Universidade Federal do Rio de Janeiro
Universidade Federal Fluminense
Pierre Auger Observatory

Galactic calibration and its long-term stability for the Auger Engineering Radio Array

Diego Correia for the Pierre Auger Collaboration

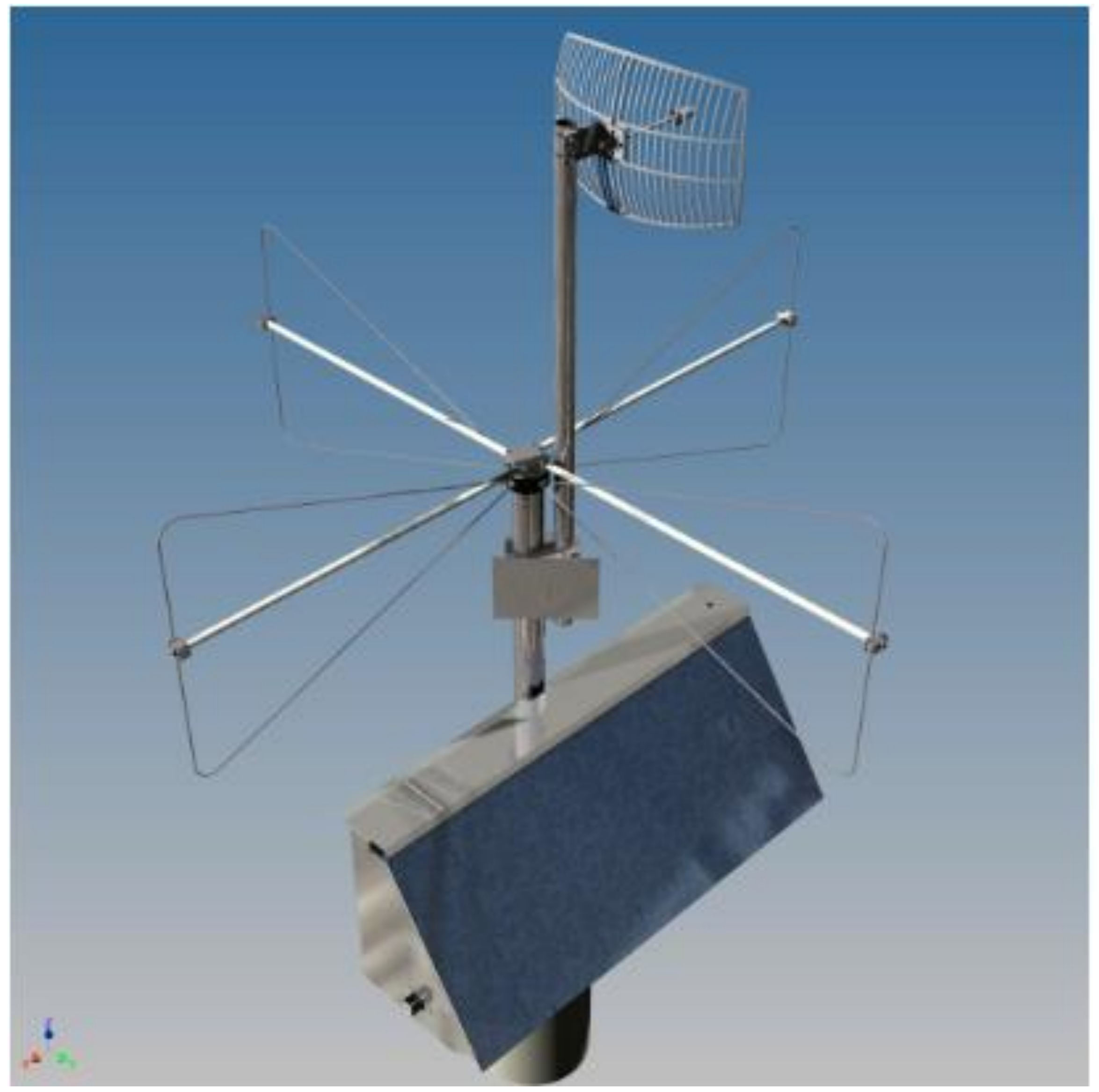
ARENA 2024

Speaker: Tim Huege

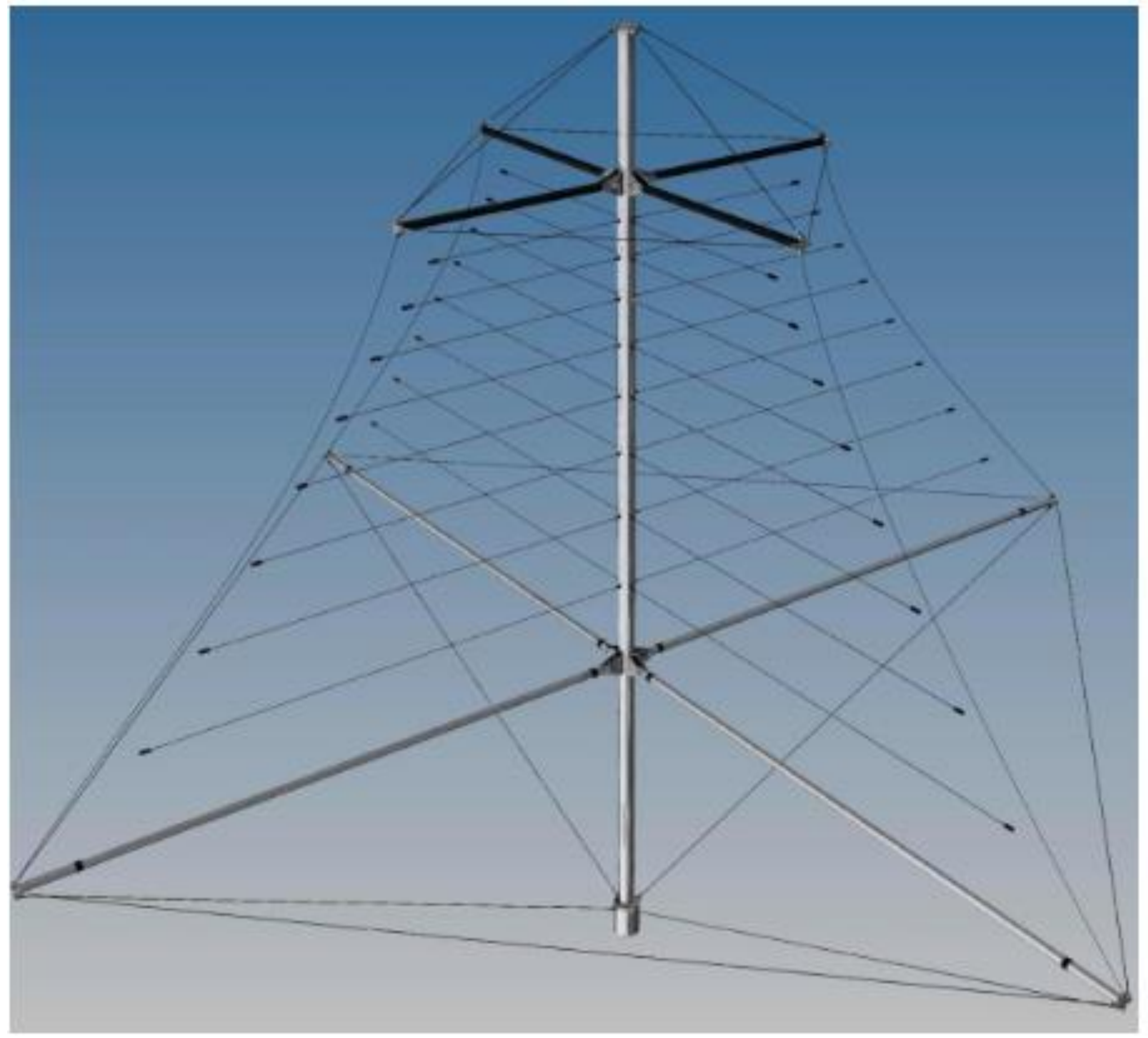
AERA - Auger Engineering Radio Array

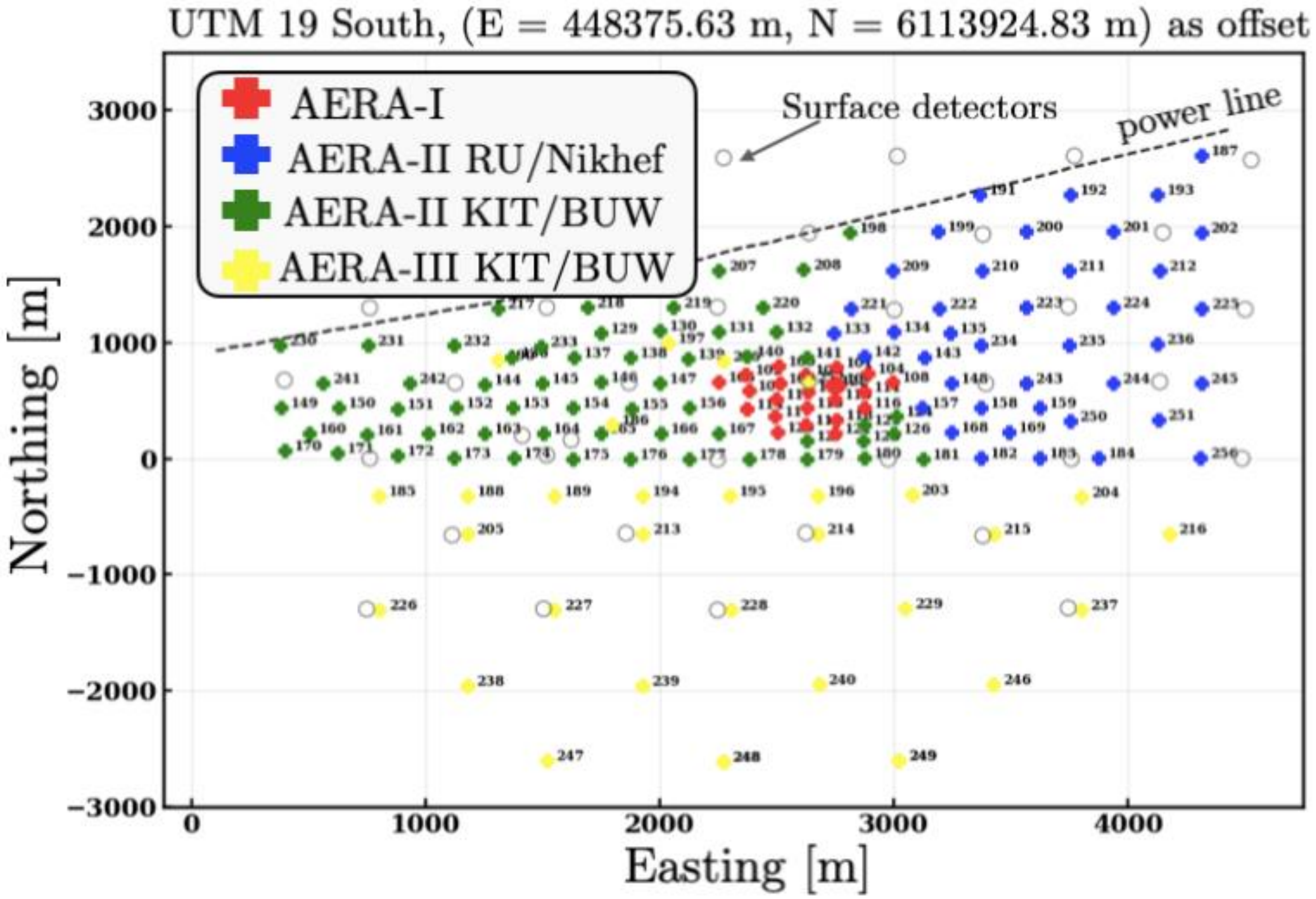
- AERA is part of the Pierre Auger Observatory
- The array spans 17 km^2 and comprises 153 autonomous radio-detector stations (RDS) operating in a frequency range of 30 MHz to 80 MHz
- 2 polarizations: East-West and North-South relative to magnetic North
- The array is composed of two types of antennas: LPDA and Butterfly

Butterfly antennas



LPDA antennas





Overview

- In this work, we use a technique based on the Galaxy's radio emission to calibrate the antennas.

  ➔ we use traces triggered periodically

Preprocessing of data

- **Narrowband RFI removal**

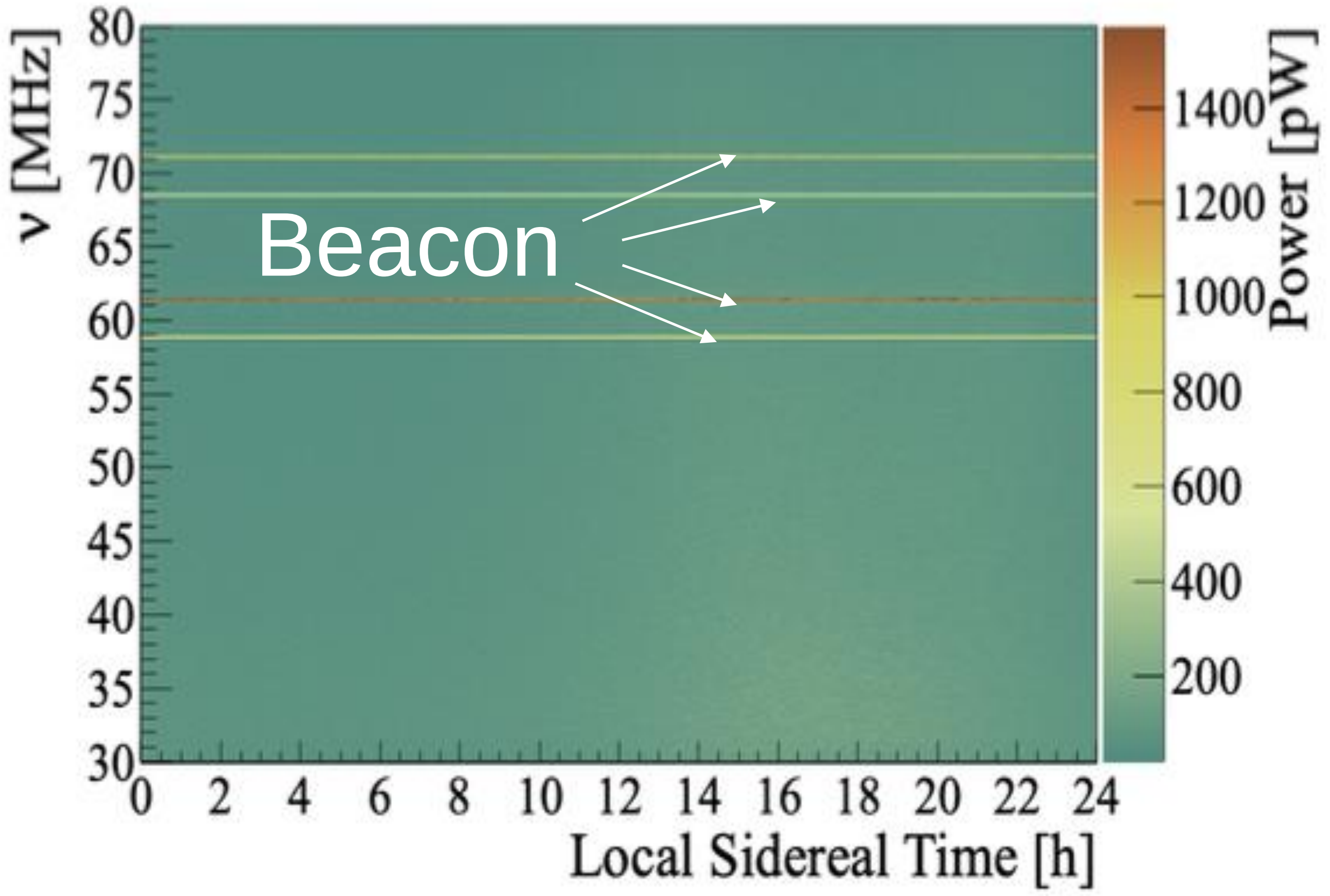
➔ We identify and remove narrowband RFI

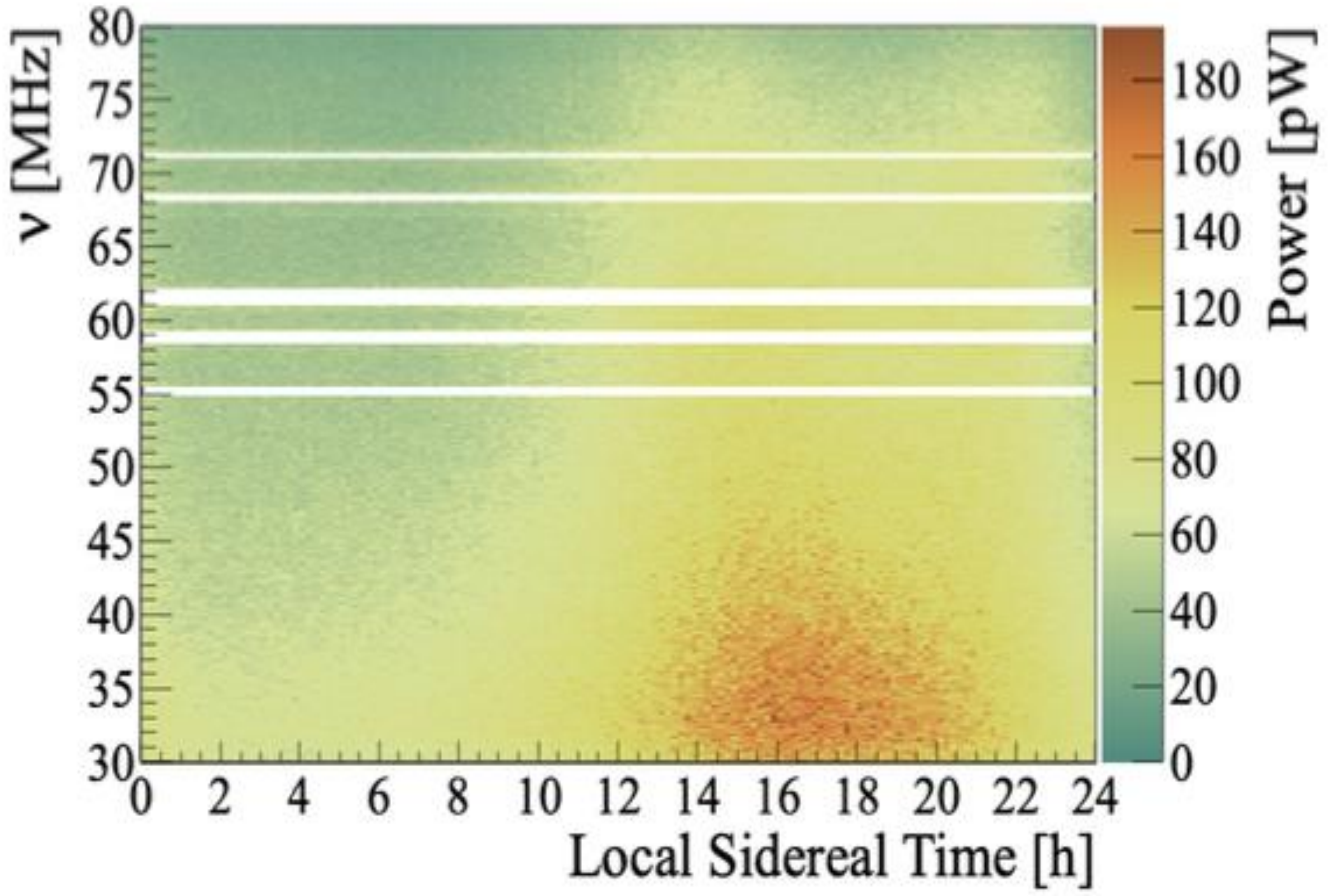
- **Broadband RFI removal**

➔ To remove broadband RFI we use a LST-dependent threshold approach

➔ Threshold as a function of the LST is determined for each antenna, month and channel.

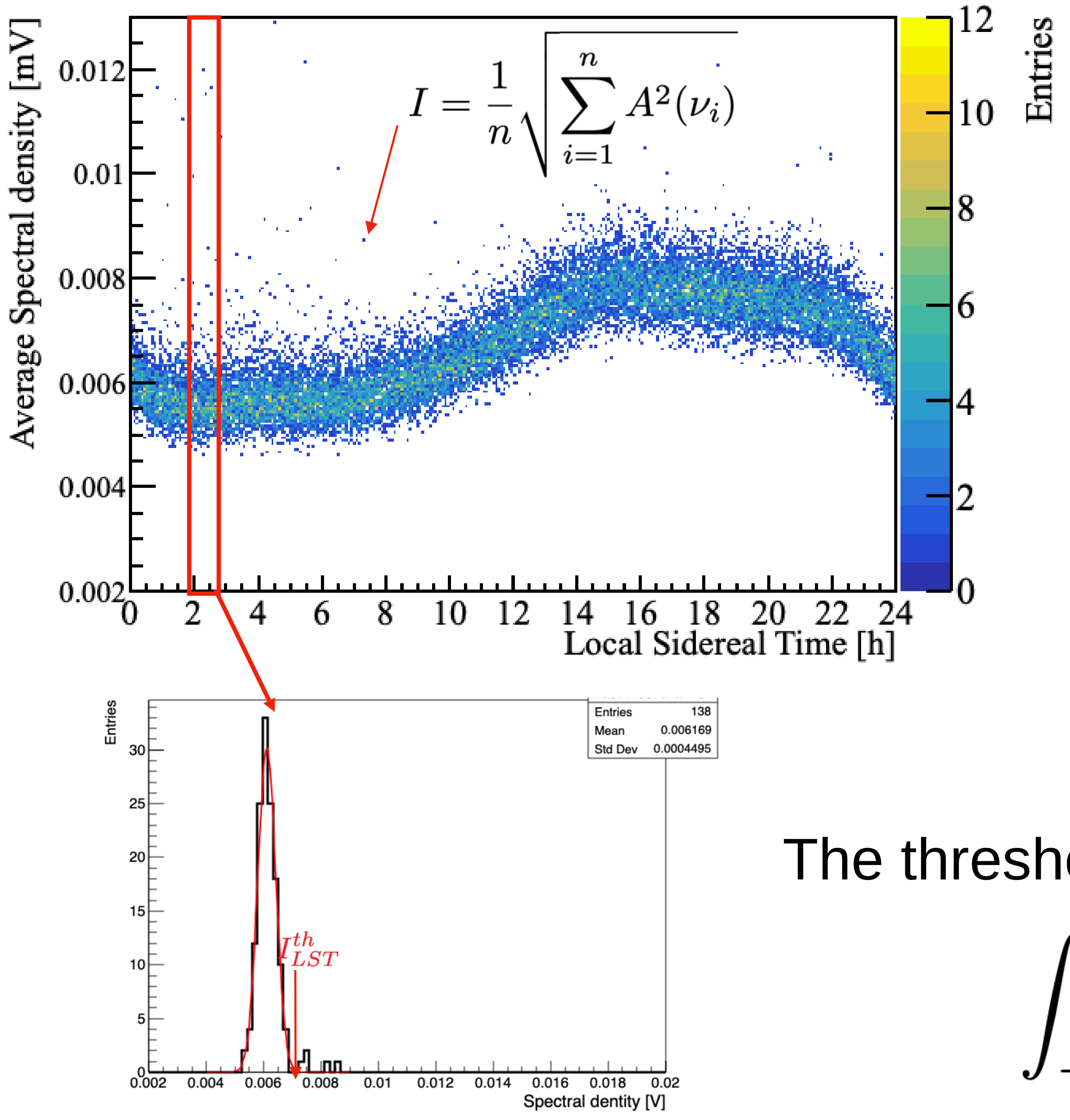
Dynamic average frequency spectrum as a function of LST

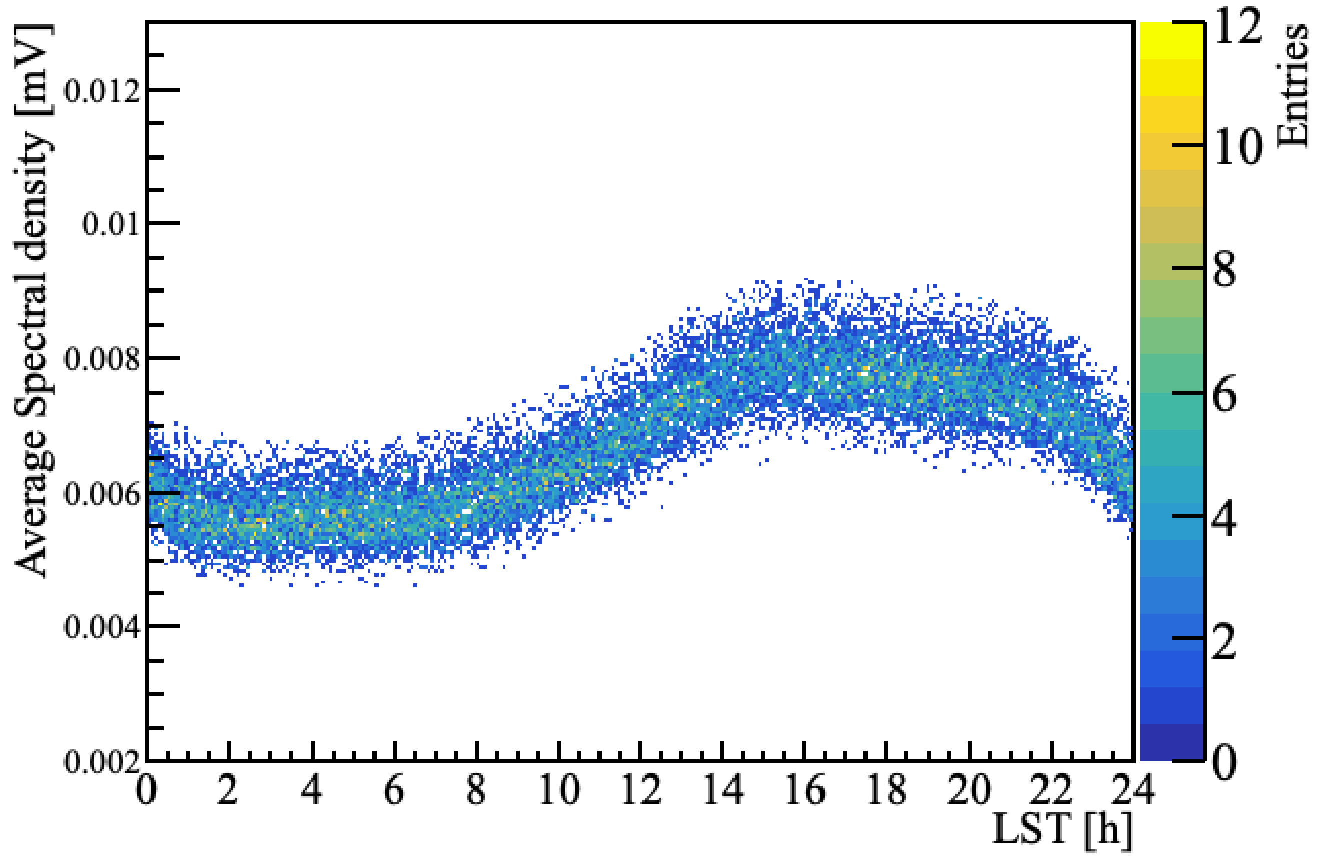




Before removing RFI

After removing RFI





The threshold is defined according to the equation

$$\int_{-\infty}^{I^{th}_{LST}} G(I;\bar{I},\sigma_I)dI = 0.9973$$

Radio sky model

Maps produced at 50 MHz showing temperature ratio model/average

- For the frequency range of the AERA stations the **background signal is dominated by Galactic emission** and the total expected power to be received by the antenna is calculated as

$$P_{\rm sky}(t,\nu) = \frac{Z_0}{Z_{\rm L}} \frac{k_B}{c^2} \int_{\Omega} \nu^2 T_{\rm sky}(\nu,\alpha,\delta) |H_e(\nu,\alpha,\delta)|^2 d\Omega$$

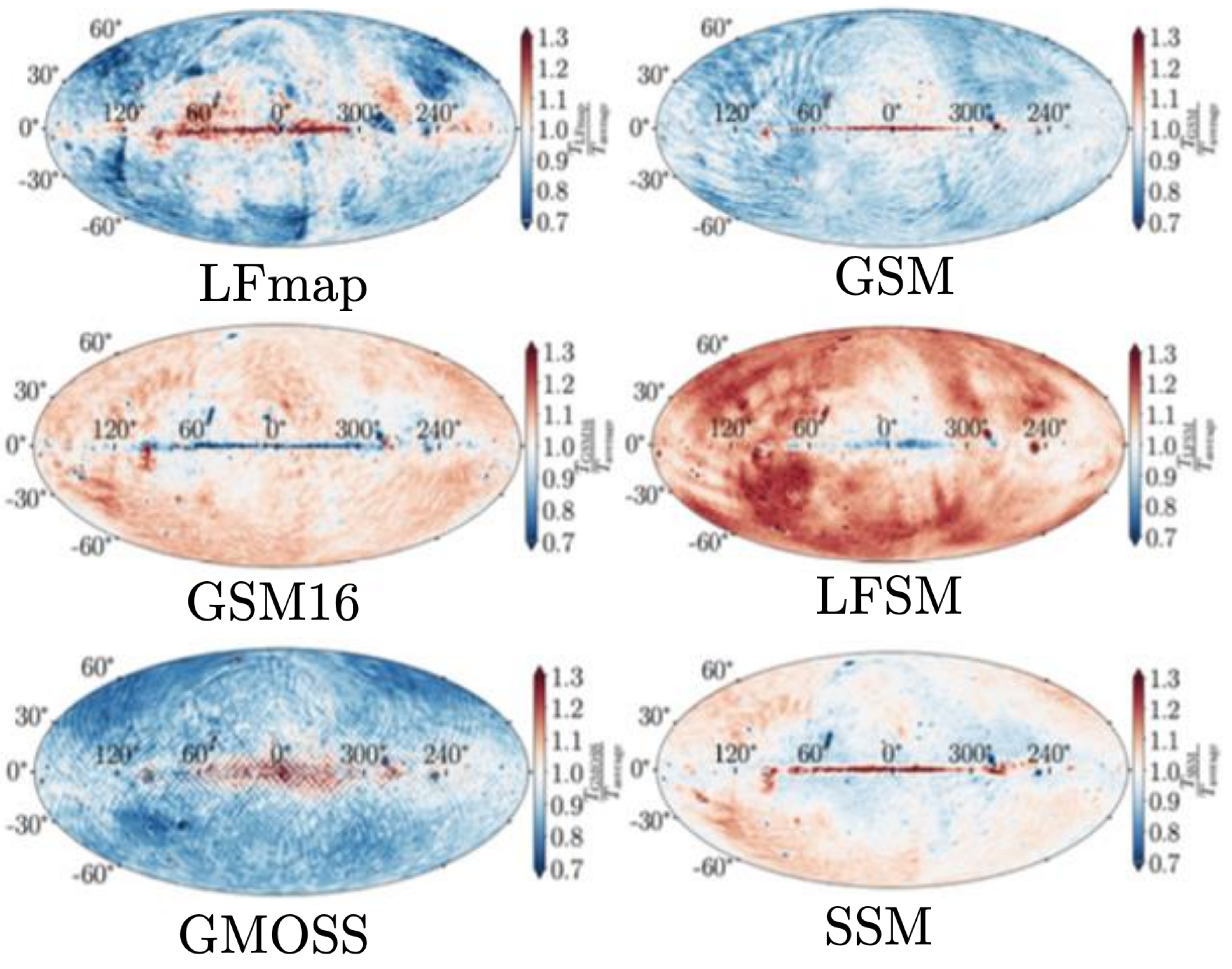
$T_{\rm sky}(\nu,\alpha,\delta)$

- There are different available models for the sky radio emission

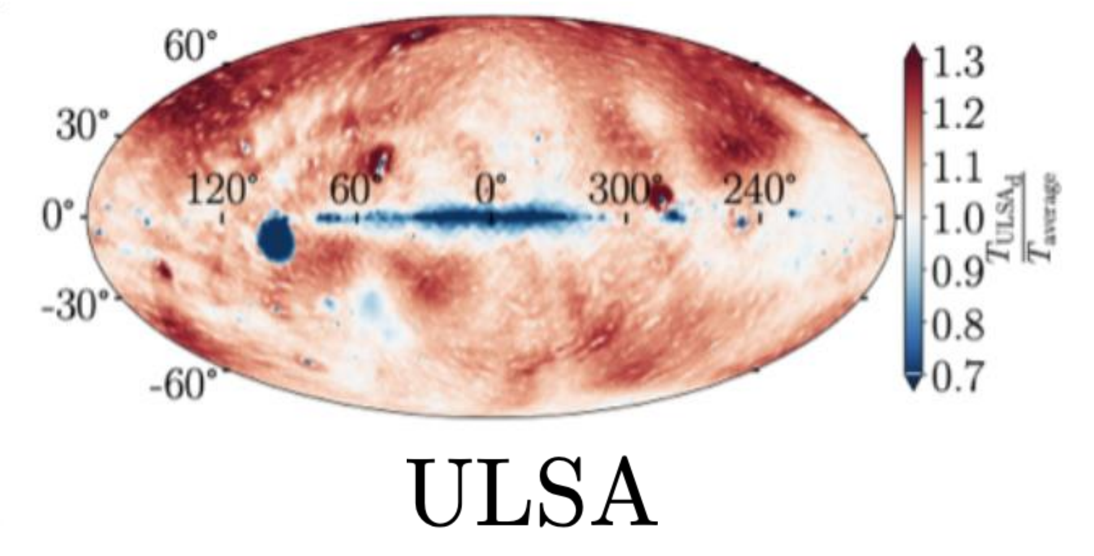
Vector Effective Length (VEL)

$$|H_e(\nu,\theta,\phi)|^2 = H_{e\theta}(\nu,\theta,\phi)^2 + H_{e\phi}(\nu,\theta,\phi)^2$$

- The Galactic calibration is performed by using the **simulated** VEL for Butterfly antennas and the **measured** VEL for LPDA antennas.



M Büsken, T Fodran, and T Huege. Uncertainties of the 30-408 MHz galactic emission as a calibration source for radio detectors in astroparticle physics. Astronomy & Astrophysics, 679:A50, 2023.



Radio sky model

Directional response of the Butterfly station at 45 MHz

- For the frequency range of the AERA stations the **background signal is dominated by Galactic emission** and the total expected power to be received by the antenna is calculated as

$$P_{\mathrm{sky}}(t,\nu) = \frac{Z_0}{Z_{\mathrm{L}}} \frac{k_B}{c^2} \int_{\Omega} \nu^2 T_{\mathrm{sky}}(\nu,\alpha,\delta) |H_e(\nu,\alpha,\delta)|^2 d\Omega$$

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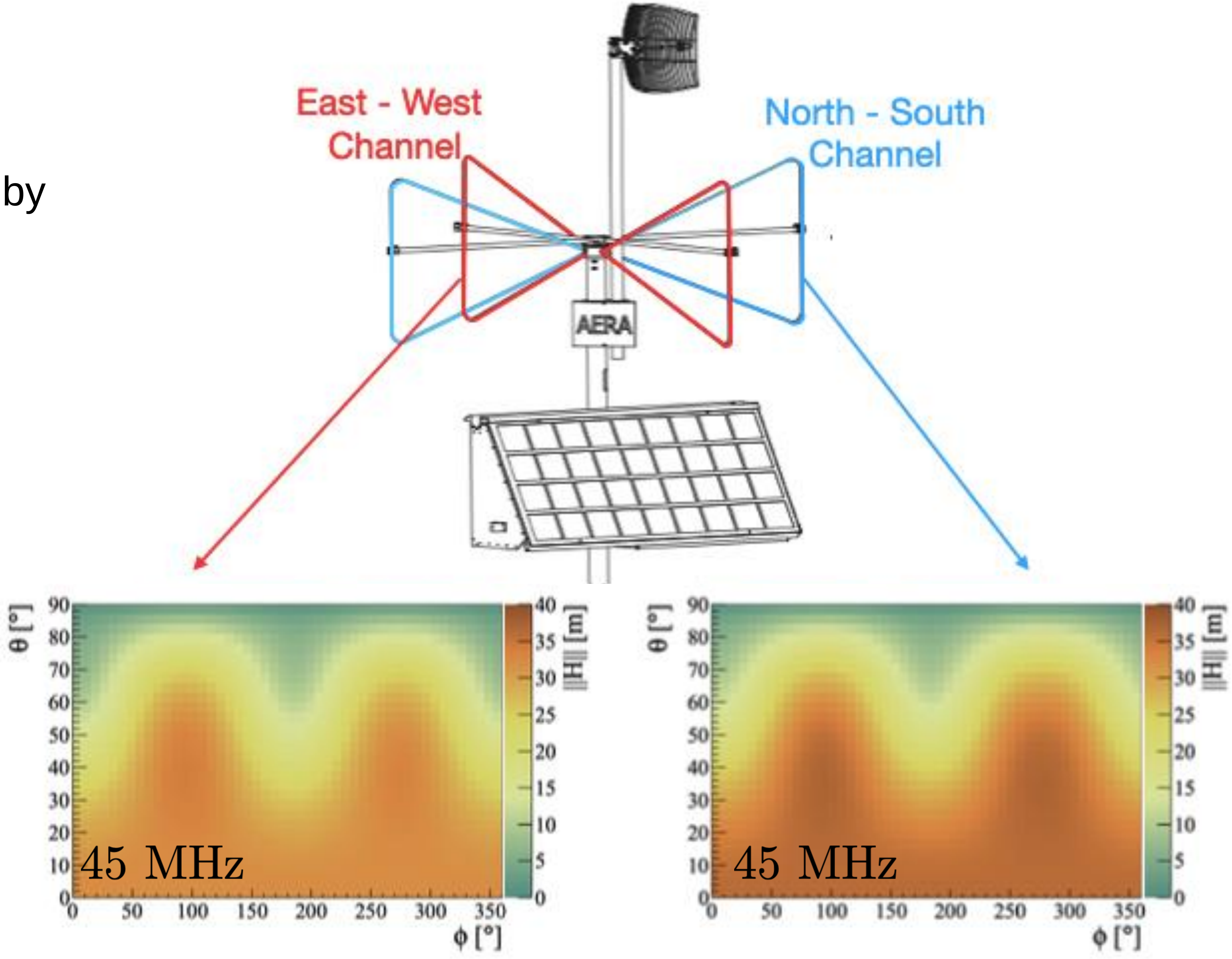

Radio sky model

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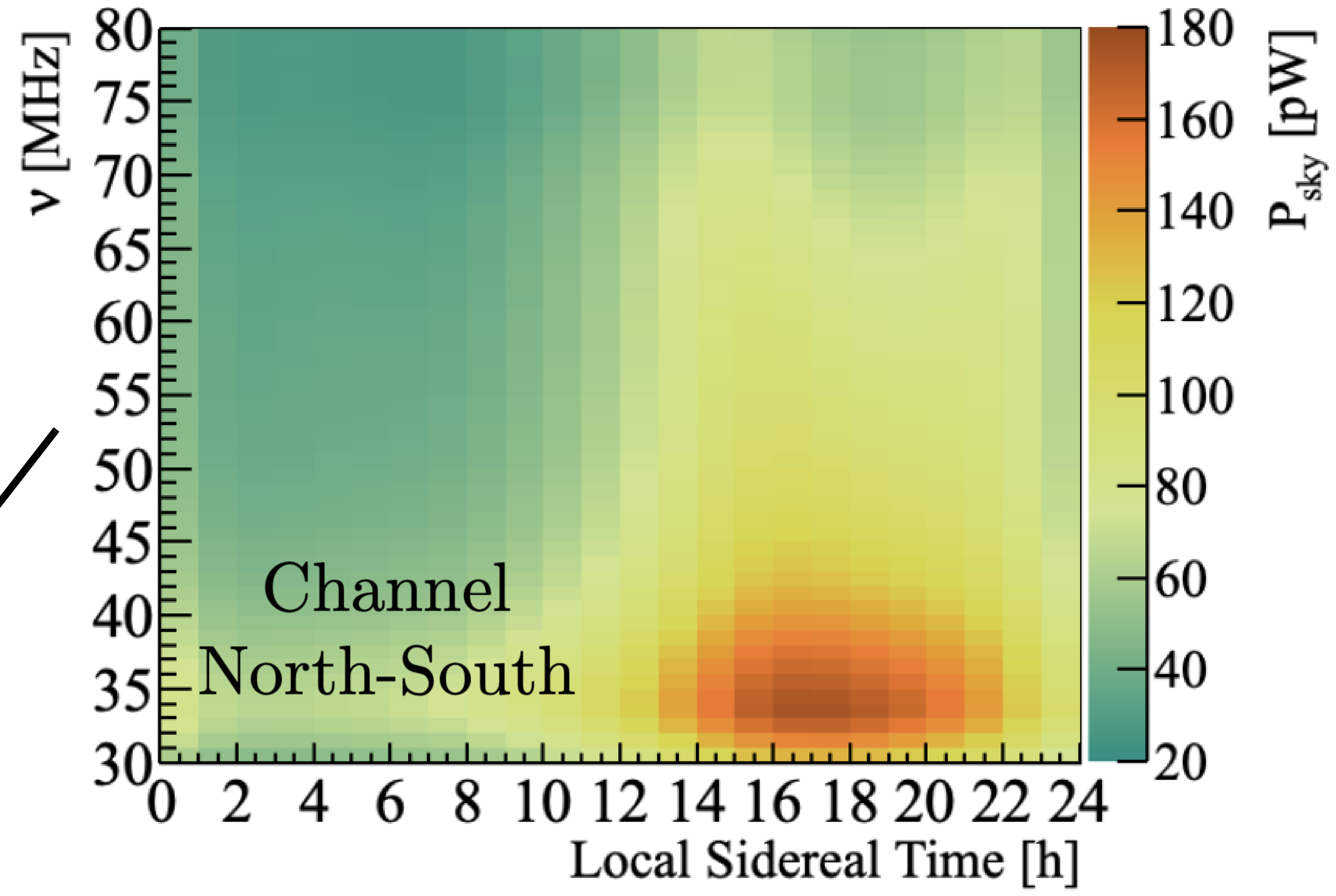
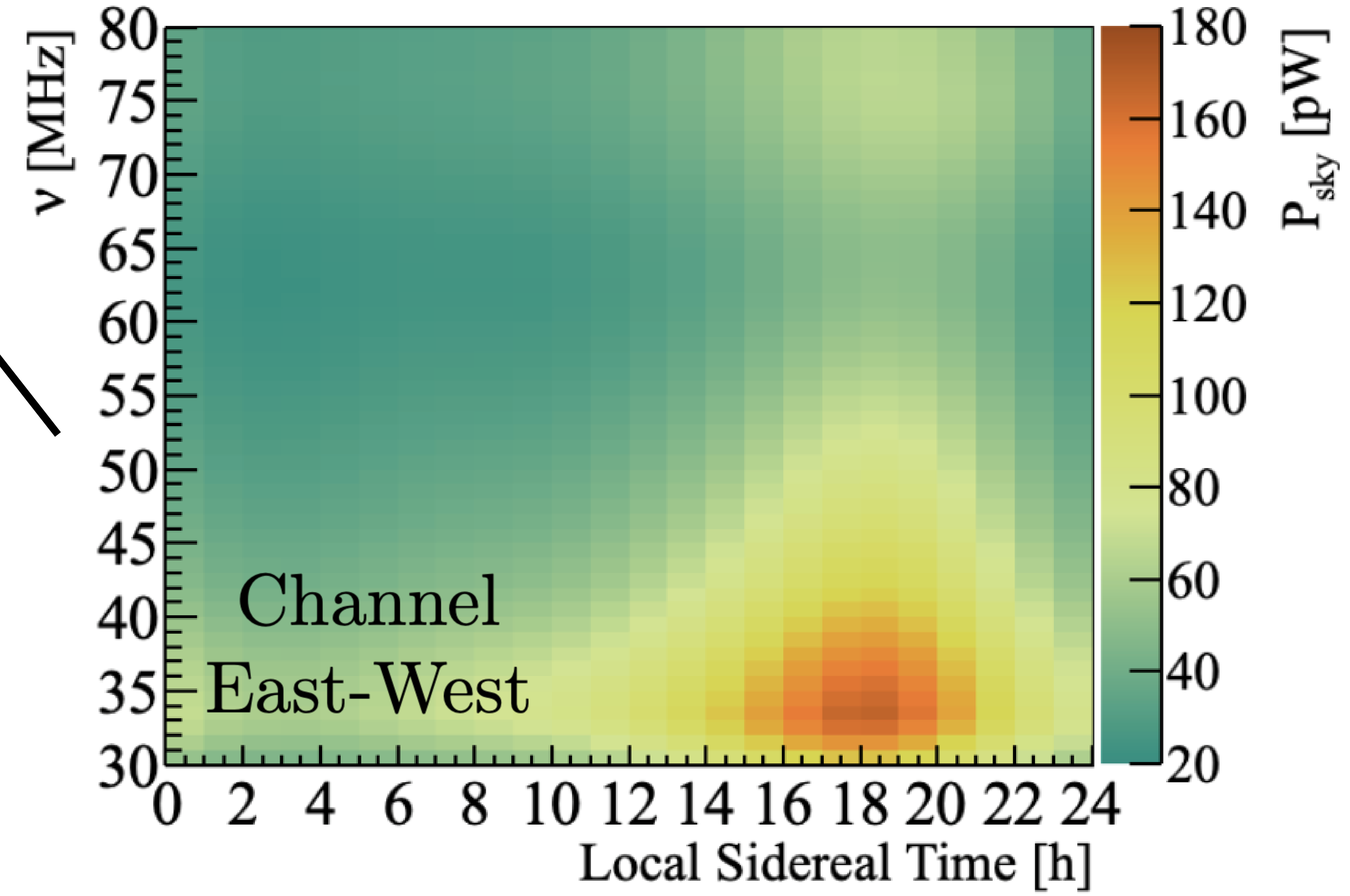
$P_{\text{sky}}(t,\nu)$

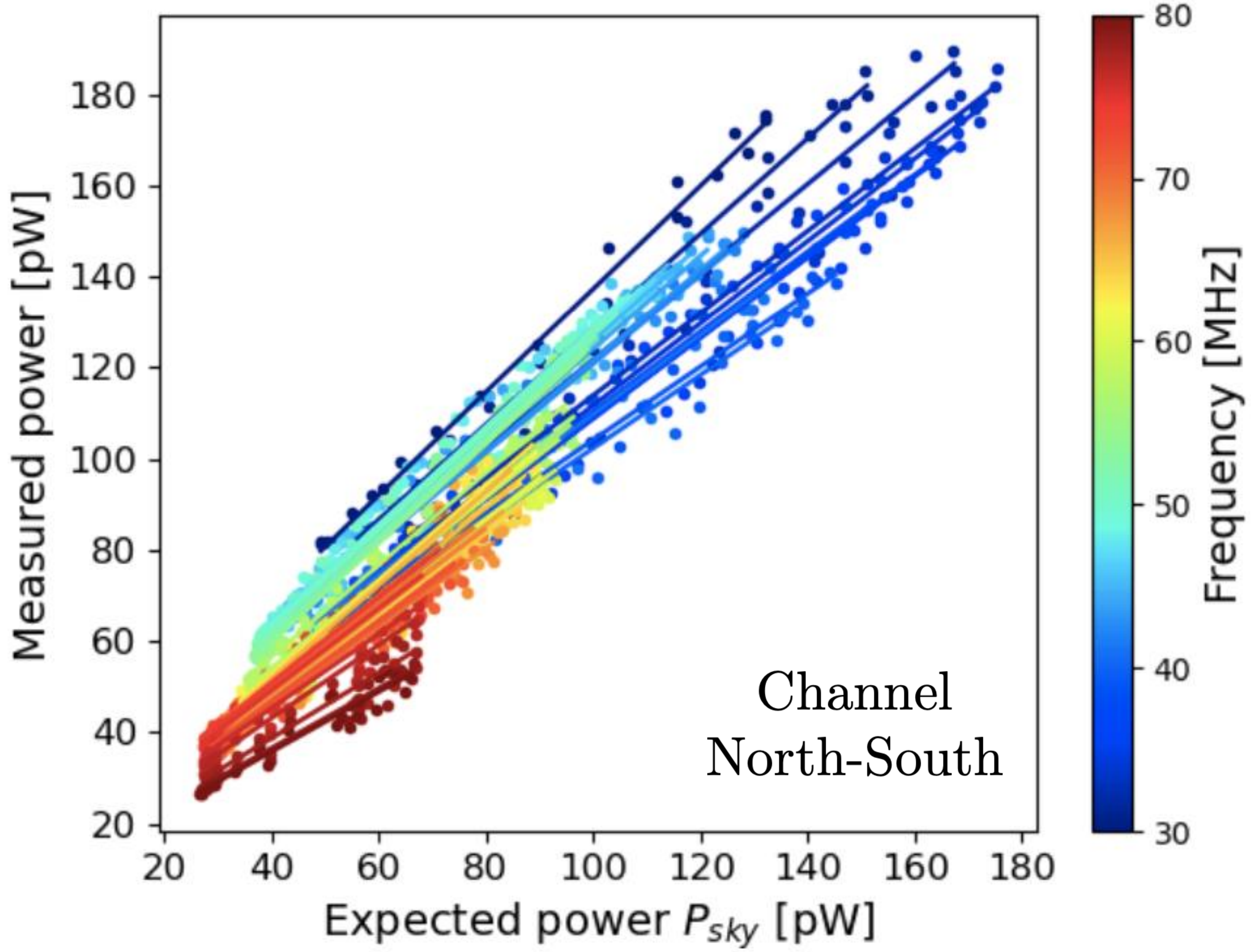


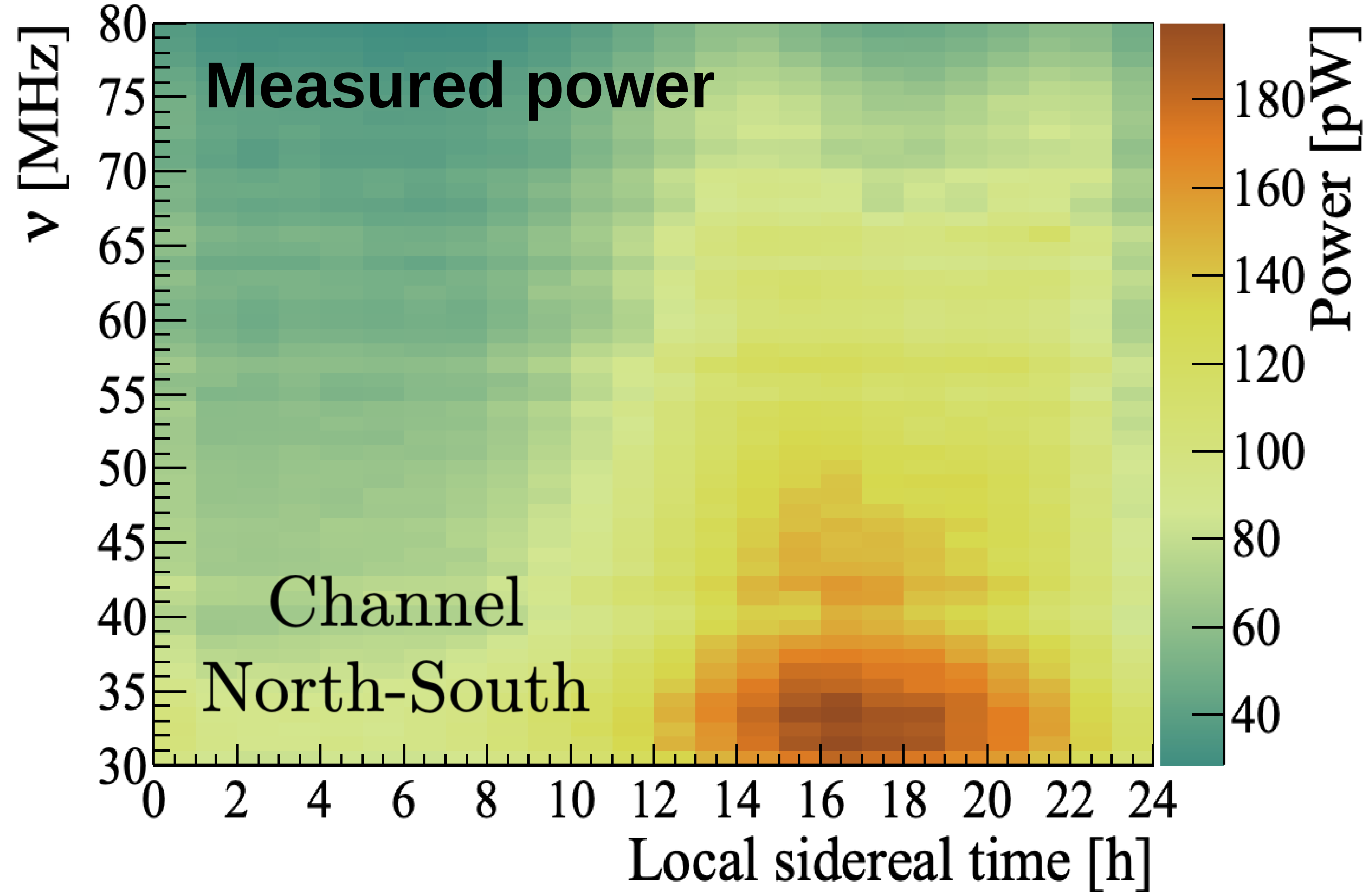


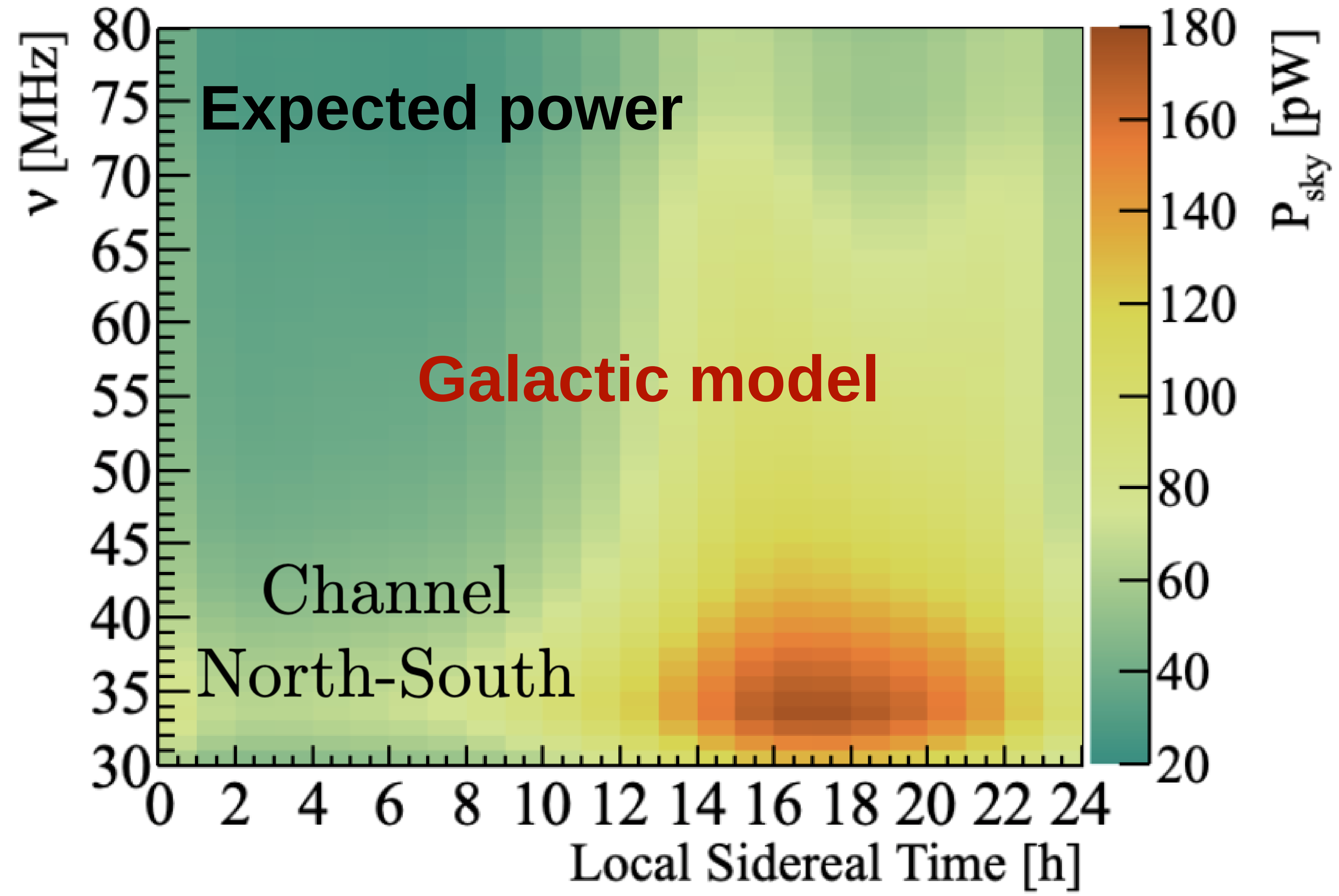
Calibration method

$$P_{model}(t,\nu) = P_{sky}(t,\nu)G_{ant}(\nu)G_{RCU}(\nu)\,C_0^2(\nu) + N_{tot}(\nu)$$

- Independent linear fit for each frequency band







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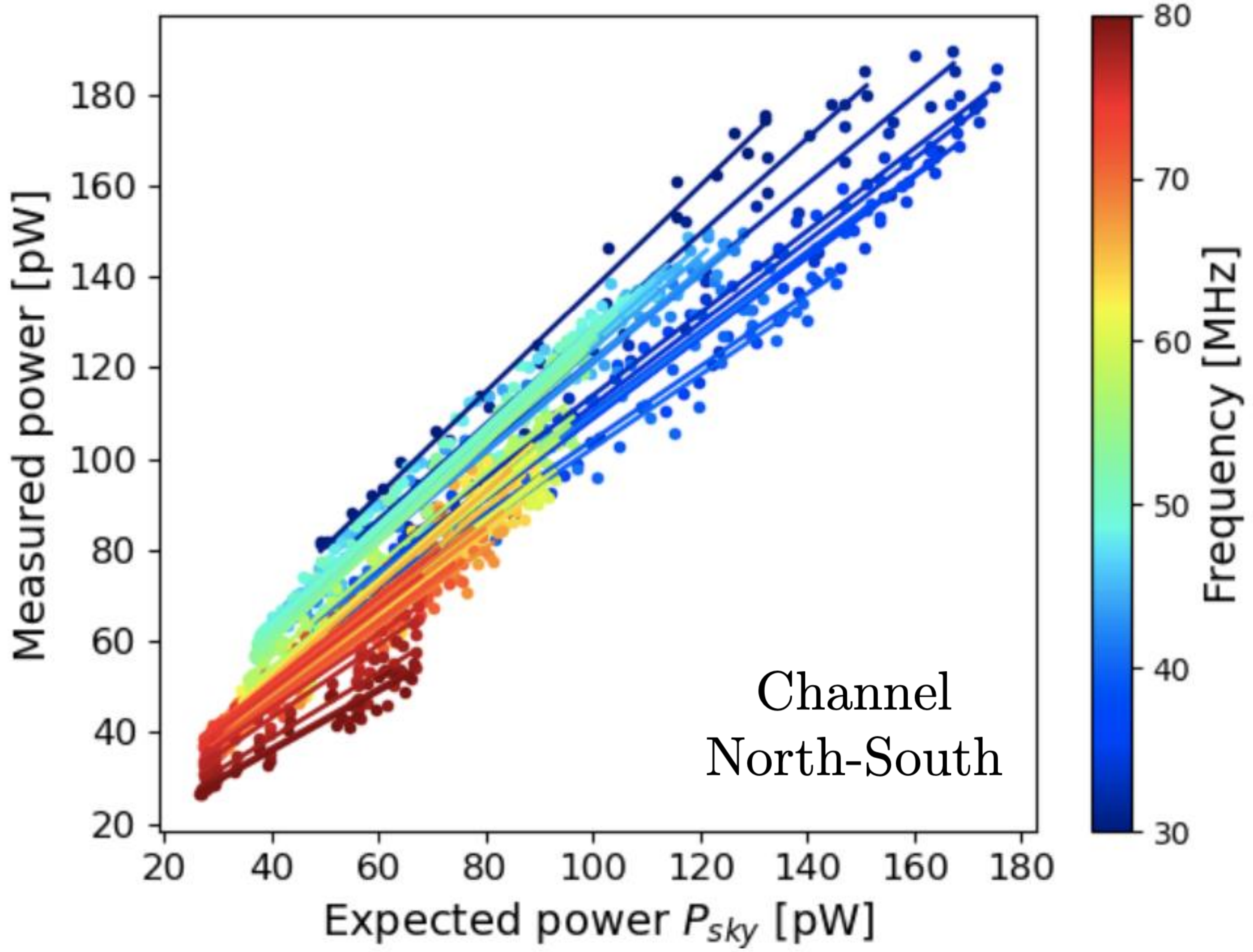
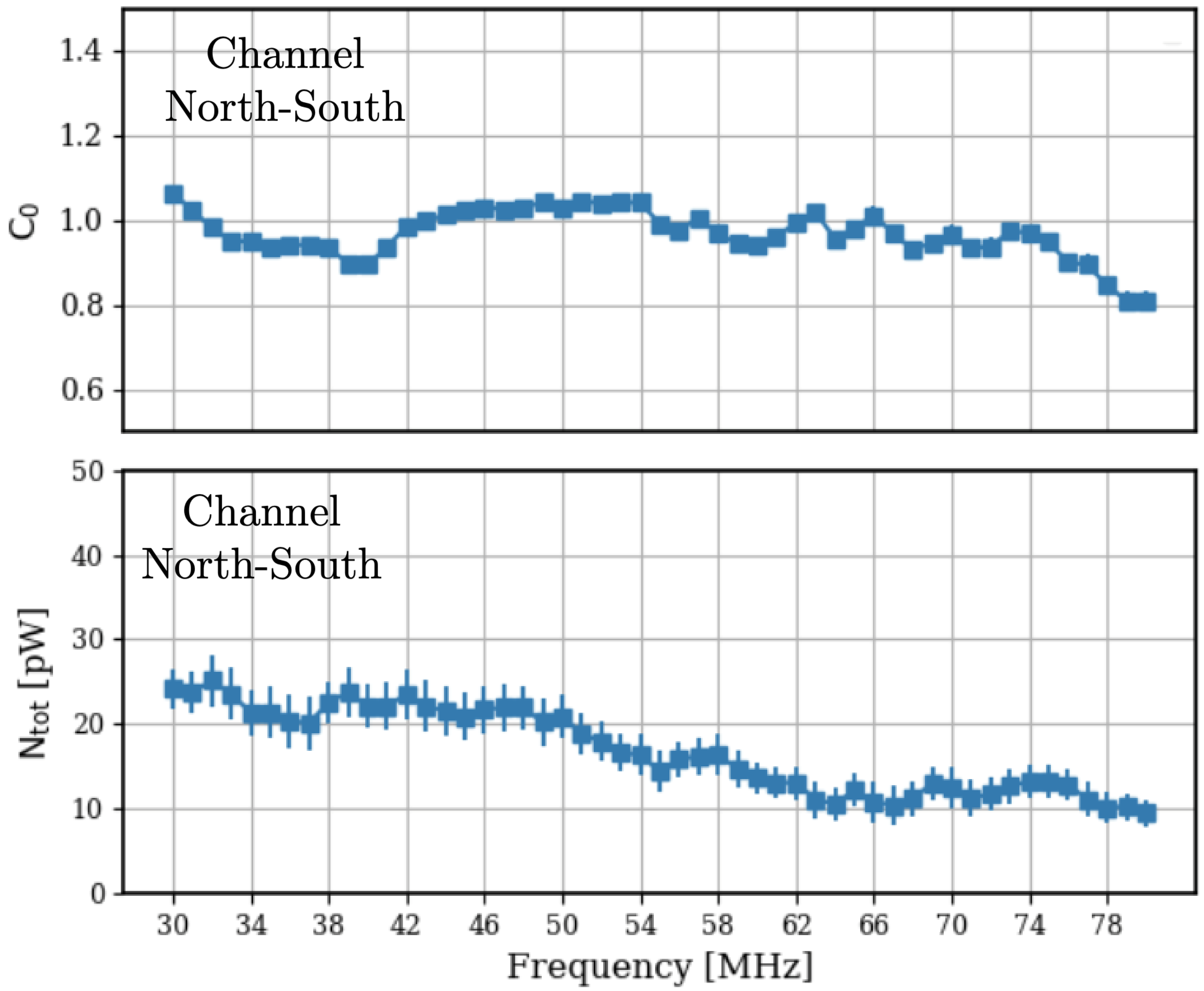




- We calculate the calibration constants for all antennas month by month from 2014 to 2020
  - 52 Butterfly stations from 2014-2020 AERA-II
  - 23 Butterfly stations from 2016-2020 AERA-III
  - 14 LPDA stations from 2017-2020
- We repeated this procedure for all 7 models we are considering

Results

$$P_{model}(t,\nu) = P_{sky}(t,\nu)G_{ant}(\nu)G_{RCU}(\nu)\,C_0^2(\nu) + N_{tot}(\nu)$$

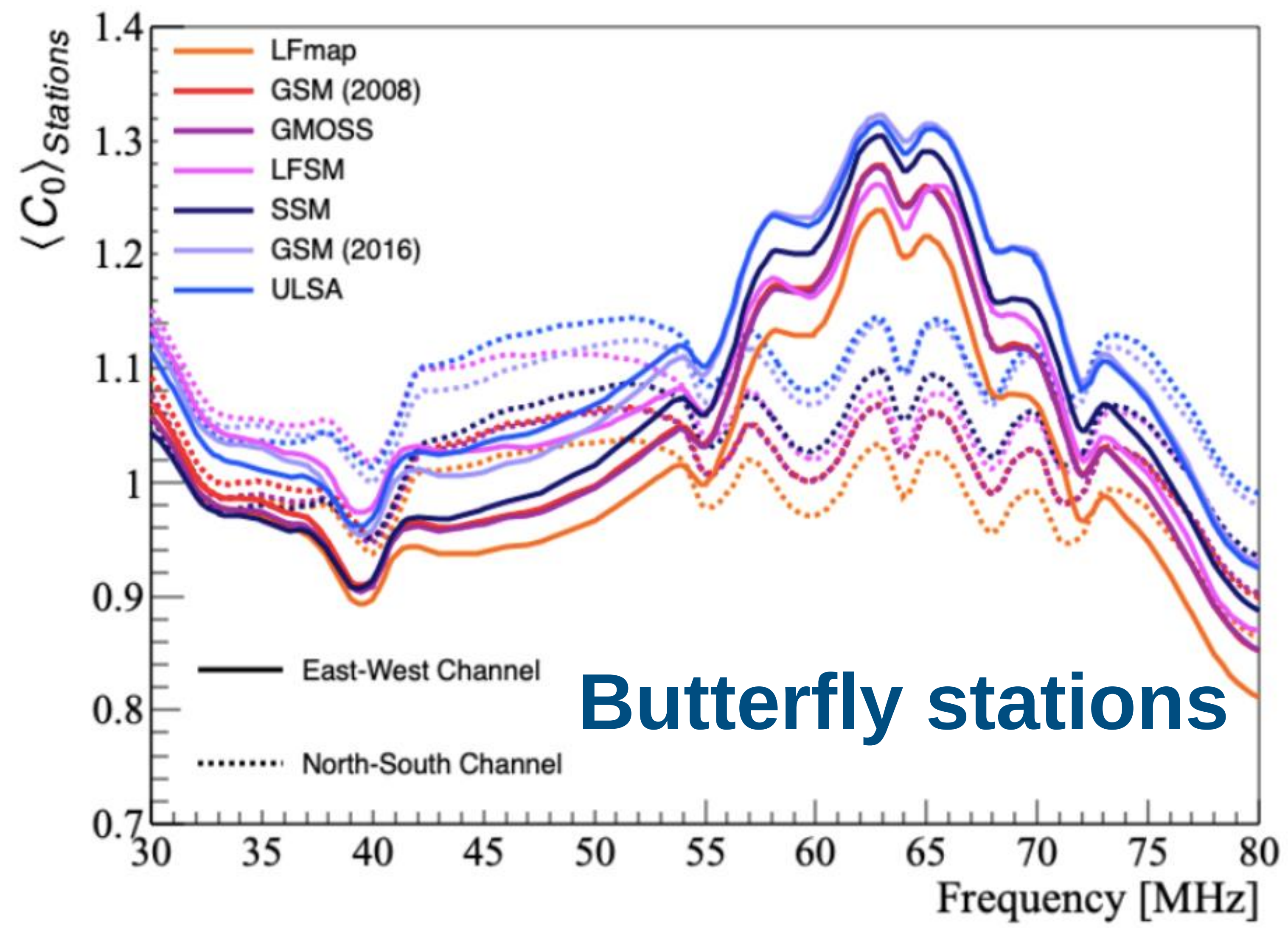
- We calculate the calibration constant for an **average model**

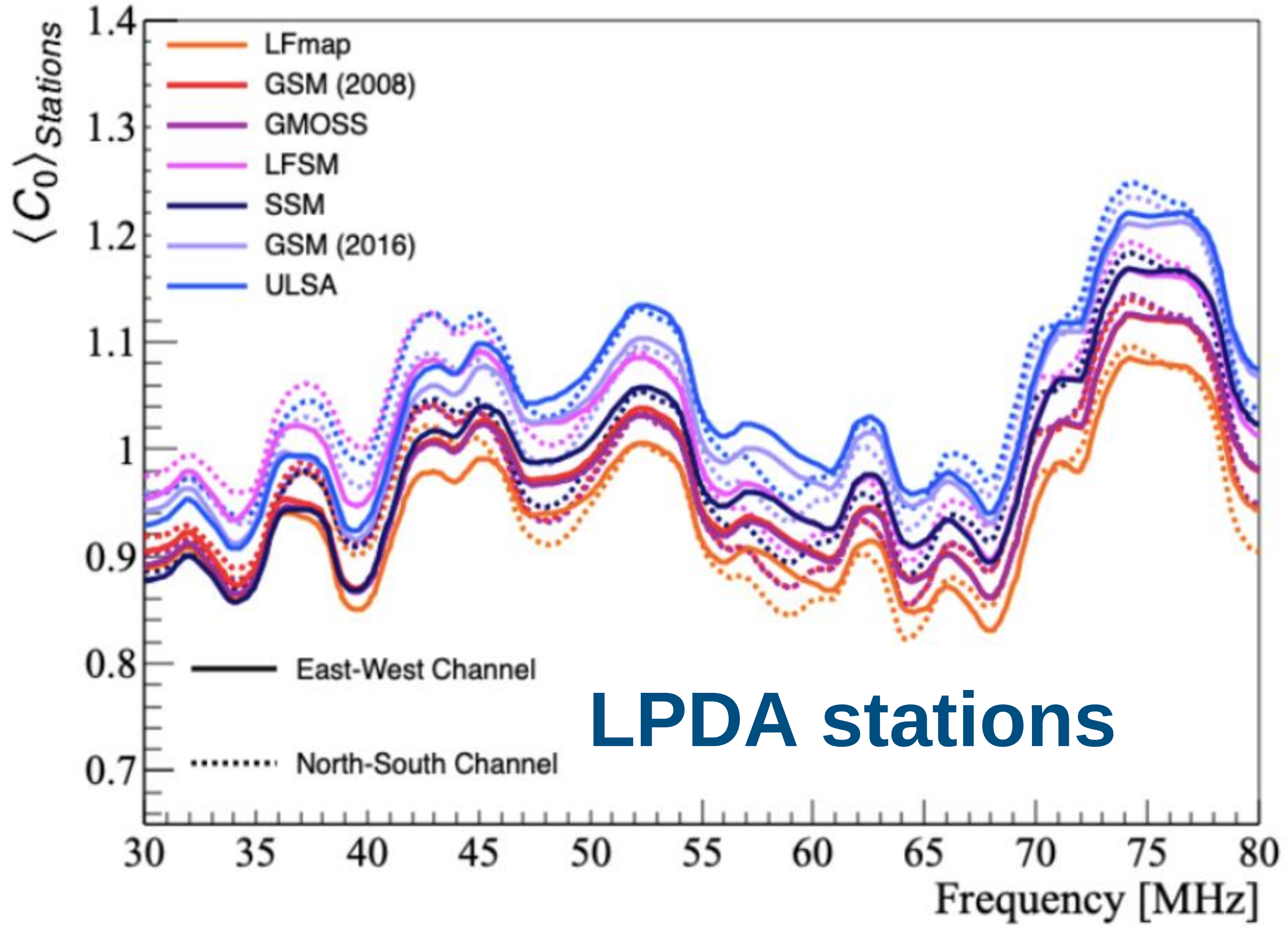
Station (channel)	$\widehat{\mathbb{C}}_0 \pm\sigma_{\text{stat}} \pm \sigma_{\text{syst}}$
Butterfly (East-West)	$1.08 \pm 0.05 \pm 0.05$
Butterfly (North-South)	$1.04 \pm 0.04 \pm 0.06$
LPDA (East-West)	$1.01 \pm 0.07 \pm 0.06$
LPDA (North-South)	$1.01 \pm 0.04 \pm 0.06$

- Calibration constants derived are **consistent with 1 within uncertainties**.

- The impact of the **systematic uncertainty** of the absolute calibration over the radio cosmic ray energy scale remains **at 6% level**.

Average calibration constant obtained for each sky temperature model





C_0 as a function of the time
(Butterfly Station - compute Aging)

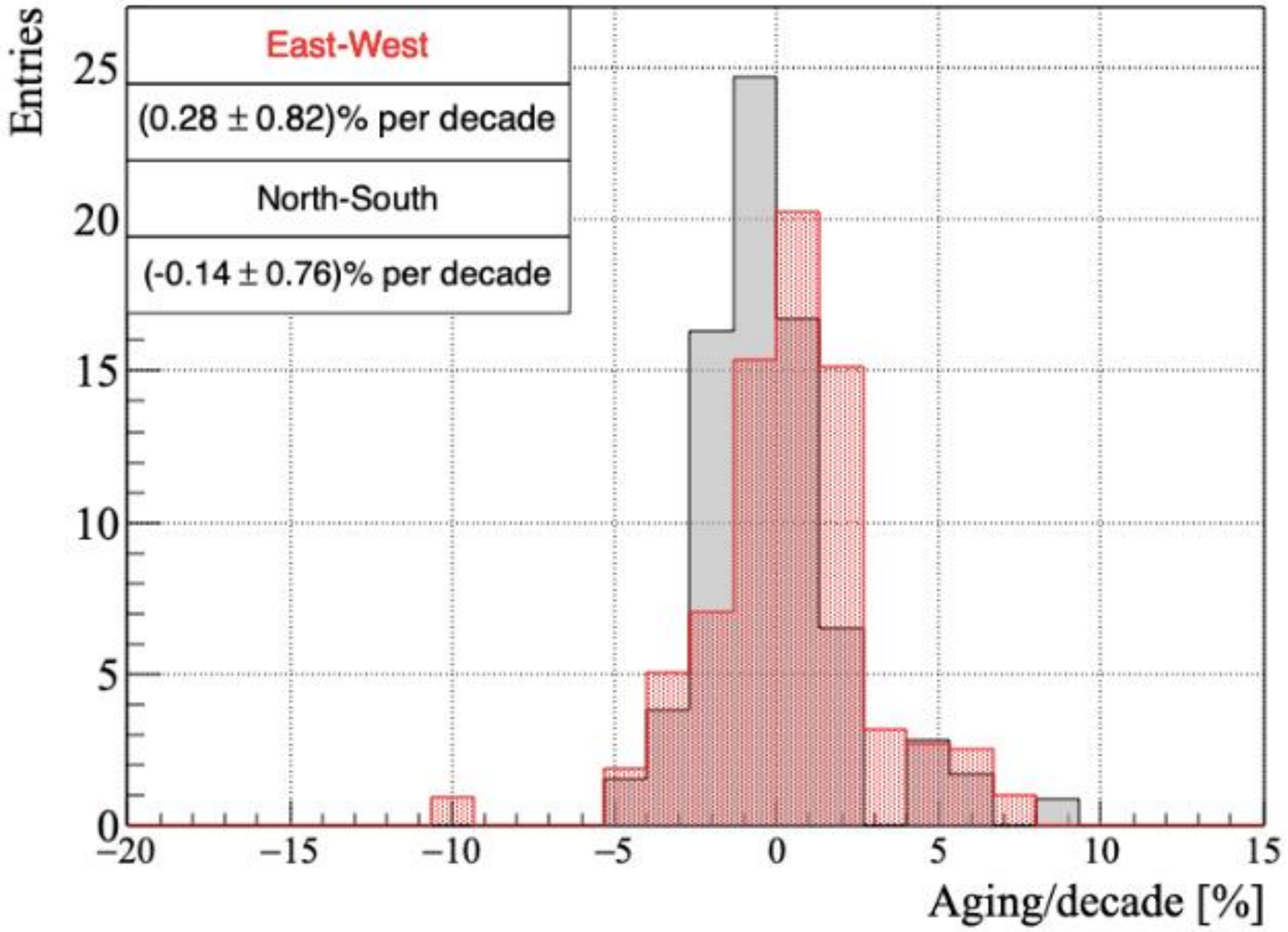
- Use a cosine + linear function to account for seasonal modulation

$$\langle \mathbb{C}_0(t') \rangle_{\text{model}} = A\cos\left(\frac{\pi}{6}t' + \phi\right) + at' + b$$

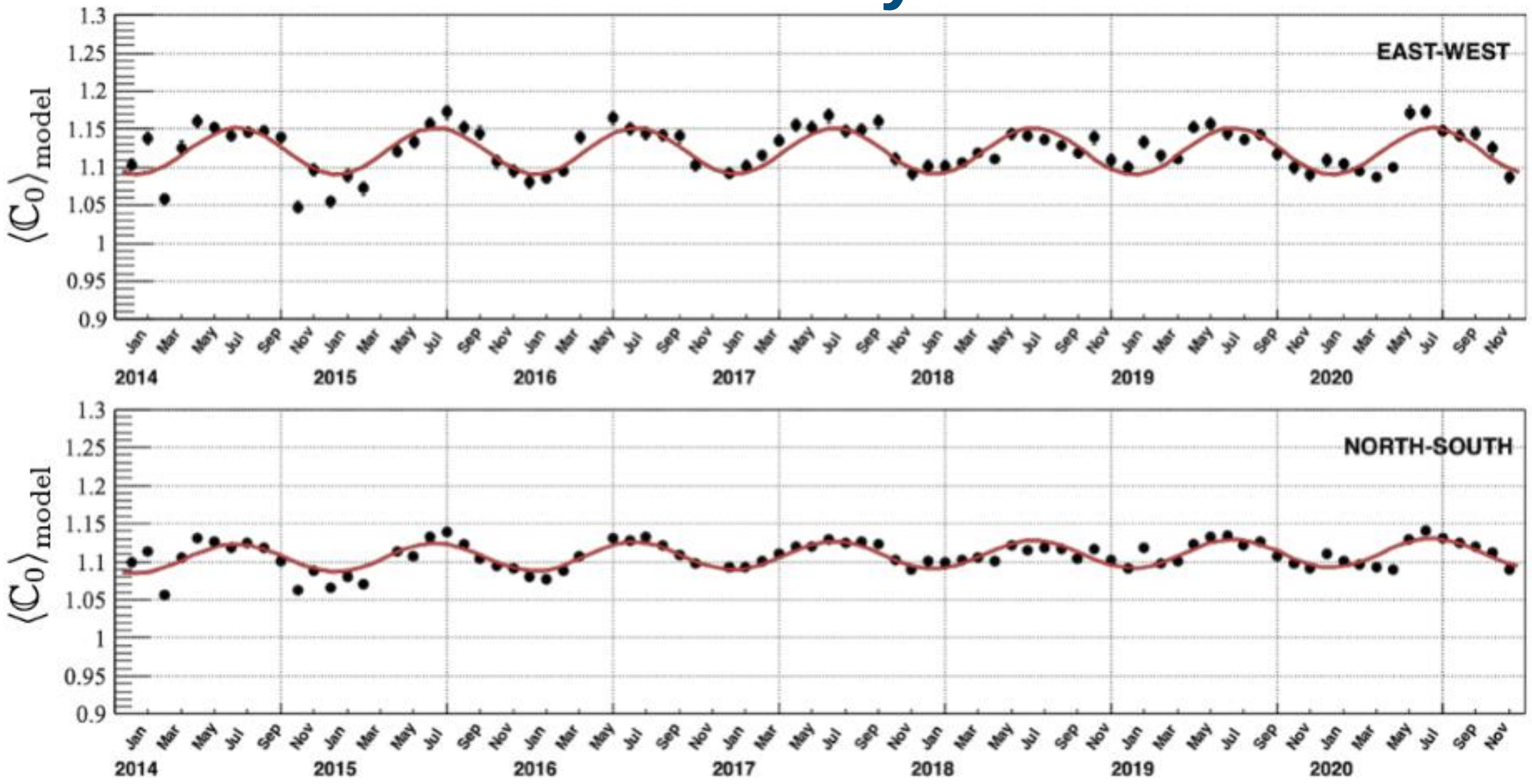
Months — Aging

Even after correcting for the temperature-dependent gain variations of amplifiers in the signal chain, a remaining **seasonal modulation with unknown origin** is observed.

- Periodically triggered data
  - ➔ 52 Butterfly stations (AERA2) from 2014 until 2020
  - ➔ 23 Butterfly stations (AERA3) from 2016 until 2020
  - ➔ 14 LPDA stations from 2017 until 2020



Butterfly station



- Error bar: RMS/$\sqrt{N}$ each month

C_0 as a function of the time

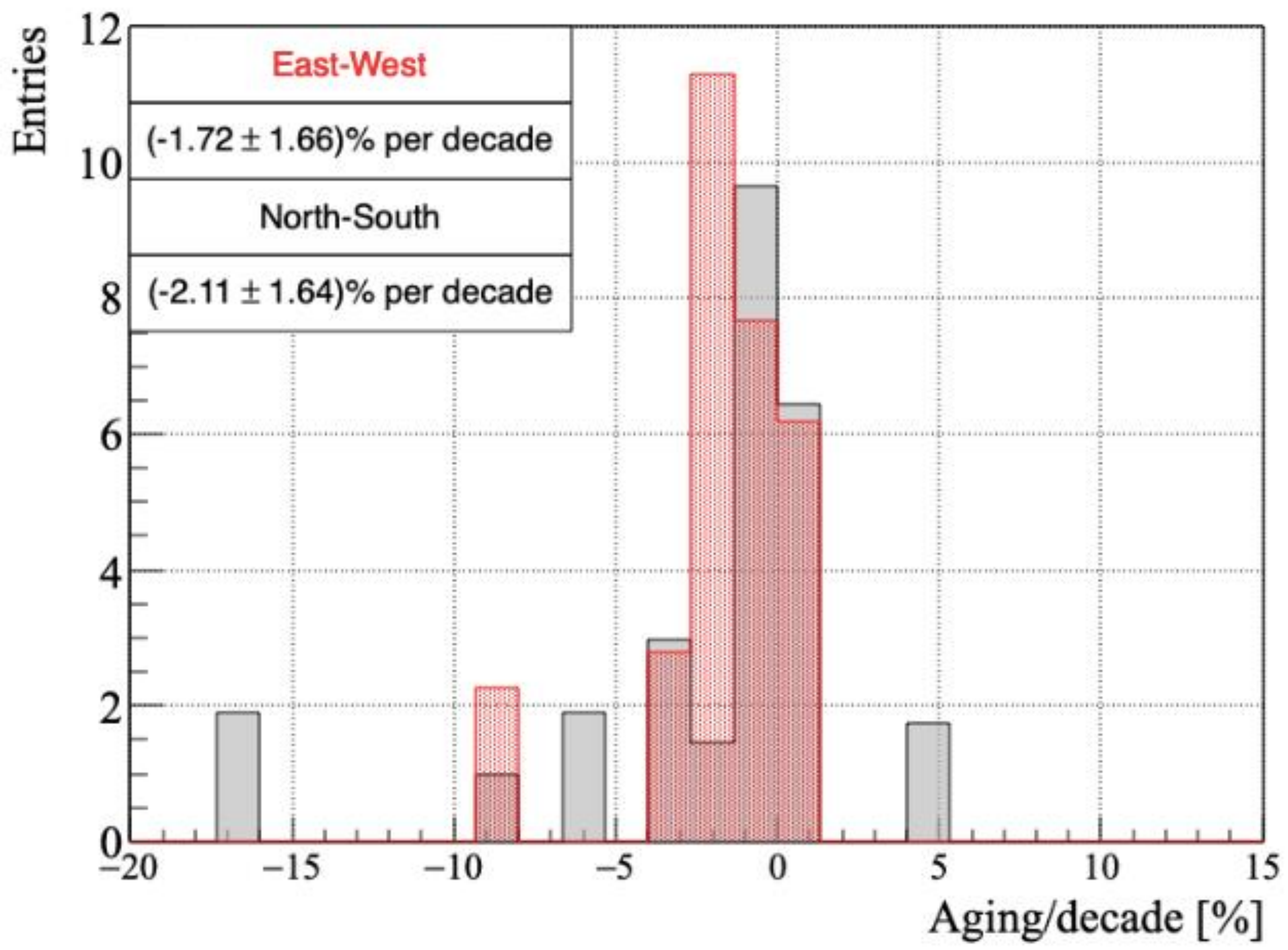
(LPDA Station - compute Aging)

- Use a cosine + linear function to account for seasonal modulation

$$\langle \mathbb{C}_0(t') \rangle_{\text{model}} = A\cos\left(\frac{\pi}{6}t' + \phi\right) + at' + b$$

Months — Aging

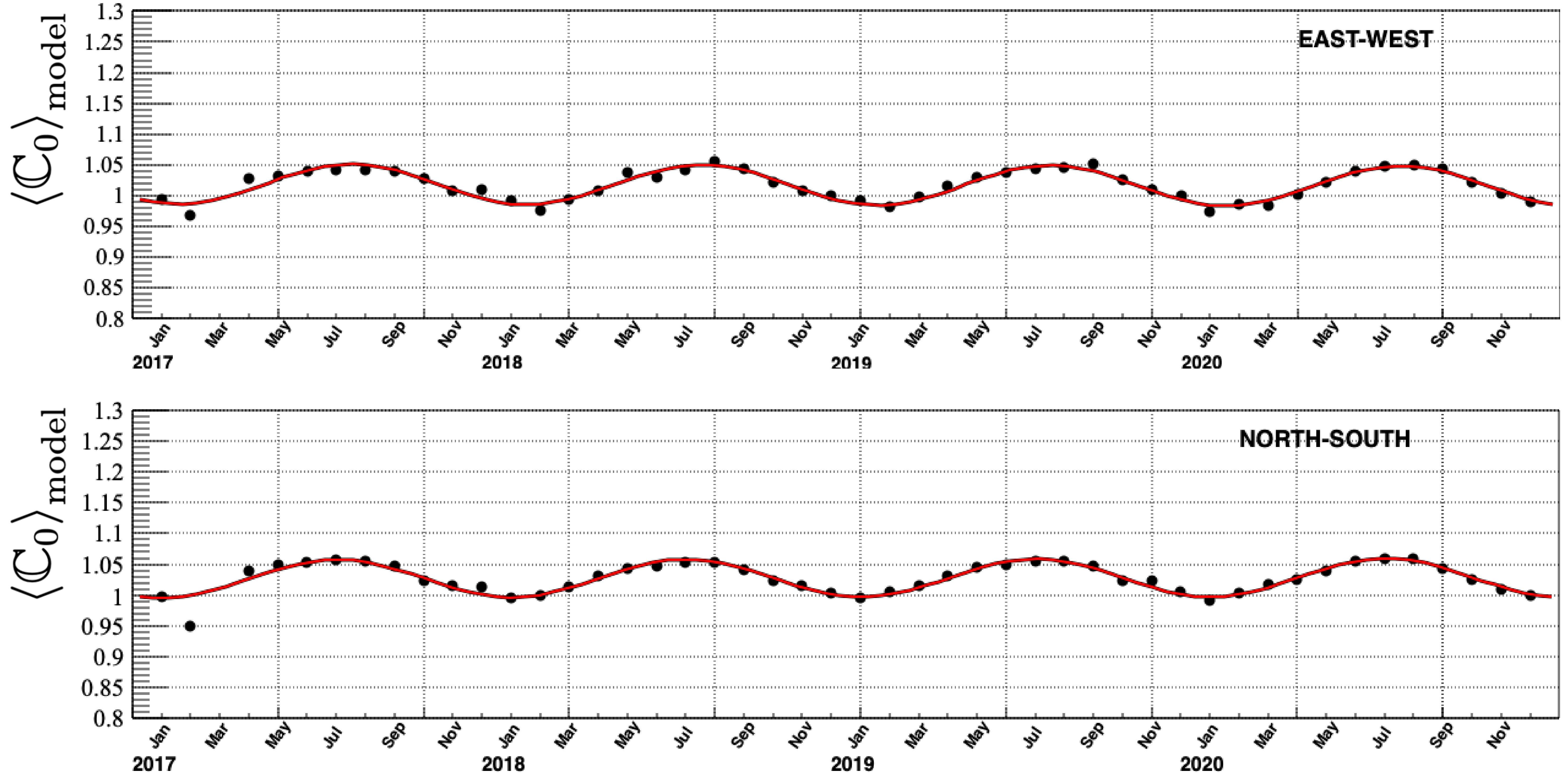
- Periodically triggered data
  - ➔ 52 Butterfly stations (AERA2) from 2014 until 2020
  - ➔ 23 Butterfly stations (AERA3) from 2016 until 2020
  - ➔ 14 LPDA stations from 2017 until 2020



Aging

Station (channel)	Aging per decade (%)
Butterfly (East-West)	0.28 ± 0.82
Butterfly (North-South)	-0.14 ± 0.76
LPDA (East-West)	-1.7 ± 1.7
LPDA (North-South)	-2.1 ± 1.6

- **Combining all antennas types and channels, we obtain an aging factor of a (-0.32 $\pm$ 0.51)% per decade.**



Conclusions

- ➔ We performed an absolute frequency-dependent Galactic calibration of AERA stations, encompassing both Butterfly and LPDA antennas, and investigated the temporal behavior of the calibration constants over a period of seven years.

- ➔ The calibration constants come out close to 1.0, i.e., the antenna simulation as well as analogue chain lab calibration have been accurate and consistent with the Galactic calibration.

- ➔ **The results show an absence of significant aging effects in the AERA antennas and shows that radio detectors can effectively monitor aging effects of other detectors operating over extended time periods.**

BACKUP

Results

- An estimate of the impact of the calibration constants on the cosmic ray energy uncertainty can be obtained by considering the average of the calibration constants obtained for each frequency

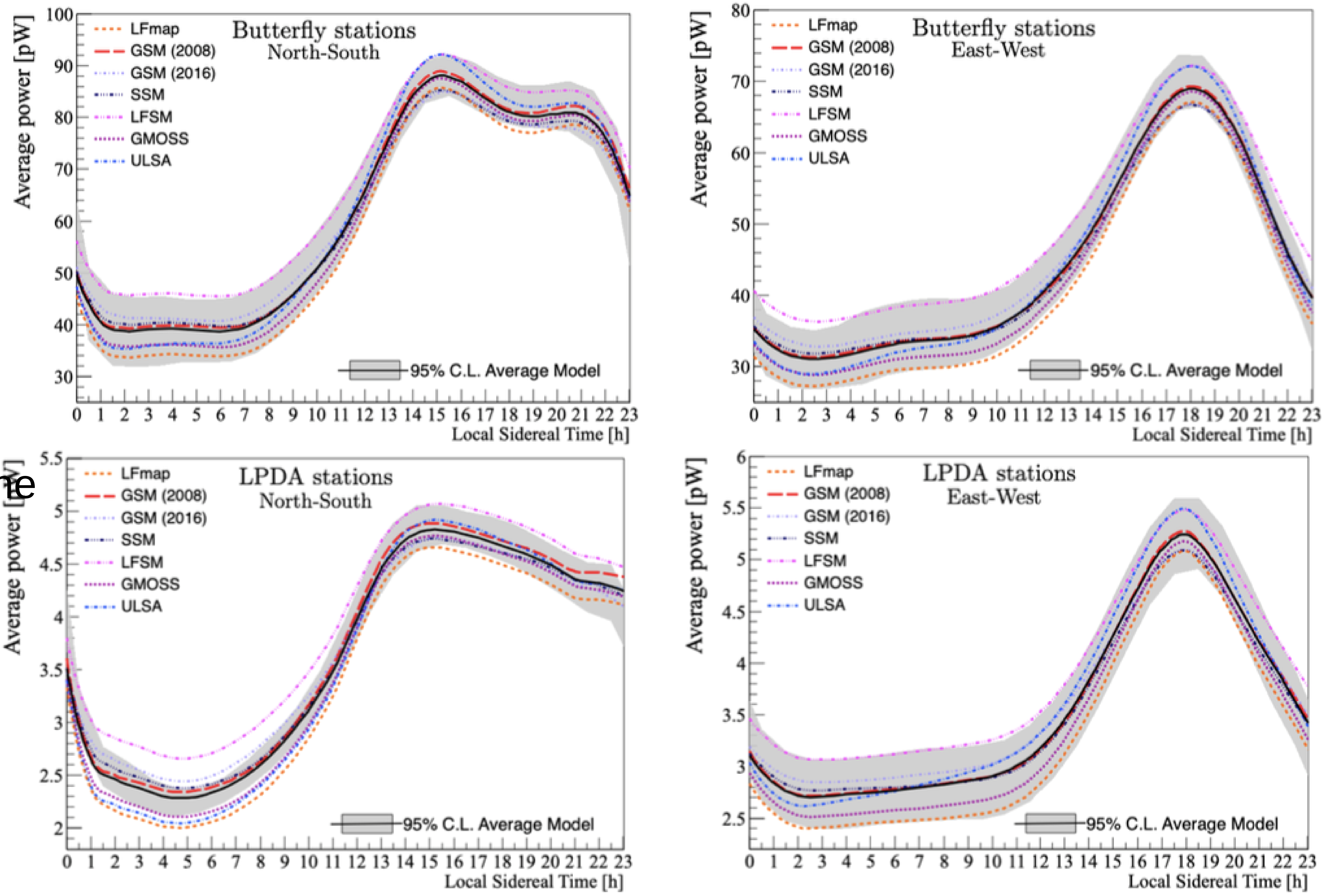
$$\mathbb{C}_0 \equiv \frac{1}{N_\nu}\sum_\nu C_0(\nu)$$

- Besides, in order to taking into account the different radio sky models, it is convenient to define

$$\langle C_0(\nu)\rangle_{\text{model}} \equiv \frac{1}{N_{\text{model}}}\sum_i C_{0,i}(\nu)$$

- We also calculated the average of the calibration constants obtained for each frequency of the average model

$$\langle \mathbb{C}_0\rangle_{\text{model}} = \frac{1}{N_\nu}\sum_\nu \langle C_0(\nu)\rangle_{\text{model}}$$



We excluded measurements between 30 MHz and 40 MHz

Results

- The statistical uncertainties ~ 5% level are estimated as the RMS of the averaged model distribution.

- The systematic uncertainty primarily arises from discrepancies among sky models and is estimated at 6% by computing the mean deviation of the averaged model with respect to the LFmap and ULSA models.

- Since the cosmic ray energy is proportional to C_0, therefore, the impact of the systematic uncertainty of the absolute calibration over the radio cosmic ray energy scale remains at 6% level.

Station (channel)	$\hat{\mathbb{C}}_0 \pm \sigma_{\mathrm{stat}} \pm \sigma_{\mathrm{syst}}$
Butterfly (East-West)	$1.08 \pm 0.05 \pm 0.05$
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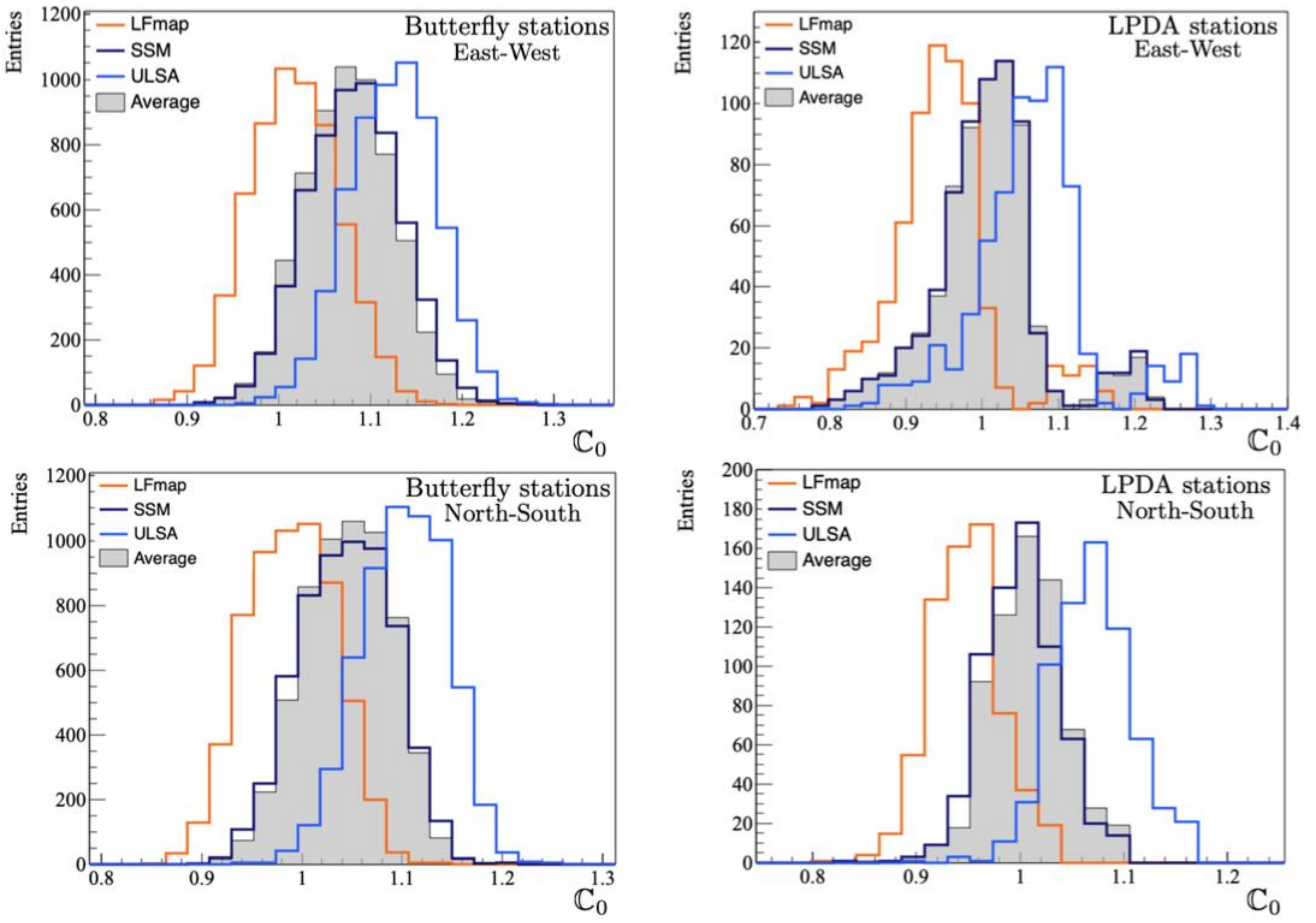

Average of the calibration constants for the different sky models $\langle \mathbb{C}_0 \rangle_{\mathrm{model}}$

- **Calibration constants derived are consistent with 1 within uncertainties, indicating good agreement with the original calibration process, which involved laboratory measurements of the analogue chain.**