SMOS for Space Weather 1st workshop, November 14, 2022, ESRIN-Rome, Italy

# SMOS Sun Brightness Temperature Estimation Algorithm: Drawbacks and Improvements

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# Introduction

- Objectives of **SMOS**: global maps of Soil Moisture (**SM**) and Ocean Salinity (**OS**)

- Instrument:
  - 2D L-band interferometer (MIRAS)
  - Y-shaped array
  - 69 equally spaced antennas

- Measurement:
  - Complex visibilities: cross-correlating the signals collected by each pair of antennas
  - Retrieve the radiometric Brightness temperature distribution
  - Retrieve Soil Moisture and Sea Surface Salinity

# Introduction

RDIS conseils

- Over the years, other applications using the SMOS data have emerged.

- One of these applications is the Solar Flux where SMOS interferometric measurements (visibilities) are used to estimate the Sun Brightness Temperature (BT) which are converted in a second step into solar flux.

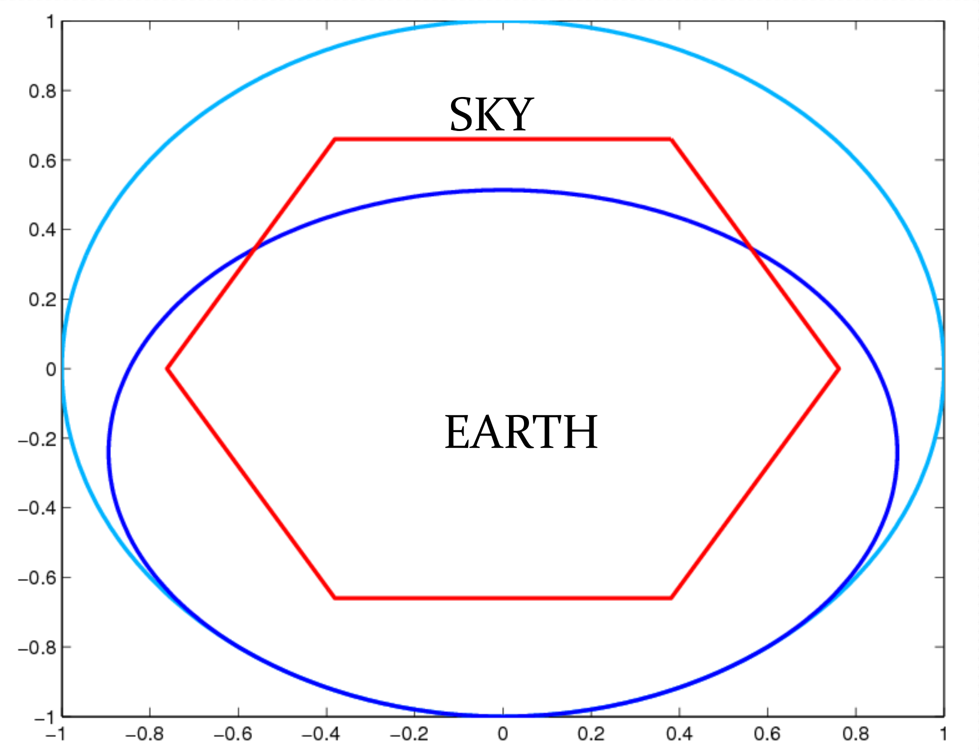
- The advantage of using SMOS is that it provides values for the Sun BT each 1.2 seconds and at different polarizations.

- However, we have some limitations due to the position of the Sun with respect to the instrument.

# SMOS Field Of View (FOV) - Aliasing

- The SMOS FOV is a unit circle (in cyan) whereas the reconstructed FOV is an 2D hexagonal field inside the unit circle because the Shannon-Nyquist sampling criterion is not respected

- **Aliasing:** As a consequence , Earth and Sky **aliasing** appear in the reconstructed hexagon



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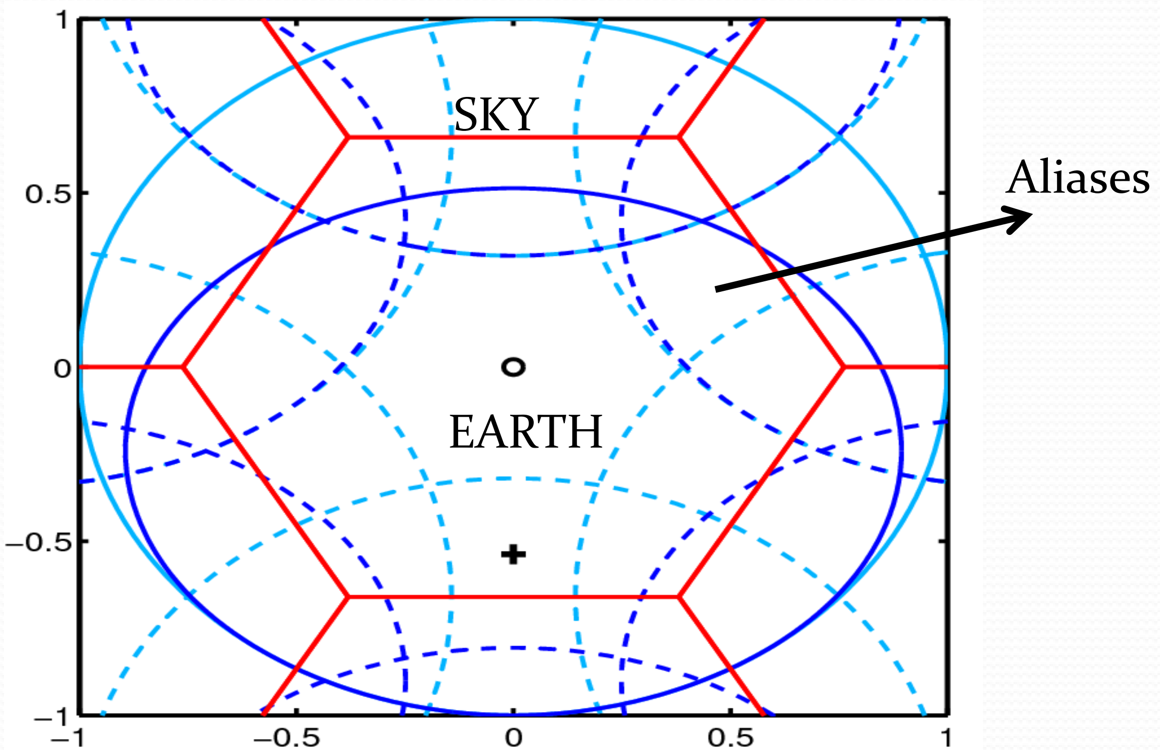
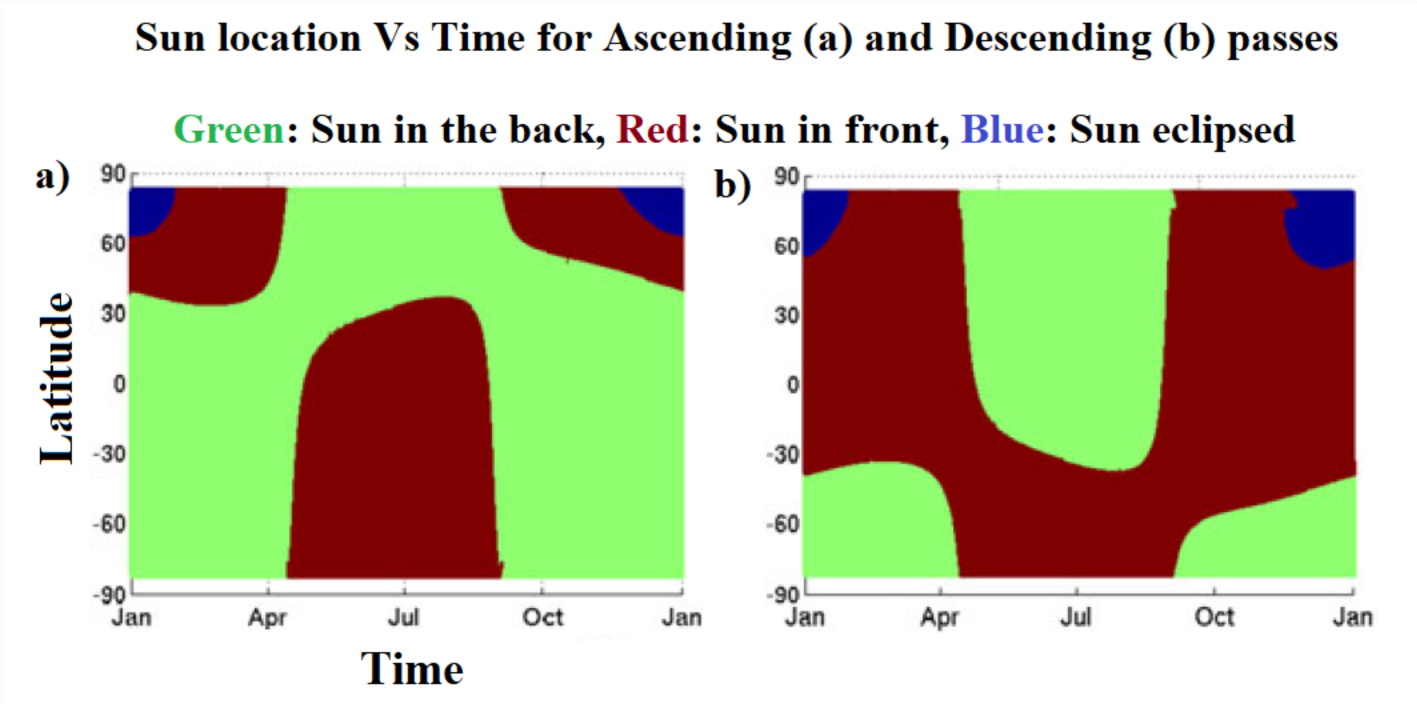


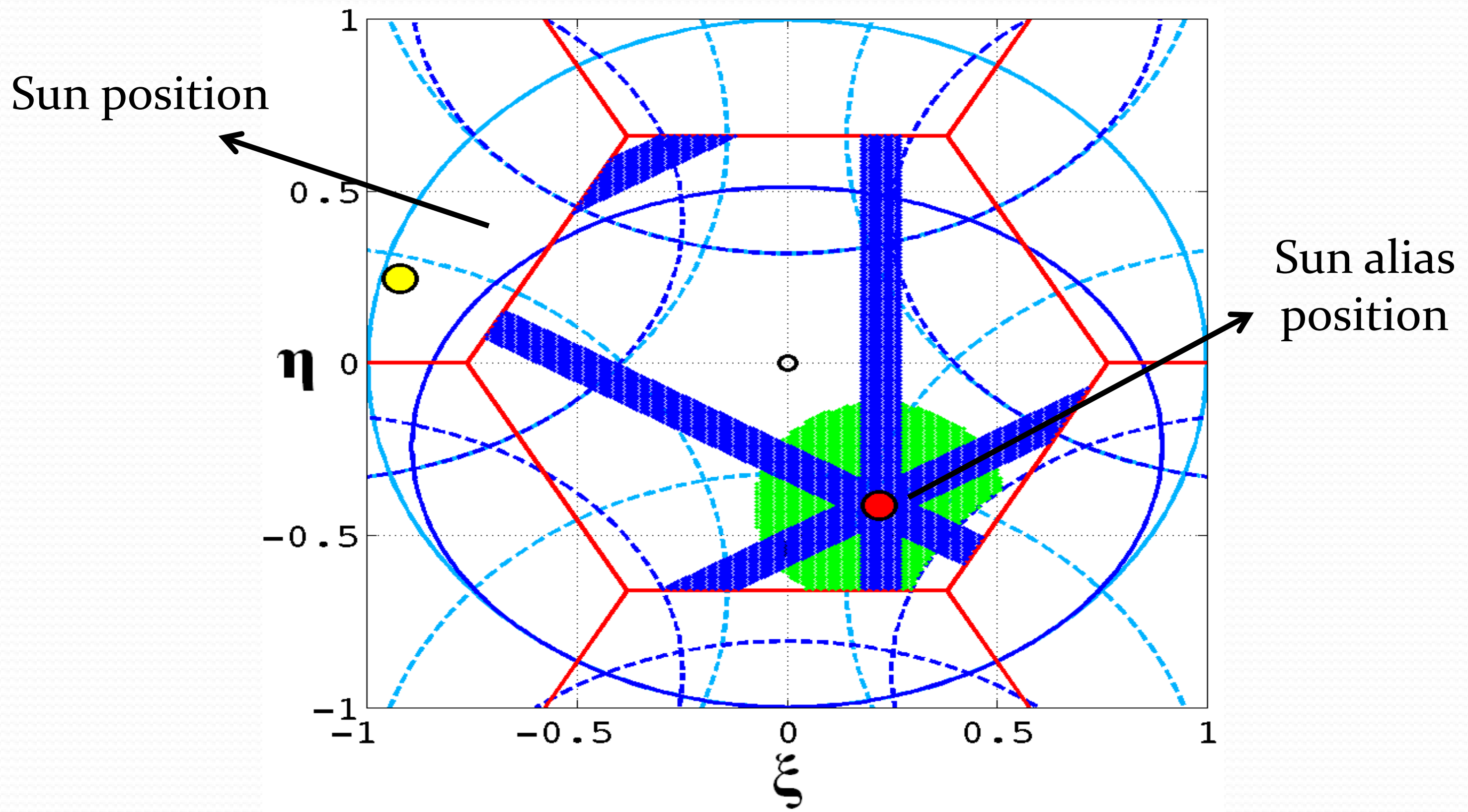
# Sun location in the SMOS data

- For SMOS, the Sun can either be in front of the satellite and thus seen by the front-lobes antenna patterns or in the back of the satellite and seen by the back-lobes antenna patterns.



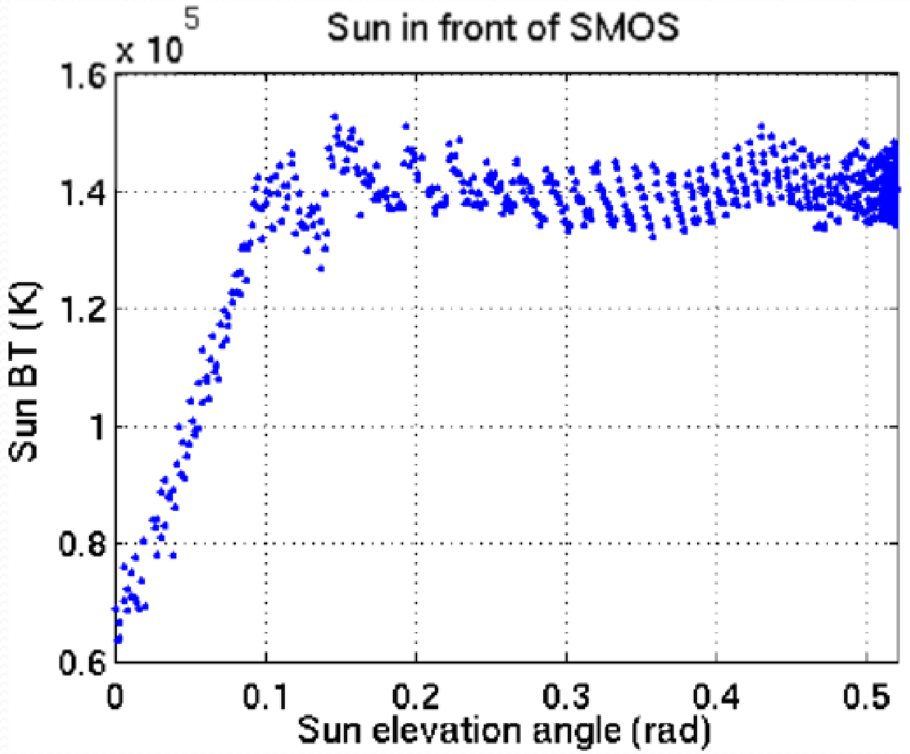
# Sun position in the SMOS FOV

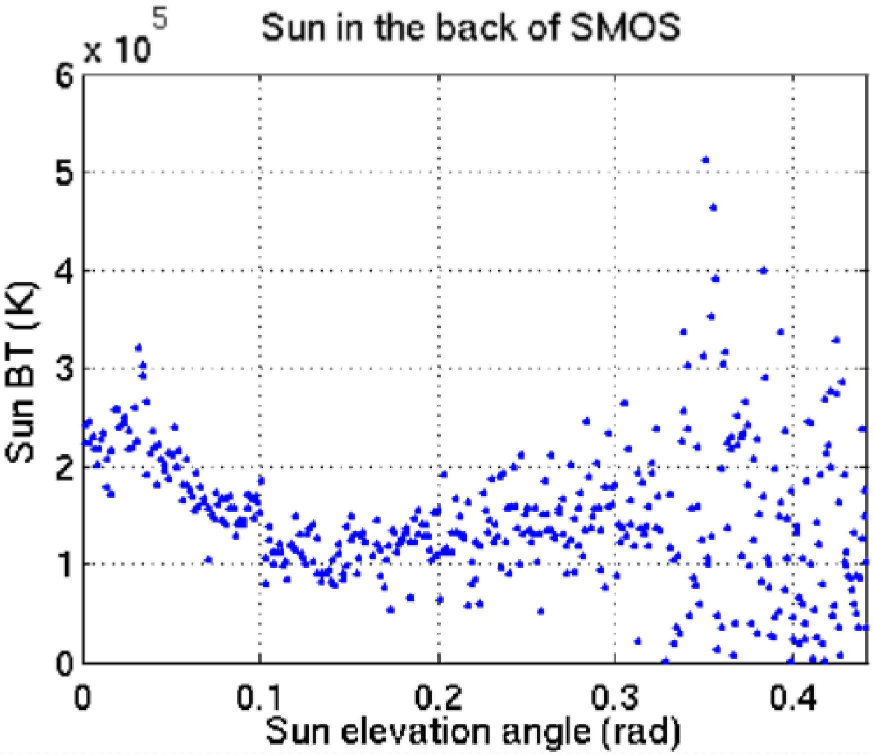
- The position of the Sun is always outside the hexagon (yellow circle).
- It impacts the SMOS images by one of its 6 aliases which falls inside the hexagon (red circle).
- Due to the natural hexagonal grid in SMOS imaging because of the Y shape of the instrument, the Sun will also impact the SMOS images through its 6 tails in the direction of the grid.



# Sun BT in SMOS L1OP

- In the SMOS Level 1 operational processor (L1OP), the Sun is an outlier where its BT is estimated and its contribution to the visibilities is removed.
- The Sun correction algorithm used in the L1OP suffers from several drawbacks:
  - Systematic under and over estimation of the Sun BT for low elevation angles (near the transition) in front and in the back respectively.
  - The variation in front is not smooth with repetitive linear stripes
  - In the back and for high elevation angles, the Sun BTs are randomly distributed and extremely noisy

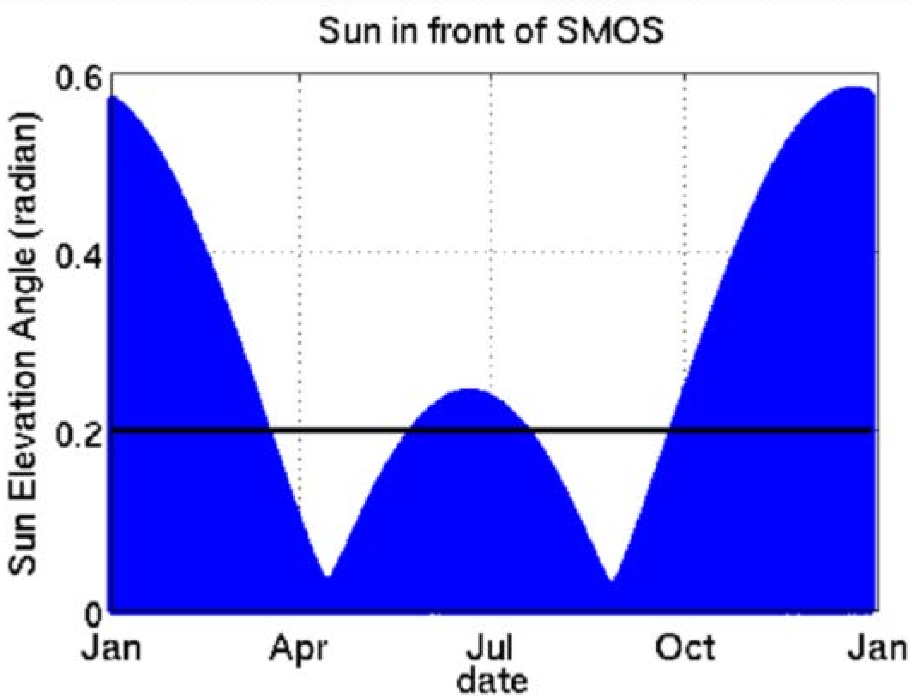


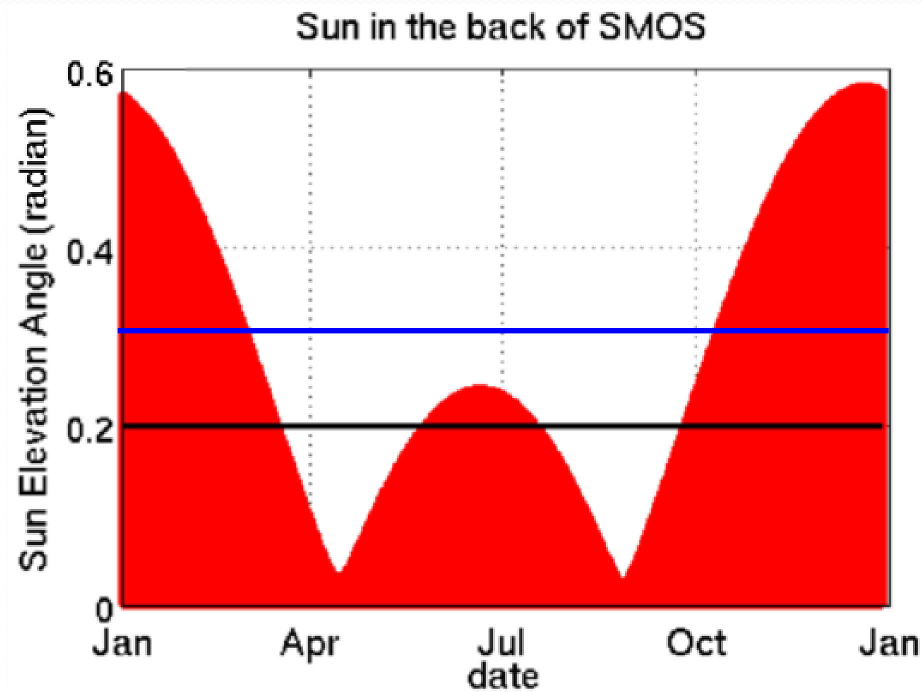



# Sun BT in SMOS L1OP

- As a consequence, most of the users are filtering all Sun BT values with a Sun elevation below **0.2 rad** which corresponds to almost 65% of measurements
- We also add that about 10% of the measurements have a Sun elevation angle above **0.3 rad** in the back of SMOS where the estimated Sun BT values are randomly distributed and cannot be used.

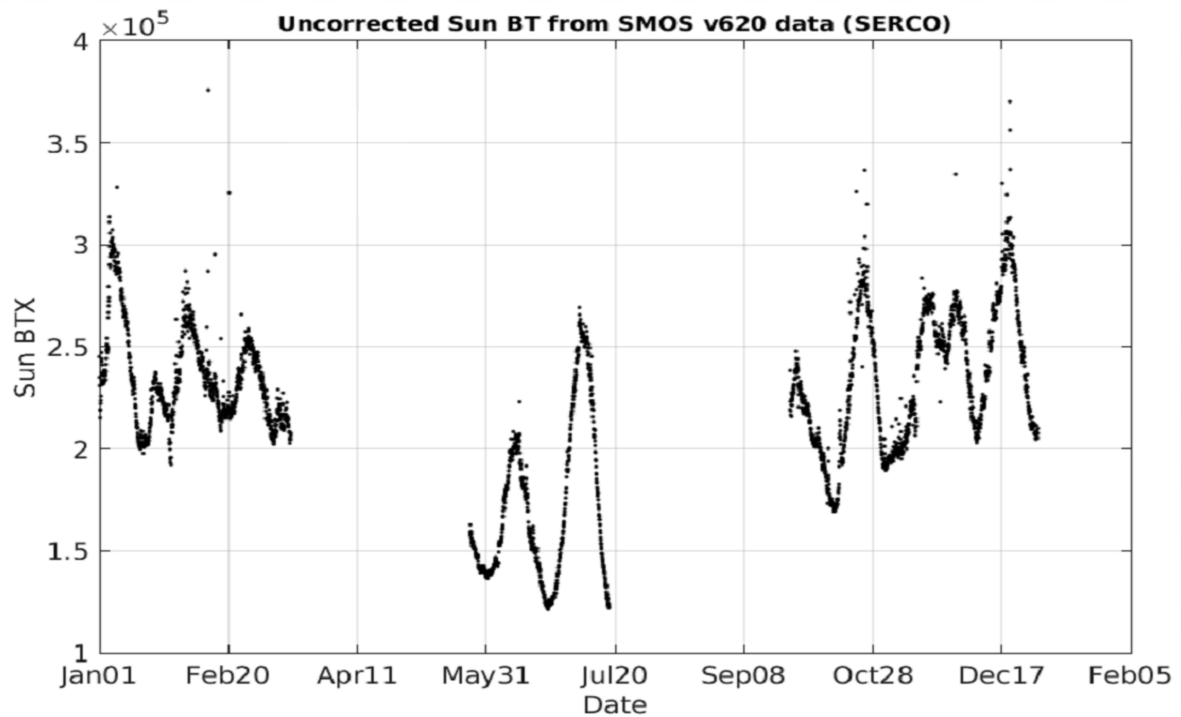
**Large gaps in the Sun BT coverage estimated by SMOS**



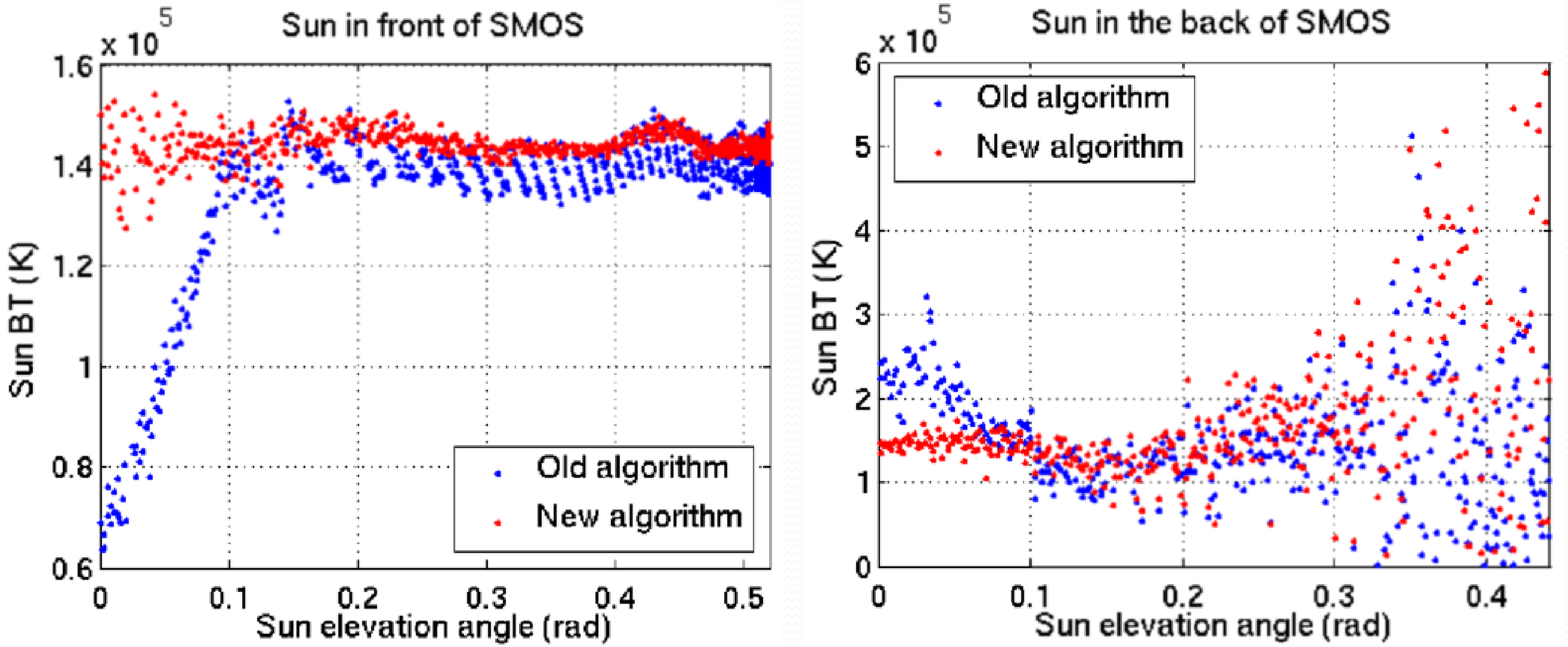
# Sun BT in SMOS L1OP

- This is confirmed by the Sun BT values obtained by SERCO using SMOS L1B products where there are no available data for several months and a calibration with radio-telescope data is needed to fill the gaps.



# Sun BT in SMOS L1OP

- In the new Sun BT algorithm, we propose solutions for 2 of the problems:
  - Improve the Sun BT values for low elevation angles in front and in the back
  - Remove the repetitive linear stripes
- The new algorithm will improve the quality and the quantity of the Sun BT.



# Sun Flare project

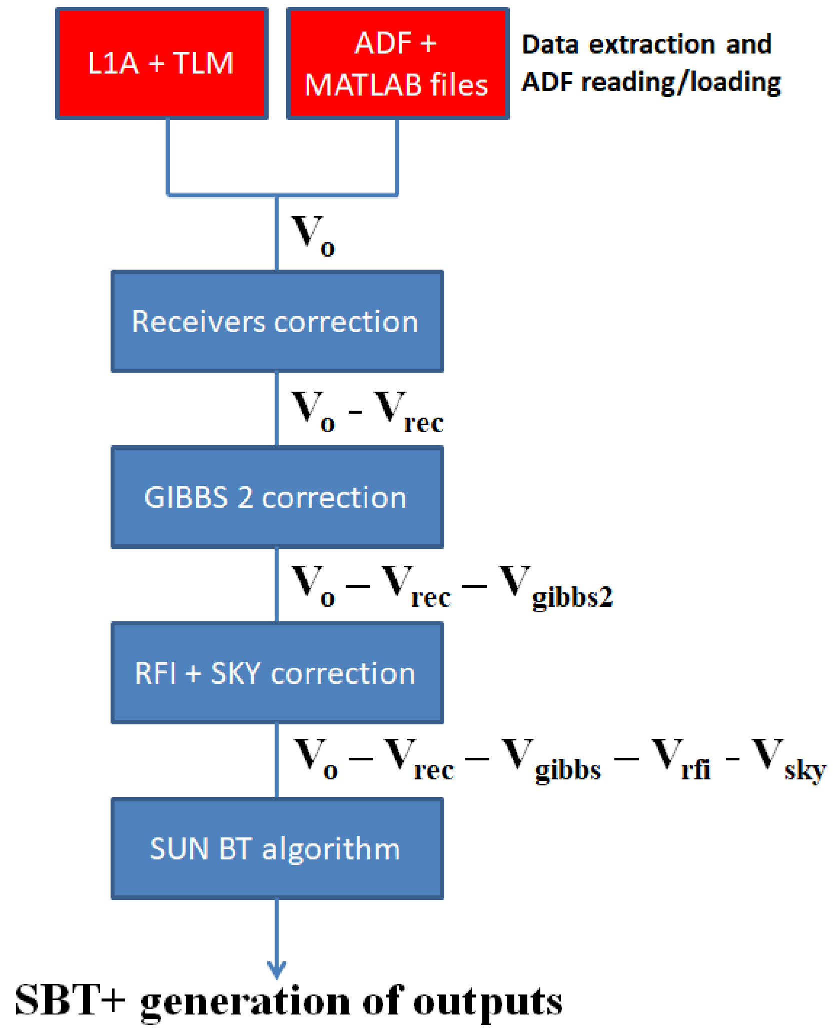
- A dedicated Sun Flare project is launched by ***ESA*** in 2021 in collaboration with ***DMR, RDA, UAH***, and ***RDIS conseils***.

- The objective of this project is to produce global measurements of the Sun flux at L band using SMOS interferometric measurements.

- Two processors are developed in parallel to achieve this goal:
  1) Sun BT processor, developed by ***RDIS conseils***, and with an improved Sun BT algorithm aims at improving the drawbacks of the algorithm used in SMOS L1OP.
  2) Sun flux processor, developed by ***DMR***, to generate the Sun flux products.

# Sun BT processor

- The processing chain contains the following tasks:



RDIS conseils

# New Sun BT algorithm

- In the SMOS L1OP, the Sun BT is estimated using the following equation:

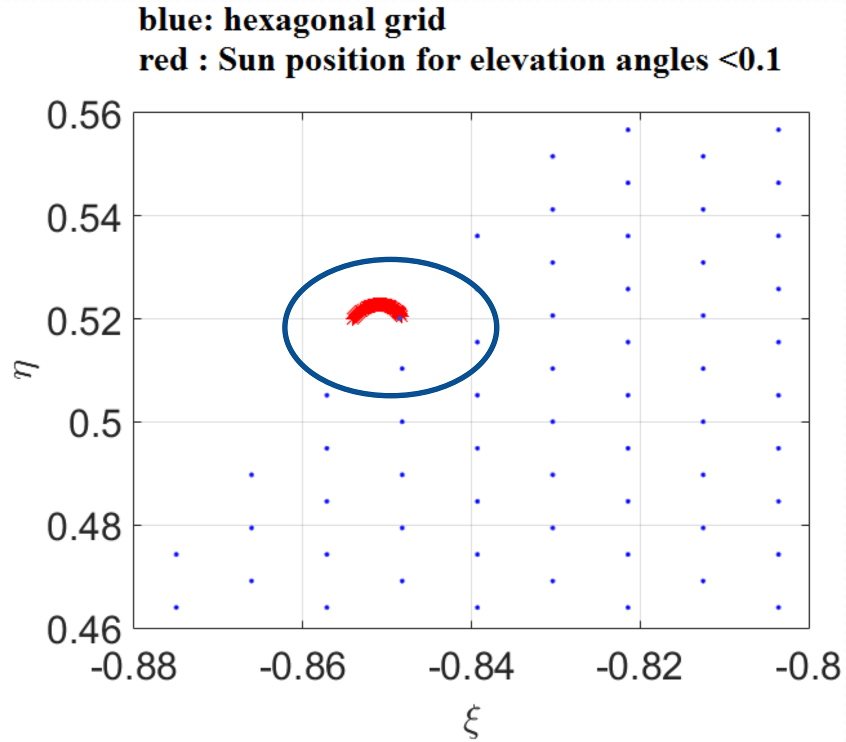
$$T_{Sun} = \frac{TF^{-1}(V)_{(\xi_s,\eta_s)} - T_{avg}}{TF^{-1}(V_{1K})_{(\xi_s,\eta_s)}}$$

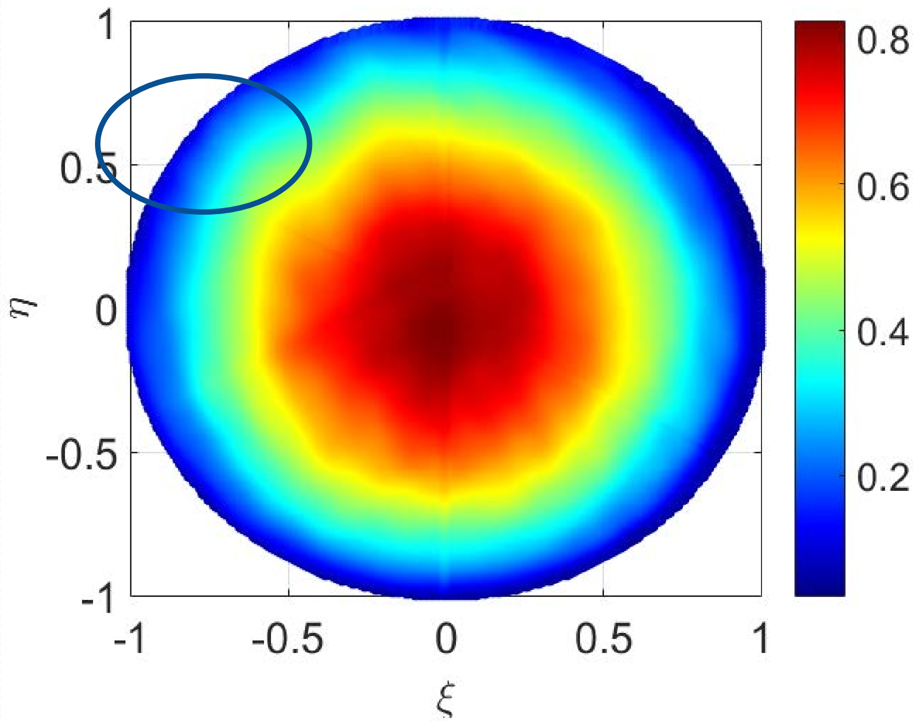
- $TF^{-1}$: Inverse Fourier transform
- $V$: SMOS visibilities
- $V_{1K}$: is the system response function which corresponds to a column of the modeling operator of SMOS calculated over the Sun position
- $T_{avg}$: The scene average BT around the Sun position

# New Sun BT algorithm

1) Improving the estimation of the Sun BT for low elevation angles:

- Origin of the problem:
  - Near the front/back lobes transition, the Sun is on the edge of the unit circle (FOV) and beyond the limit of the maximum radius of the (**ξ**,**η**) grid.
  - The value of the Interpolated Antenna Pattern (**IAP**) at the Sun position is far from its real value (since a nearest neighbor interpolation is applied)



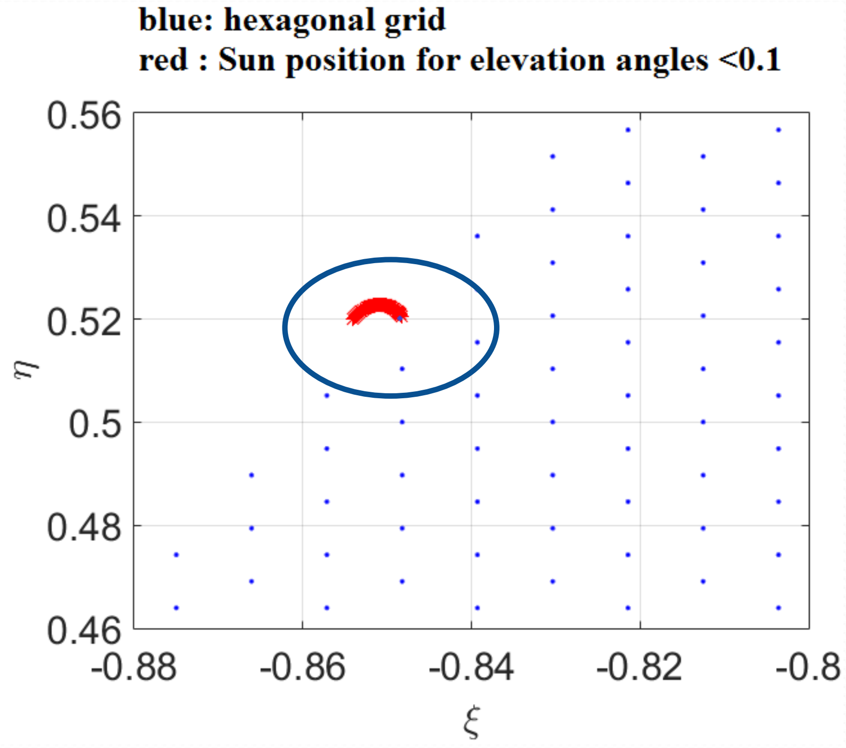



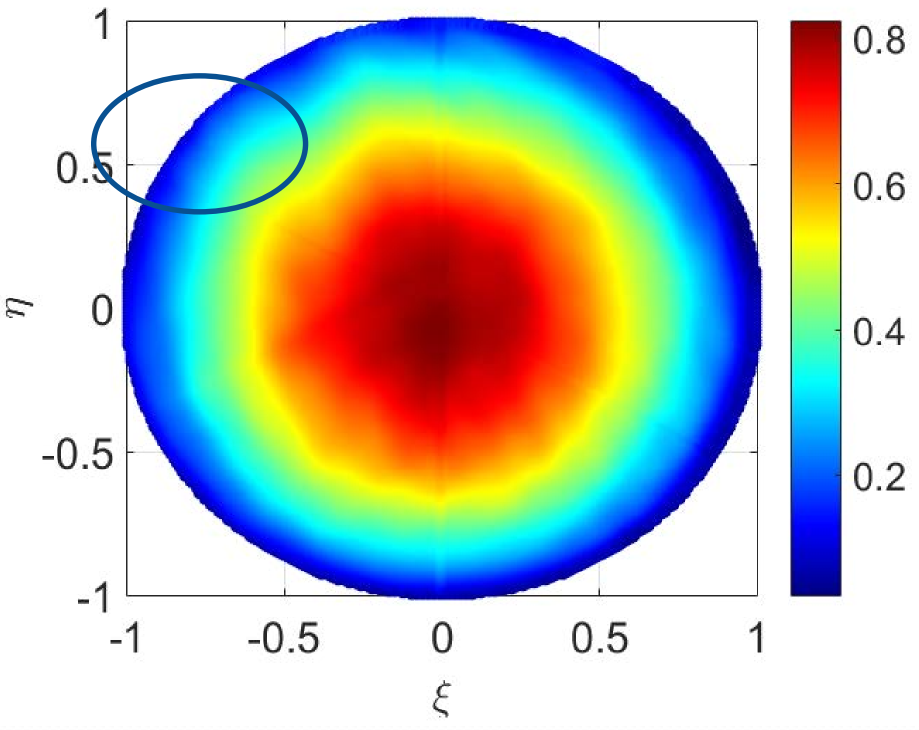
# New Sun BT algorithm

1) Improving the estimation of the Sun BT for low elevation angles:

- Origin of the problem:
  - **If the Sun is in front:** the **IAP** is higher leading to lower estimated Sun BTs than the expected values.

**IAP** is higher >>> $\mathbf{TF^{-1}(V_{1K})}$ is higher >>> $\mathbf{T_{sun}}$ is lower



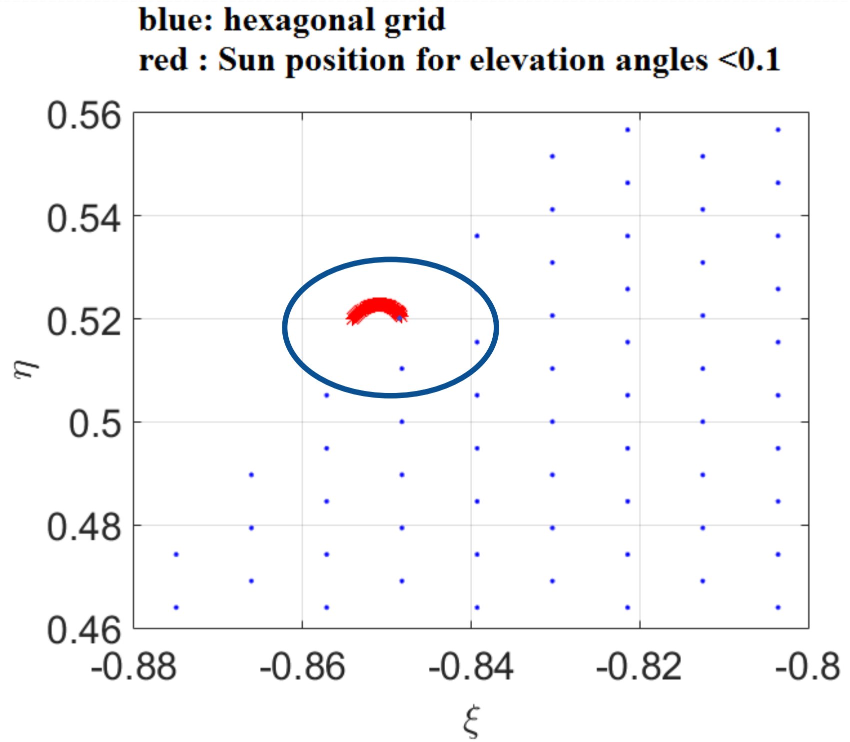



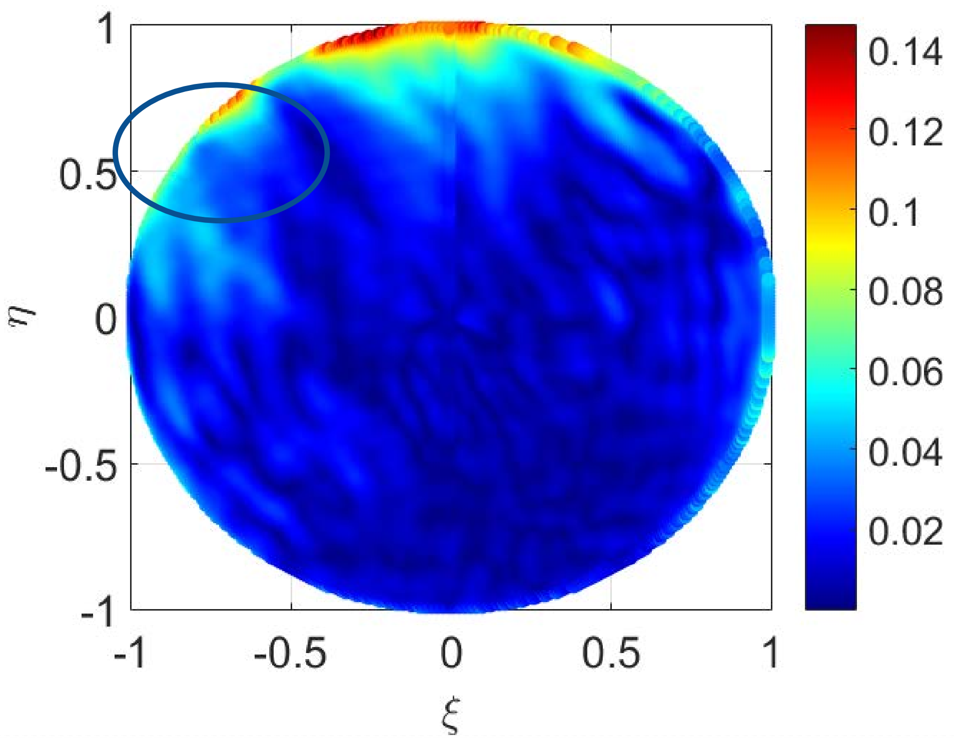
# New Sun BT algorithm

1) Improving the estimation of the Sun BT for low elevation angles:

- Origin of the problem:
  - **If the Sun is in the back**: the **IAP** is lower leading to higher estimated Sun BTs than the expected values.

**IAP** is lower >>> **TF**$^{-1}$**(V**$_{1K}$**)** is lower >>> **T**$_{sun}$ is higher



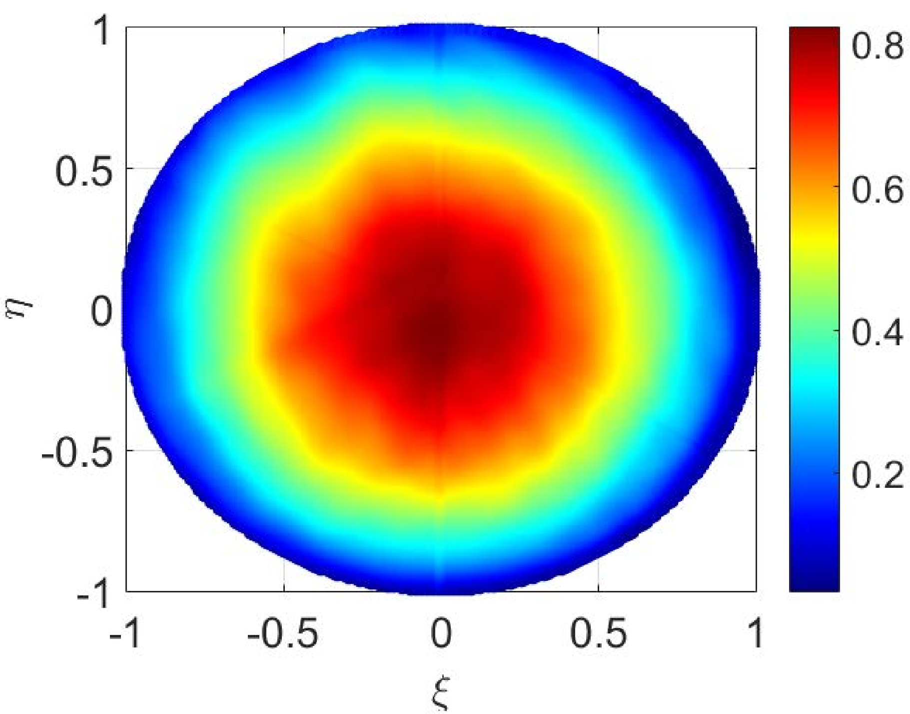



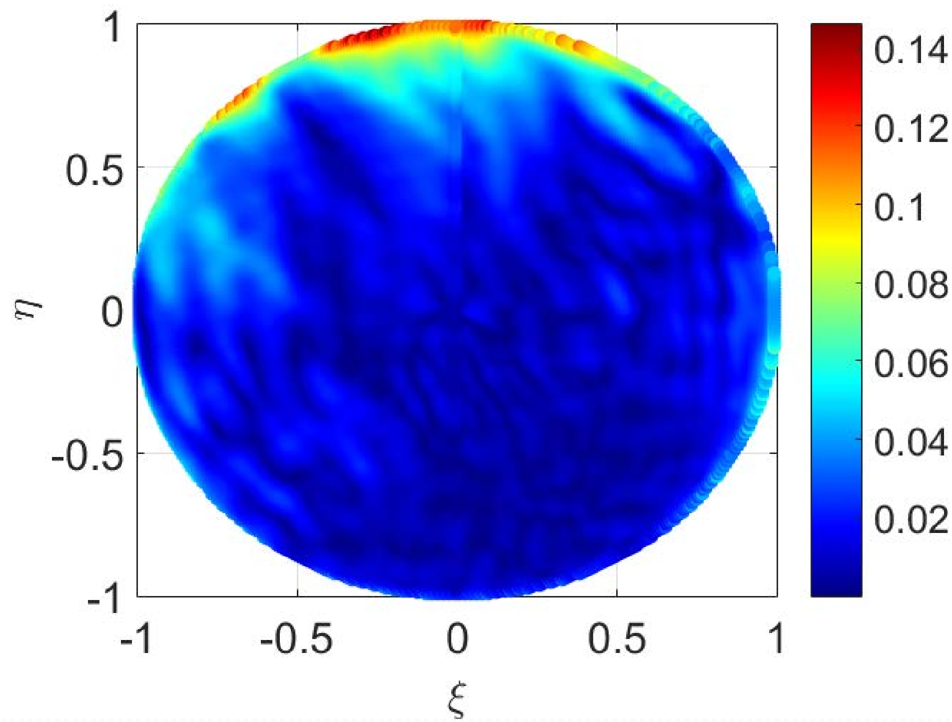
# New Sun BT algorithm



1) Improving the estimation of the Sun BT for low elevation angles:

- Proposed solution:
  - Instead of using the antenna patterns in the (**ξ,η**) grid and using the front-lobes and back-lobes separately, we propose to use the angular antenna patterns defined over (**θ,φ**) for both front-lobes and back-lobes.



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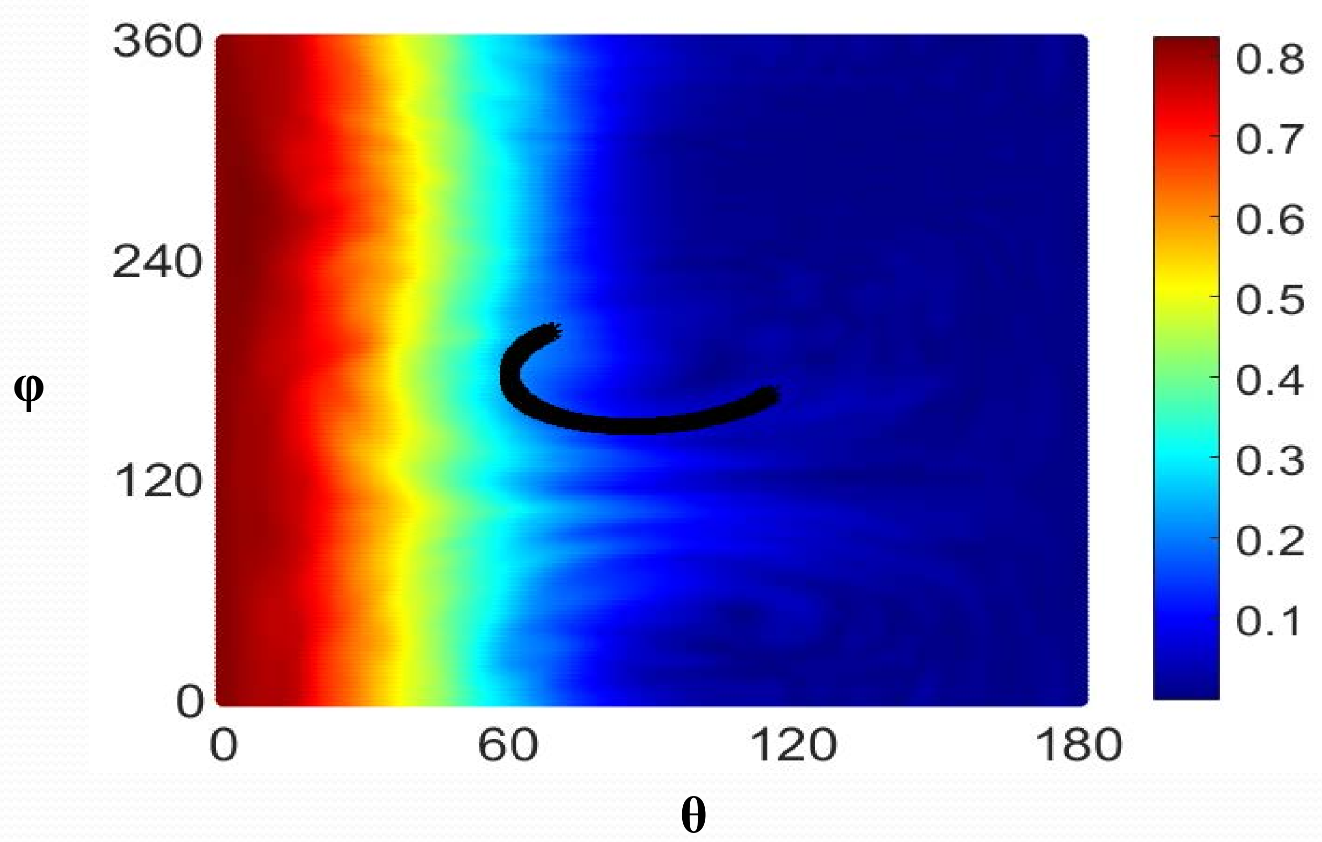


# New Sun BT algorithm

2) Reducing the linear stripes and making the variation much smoother:

- Even though the $V_{1K}$ is calculated over the exact Sun position, the Sun BT is estimated over the pixel with the maximum value of the inverse fast Fourier transform of $V_{1K}$.

$$T_{Sun} = \frac{TF^{-1}(V)_{(\xi_s,\eta_s)} - T_{avg}}{TF^{-1}(V_{1K})_{(\xi_s,\eta_s)}}$$

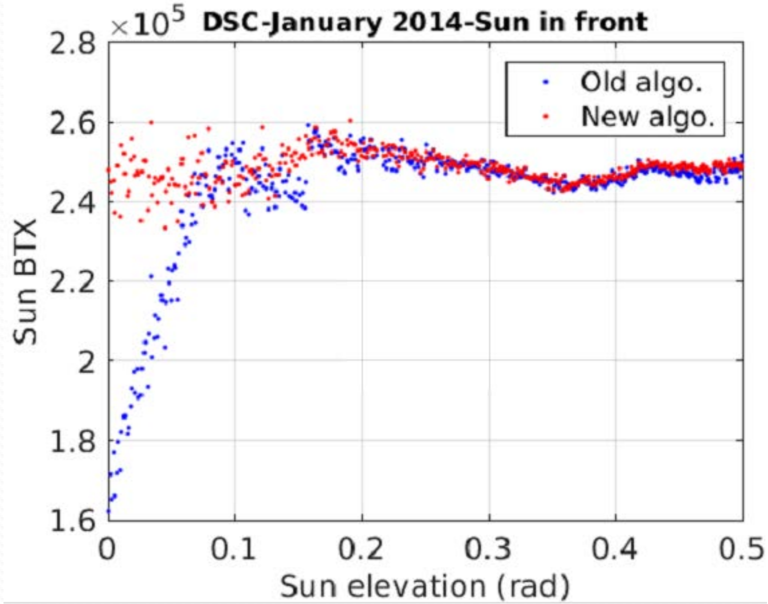
- Origin of the problem:
  - We apply an ***IFFT*** over $V_{1K}$ and get the index (***I***) of the maximum value
  - We apply the ***IFFT*** over V and get its value at the index (***I***)
  - This approximation means that for a certain number of snapshots, the index (***I***) is the same and then changes to a neighbor pixel (***I2***) for another range of snapshots and so on. For each range, the estimated Sun BTs for each range are dependant thus leading to the linear stripes.

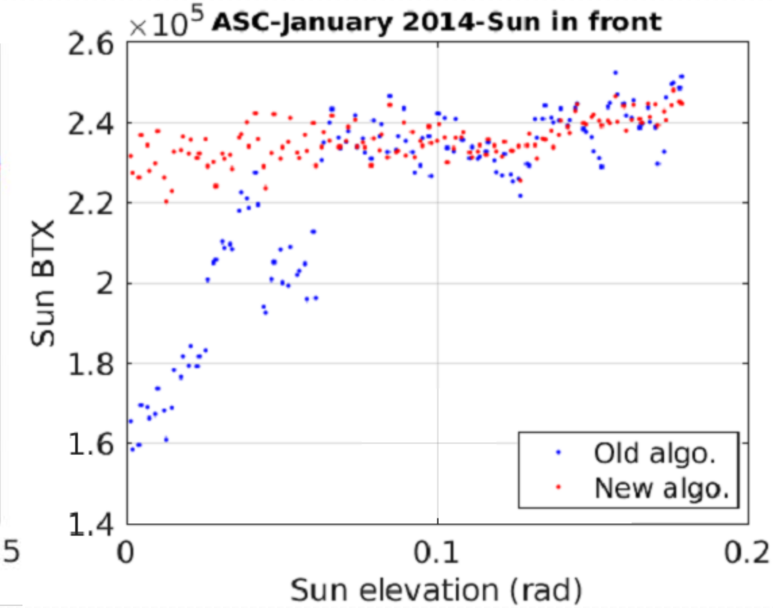
- Proposed solution:
  - Apply the above equation without any approximation by using an analytic discrete inverse Fourier transform on the exact position of the Sun alias ($\boldsymbol{\xi_s}$,$\boldsymbol{\eta_s}$) for V and $V_{1K}$

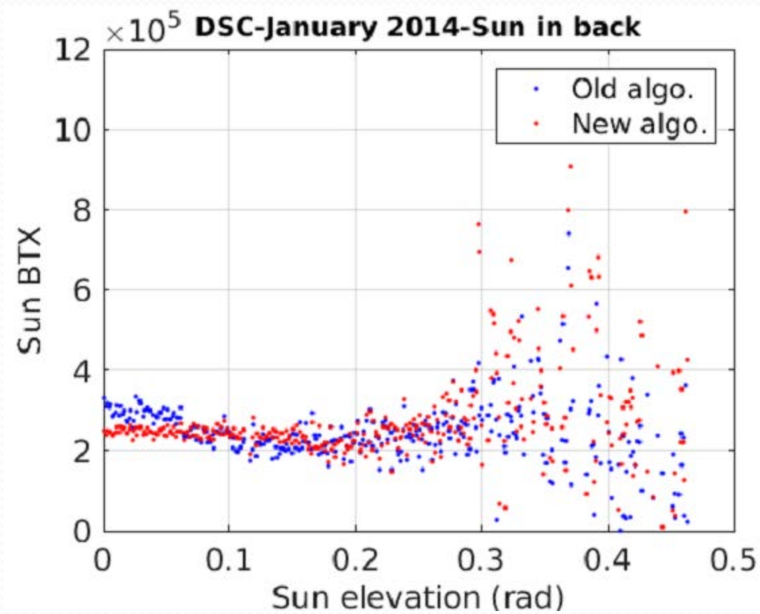
RDIS conseils

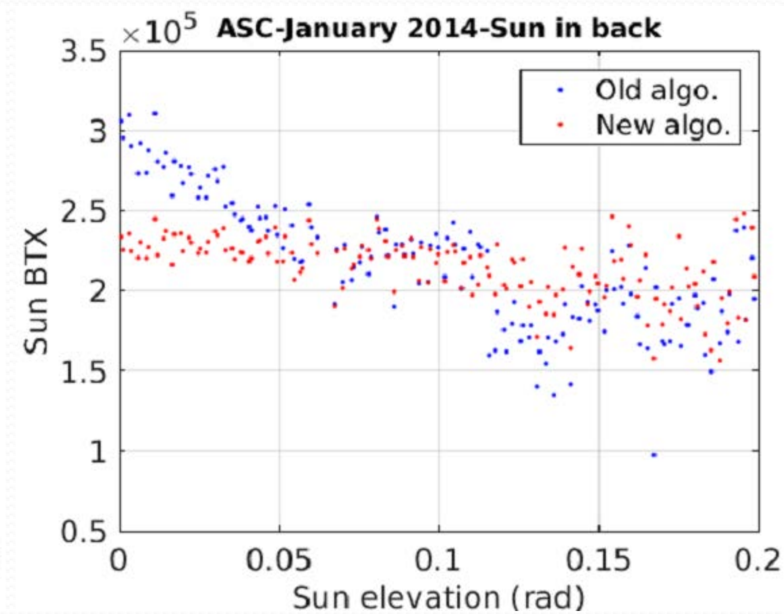
# Results (1): comparing single orbits

- Old Vs New algorithm with respect to Sun elevation angle: One orbit per mor



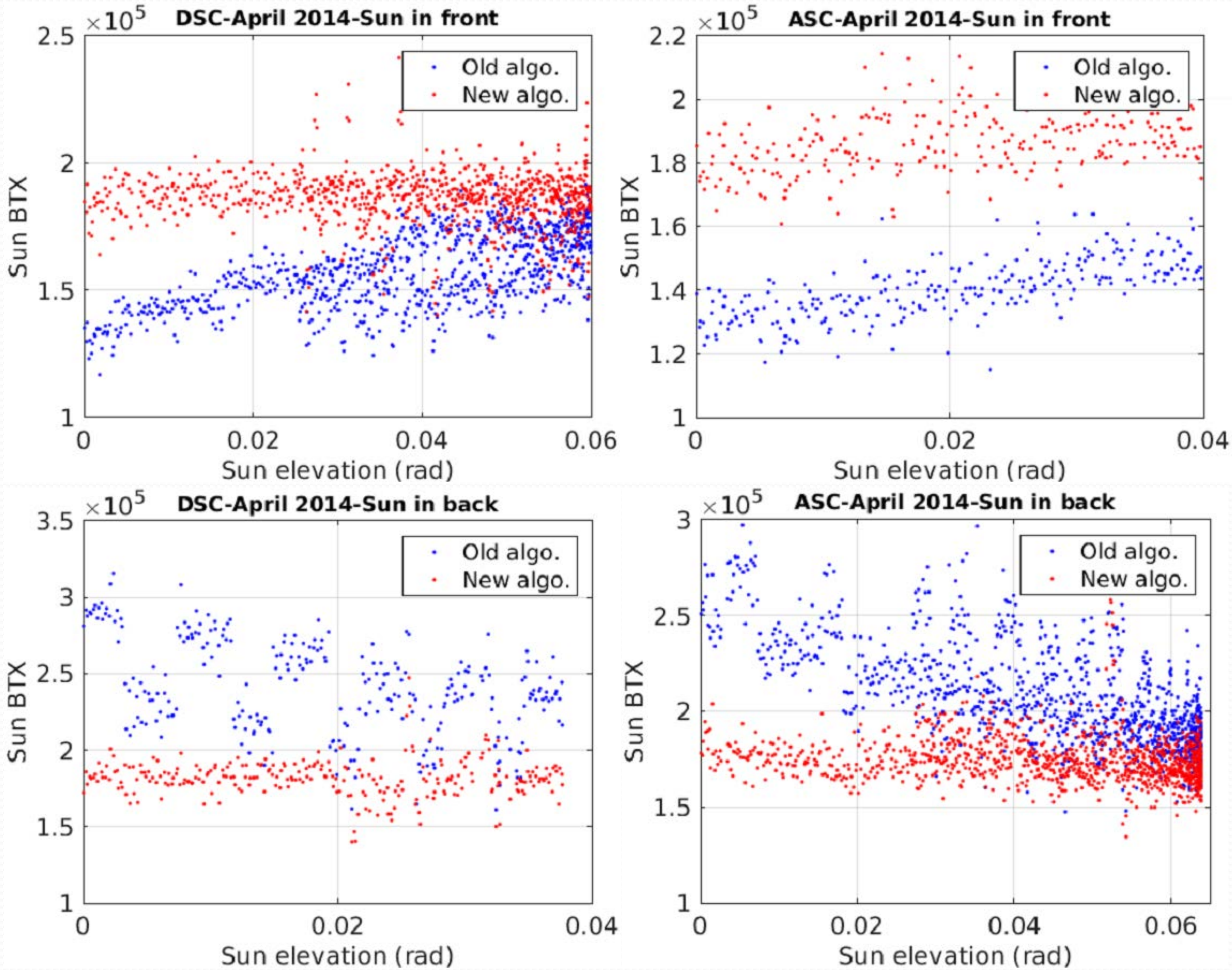



RDIS conseils

# Results (1): comparing single orbits

- Old Vs New algorithm with respect to Sun elevation angle: One orbit per mon



RDIS conseils

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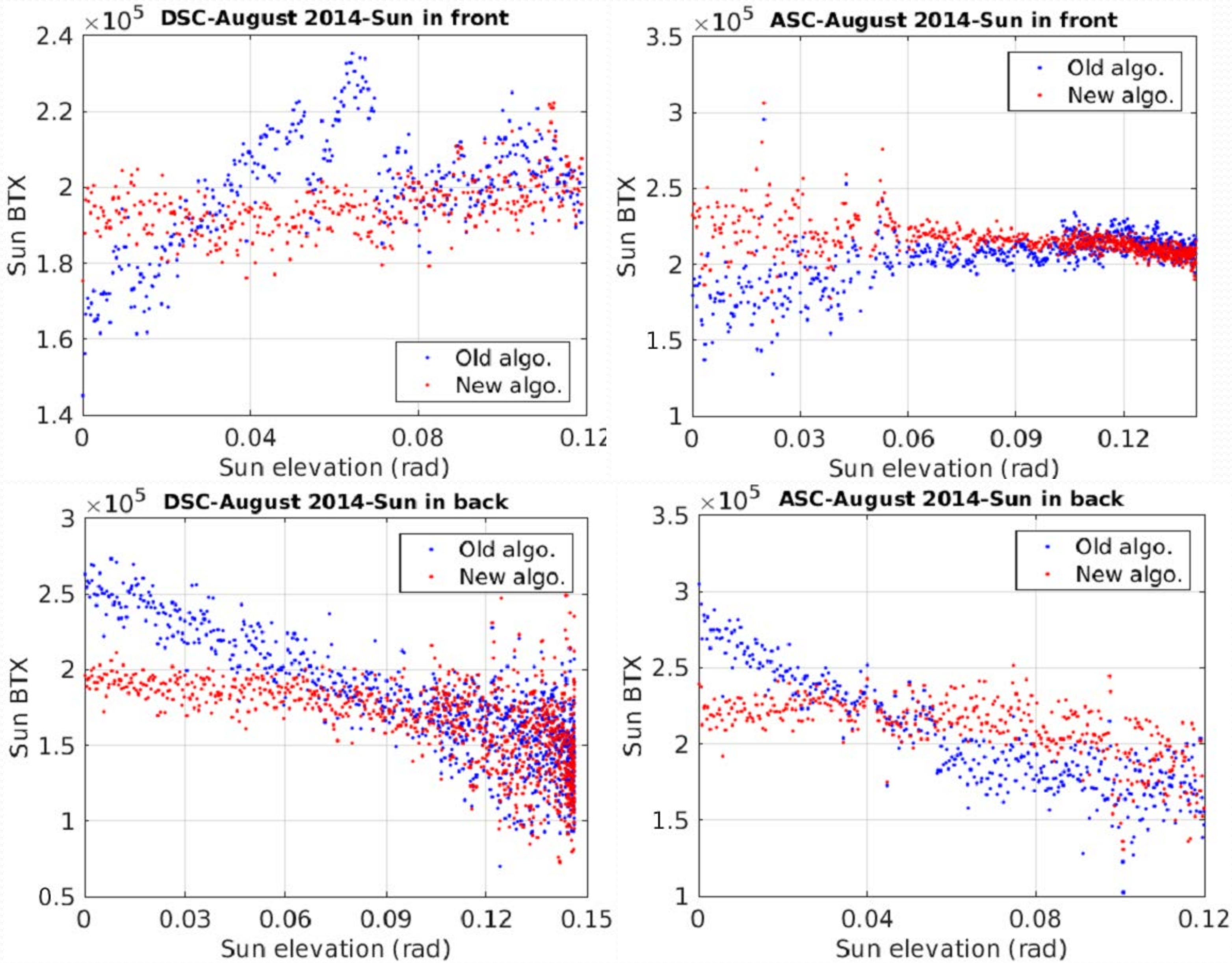

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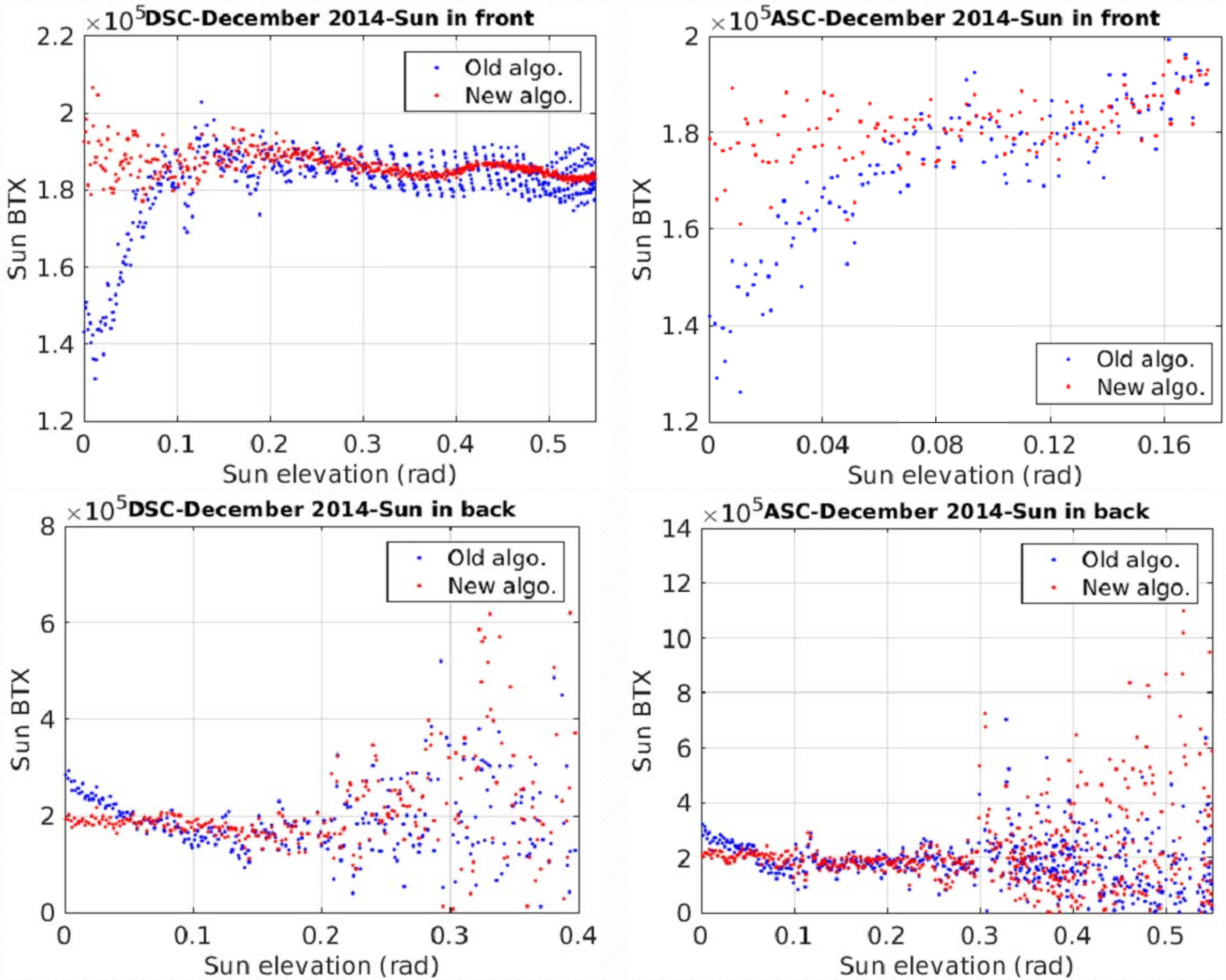
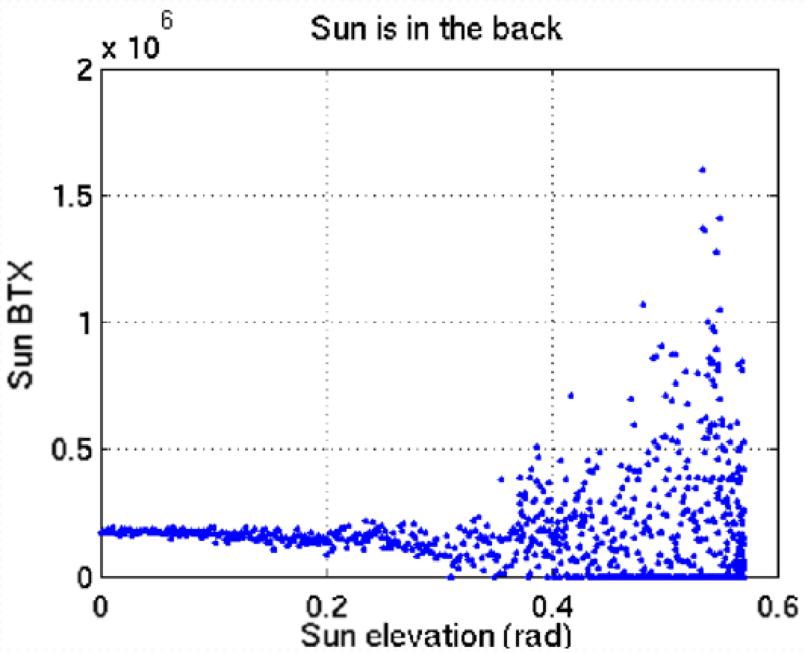
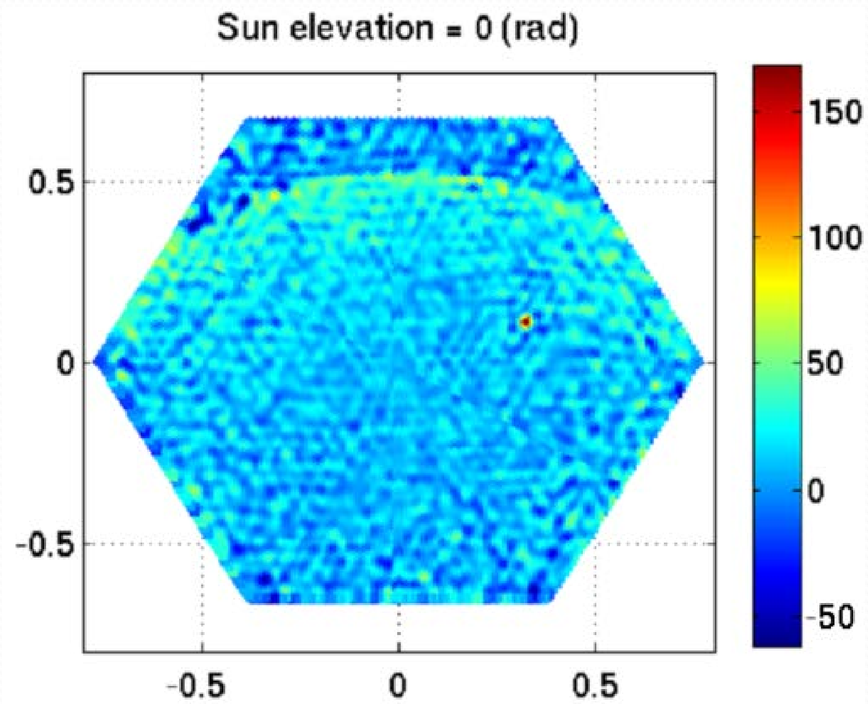


# Sun BT for High Elevation Angles in the Back



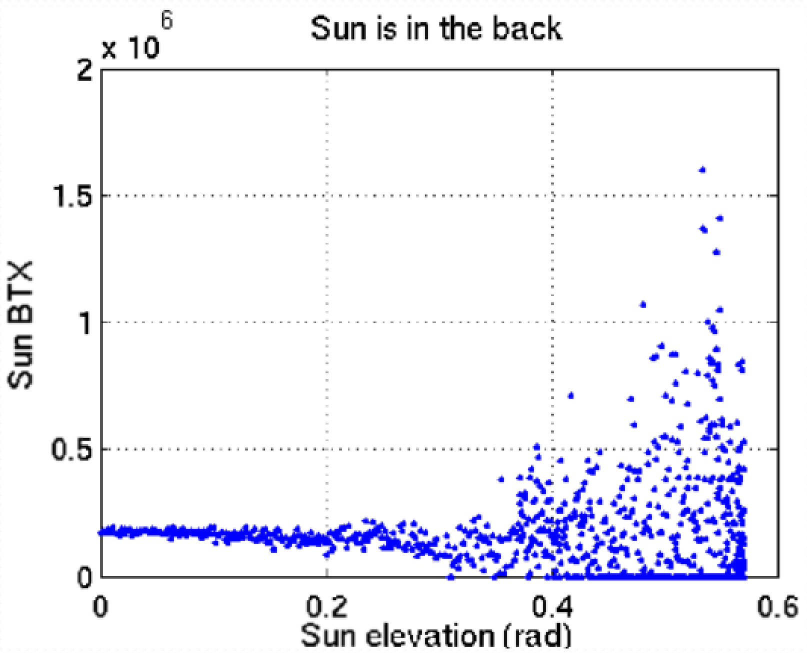
- The estimated Sun BT values for high Sun elevation angles in the back are randomly distributed negative/positive values
- For these snapshots, the Sun radiation is extremely low within the visibilities because the amplitude of the antenna patterns in the back is extremely small.
- The Sun signal to noise ratio is very small and thus explaining the random distribution of the Sun BT values.

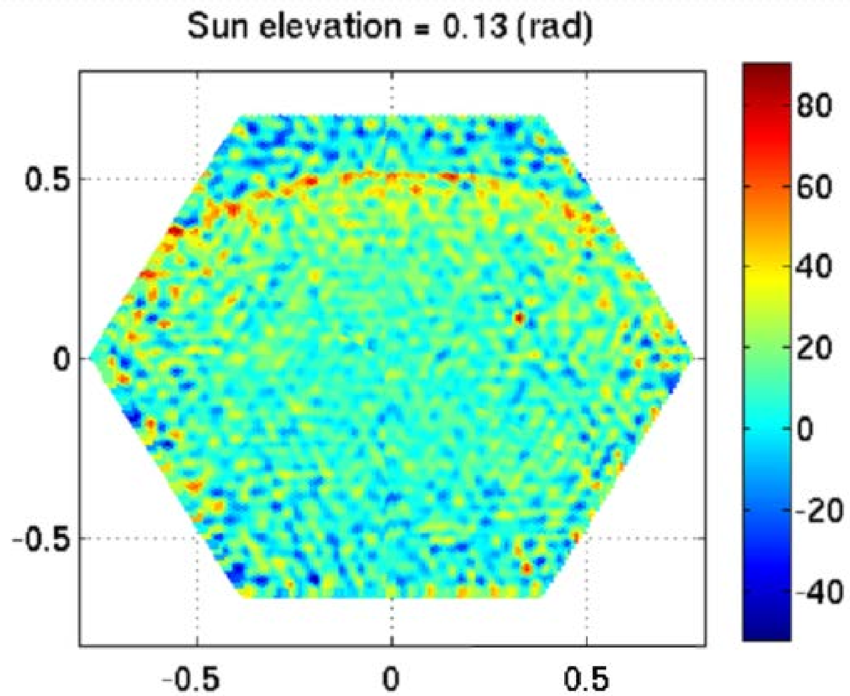


# Sun BT for High Elevation Angles in the Back

- The estimated Sun BT values for high Sun elevation angles in the back are randomly distributed with values going from **0** to more than **6x10$^5$**
- For these snapshots, the Sun radiation is extremely low within the visibilities because the amplitude of the antenna patterns are extremely small.
- The Sun signal to noise ratio is very small and thus explaining the random distribution of the Sun BT values.



RDIS conseils

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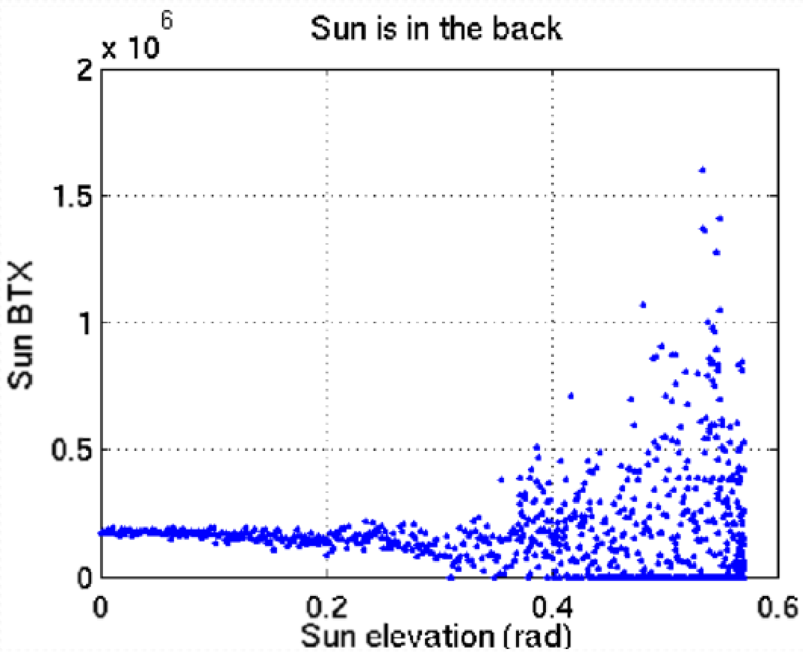


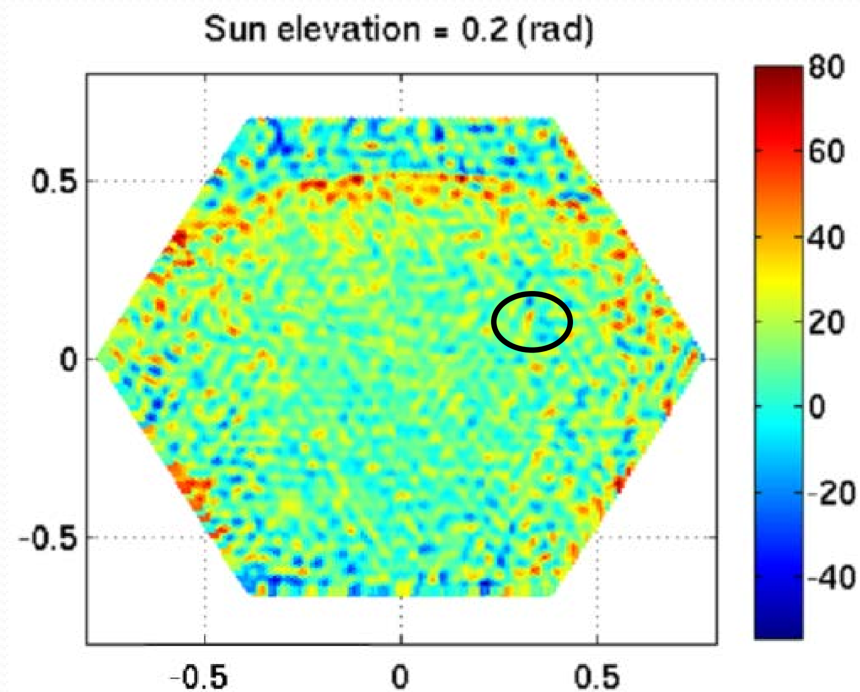

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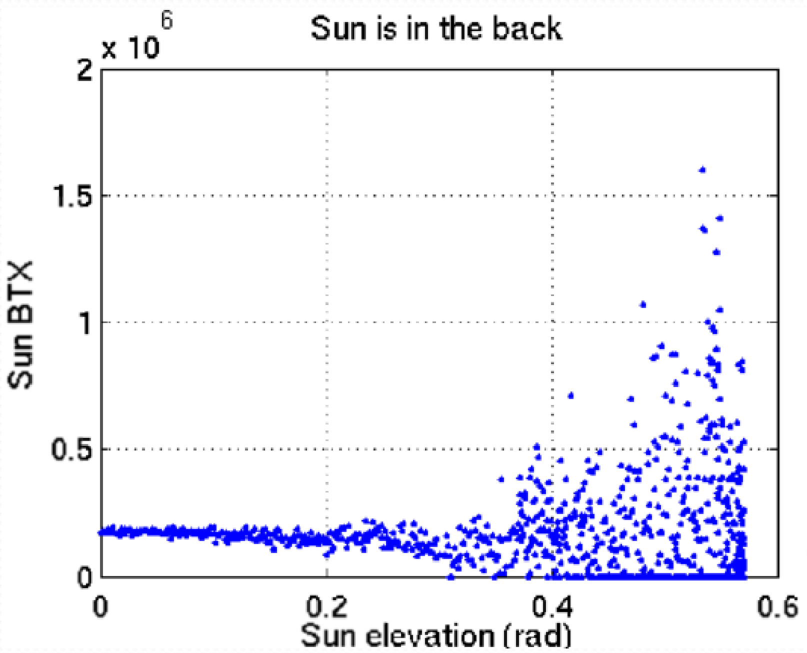
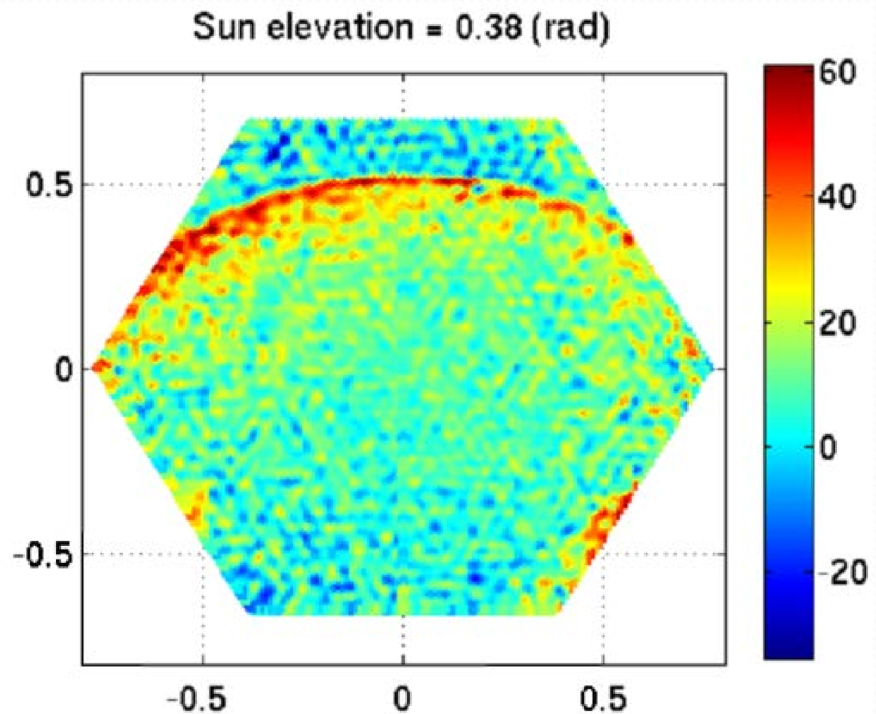
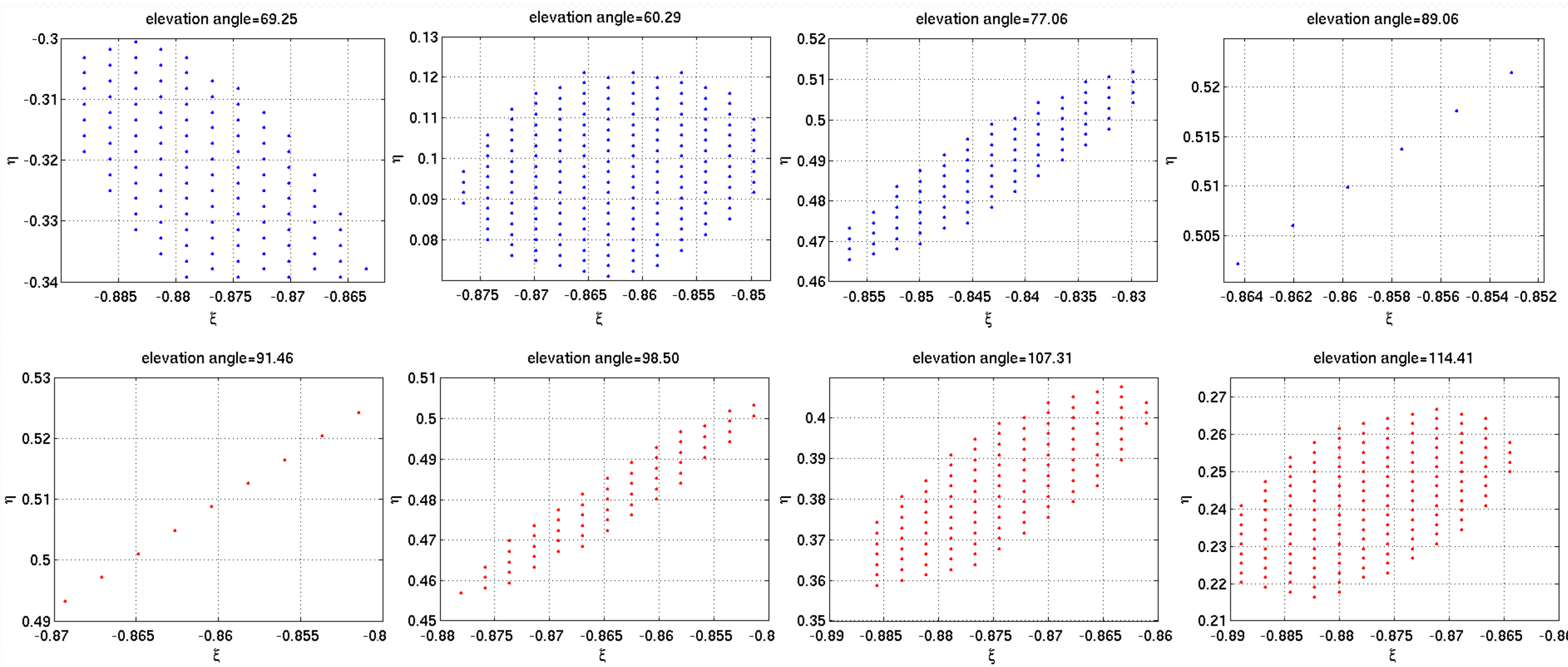


RDIS conseils

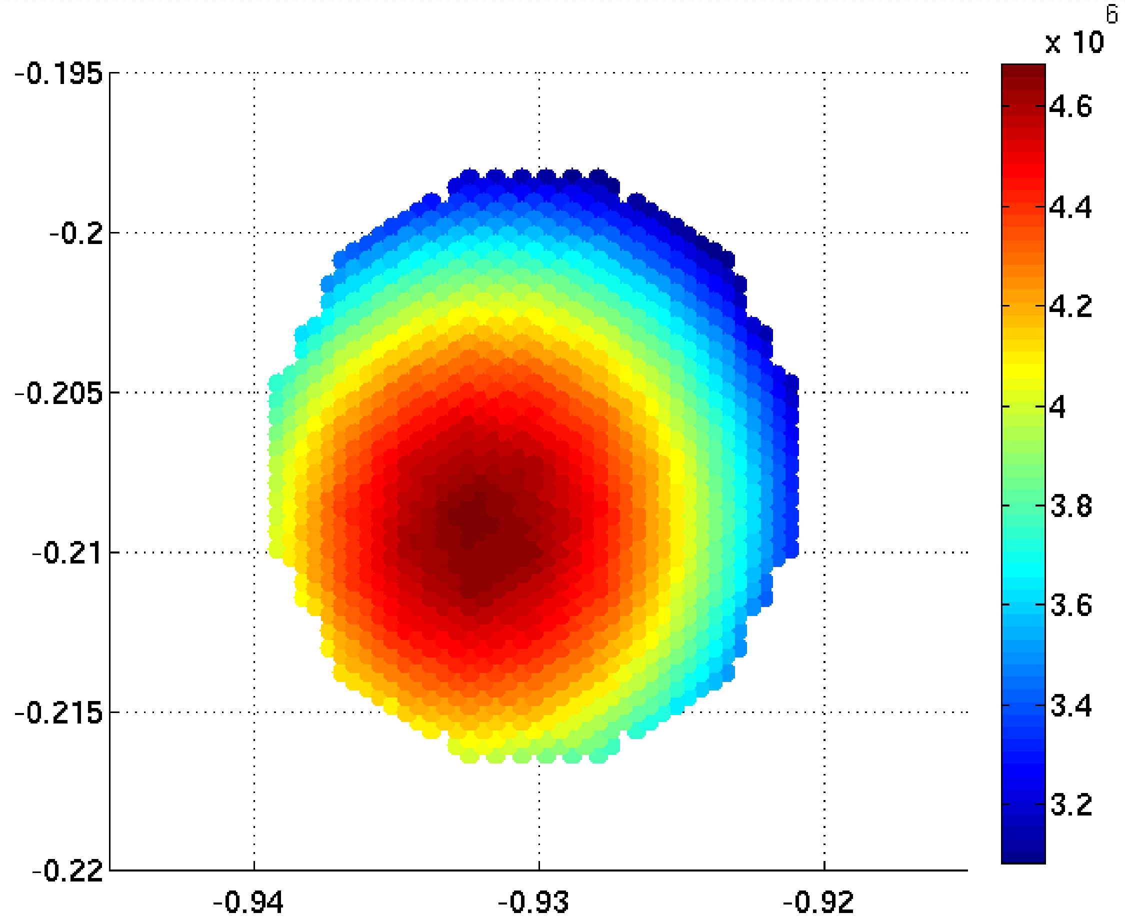
# Sun BT Multiple Point Algorithm

- The idea is to extend the new Sun BT algorithm over a fine grid around the center of the Sun disk.
- When projecting the Sun disc over the FOV of SMOS, it is no longer a disc but an ellipsoid that changes size and direction as the satellite move.
- When the Sun is far from the edge of unit circle, the ellipsoid is at its maximum and it shrinks as we approach the front/back transition point where the Sun disc is nearly seen as an arc of a few single points.



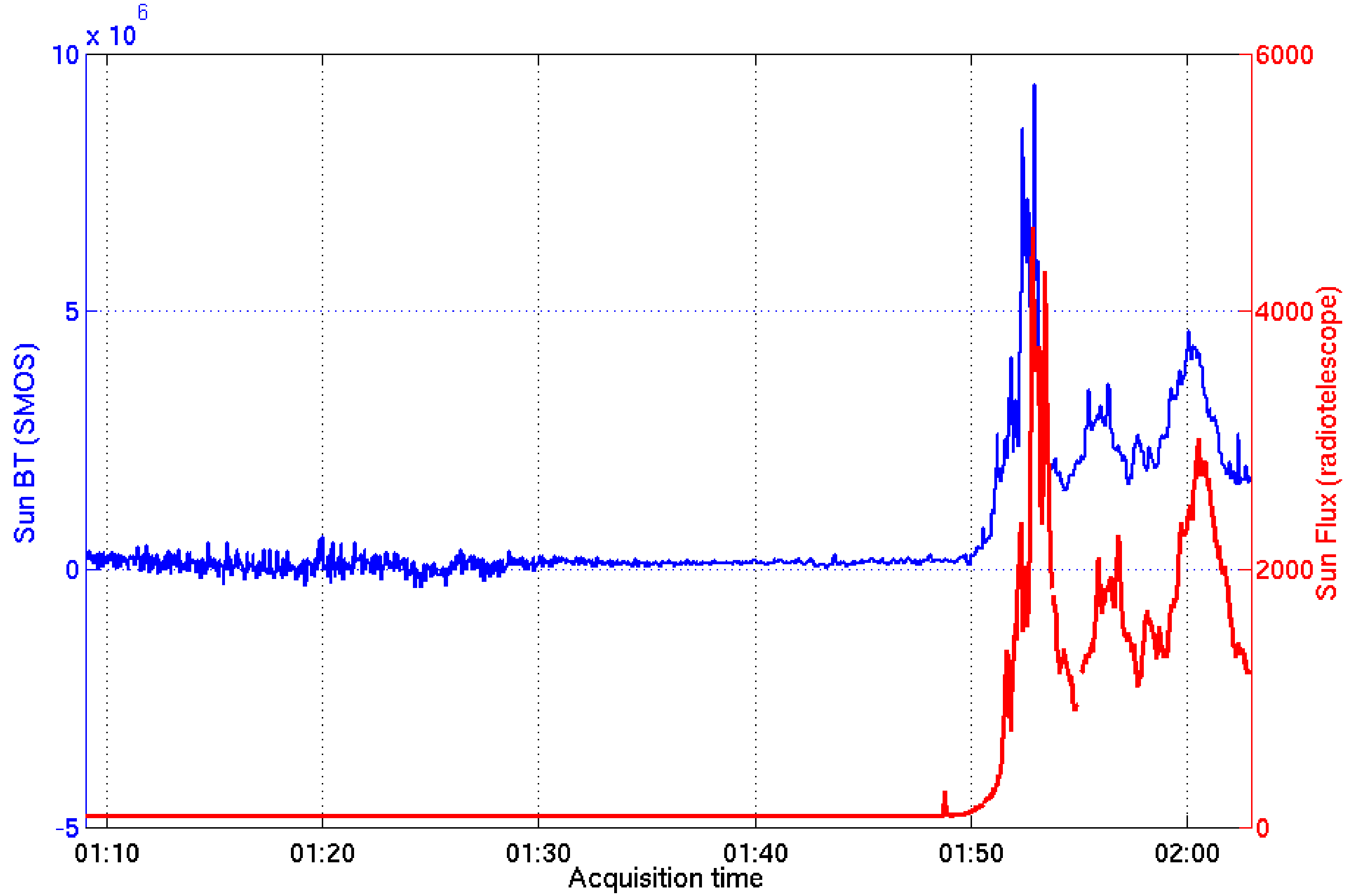
# Sun BT Multiple Point Algorithm

▪ An example of the Sun BT estimated using the multiple point algorithm and then re-interpolated to a much finer grid.



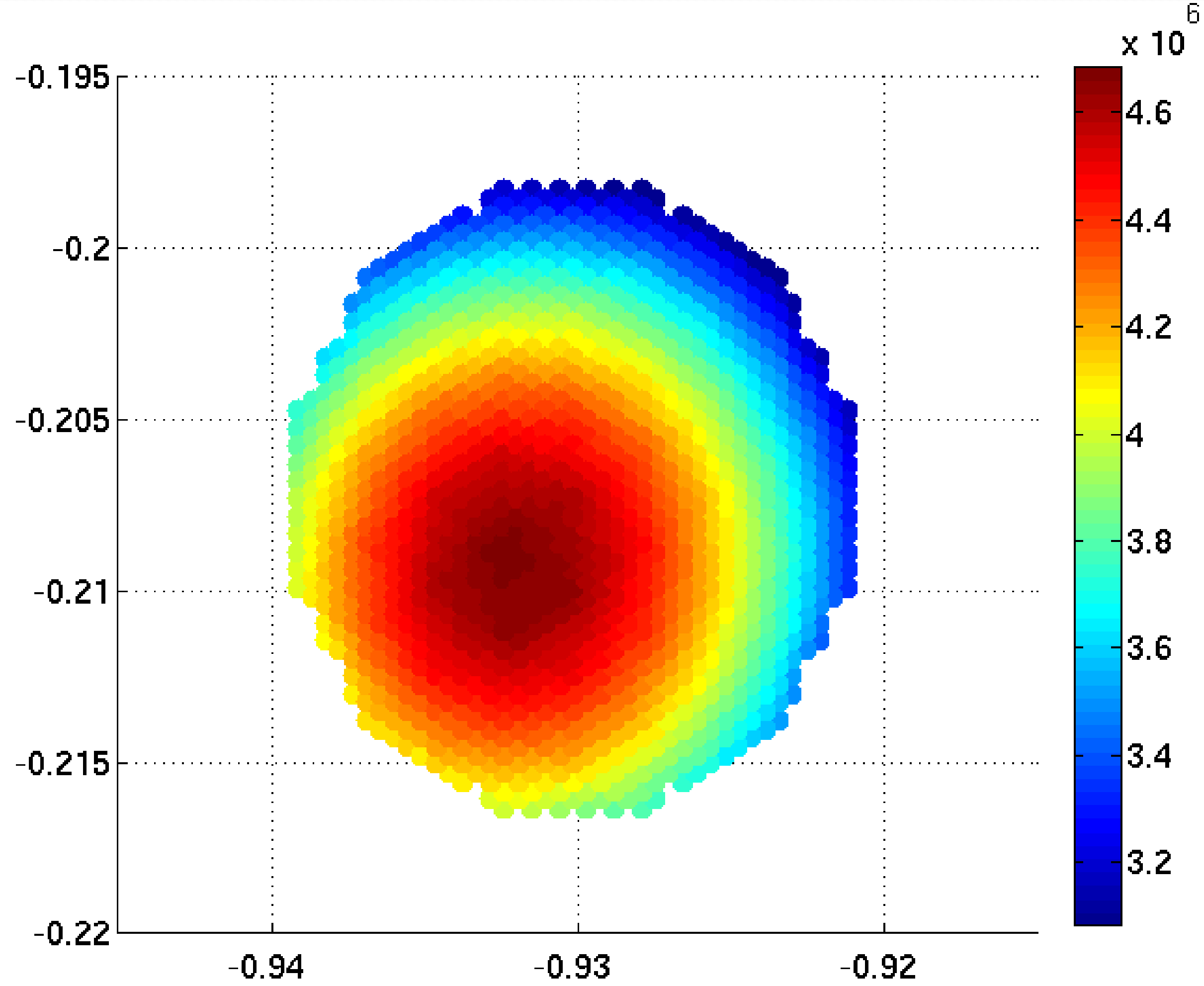
# Solar radio burst in front

- From Radio-telescope data, we have a solar radio burst in February 15, 2011.
- This burst happened when the Sun is in front of SMOS.
- The corresponding L1A product is processed using the new Sun BT algorithm.
- The estimated Sun BT are compared to the solar flux values from radio-telescope



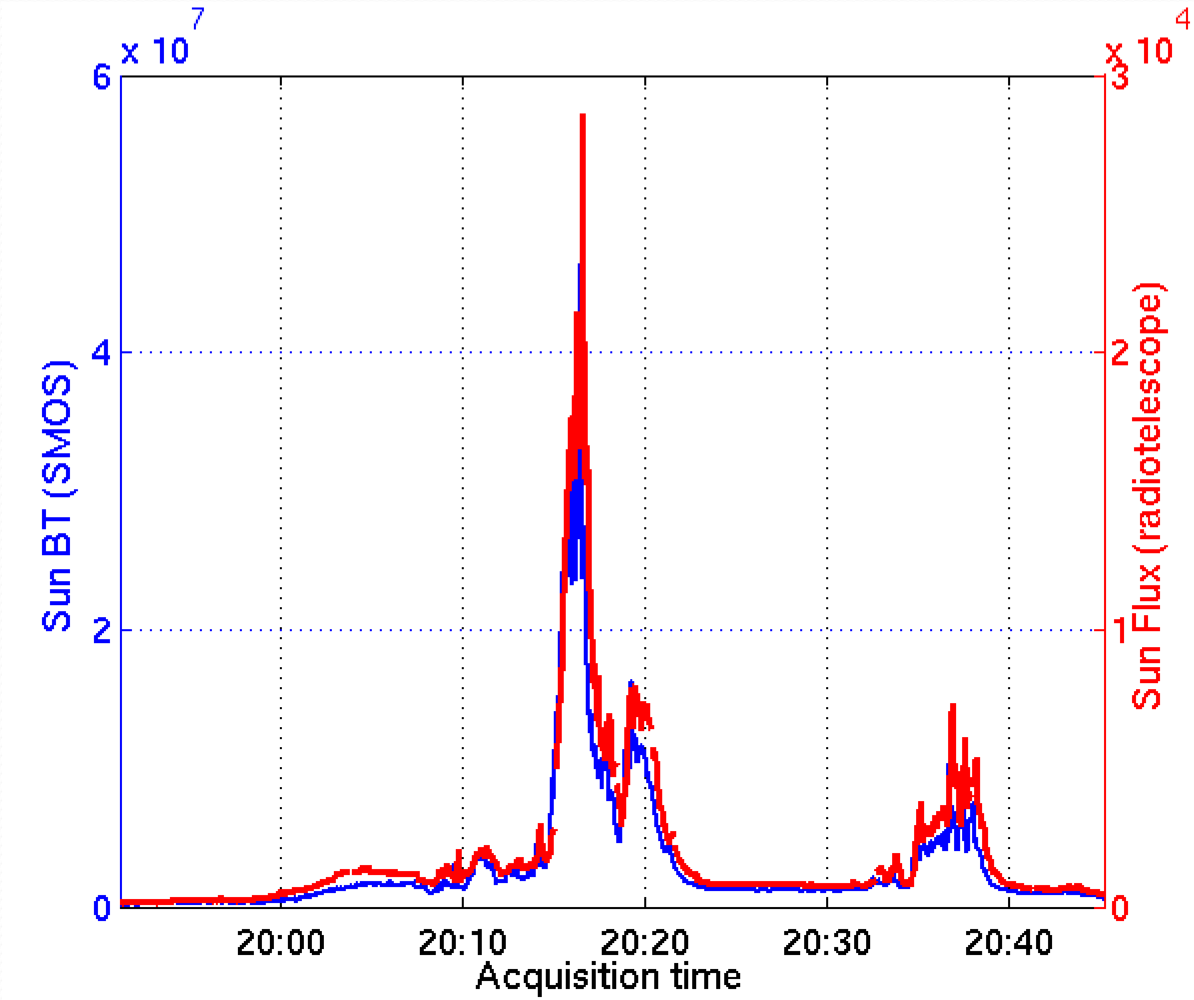
# Solar radio burst in front

- For the solar burst at 02h:00, its maximum is identified by radio-telescope as near the center of the disk.
- This is also confirmed by SMOS by estimating the Sun BT within the Sun disk, and then interpolating them over a very fine grid.



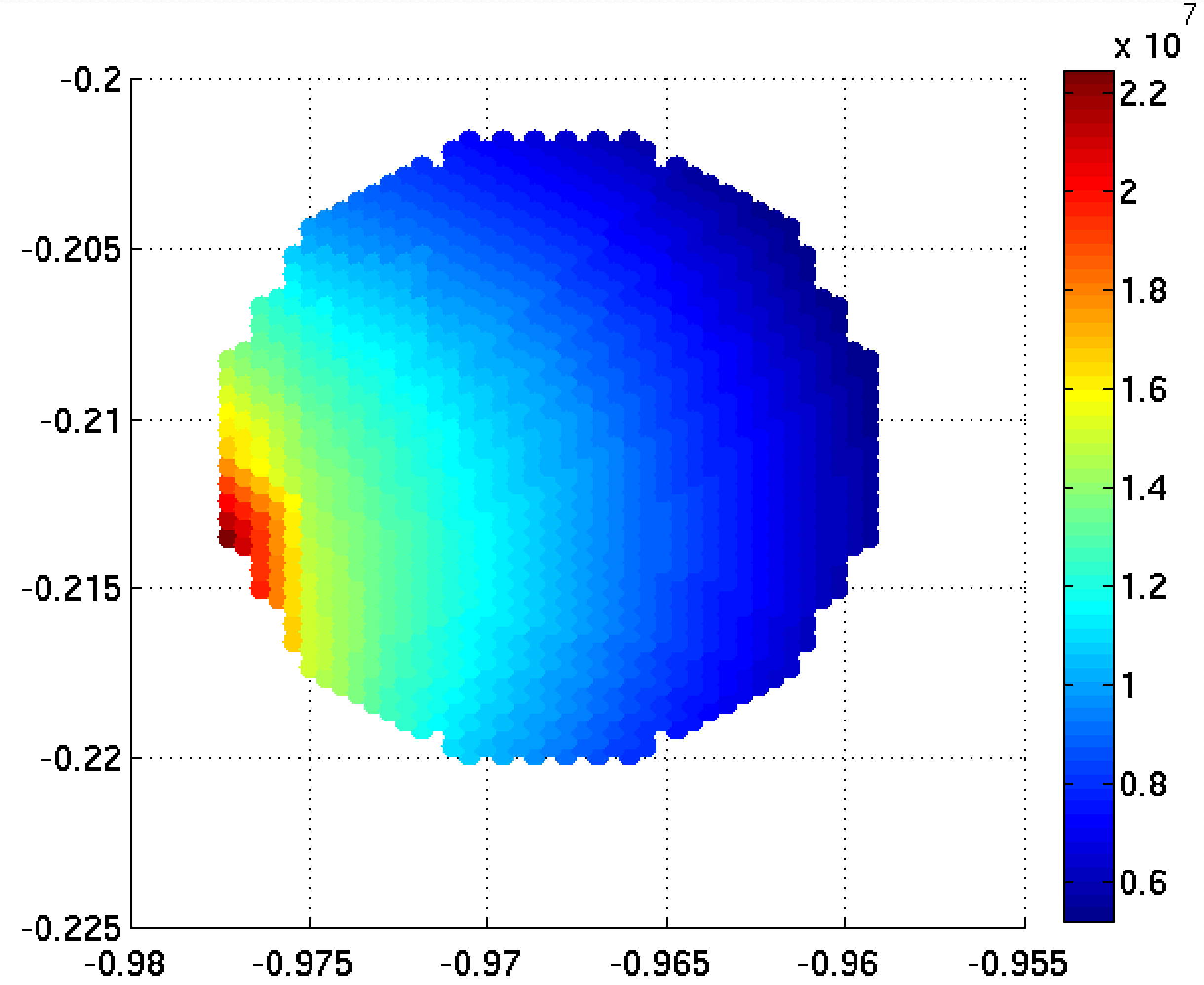
# Solar radio burst in front

- Another example of solar radio burst when the Sun is in front of SMOS is in March 7, 2011 .
- Again, the solar radio bursts detected by SMOS are well aligned with those of the Sun flux from radio-telescope



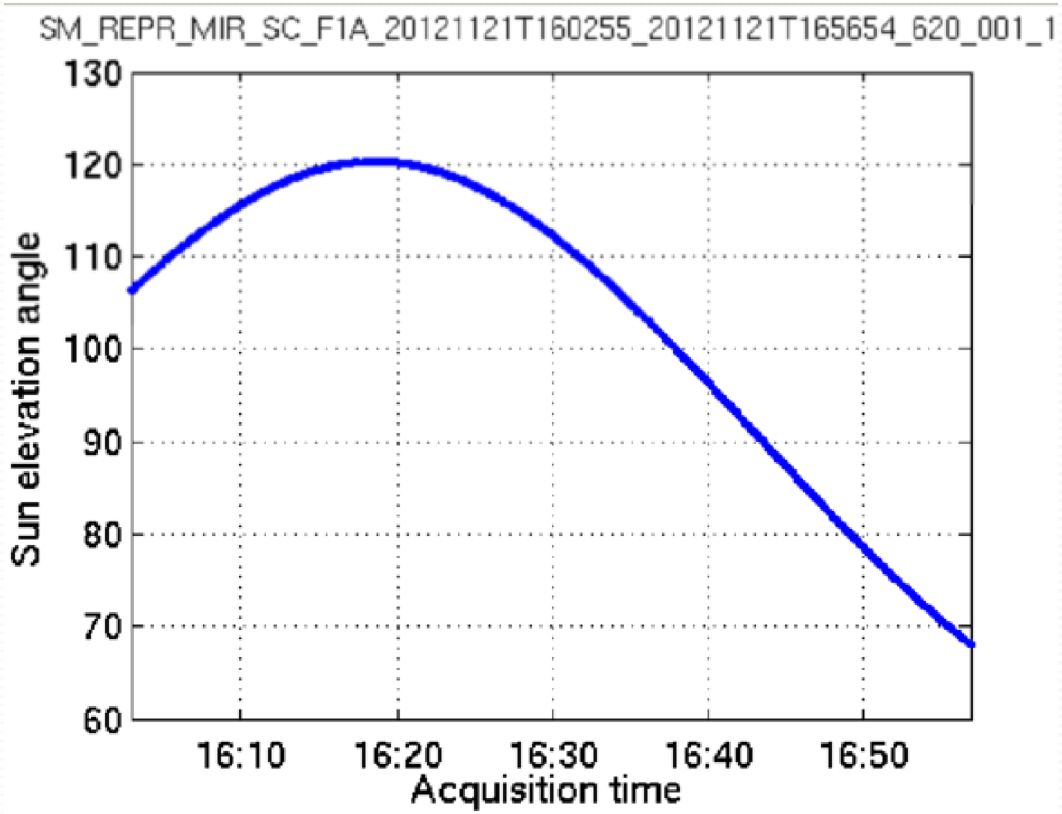
# Solar radio burst in front

- For the solar burst at 20h:35, its maximum is identified by radio-telescope as near the limb.
- This is also confirmed by SMOS by estimating the Sun BT within the Sun disk, and then interpolating them over a very fine grid.



# Solar radio burst in the back

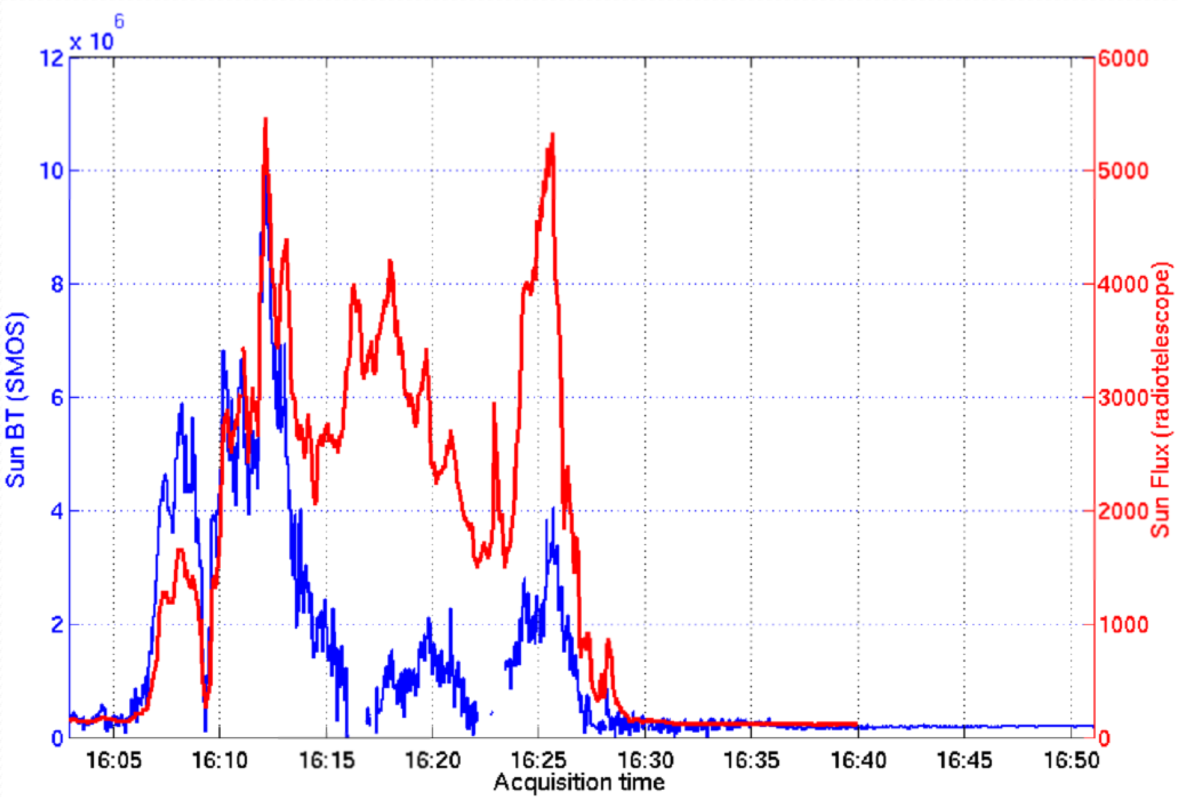
- We have a Solar radio burst in November 21, 2012 at 16:15 (UTC).
- This burst happened when the Sun was in the back of SMOS and for high elevation angle (above 120º)
- At such elevation angles, the Sun signal to noise ratio is very small within the visibilities, and normally the Sun BT is not well estimated.



RDIS conseils

# Solar radio burst in the back

- In this example, we can distinguish easily the peak at 16:15 UTC identifying the presence of a Solar radio burst.
- Also, the variation of the Sun BT is in line with that obtained by radio-telescope
- This example shows that even though the Sun BT in the back for high Sun elevation angles are randomly distributed and far from the expected values for quiet Sun,  we can still manage to detect Solar radio bursts.



# Conclusions

- A dedicated Sun BT processor has been developed as part of the Solar Flare project with an improved Sun BT algorithm.
- Solutions for two problems in the SMOS products have been proposed:
  - To improve the estimation the Sun BT for low elevation angles, we propose to replace the current antenna patterns in the ($\boldsymbol{\xi},\boldsymbol{\eta}$) grid by the angular antenna patterns in the **($\theta,\varphi$)** grid.
  - To reduce the linear stripes and smoothen the variation of the Sun BT, we propose to use a discrete inverse Fourier transform over the exact Sun position instead of an inverse Fast Fourier transform and then calculating the Sun BT over the closest grid point to the Sun position.
- The new Sun BT algorithm has also been extended to estimate the Sun BT for the entire Sun disc.
- The new algorithm will improve the quality of the data by smoothing its temporal variation but also the quantity of the data by allowing an almost full retrieval of the Sun BT without the need of filtering the data for low elevation angles as done with the SMOS operational products.

RDIS conseils

SMOS

**Thank you for your attention.**
**Questions?**

# Annex

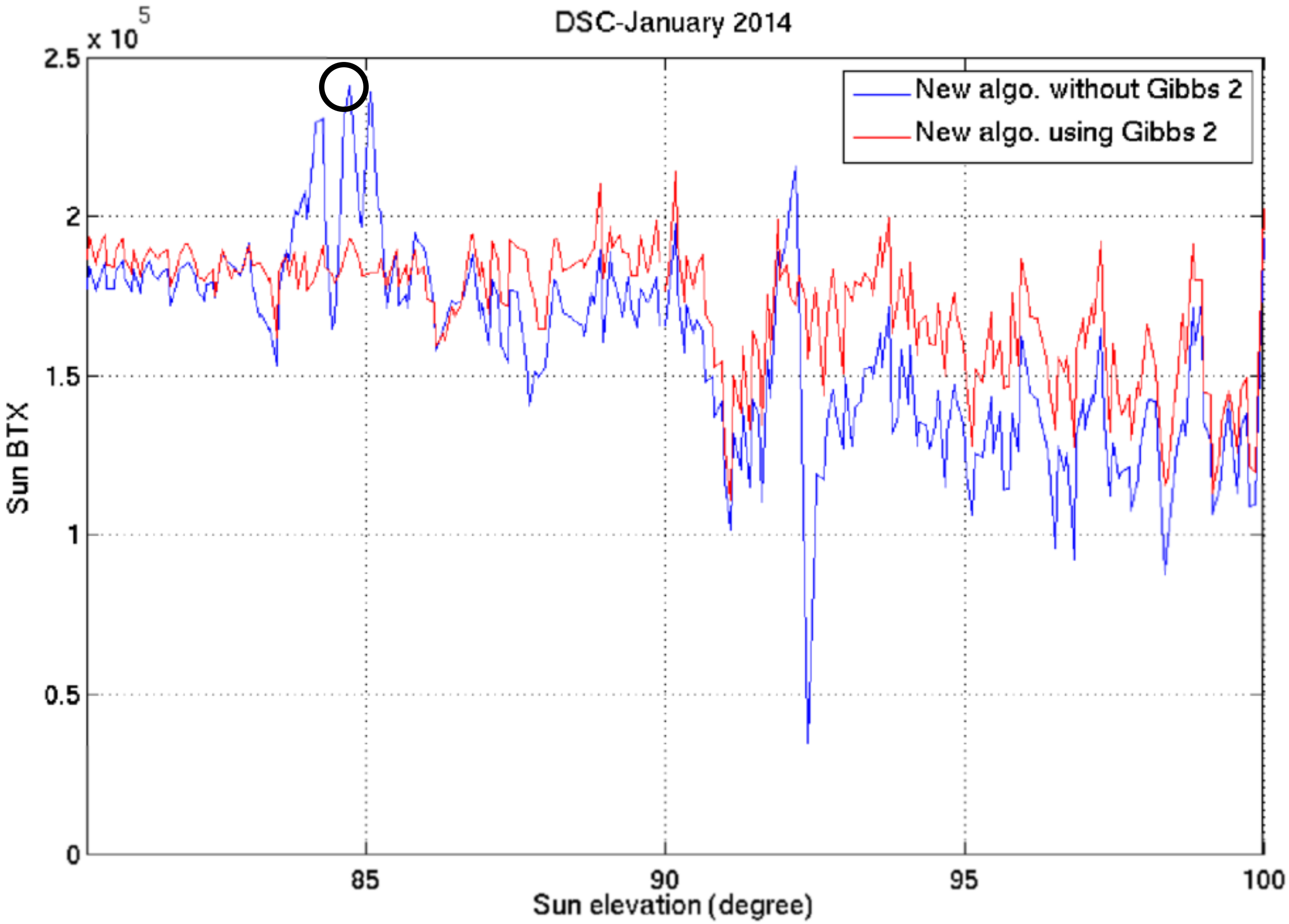
# Impact of Gibbs 2

- The Gibbs 2 algorithm consist of simulating an artificial scene close to the observed one and remove its contribution from the visibilities.
- We use a Fresnel model over ocean and an estimated constant BT over Land
- We also use a dynamic Land/Ocean/Ice Mask where the Sea Ice pixels are considered as Land.
- By this, we reduce as much as possible the Land/Ocean/Ice transition and thus reducing the errors that can occur in the tem "$\boldsymbol{T_{avg}}$" of the Sun BT formulation

$$T_{Sun} = \frac{TF^{-1}(V)_{(\xi_s,\eta_s)} - T_{avg}}{TF^{-1}(V_{1K})_{(\xi_s,\eta_s)}}$$

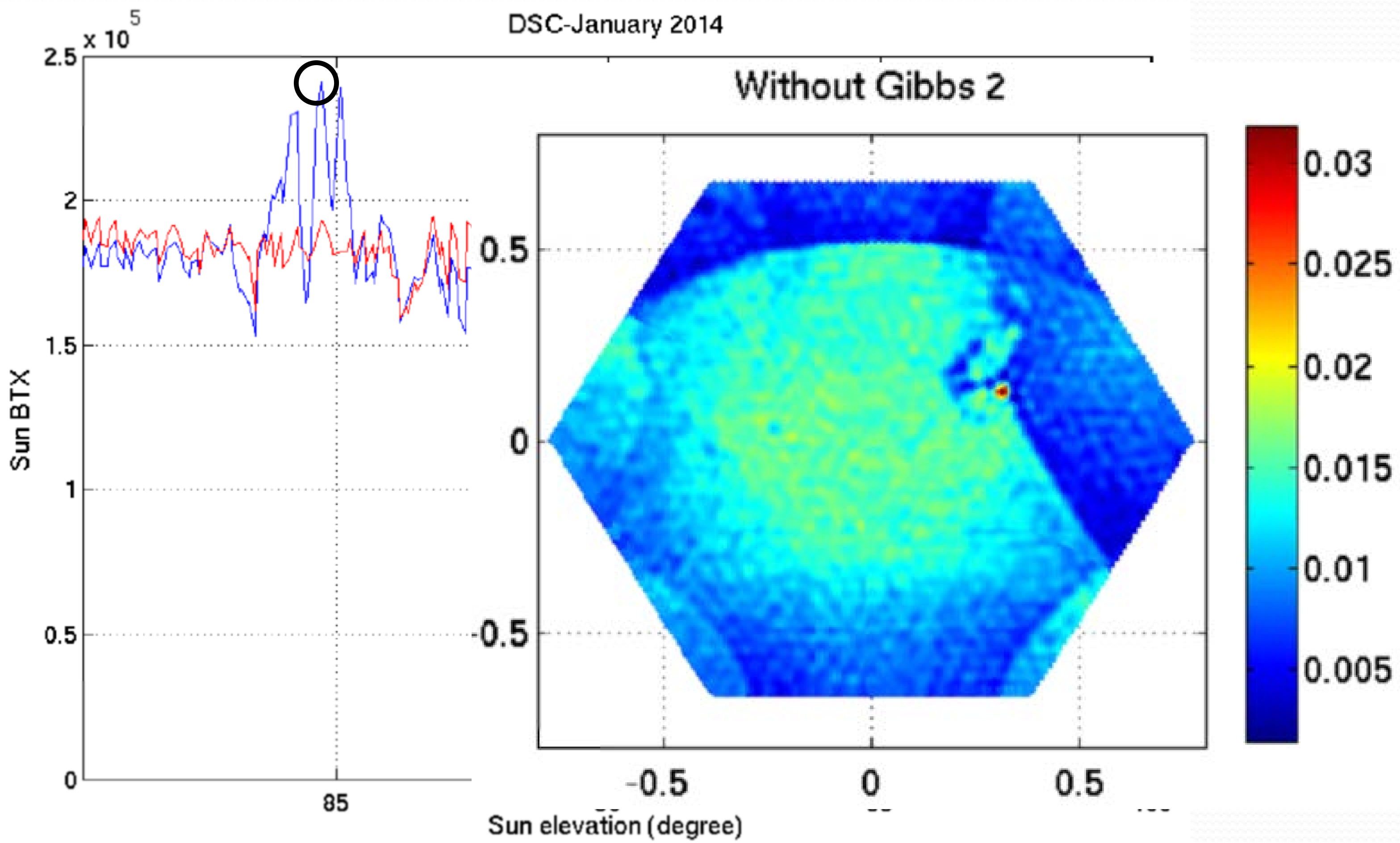
# Impact of Gibbs 2

- Some examples of using or not the Gibbs 2 algorithm before the estimation of the Sun BT
- **Example (1)**



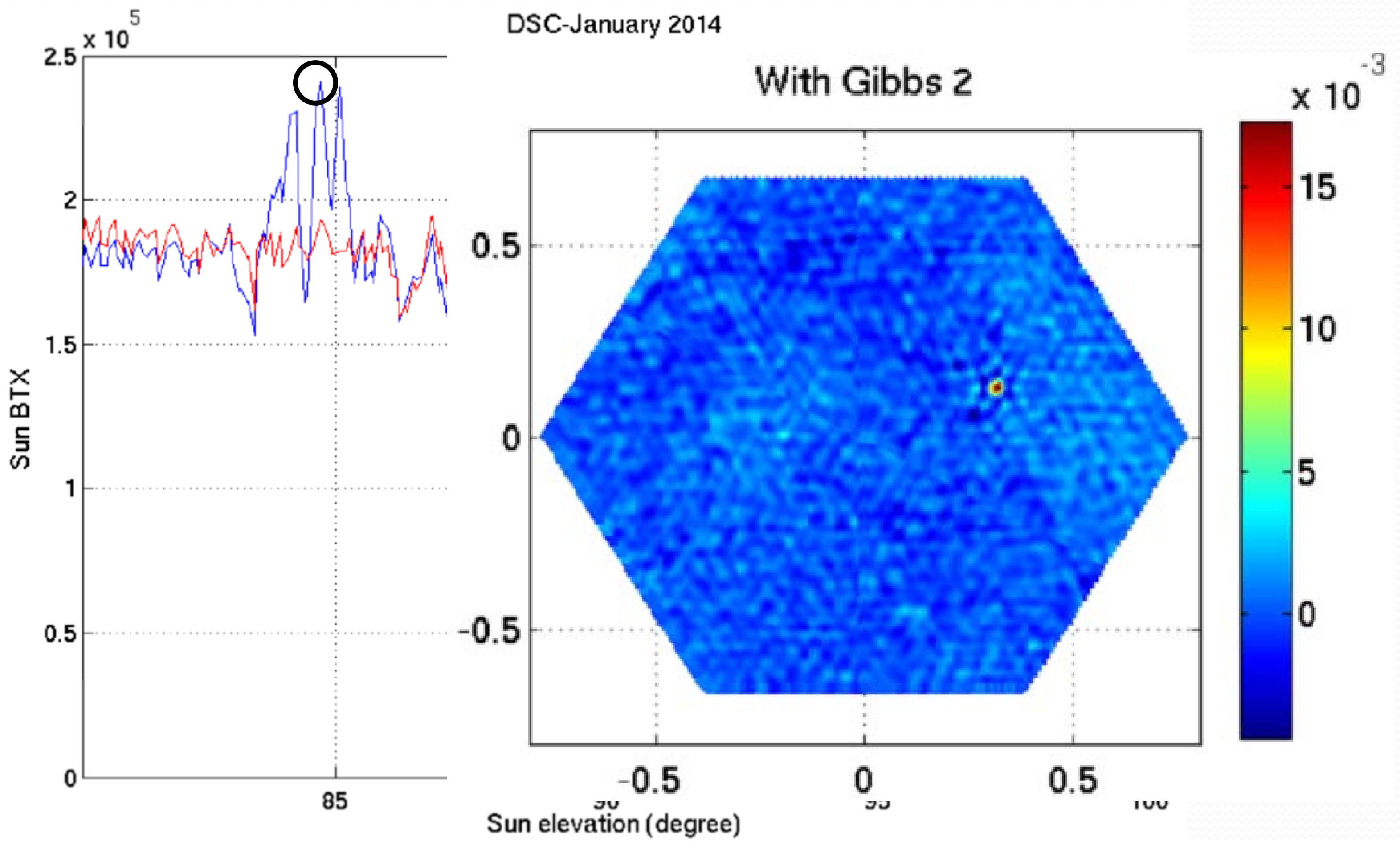
# Impact of Gibbs 2

- Some examples of using or not the Gibbs 2 algorithm before the estimation of the Sun BT
- **Example (1)**



# Impact of Gibbs 2

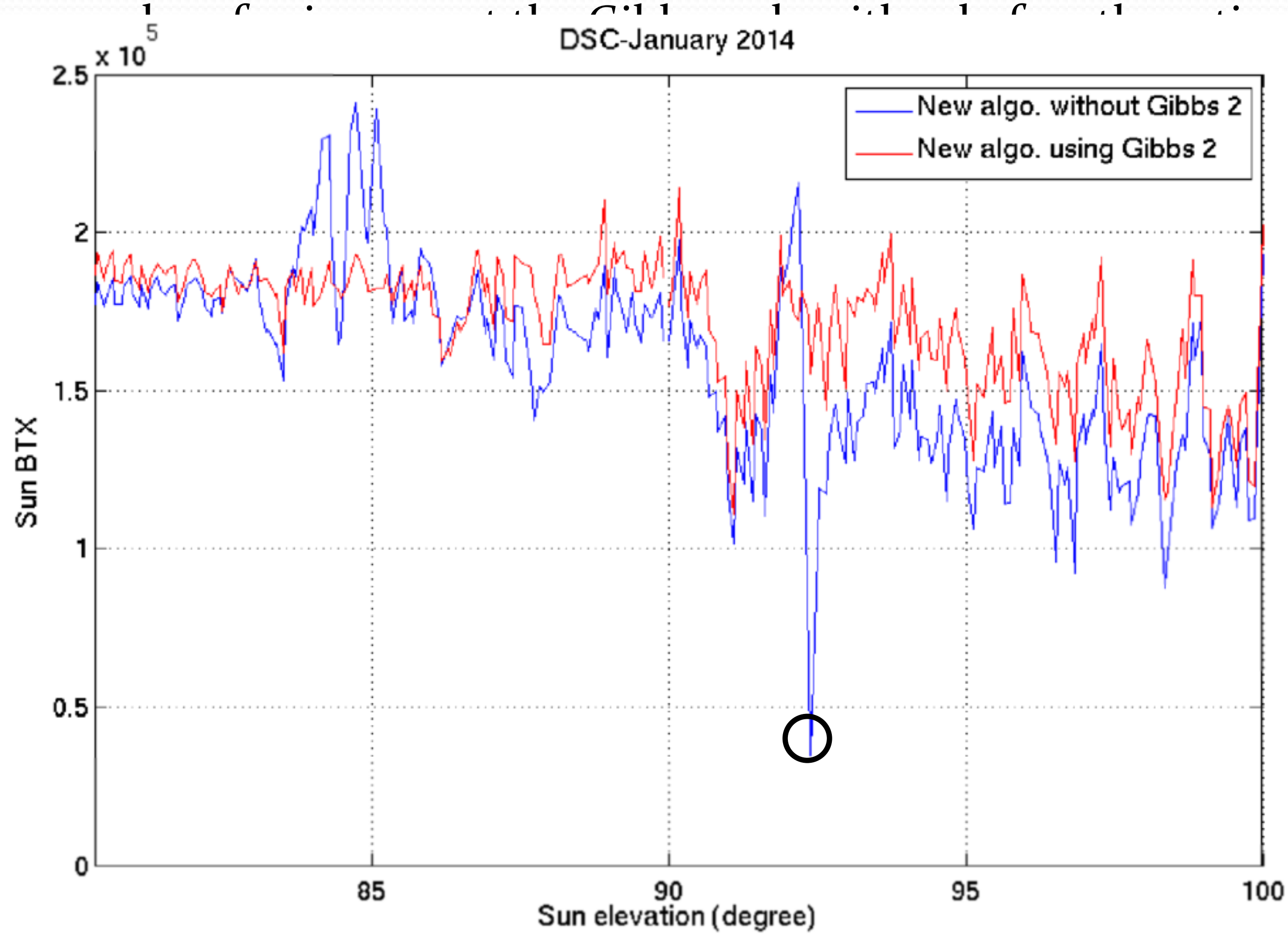
- Some examples of using or not the Gibbs 2 algorithm before the estimation of the Sun BT
- **Example (1)**



# Impact of Gibbs 2

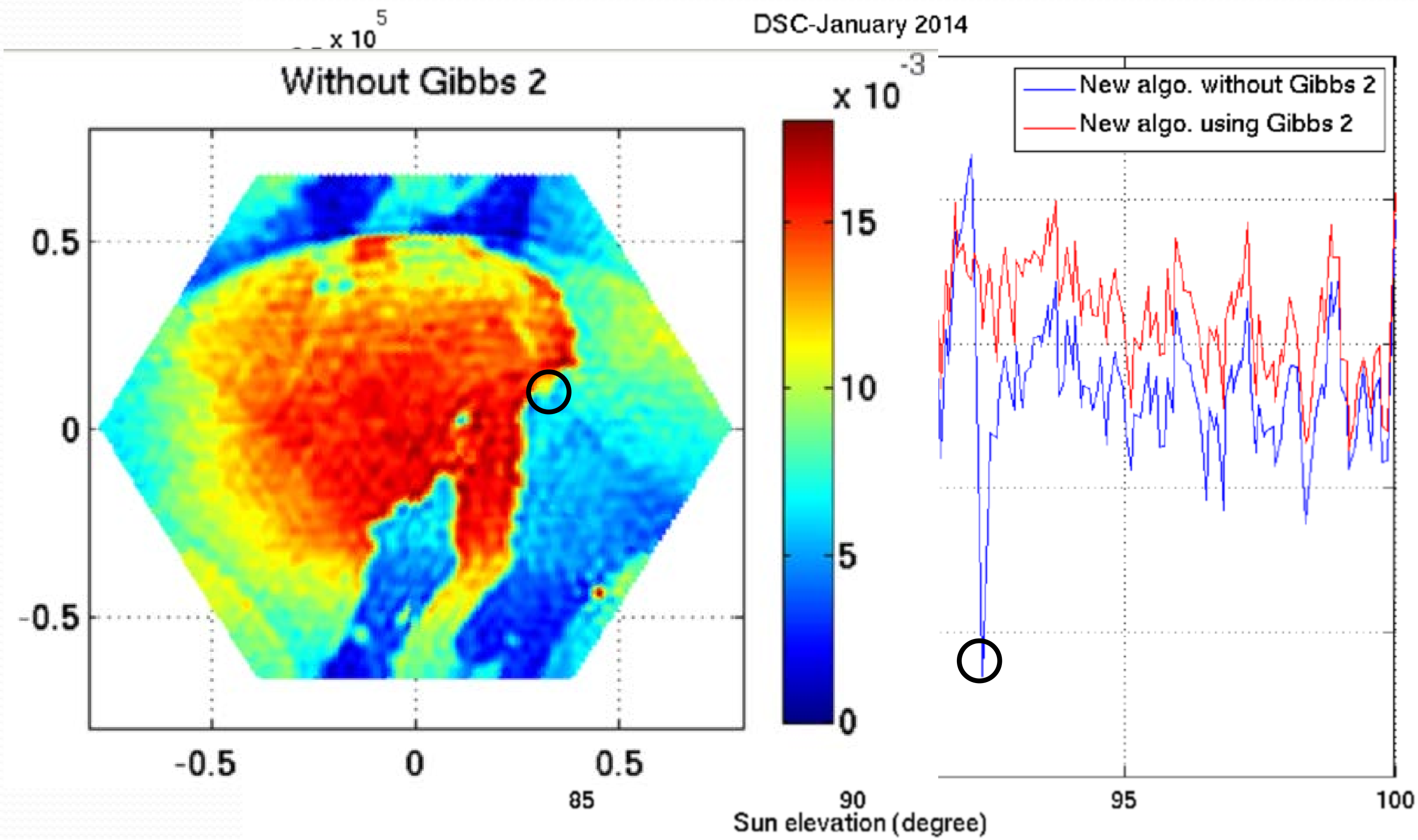
RDIS conseils

- The Gibbs 2 algorithm consist of simulating an artificial scene close to the obsesrved one and remove its contribution from the visibilities.
- We use a Fresnel model over ocean and an estimated constant BT over Land Some … tion of the Sun B…
- **Exam…**



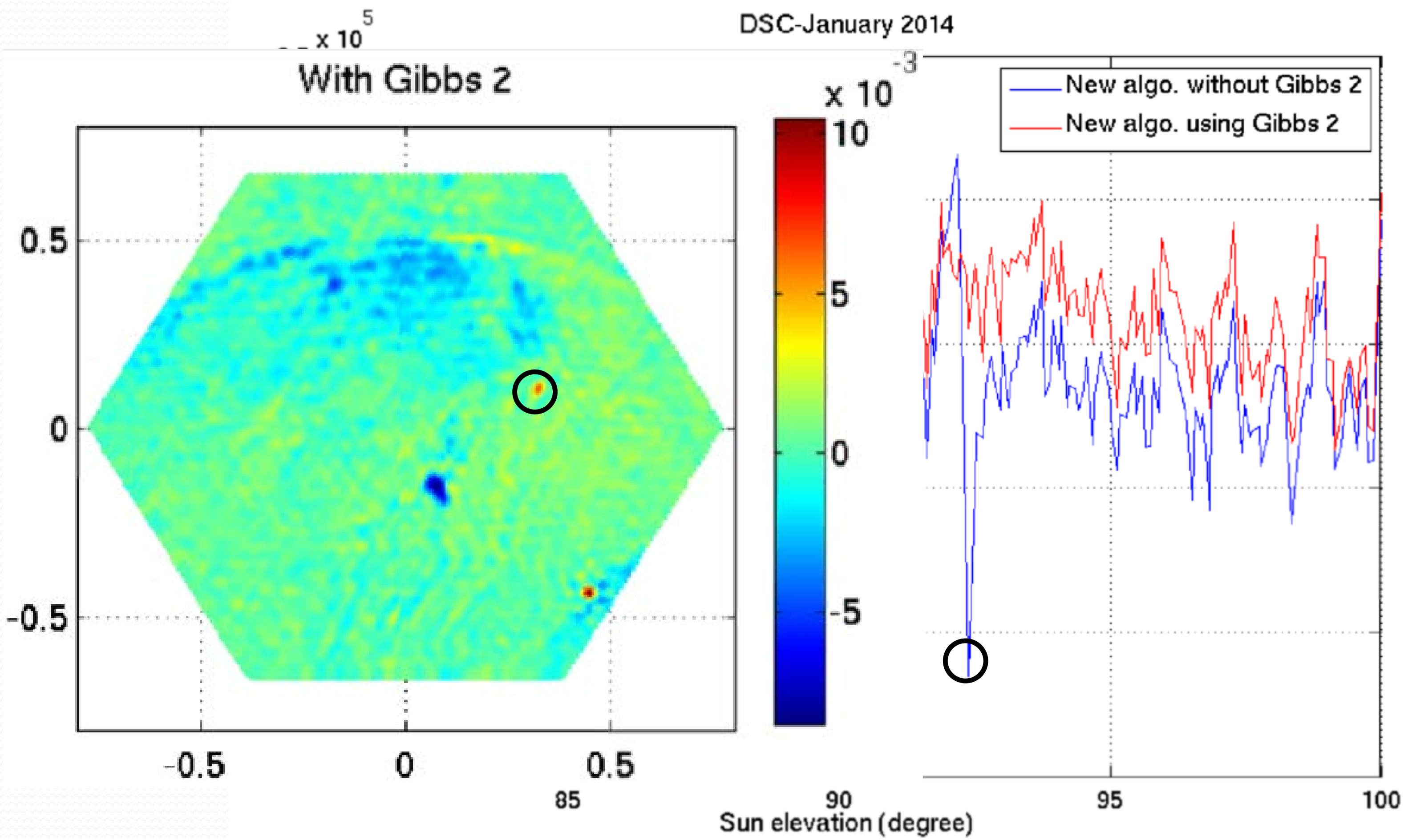
# Impact of Gibbs 2

- Some examples of using or not the Gibbs 2 algorithm before the estimation of the Sun BT
- **Example (1)**



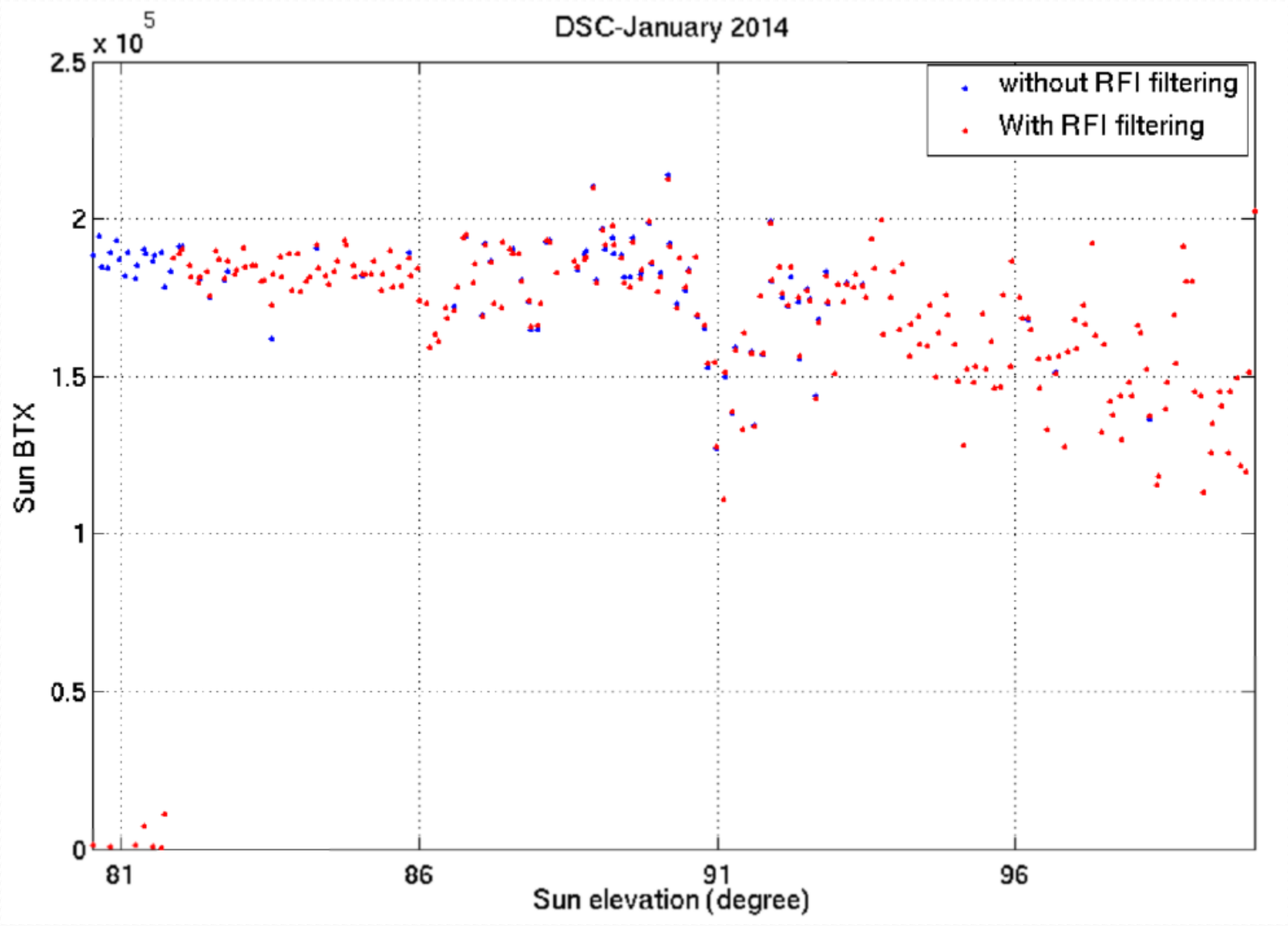
# Impact of Gibbs 2

- Some examples of using or not the Gibbs 2 algorithm before the estimation of the Sun BT
- **Example (1)**



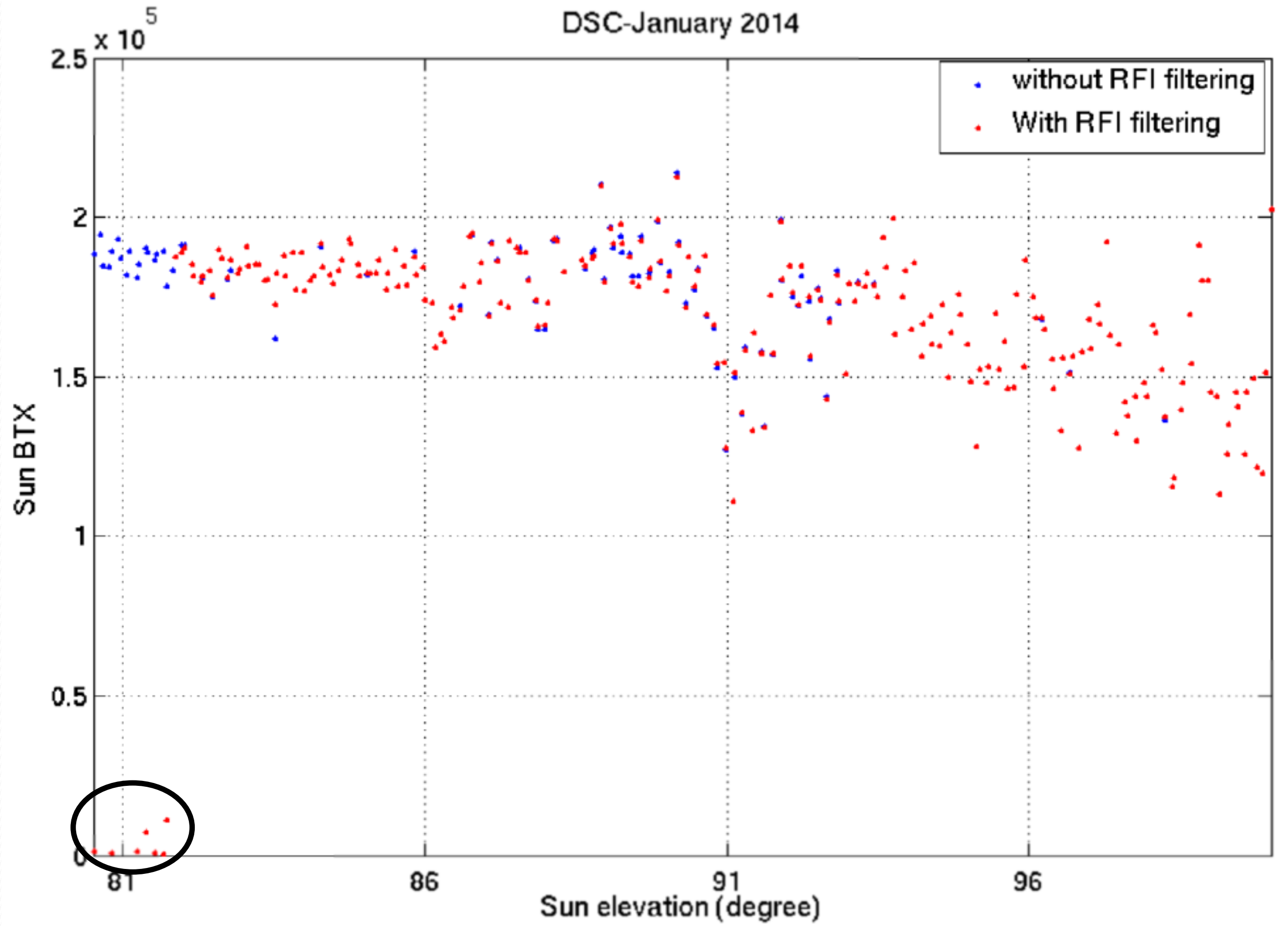
# Impact of RFI

- Examples of using or not the RFI filtering before the estimation of the Sun BT
- **Example (1): RFI source close to the Sun**



# Impact of RFI

- Examples of using or not the RFI filtering before the estimation of the Sun BT
- **Example (1): RFI source close to the Sun**



# Impact of RFI

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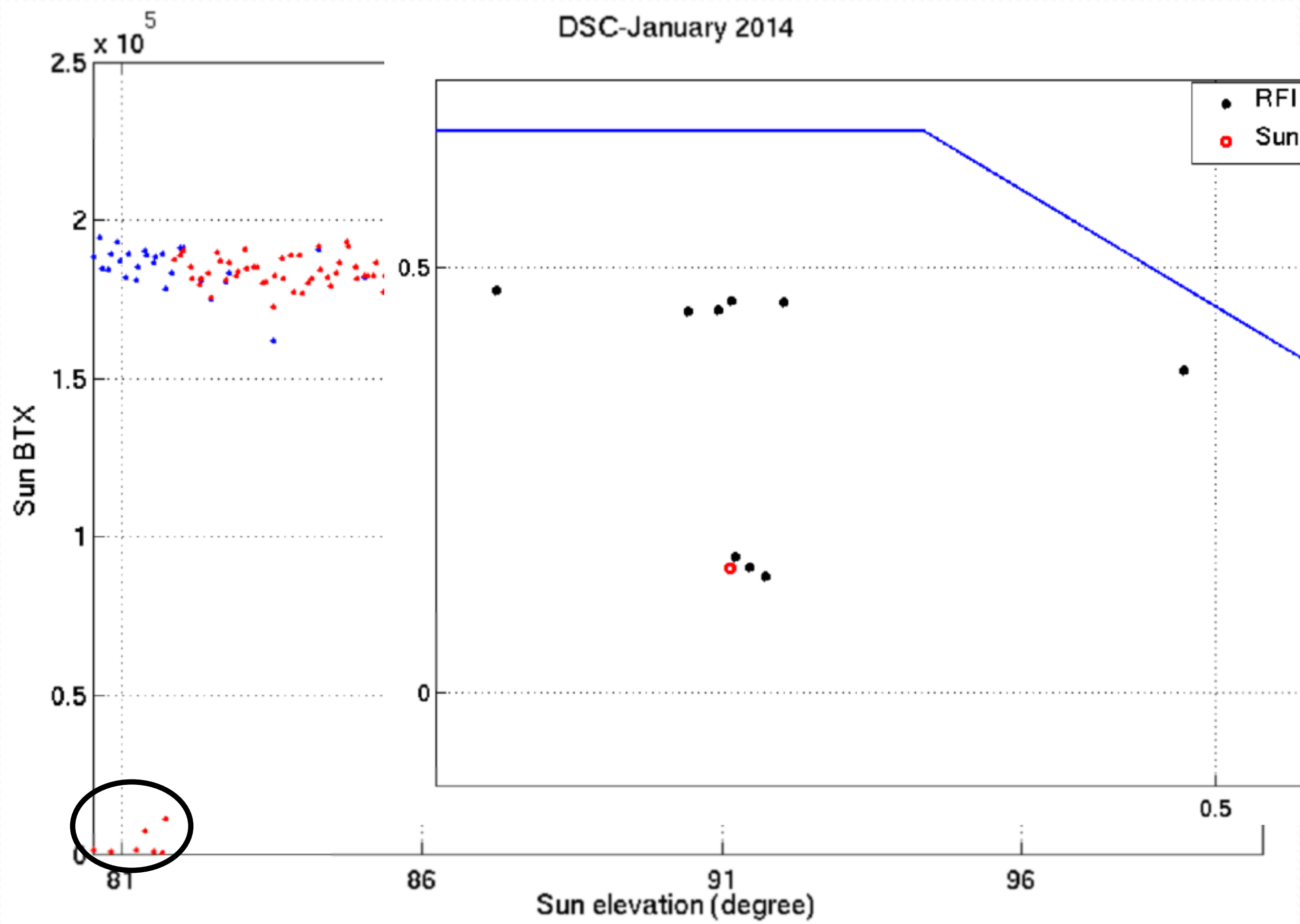

# Sun BT for High Elevation Angles in the Back

- The Sun BT (type 3 algorithm) is estimated using the following equation:

$$T_{Sun} = \frac{TF^{-1}(V)_{(\xi_s,\eta_s)} - T_{avg}}{TF^{-1}(V_{1K})_{(\xi_s,\eta_s)}}$$