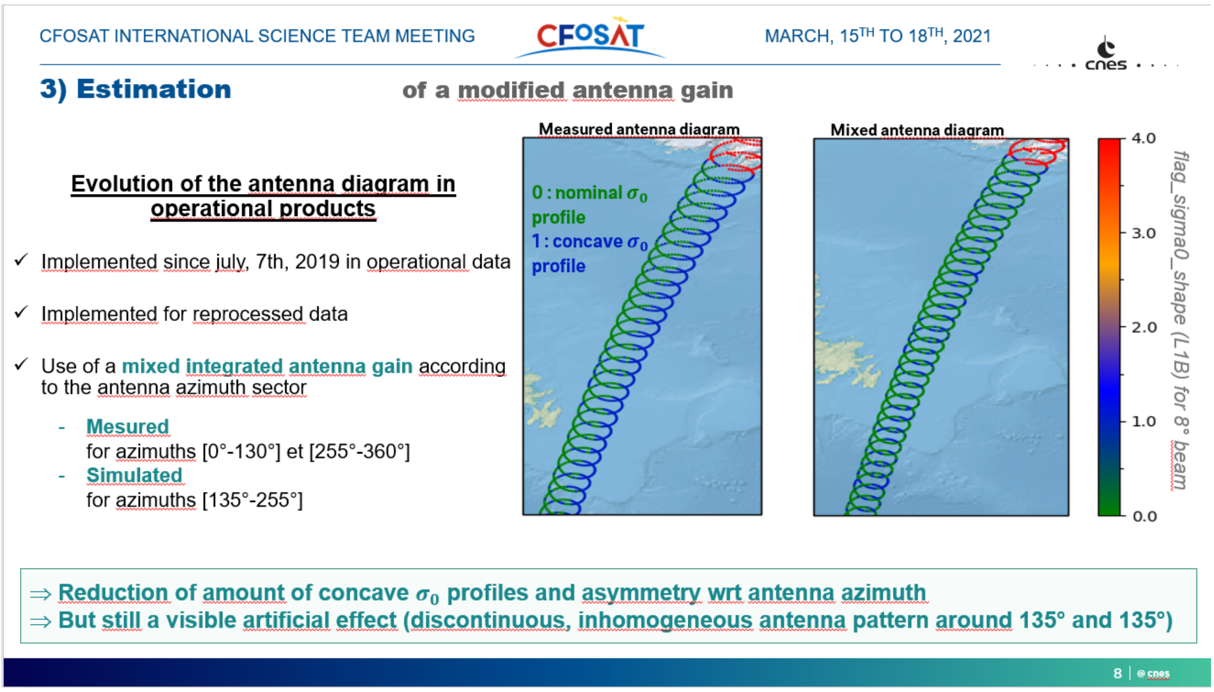
This anomaly on the shape of the sigma0 profiles is explained by the **limits of the antenna gain measurement's precision**.

Among all corrections applied to the received power to compute sigma0 profiles in the L1A processing, the correction of the antenna gain is done. To do so, the integrated antenna gain is pre-calculated for each beam, corresponding elevation bin, azimuth bin between 0° and 36°, roll and pitch mispointing angle bin. It is estimated using the **antenna pattern measured on-ground**, with a **precision of 0.25dB**. This precision is mainly related to errors in the measurement of the maximum gain position, for a given beam, elevation and azimuth.

By definition of SWIM geometry, sigma0 profiles are acquired for large swaths with a wide elevation range for each beam. At the center of the swath, the impact of such a measurement precision is negligable. But **at the edges of the swath**, a 0.25dB measurement precision of the antenna gain **results in an error of ~1-2 dBs in the estimated sigma0 profile**.

Thus, the **measurement precision** of the antenna gain is **not sufficient to estimate accurate enough sigma0 profiles**.

There is a **need to estimate an adapted integrated antenna gain** which could compensate this lack of precision in the most impacted azimuth directions.



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3) Estimation of a modified antenna gain

Evolution of the antenna diagram in operational products

- ✓ Implemented since july, 7th, 2019 in operational data
- ✓ Implemented for reprocessed data
- ✓ Use of a **mixed integrated antenna gain** according to the antenna azimuth sector
  - **Mesured** for azimuths [0°-130°] et [255°-360°]
  - **Simulated** for azimuths [135°-255°]

⇒ Reduction of amount of concave σ_0 profiles and asymmetry wrt antenna azimuth
⇒ But still a visible artificial effect (discontinuous, inhomogeneous antenna pattern around 135° and 135°)

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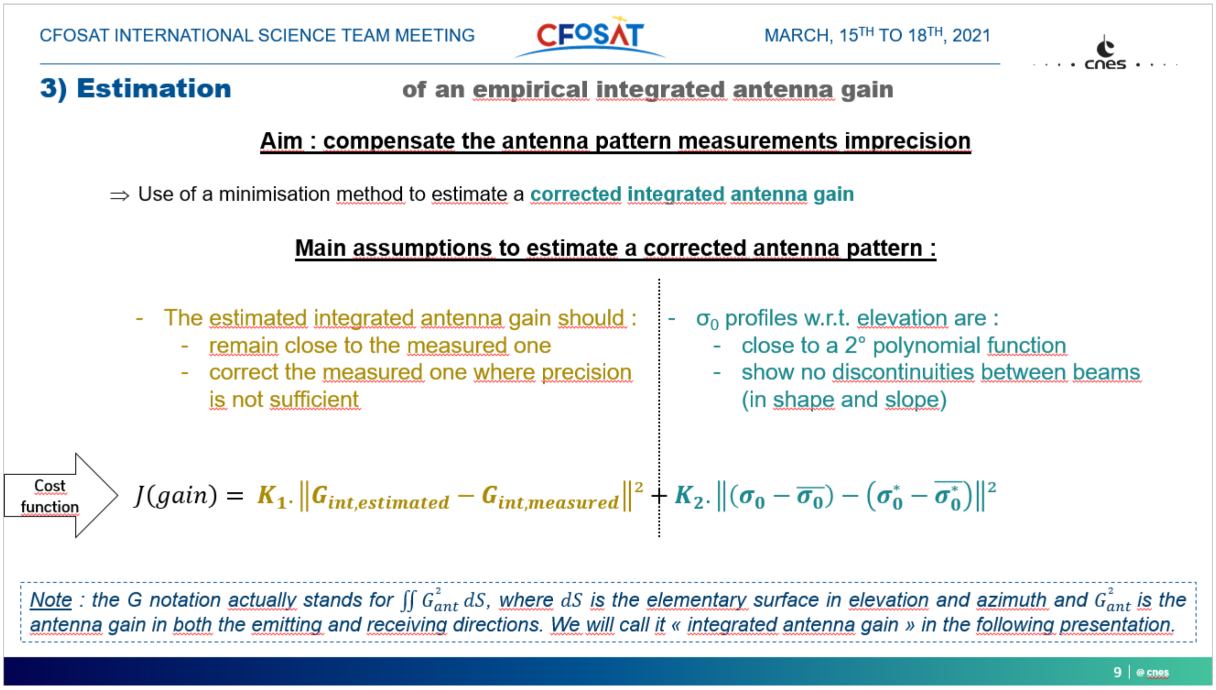
A first implementation of a **modified integrated antenna gain** was done, by **coupling measurements and simulations** of the antenna pattern. A pre-calculated integrated antenna gain was computed from the simulated antenna pattern, for each beam, elevation, azimuth and mispointing angle. This new integrated antenna gain was used for azimuths that were impacted by the lack of precision in the measurement antenna gain. For the other azimuth directions, the initial integrated antenna gain, computed from the measured antenna pattern, was used.

This new mixed integrated antenna gain was **implemented in the operational products since july, 2019** (in v. 4.3.2).

The figure on the left hand side is the same figure as in slide 6 (flag_sigma0_shape for the 8° beam using the measured antenna gain) and the right hand side figure shows the same parameter after applying the mixed integrated antenna gain.

We clearly see that the assymetry of the impact of the antena gain’s measurement precision is reduced along the track, as much more sigma0 profiles recover their nominal shape (flag=0). However, there is still a residual assymetry related to discontinuity between the measured and simulated-derived integrated antenna gains.

This solution is thus a **first step towards a reduction of the impact of measurement imprecision of the antenna pattern**.



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3) Estimation of an empirical integrated antenna gain

Aim : compensate the antenna pattern measurements imprecision

⇒ Use of a minimisation method to estimate a **corrected integrated antenna gain**

Main assumptions to estimate a corrected antenna pattern :

- The estimated integrated antenna gain should :
  - remain close to the measured one
  - correct the measured one where precision is not sufficient

- σ_0 profiles w.r.t. elevation are :
  - close to a 2° polynomial function
  - show no discontinuities between beams (in shape and slope)

Cost function

$$J(gain) = \boldsymbol{K_1}.\left\|\boldsymbol{G_{int,estimated}} - \boldsymbol{G_{int,measured}}\right\|^2 + \boldsymbol{K_2}.\left\|(\boldsymbol{\sigma_0} - \overline{\boldsymbol{\sigma_0}}) - (\boldsymbol{\sigma_0^*} - \overline{\boldsymbol{\sigma_0^*}})\right\|^2$$

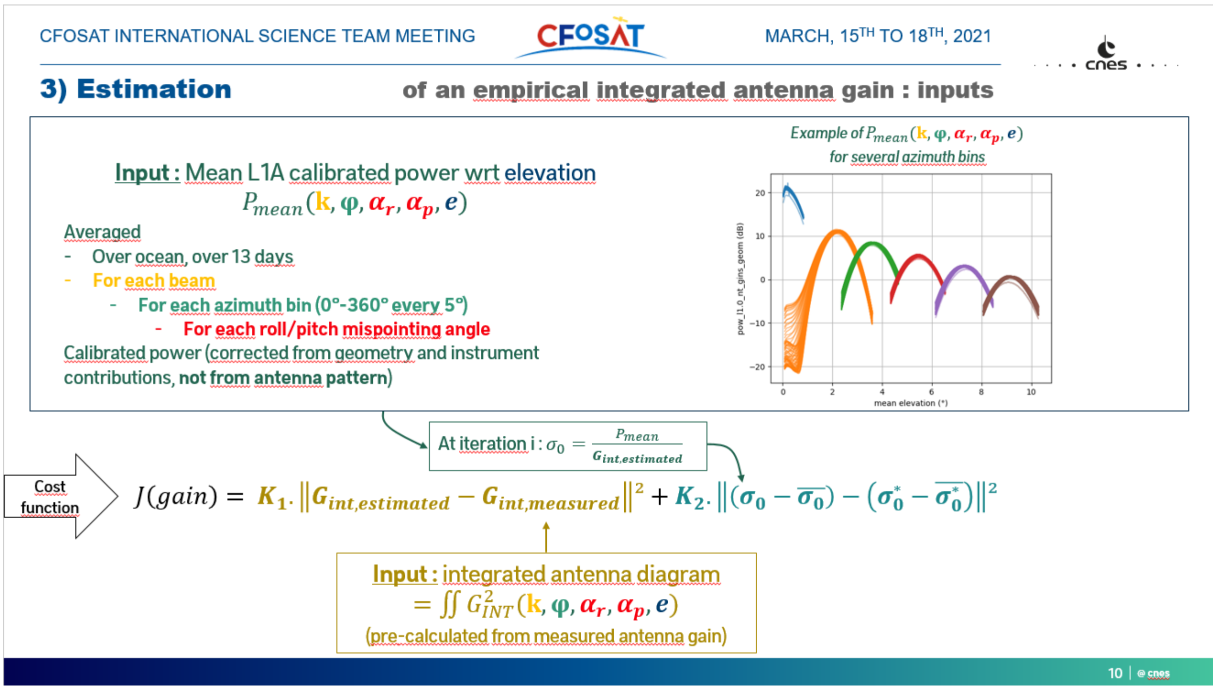
Note : the G notation actually stands for $\iint G_{ant}^2\,dS$, where dS is the elementary surface in elevation and azimuth and G_{ant}^2 is the antenna gain in both the emitting and receiving directions. We will call it « integrated antenna gain » in the following presentation.

An **empirial method** was then developped to **estimate a new integrated antenna gain that is adapted for all azimuth directions**.

To correct the measured-derived integrated antenna gain in the azimuth directions where the sigma0 profiles are the most degraded (concave shape with respect to elevation), we used a minimisation method, with the following assumptions :

- The estimated integrated antenna gain remains close to the measured-derived one (yellow term in the equation)
- Sigma0 profiles should show
  - variations with respect to all beams' elevations which are similar to a 2° polynomial function (σ_0^* in the equation). This assumption is based on the geophysical behaviour of the sigma0 with respect to elevation, related to the geometric optics theory
  - this is why we compute the distance between σ_0 and σ_0^*
  - no discontinuities in the shape and slope bewteen the different beams
  - this is why we « normalize » σ_0 (and σ_0^*) by its mean over each beams' elevations, $\overline{\sigma_0}$ ($\overline{\sigma_0^*}$).

These assumptions are translated mathematically in the shown **cost function** defined by two main operators.



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3) Estimation of an empirical integrated antenna gain : inputs

Input : Mean L1A calibrated power wrt elevation

$$P_{mean}(\mathbf{k}, \boldsymbol{\varphi}, \boldsymbol{\alpha_r}, \boldsymbol{\alpha_p}, \boldsymbol{e})$$

Averaged

- Over ocean, over 13 days
- For each beam
  - For each azimuth bin (0°-360° every 5°)
    - For each roll/pitch mispointing angle

Calibrated power (corrected from geometry and instrument contributions, **not from antenna pattern**)

Example of $P_{mean}(\mathbf{k}, \boldsymbol{\varphi}, \boldsymbol{\alpha_r}, \boldsymbol{\alpha_p}, \boldsymbol{e})$

for several azimuth bins

At iteration i : $\sigma_0 = \frac{P_{mean}}{G_{int,estimated}}$

$$J(gain) = \boldsymbol{K_1}.\left\|\boldsymbol{G_{int,estimated}} - \boldsymbol{G_{int,measured}}\right\|^2 + \boldsymbol{K_2}.\left\|(\boldsymbol{\sigma_0} - \overline{\boldsymbol{\sigma_0}}) - (\boldsymbol{\sigma_0^*} - \overline{\boldsymbol{\sigma_0^*}})\right\|^2$$

Input : integrated antenna diagram

$$= \iint G_{INT}^2(\mathbf{k}, \boldsymbol{\varphi}, \boldsymbol{\alpha_r}, \boldsymbol{\alpha_p}, \boldsymbol{e})$$

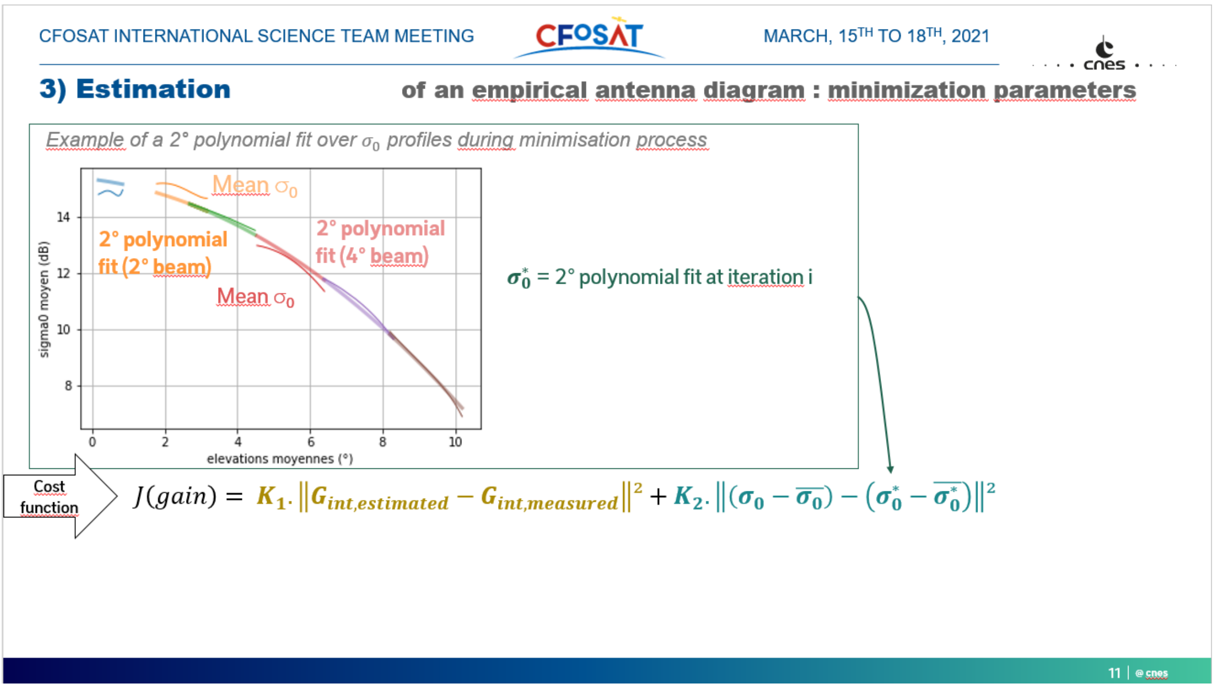
(pre-calculated from measured antenna gain)

The **minimzation process** is applied for each 5° azimuth sector (between 0°-360°) and for each roll and pitch mispointing angle bin, beween +/-0.01°, every 0.001°, in order to cover all possible mispointing situations.

Lets describe the cost function's **inputs** for a given azimuth, roll and pitch mispointing angle bin :

- In the yellow term, we compute the **measured-derived integrated antenna gain** by interpolating the antenna diagram (initially measured on-ground in 8 regular azimuth directions between 0° and 360°), for each beam.
- In the blue term, the **input sigma0 profile** is computed by dividing the received power Pmean by the integrated antenna gain, estimated at iteration 0.
  - The received power is the **measured received power corrected from all geometrical and instrumental contributions** (except from the antenna contribution). It is **averaged over ocean during 13 days** (one cycle), in the given azimuth bin range
  - The integrated antenna gain at iteration 0 is the **background integrated antenna gain**. It is set to a constant value with respect to elevation . Note that the background integrated antenna gain has a low impact on the retreived integrated antenna gain

At each iteration, a new estimated integrated antenna gain is computed used to estimate a new sigma0 profile. Once the green and yellow conditons are reached, the estimated integrated antenna gain remains the solution.



3) Estimation of an empirical antenna diagram : minimization parameters

Example of a 2° polynomial fit over σ_0 profiles during minimisation process

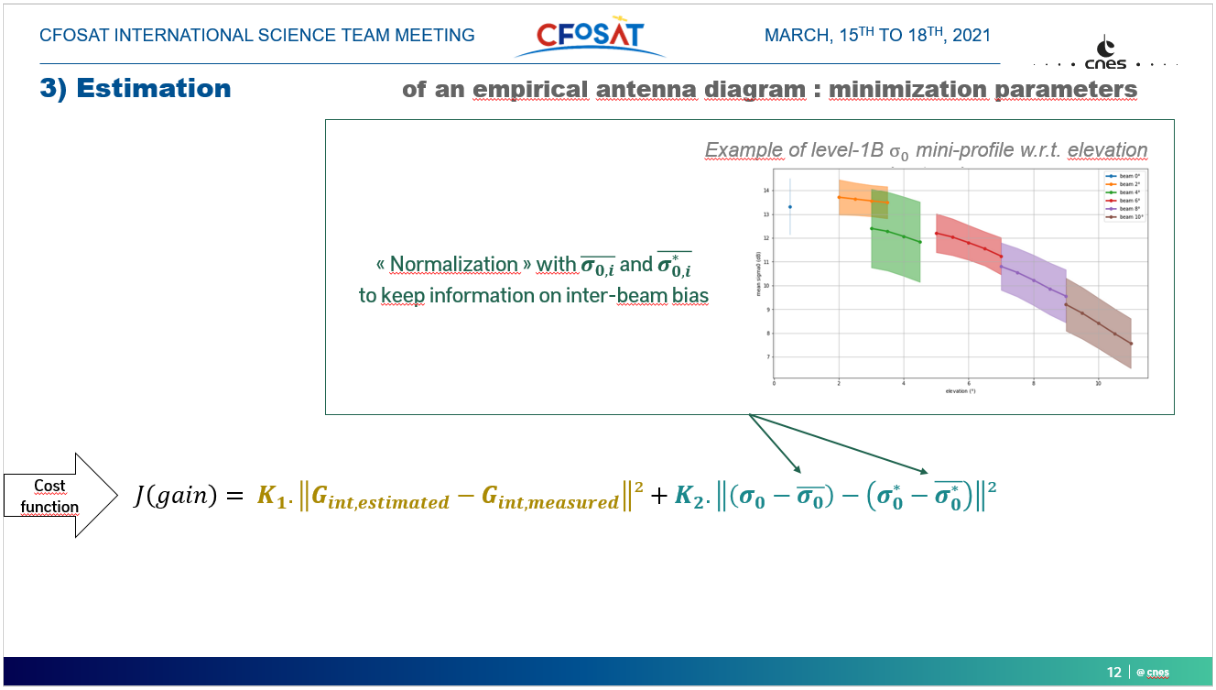
σ_0^* = 2° polynomial fit at iteration i

Cost function

$$J(gain) = K_1 . \left\| G_{int,estimated} - G_{int,measured} \right\|^2 + K_2 . \left\| (\sigma_0 - \overline{\sigma_0}) - (\sigma_0^* - \overline{\sigma_0^*}) \right\|^2$$

We describe here the other cost functions’s parameters :
The sigma0 star represents the **2° polynomial fit** of the estimated sigma0 profile.
The illustration shows an example for iteration i :

- the thin lines are the estimated sigma0 profile after dividing the input averaged corrected power by the i-estimated integrated antenna gain.
- The thick lines are the 2°polynimial fit. It is fitted over the global sigma0 profiles (all elevations)



3) Estimation of an empirical antenna diagram : minimization parameters

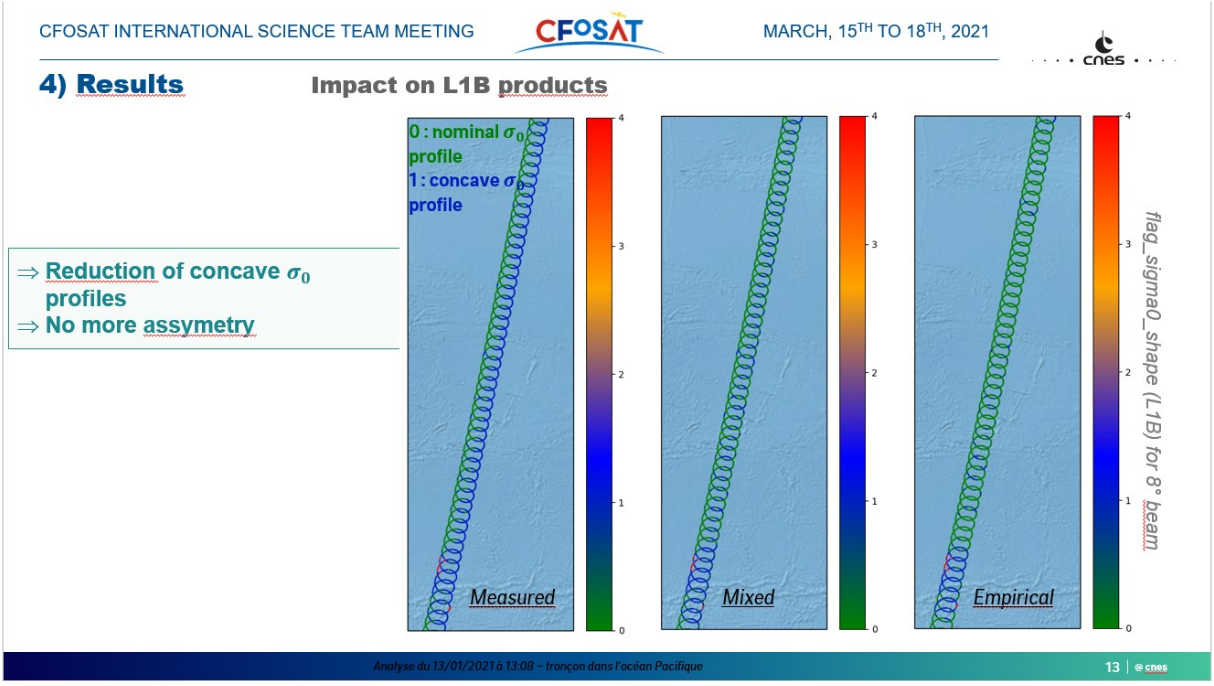
Example of level-1B σ_0 mini-profile w.r.t. elevation

« Normalization » with $\overline{\sigma_{0,i}}$ and $\overline{\sigma_{0,i}^*}$
to keep information on inter-beam bias

Cost function

$$J(gain) = K_1 . \left\| G_{int,estimated} - G_{int,measured} \right\|^2 + K_2 . \left\| (\sigma_0 - \overline{\sigma_0}) - (\sigma_0^* - \overline{\sigma_0^*}) \right\|^2$$

The sigma0 bar represents the **mean value of the sigma0 profile**, computed over all elevations for each beam, for both the estimated and fitted sigma0 profiles.
This allows to estimate an integrated antenna gain that allows the corresponding sigma0 profile to fit a 2° polynomial function of elevation, while **keeping the information of the inter-beam biases**, that are totally independent from the antenna contribution.
The illustration on the right hand side shows an example of L2 mean mini-profiles. We clearly see the inter-beam biases between the 2° and 4° beams , and smaller biases between the spectrum beams. These inter-beam biases are not yet corrected and when they will be, they will be corrected in the level 2 processing.



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4) Results

Impact on L1B products

⇒ **Reduction of concave σ_0 profiles**

⇒ **No more assymetry**

Analyse du 13/01/2021 à 13:08 – tronçon dans l'océan Pacifique

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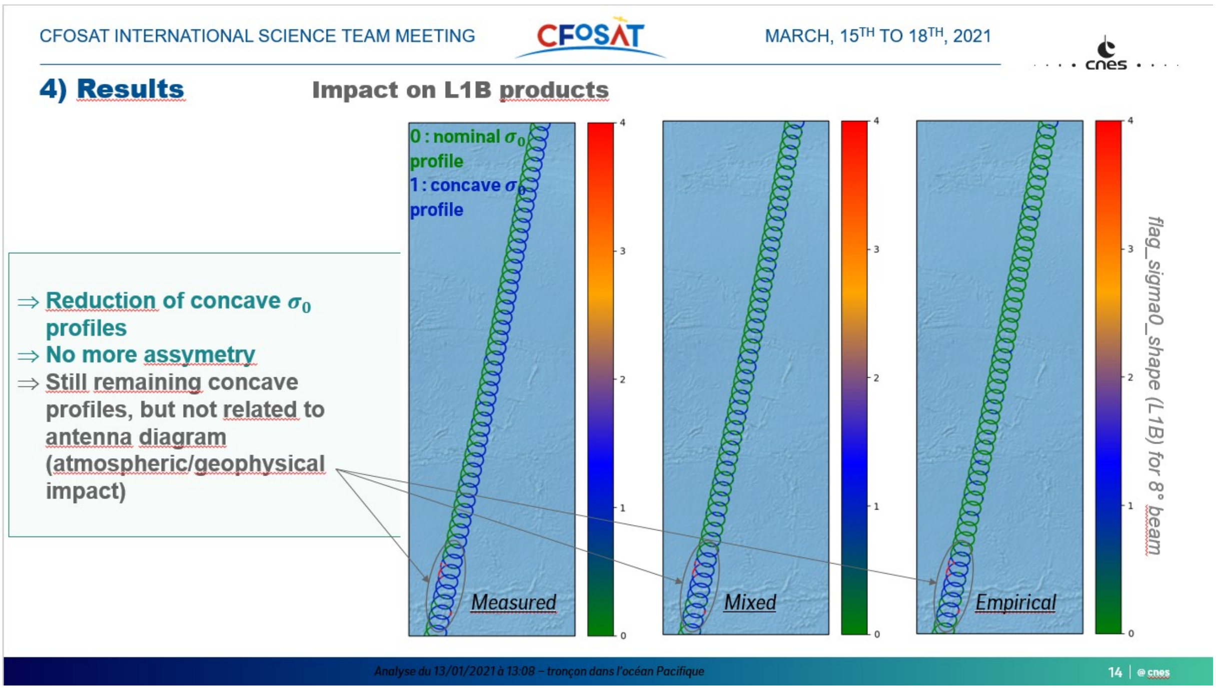
The impact of the estimated integrated antenna gain on sigma0 profiles is first evaluated by analysing the **L1B flag on the shape of the sigma0 profiles**.

These pannels compare the *flag_sigma0_shape* flag along a sample of SWIM's track over ocean, for the 8° beam, using the

- (left pannel) **measured-derived** integrated antenna gain ;
- (middle pannel) **mixed-derived** integrated antenna gain ;
- (right pannel) **estimated** empirical integrated antenna gain.

We clearly see :

- the reduction of the symetric impact of the antenna gain measurement's imprecision along the track (no alternance of green and blue colors).
- the significant reduction of flag values at 1 (blue color) and the significant increase of flag values at 0 (green color), meaning that the sigma0 profiles retrieve a nominal shape, that is within TRMM thresholds.



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4) Results

Impact on L1B products

0 : nominal σ_0 profile
1 : concave σ_0 profile

- ⇒ **Reduction of concave σ_0 profiles**
- ⇒ **No more assymetry**
- ⇒ **Still remaining concave profiles, but not related to antenna diagram (atmospheric/geophysical impact)**

Analyse du 13/01/2021 à 13:08 – tronçon dans l'océan Pacifique

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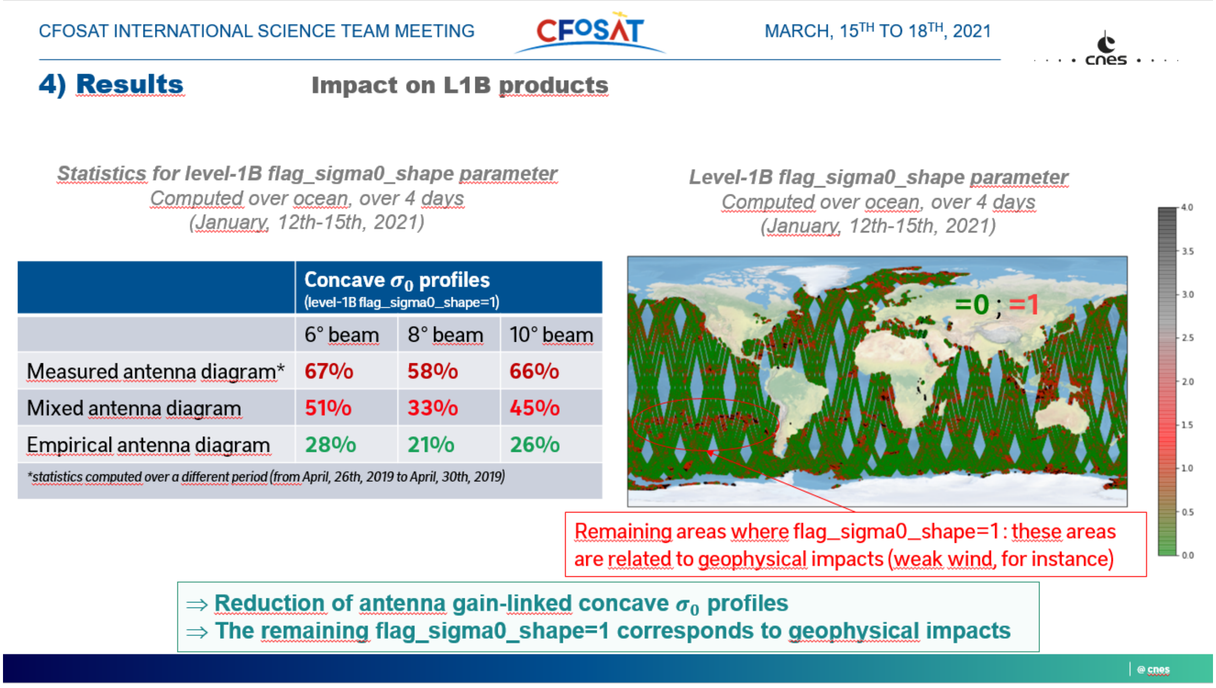
We also notice an area at the bottom of each pannel which **does not seem impacted by the integrated antenna gain** : flag_sigma0_shape's values remain at 1 (or even 4, meaning that the fitting process of the sigma0 profile did not converge), and no symmetric effect of the flag's values is seen.
This area may be impacted by a **geophysical phenomenon** (atmospheric attenuation or another effect of the surface).
This is a positive result as it shows that the estimated empirical integrated antenna gain **does not compensate for any geophysical effect**, it only corrects the measured integrated antenna gain in the azimuth directions impacted by a lack of precision in its measurement.



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4) Results

Impact on L1B products

Statistics for level-1B flag_sigma0_shape parameter
Computed over ocean, over 4 days
(January, 12th-15th, 2021)

	Concave σ_0 profiles (level-1B flag_sigma0_shape=1)		
	6° beam	8° beam	10° beam
Measured antenna diagram*	67%	58%	66%
Mixed antenna diagram	51%	33%	45%
Empirical antenna diagram	28%	21%	26%

*statistics computed over a different period (from April, 26th, 2019 to April, 30th, 2019)

Level-1B flag_sigma0_shape parameter
Computed over ocean, over 4 days
(January, 12th-15th, 2021)

Remaining areas where flag_sigma0_shape=1 : these areas are related to geophysical impacts (weak wind, for instance)

⇒ Reduction of antenna gain-linked concave σ_0 profiles
⇒ The remaining flag_sigma0_shape=1 corresponds to geophysical impacts

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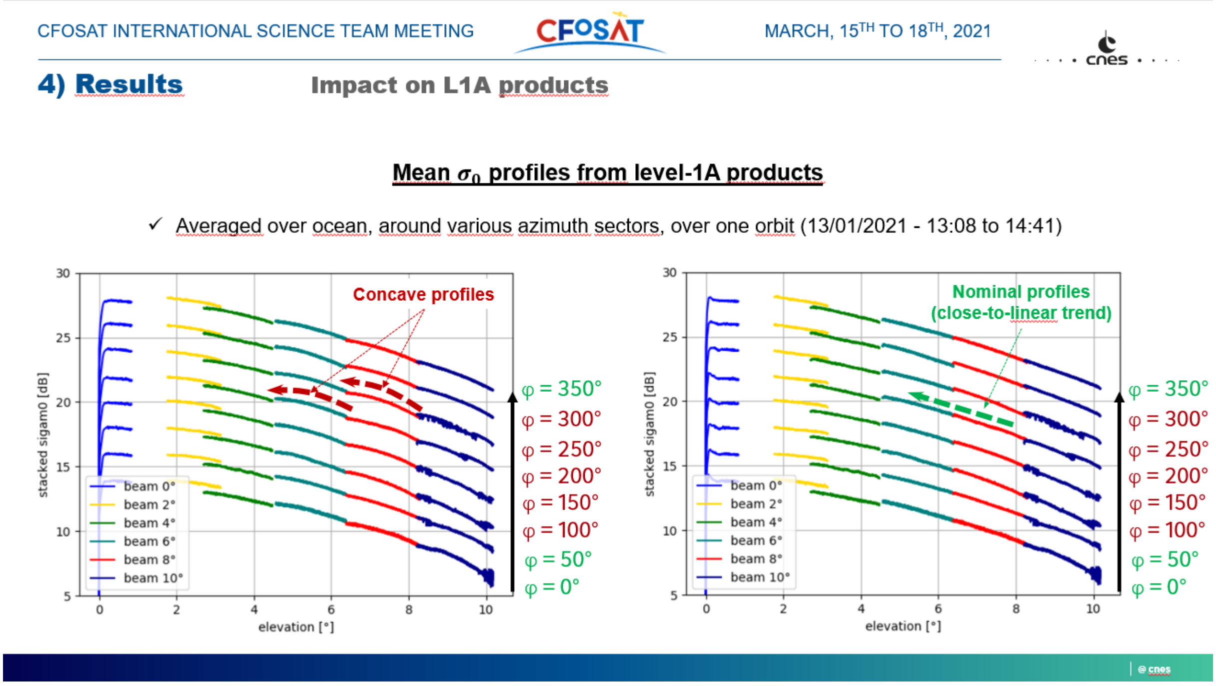
This table shows the **percentage of « concave-shaped » sigma0 profiles** with respect to elevation (L1B flag_sigma0_shape=1), for each spectrum beams, over ocean, over a 4 days dataset of SWIM L1B products, either using the measured-derived, the mixed measured/simulated-derived or the empirical integrated antenna gain. They are **decreased by a factor of 3** when using the empirical integrated antenna gain.
This means that **more sigma0 profiles** will be used to **compute the 2D-directional wave spectra** and related wave parameters (they are not used if the flag_sigma0_shape = 1). It was not tested yet, but this should decrease the noise in the estimated directional wave spectra.



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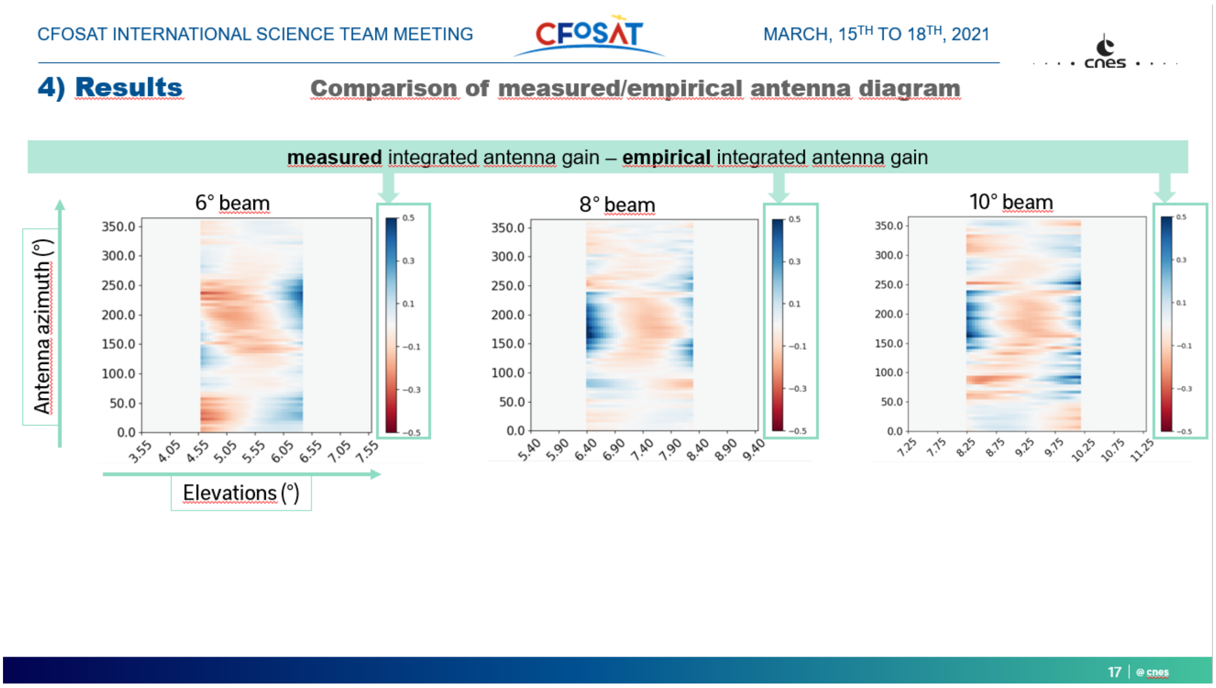
4) Results Impact on L1A products

Mean σ_0 profiles from level-1A products

✓ Averaged over ocean, around various azimuth sectors, over one orbit (13/01/2021 - 13:08 to 14:41)

The **impact** of the estimated empirical integrated antenna gain is also **evaluated over L1A sigma0 profiles**. The figure on the left hand is the same as the one shown in slide 5. The figure on the right is the same one, but after implementing the empirical integrated antenna gain. We can see that the sigma0 profiles, averaged over one orbit over ocean, and around azimuths 150°-200°-250° **are no longer concave** and show a **nominal variations** with respect to elevation.



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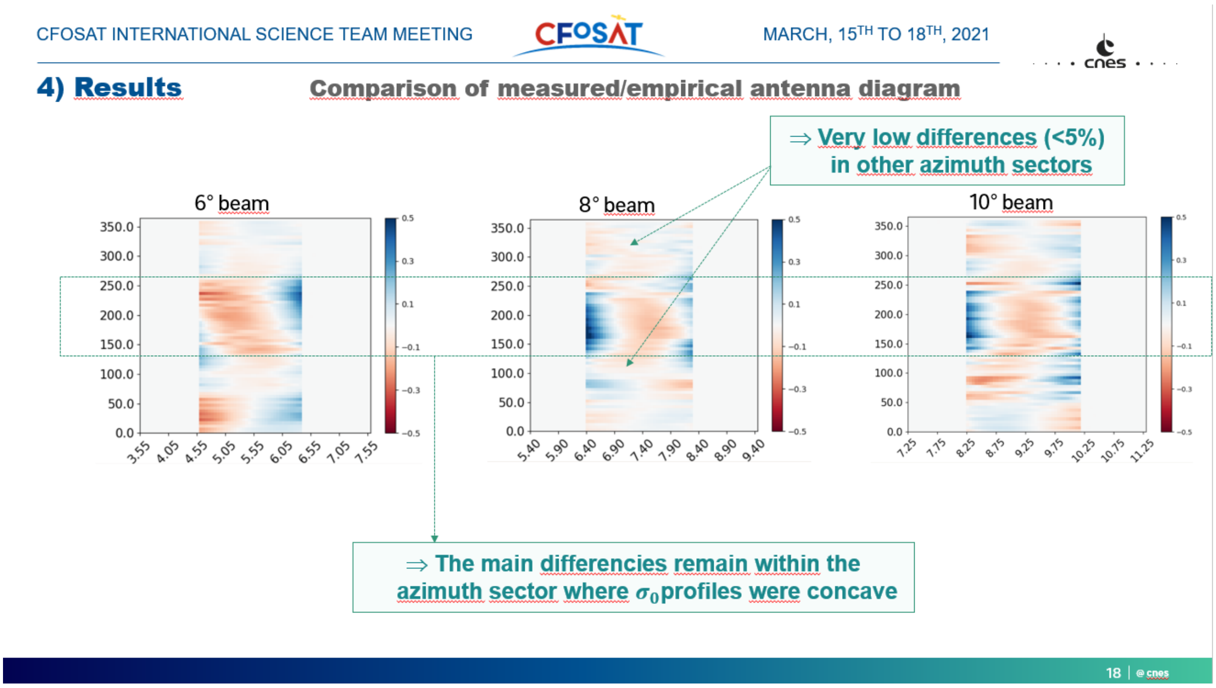
4) Results

Comparison of measured/empirical antenna diagram

measured integrated antenna gain – **empirical** integrated antenna gain

Finally, the empirical integrated antenna gain is compared to the measured-derived one, for each spectrum beam. The x axis is the elevation corresponding to each beam and the y axis is the azimuth directions. **Differences vary between +/- 0,5 dB**.



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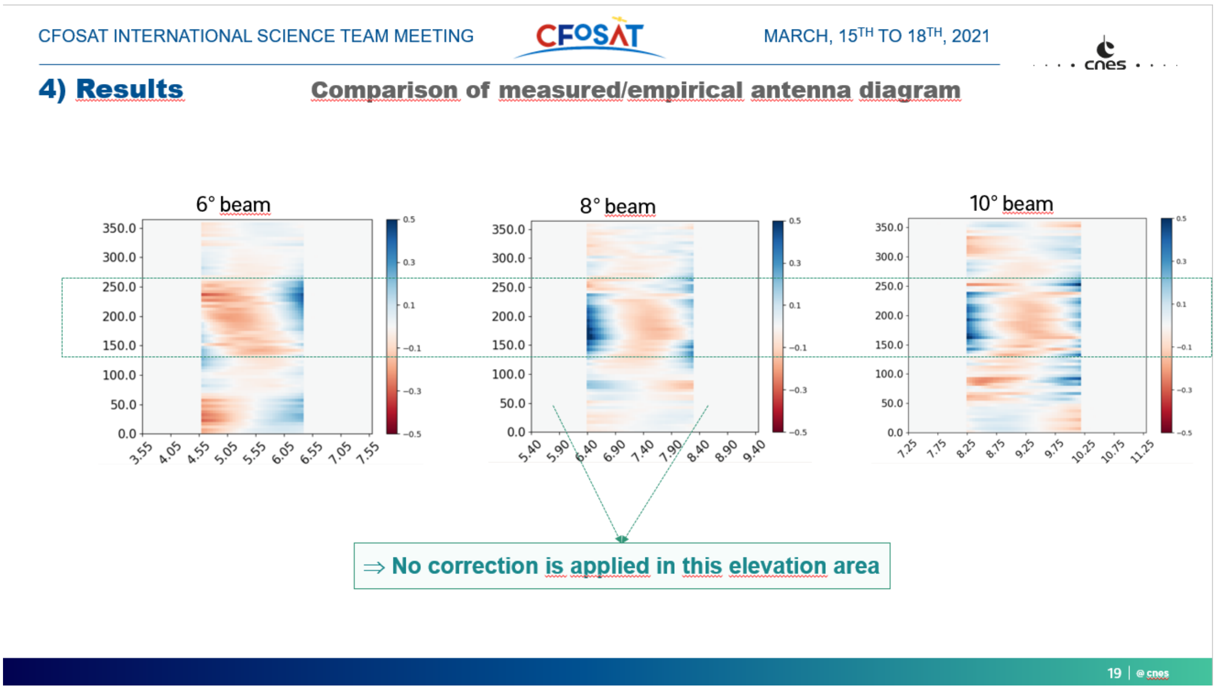
4) Results

Comparison of measured/empirical antenna diagram

⇒ Very low differences (<5%) in other azimuth sectors

⇒ The main differencies remain within the azimuth sector where $\sigma_0$profiles were concave

We can notice that the main **differences** seen for each beam are **within the ~150°-250° azimuth sector**, the same sector where the L1B flag_sigma0_shape was = 1 when using the measured-derived integrated antenna gain. This confirms the **efficiency of the optimization method** to mainly **correct the affected azimuths**.



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4) Results

Comparison of measured/empirical antenna diagram

⇒ No correction is applied in this elevation area

The estimation of the empirial integrated antenna gain was **only done over the reliable part of the swath**, thus differences are 0 for elevations out of this part of the swath.

Conclusions – foreseen evolutions

- ✓ The **received power** is corrected from all **geometric** and **instrumental contributions** in the **L1A** processing to **retreive sigma0 profiles** with respect to elevation.
- ✓ Among them, the **antenna gain** is removed from the signal. It is **measured on-ground** and the integrated antenna gain is pre-calculated for each azimuth direction and mispointing situations
- ✓ The insufficient measurement precision of the antenna gain impacts the estimated sigma0 profiles at certain azimuth directions

⇒ An empirical method was developped to estimate **a new integrated antenna gain**

  - ✓ That **corrects the measured antenna gain** where precision is not sufficient
  - ✓ Based on the assumption that **σ0 profiles are close to a 2° polynomial function** of elevation
  - ✓ This method is adaptable (to broader acquisition windows for instance)

⇒ This new antenna gain

  - ✓ **Eliminates artificial effects** from the antenna gain imprecision and **does not impact any geophysical effects** (from atmosphere or surface) on the signal
  - ✓ Could **improve the Modulation Transfer Function** estimation, used to **compute the directional wave spectra** (will be further analyzed)
  - ✓ Will be **applied in the next operational processing evolution**