Satellite Contamination on MeerKATs’ SD HI IM

UNIVERSITY of the WESTERN CAPE

RESPICE PROSPICE

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NRF National Research Foundation

SARAO South African Radio Astronomy Observatory

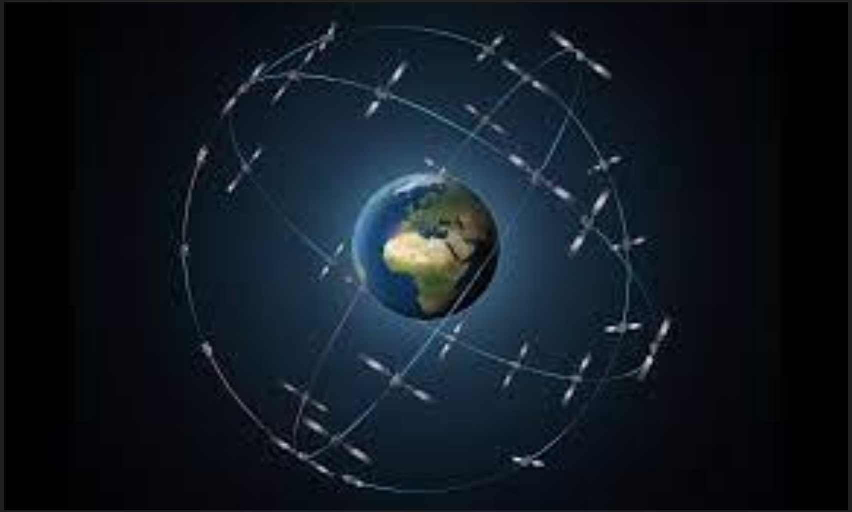
CRC Centre for Radio Cosmology

SISSA/IFPU: 25 May 2022

First things:

Artificial Satellites

Credit:



Credit:

First things:

Artificial Satellites

4 global satellite systems
2 regional satellite systems
1 geostationary system

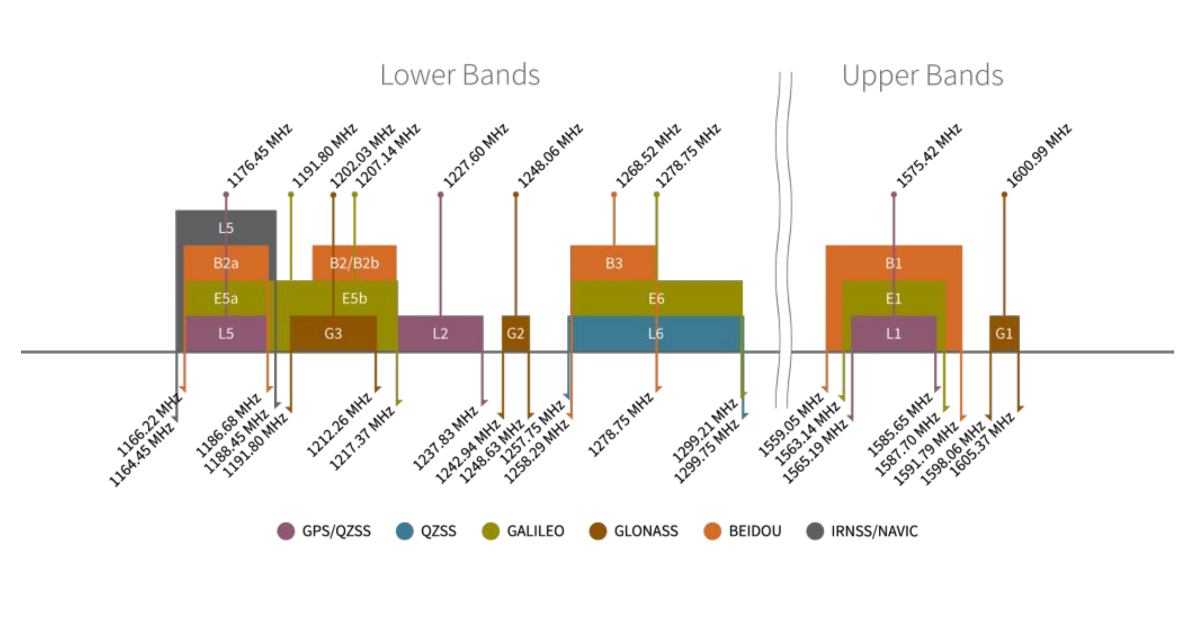
~ 160 satellites

Producer of Radio Frequency Interference

Credit:

First things:

Artificial Satellites



4 global satellite systems
2 regional satellite systems
1 geostationary system

~ 160 satellites

Producer of Radio Frequency Interference

[Credit]

First things:

<u>Artificial Satellites</u>

[Credit]

Mega-constellations:
Starlink, OneWeb, Kuiper

Communication based

Bands: 10.7-12.7 GHz Starlink
12-18 GHz Oneweb
As Stuart mentioned

MeerKAT/MeerKLASS

HI intensity mapping with MeerKAT: Calibration pipeline for multi-dish autocorrelation observations

Wang et al 2020

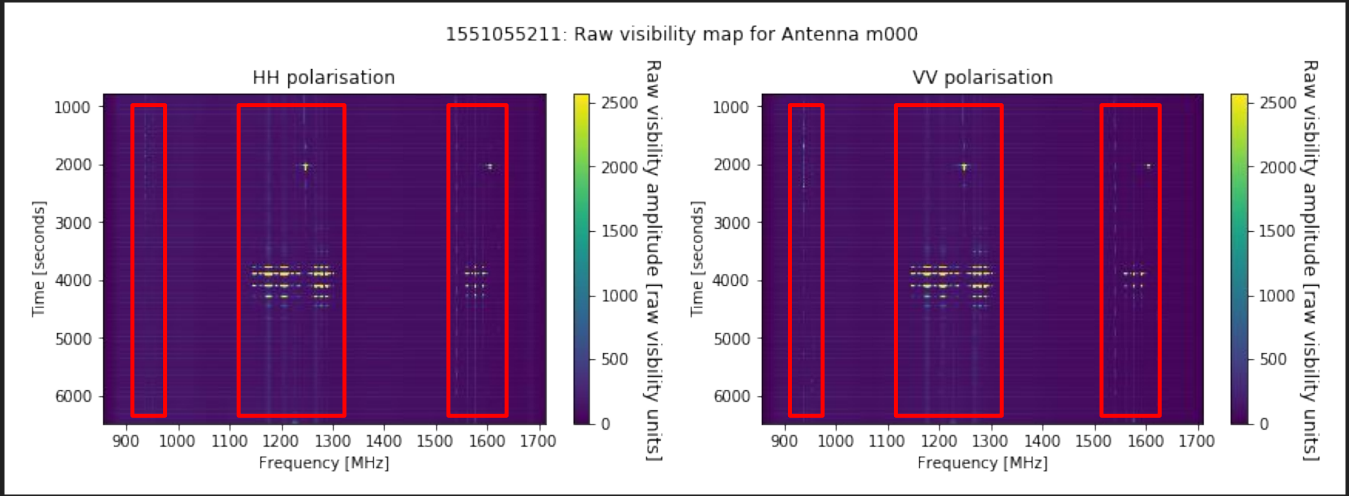
Potential Impact of Global Navigation Satellite Services on Total Power HI Intensity Mapping Surveys

Harper 2018

MeerKAT/MeerKLASS

HI intensity mapping with MeerKAT: Calibration pipeline for multi-dish autocorrelation observations

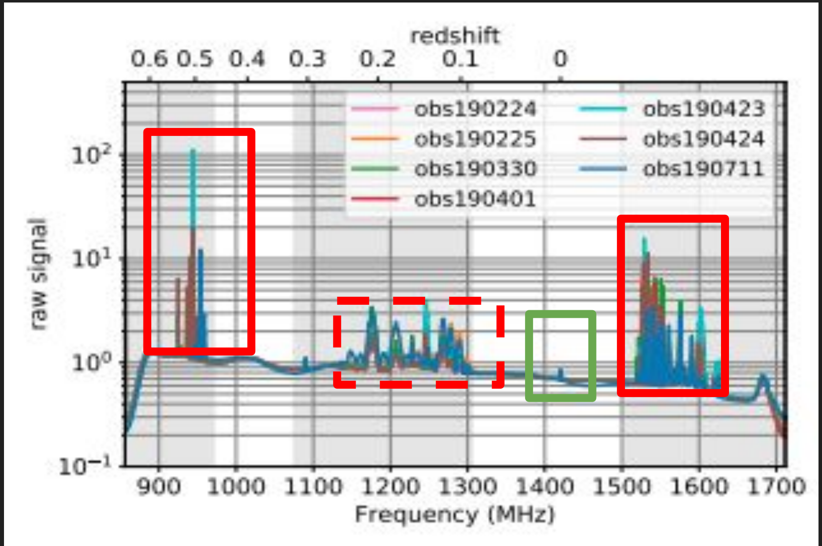
[Wang. J 2020]



MeerKAT/MeerKLASS

HI intensity mapping with MeerKAT: Calibration pipeline for multi-dish autocorrelation observations

Wang. et al 2020



Multiple observations

Larger than the HI signal

Area of interest: 1000-1500 MHz

Construct a simulation

Comprised of 3 sections:

- Handling MeerKAT data (specific)
  - Satellite position & Telescope Beam (generic)
    - Constellation estimation & Fitting (generic)

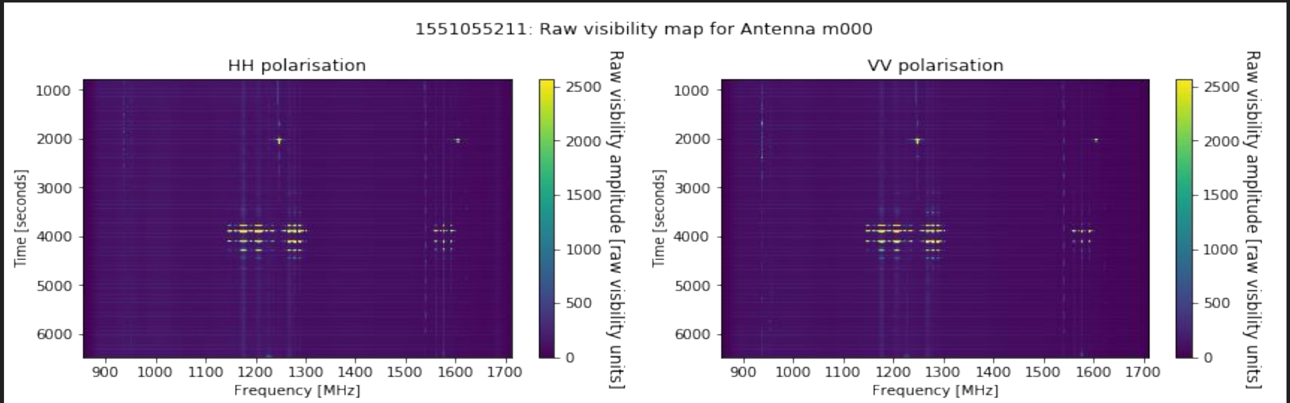
Handling MeerKAT data

Looking at 1 observation: 1551055211
2019-02-25 : 02:40:11

Method applies to each receiver

Receivers added together

All dishes averaged together



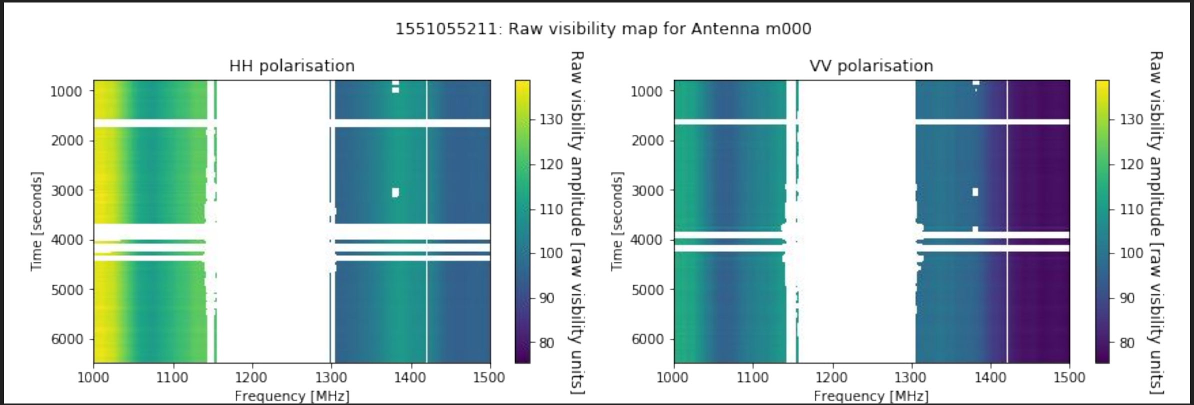
Handling MeerKAT data

Looking at 1 observation: 1551055211
2019-02-25 : 02:40:11

A flag is applied in the pipeline

Looking at the frequency of interest

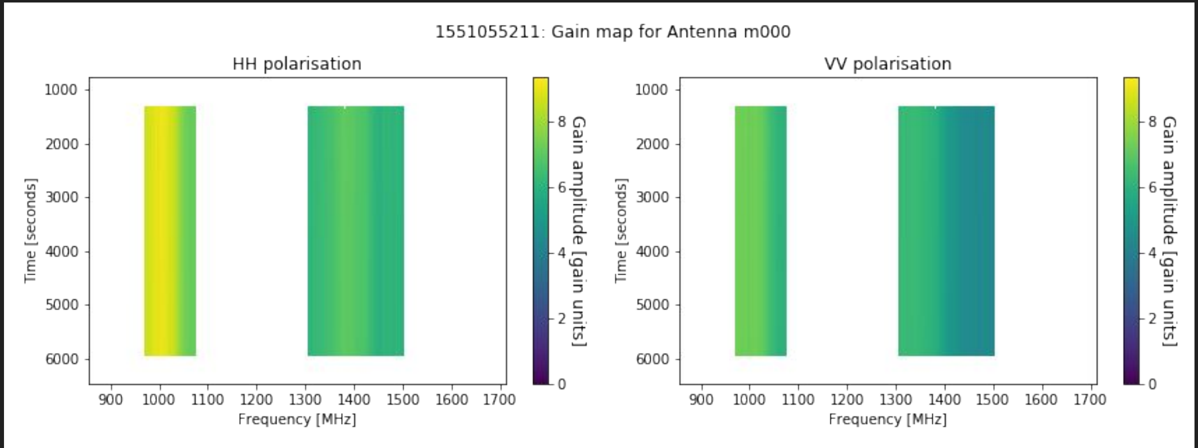
Time is noted: nd_s0
Noise diode off, scan period



Handling MeerKAT data

Information from the gain maps

Need completeness to recalibrate the data

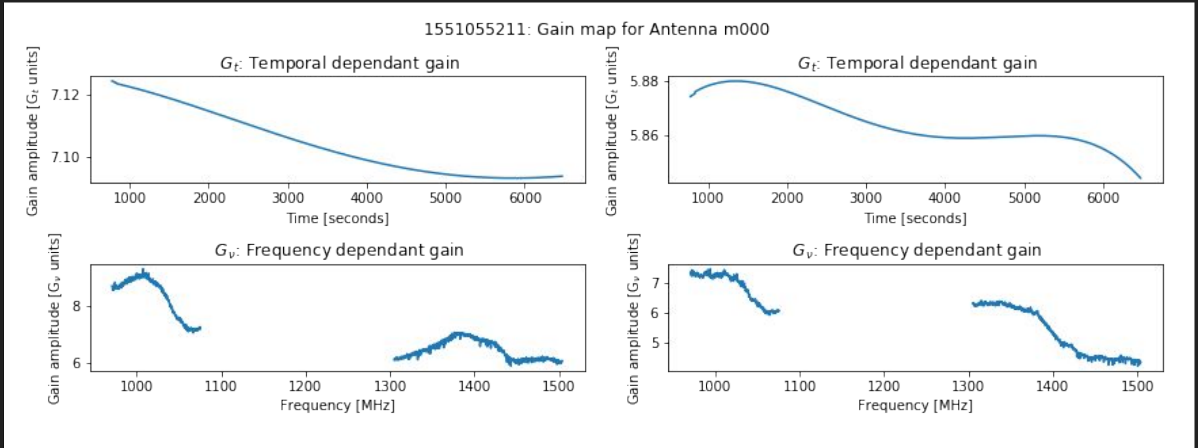


Handling MeerKAT data

Information from the calibration

Need completeness to recalibrate the data.

Frequency space requires interpolation.



Handling MeerKAT data

Information from the calibration

Need completeness to recalibrate the data.

Frequency space requires interpolation.

Applying a method from SCP data with Yi-Chao

$$G(\nu, t) = G_\nu \times G_t$$

Removing the temporal gain contribution from the raw visibility.

$$a1_{\mathrm{true}} = \frac{RV}{G_t}$$

Removing background models from the sky

$$a1 = \frac{RV}{G_t \times \mathrm{BG}}$$

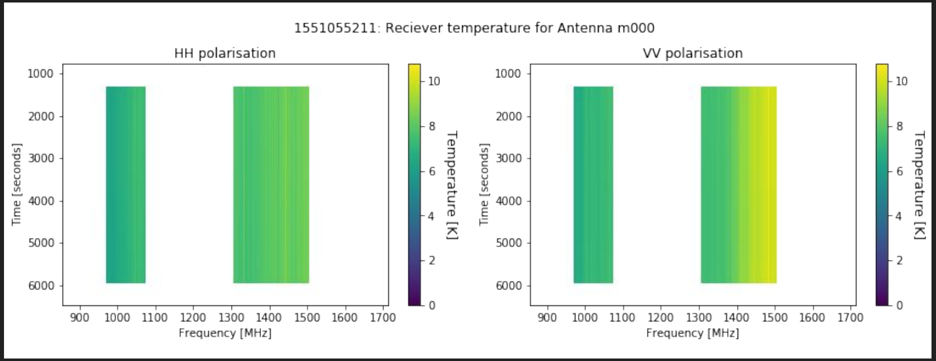
Averaging down the temporal component.

$$a2 = a1_\nu$$

Removing the average of $a2$

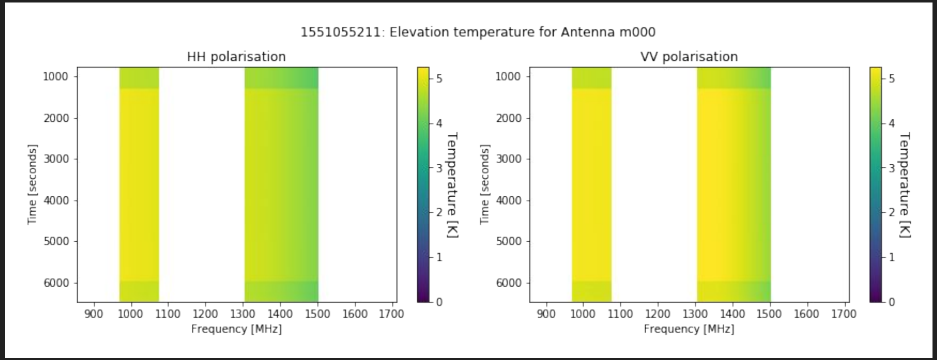
$$a3 = \frac{a2}{\bar{a2}}$$

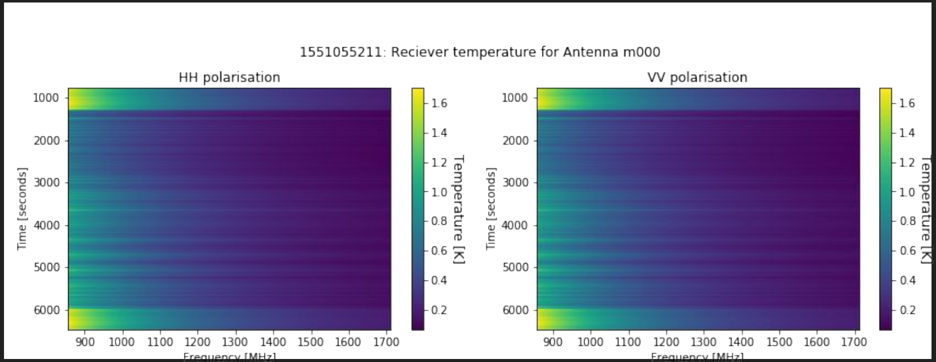
Handling MeerKAT data



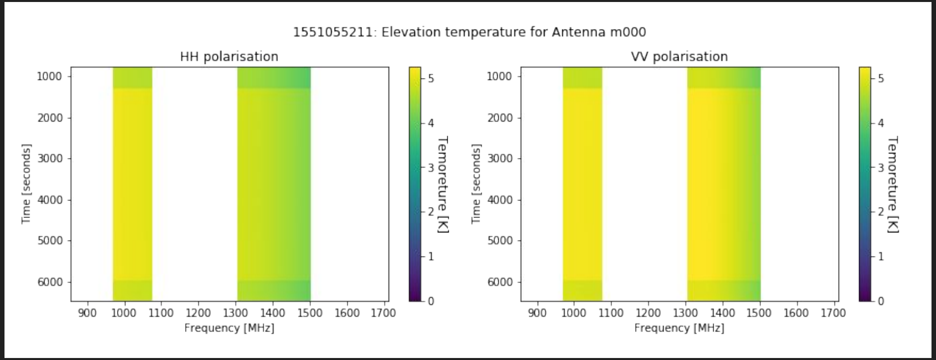
Background temperature

Receiver, Elevation, Galactic, CMB

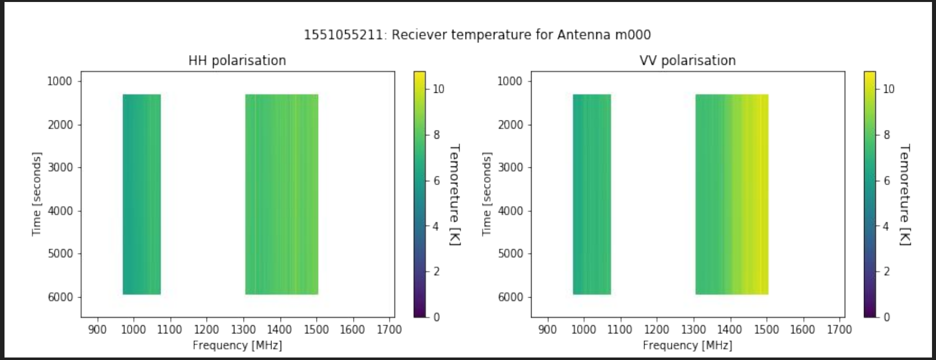




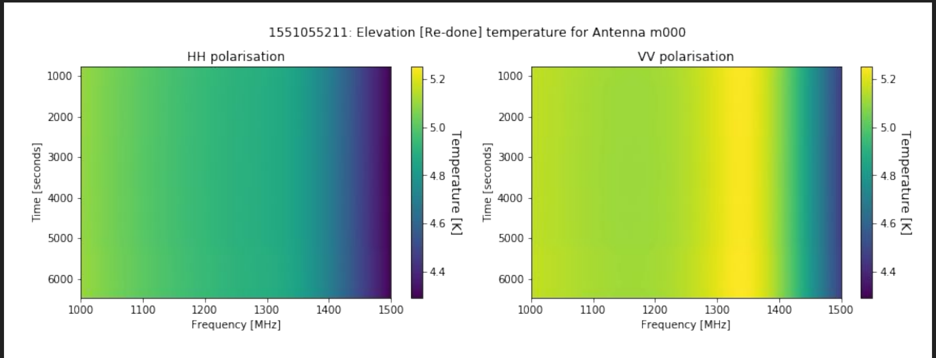
Handling MeerKAT data

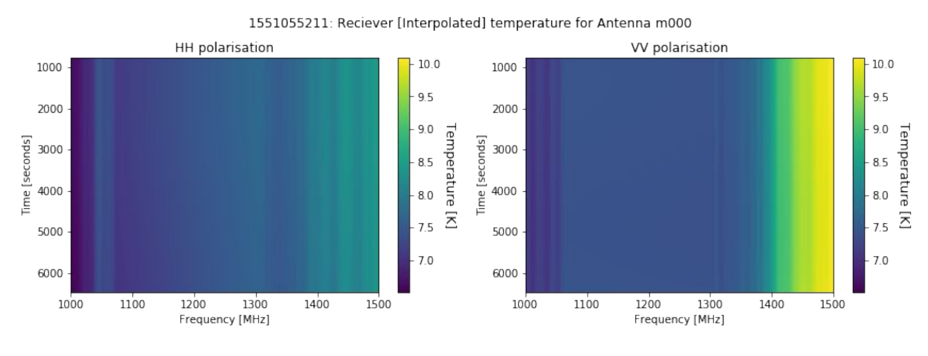


A code to complete the elevation temperature [Jingying]



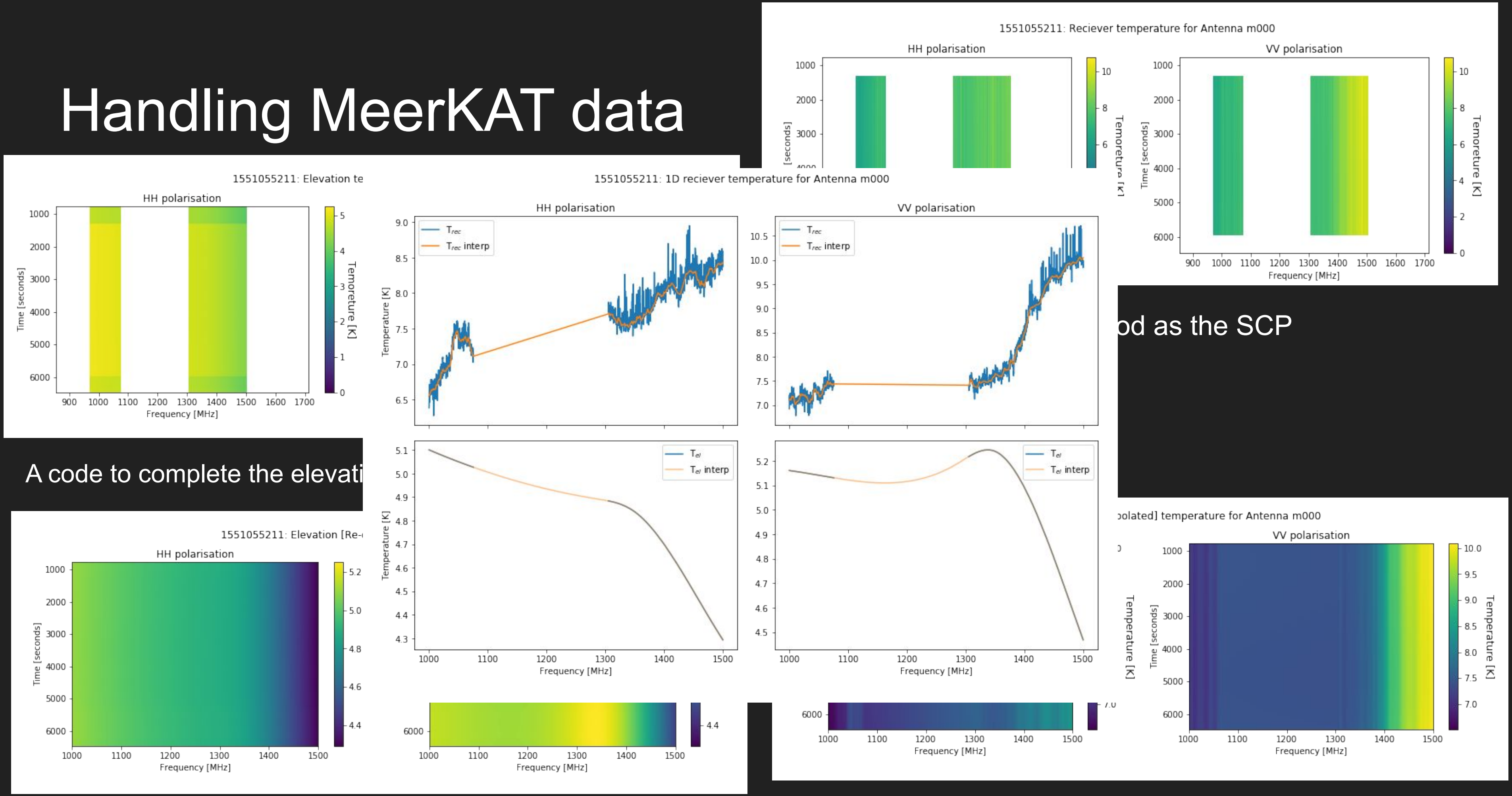
A similar method as the SCP





Looking at nd_s0 & Frequency choice

Handling MeerKAT data



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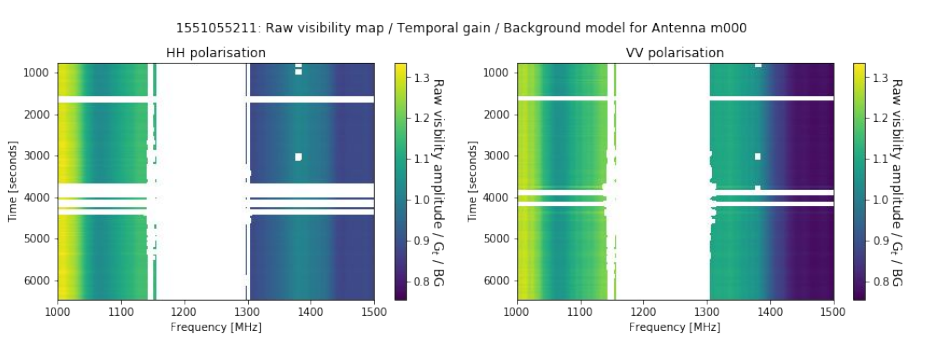
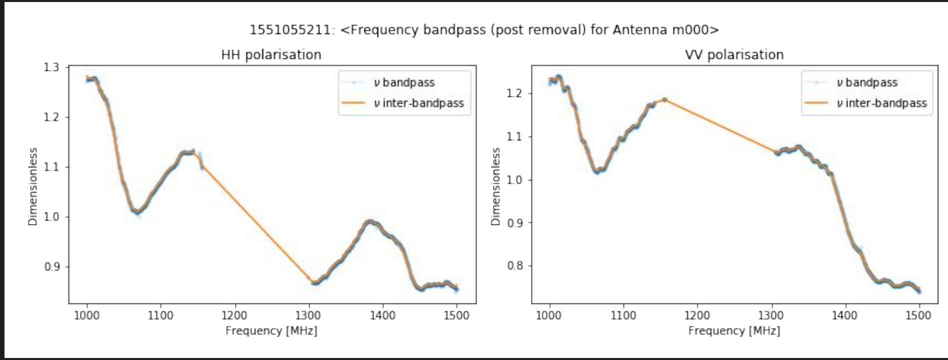
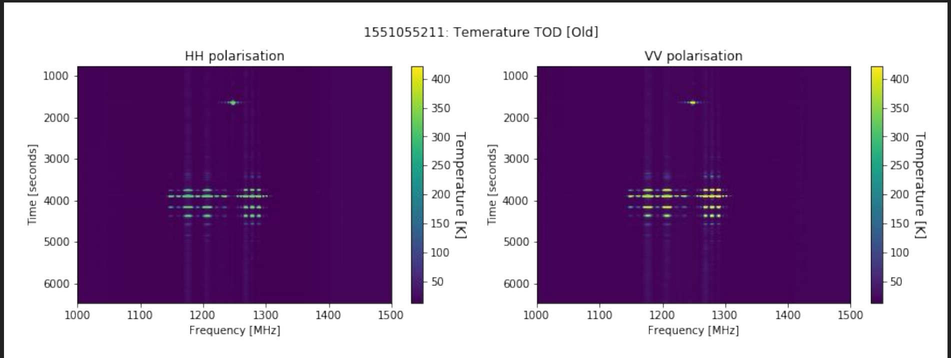
Handling MeerKAT data





Satellite infused TOD

a3 term



Satellite infused TOD

Satellite positioning & Telescope beam

Second stage:

Designed to be (radio) instrument independant

Satellite Positioning:

1. Tracking of satellites with respect to the telescope pointing
2. Identifying periods when satellite contamination is inevitable

Telescope beam:

i. Flexible beam application

Satellite positioning

Satellite Tracking:

Make use of the python package Skyfield and the positioning data (TLE) from CelesTrak

```
STARLINK-1007
1 44713C 19074A   22144.05382058  .00007555  00000-0  50641-3 0  1447
2 44713  53.0529 286.9678 0001557  63.1676 203.9990 15.06377160    17
STARLINK-1008
1 44714C 19074B   22144.03178469 -.00031975  00000-0 -21435-2 0  1448
2 44714  53.0528 287.0862 0001356  59.5787 202.8455 15.06410800    16
STARLINK-1009
1 44715C 19074C   22144.08940847 -.00009778  00000-0 -65539-3 0  1441
2 44715  53.0543 286.8287 0001301  76.6335 198.4981 15.06396236    11
```

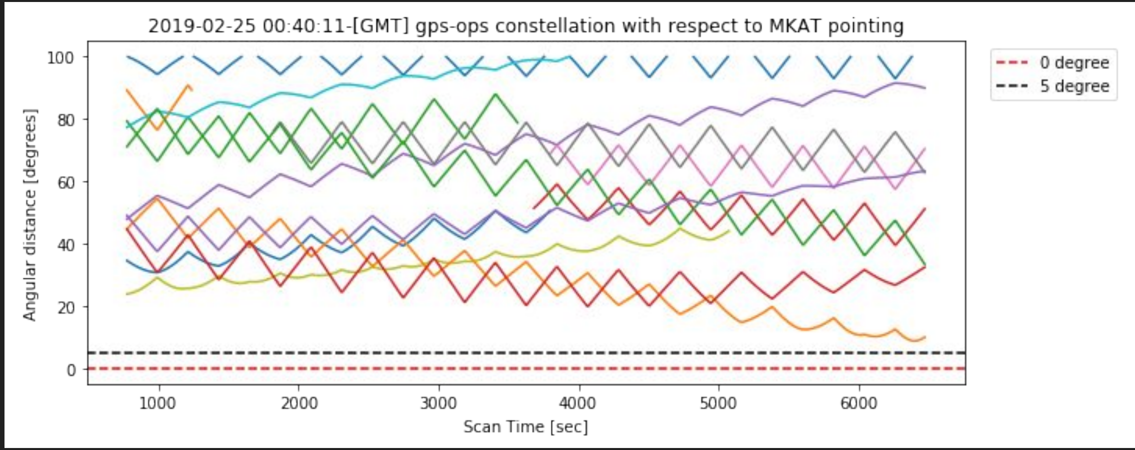
Credit:

Satellite positioning

Satellite Tracking:

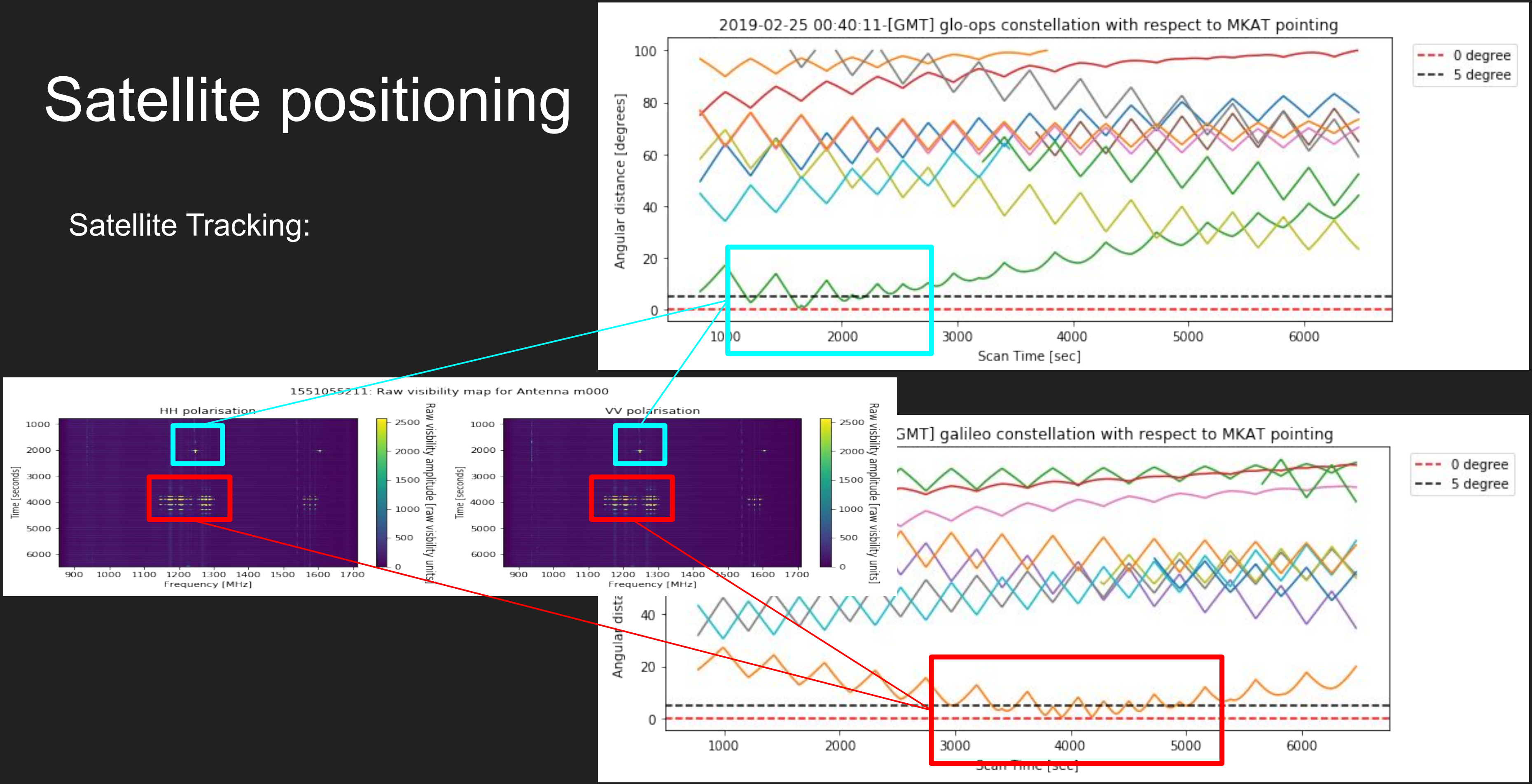
With respect to the telescope:

1. Timeline of observation [nd_s0]
2. Positional information of the telescope [Lat & Long]
3. Scanning strategy



Satellite positioning

Satellite Tracking:



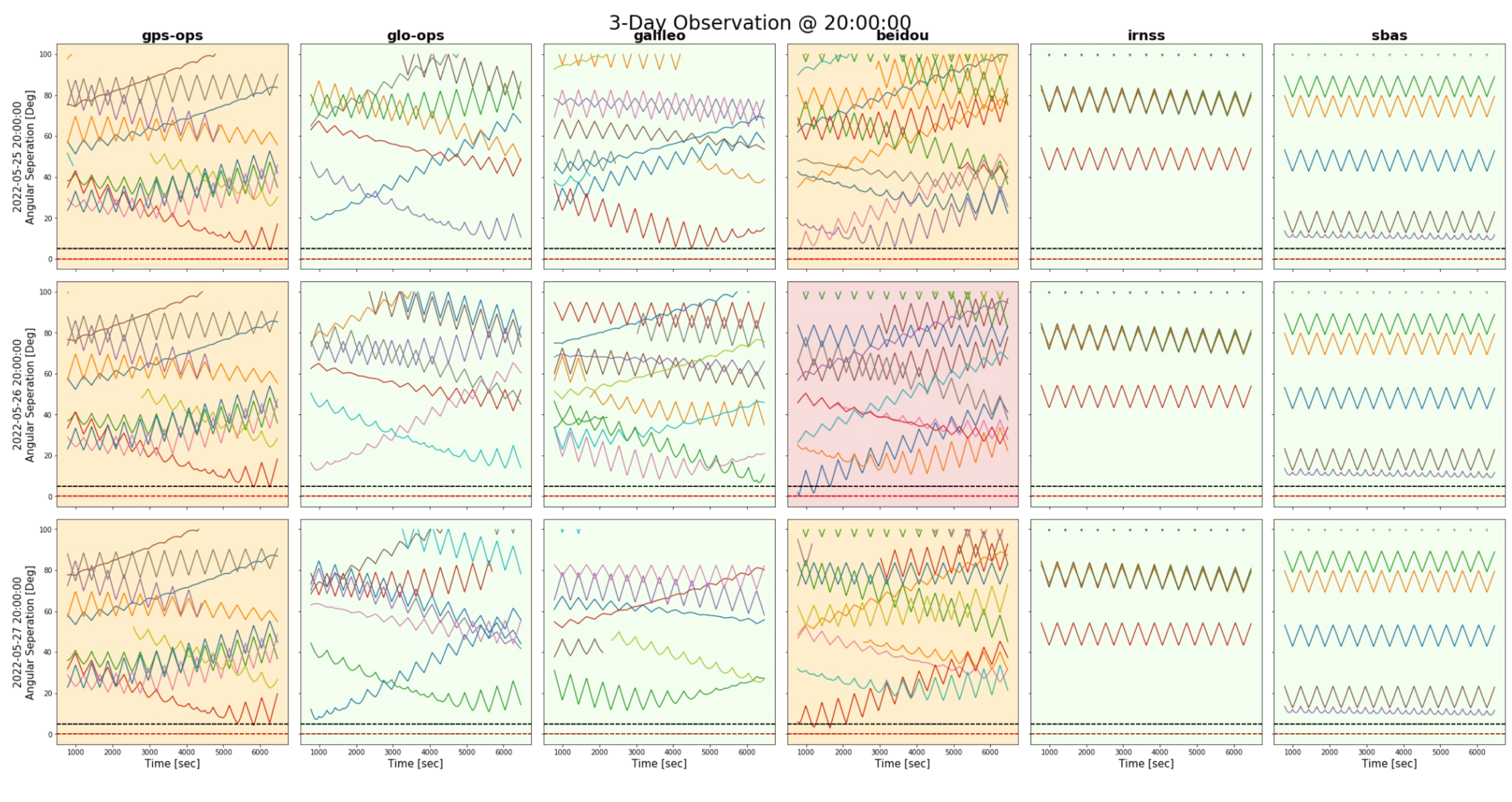
Satellite positioning

Satellite forecast

8pm@night

~ 1.5 hours

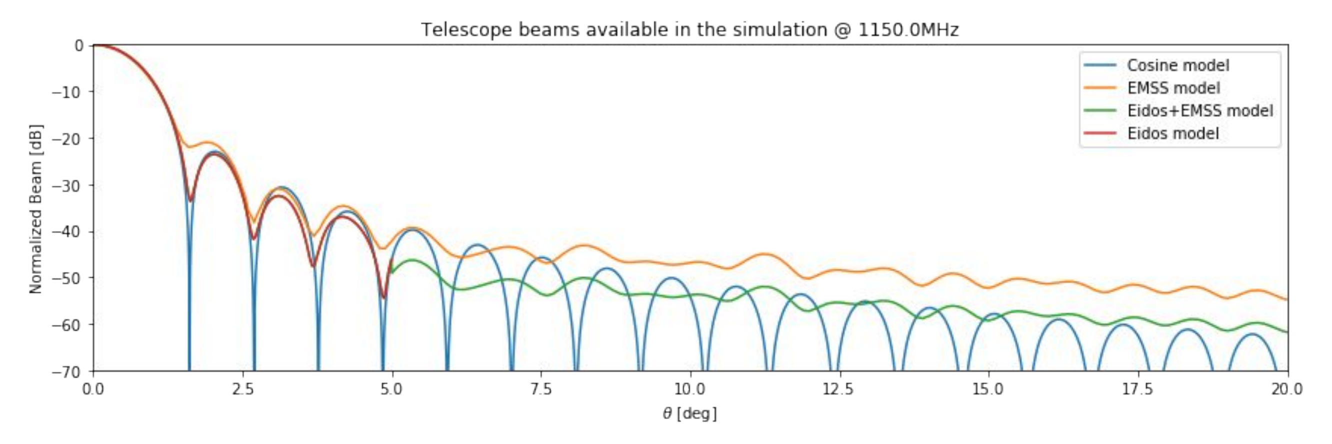
Same scan~WiggleZ



Telescope beam

Multiple beam options:

1. Eidos beam [Asad 2019]
2. Cosine beam
3. EMSS beam [SARAO engineers, In use]
4. Eidos+EMSS beam [work in progress]

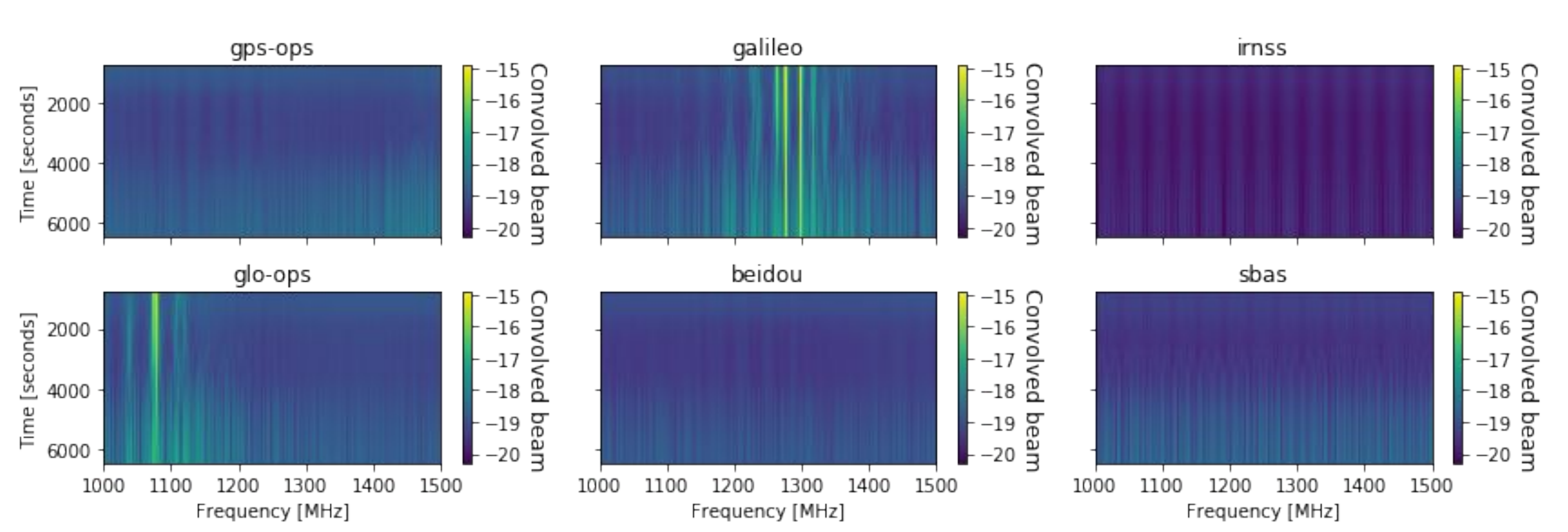


Note: Assuming beam symmetry

Satellite position X Telescope beam

1. Each satellite's angular position is calculate with the telescope beam
2. We include radius information from each individual satellite.

3. Each constellation is the sum of all the individual satellite contributions



Constellation estimation & fitting

Third stage:

Simulating satellite signal

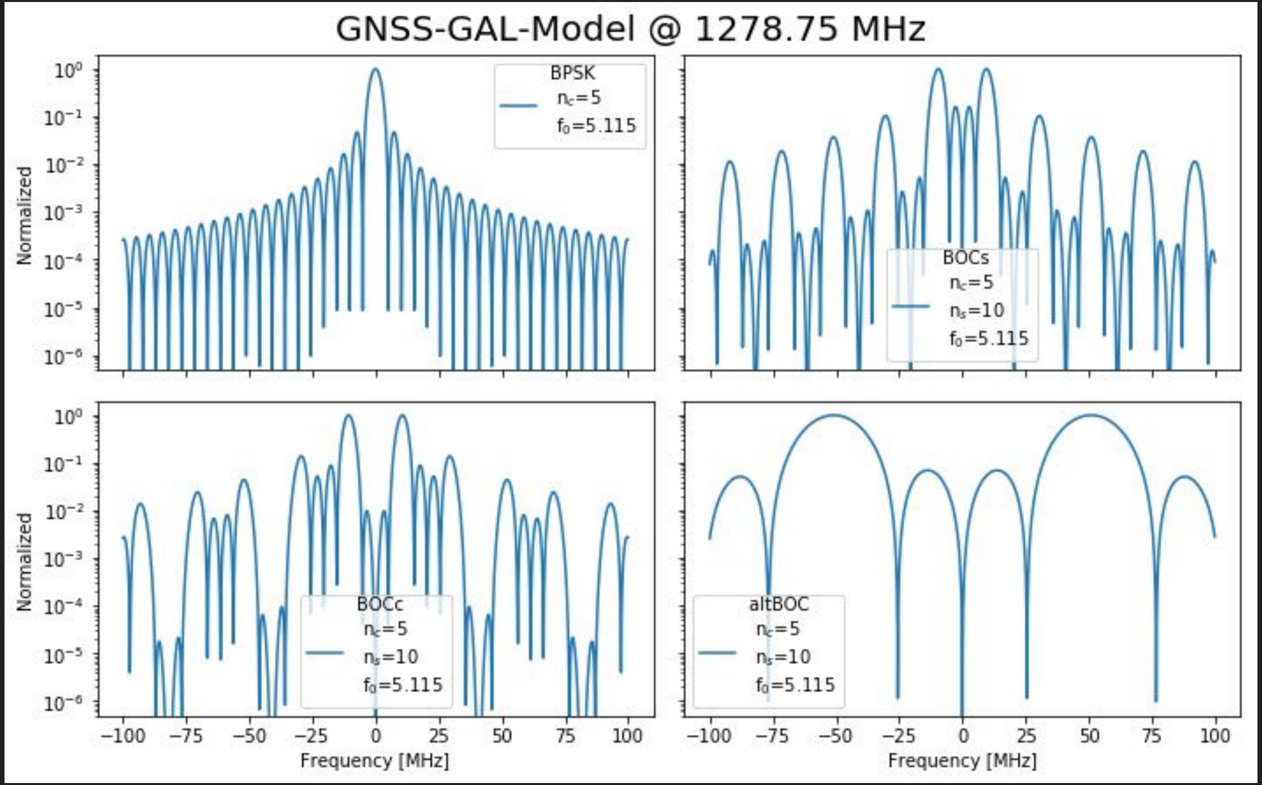
Constellation estimation:

1. Constellation signal catalogue
2. Chi Square fitting estimation

Constellation signal catalogue

	Sys	Band	Signal	Frequency[MHz]	Modulation	Rate(MHz)	P_t (dBW)	G_t (dBi)	Alpha
0	GPS	L1	P(Y)	1575.420	BPSK(10)	10.2300	13.5	13.5	1.5
1	GPS	L1	C/A	1575.420	BPSK(1)	1.0230	16.5	13.5	1.5
2	GPS	L1	L1C-D	1575.420	TMBOC(6,1,4/33)	1.0230	10.0	10.0	1.5
3	GPS	L1	M-D	1575.420	BOC(10,5)	5.1150	18.2	13.5	1.5
4	GPS	L2	P(Y)	1227.600	BPSK(10)	10.2300	10.0	10.0	1.5
5	GPS	L2	L2CM	1227.600	BPSK(1)	0.5115	10.0	10.0	1.5
6	GPS	L2	M-D	1227.600	BOC(10,5)	5.1150	16.0	13.5	1.5
7	GPS	L5	L5I	1176.450	BPSK(10)	10.2300	18.0	18.0	1.0
8	GLO	L1	L1SF(P)	1602.000	BPSK(5)	5.1100	10.0	10.0	0.6
9	GLO	L2	L2SF(P)	1245.100	BPSK(5)	5.1100	10.0	10.0	0.6
10	GLO	L2	L2OF(C/A)	1245.100	BPSK(0.5)	0.5110	10.0	10.0	0.6
11	GLO	L3	L3OC-D	1202.025	BPSK(10)	10.2300	10.0	10.0	0.6
12	GLO	L2	L2OC-D	1248.300	BPSK(1)	1.0230	13.0	12.0	0.6
13	GLO	L2	L2OC-P	1248.300	BOC(1,1)	0.5115	5.0	5.0	0.6
14	GAL	E1	OS-D(B)	1575.420	CBOC(6,1,1/11)	1.0230	10.0	10.0	0.6
15	GAL	E6	CS-P(C)	1278.750	BPSK(5)	5.1150	16.0	15.0	0.6

Satellite frequency structure



$$P_{\mathrm{BPSK}}(\nu, n_c) = \frac{\mathrm{sinc}(\nu/[n_c f_0])}{\sqrt{n_c f_0}}$$

Sinusoidal structure

Satellite Temperature

Beam model

Fitting parameter

Frequency structure

$$T_{\rm sat}(\Omega,\nu) = G_r(\nu)\frac{B_r(\Omega,\nu)}{r_{\rm sat}^2}\frac{\alpha P_{\rm sat}}{k_b\delta\nu}\frac{c^2}{4\pi\nu^2}$$

Distance of satellite

$$P_{\rm sat} = \frac{G_t P_t}{4\pi}$$

Transmitted gain

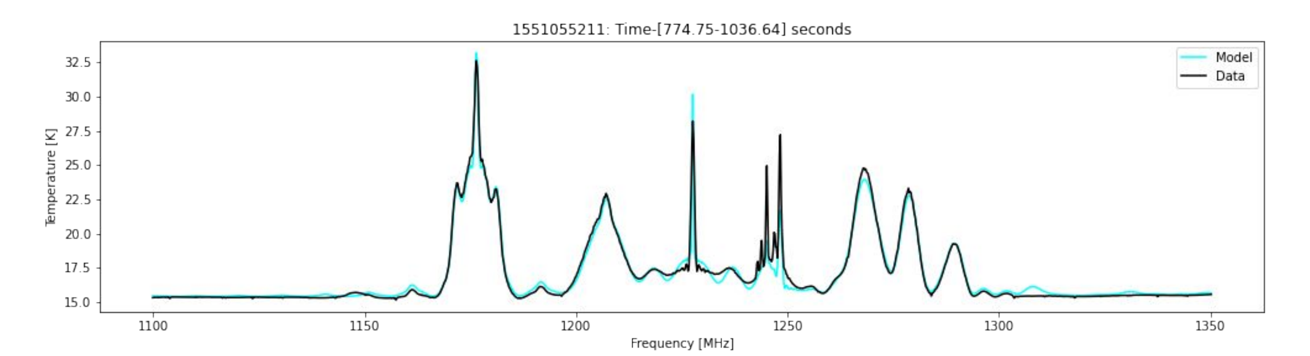
Transmitted power

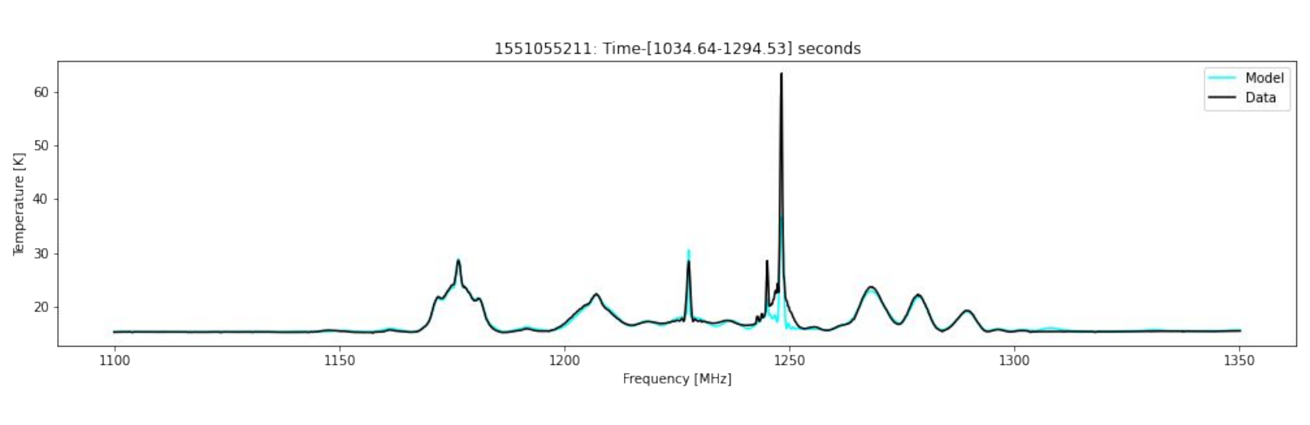
$$\chi^2 = \frac{\mathrm{Data} - T_{\rm sats}}{\sigma^2}$$

$$\sigma^2 = \frac{Data^2}{\delta t \delta \nu}$$

Chi square fitting & Radiometer Eq

Constellation estimation: Fitting alpha terms

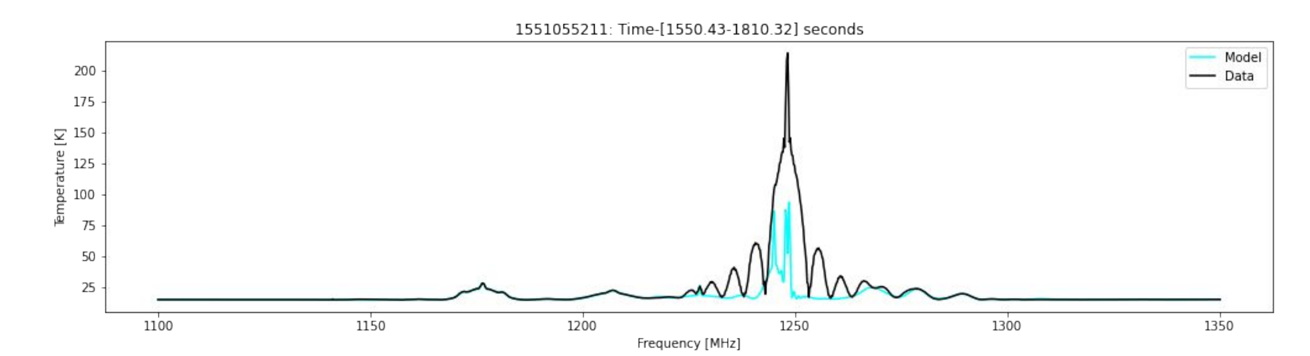


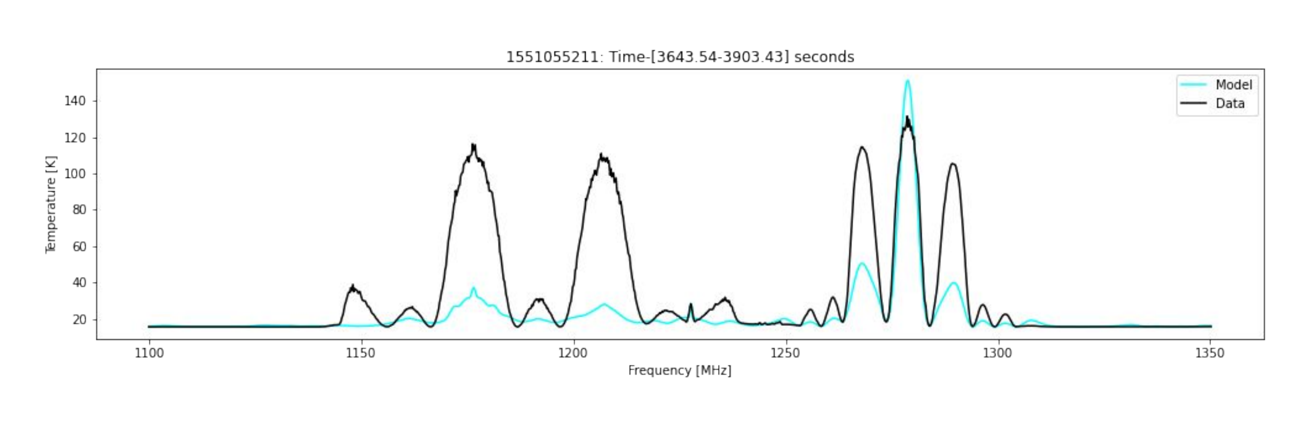


Fitting in smaller time chunks

Far from satellite intrusion

Constellation estimation: Fitting alpha terms



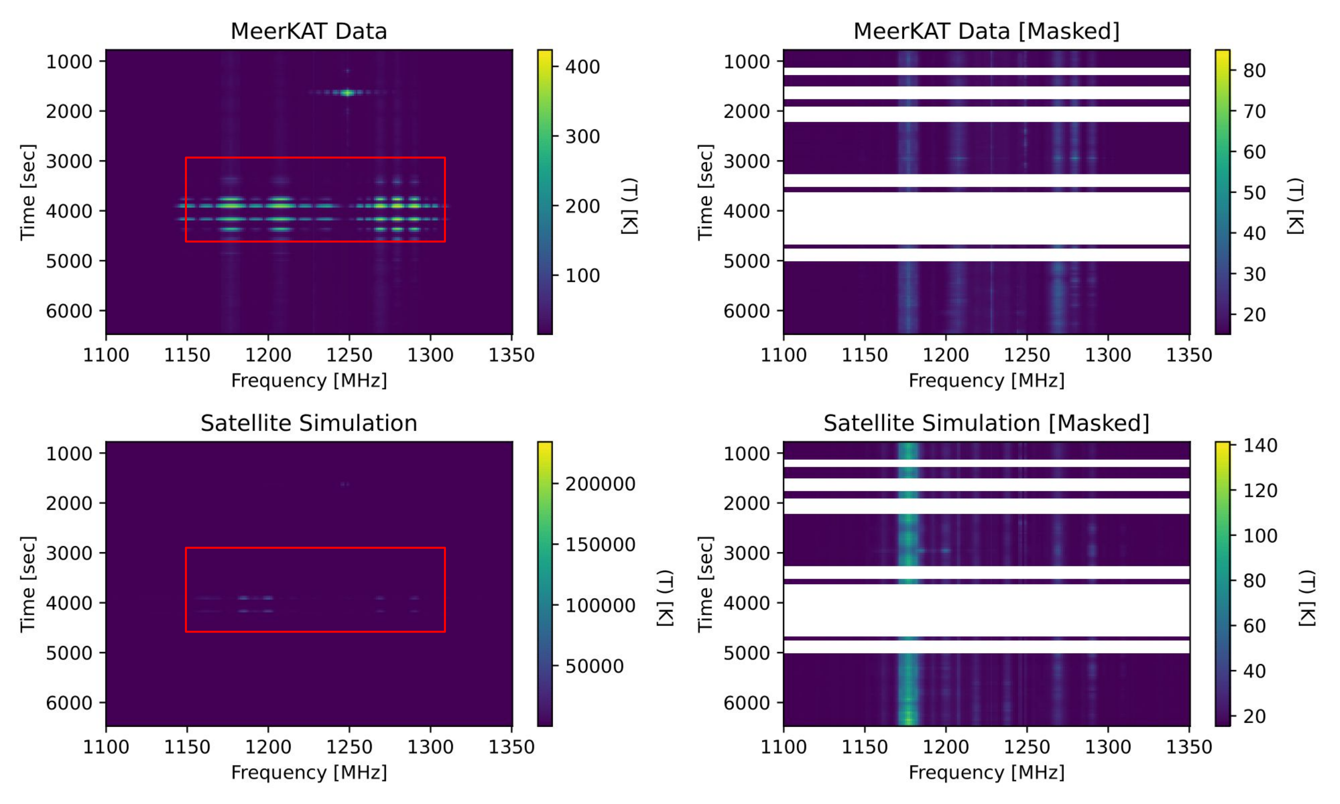


Fitting in smaller time chunks

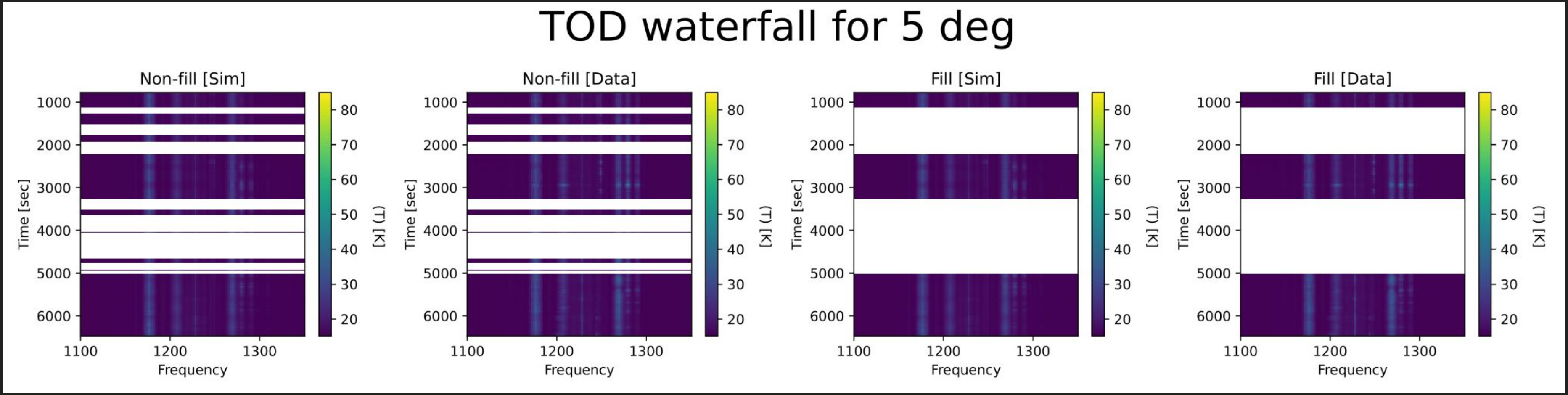
Near satellite intrusion

Simulation struggles to understand saturation

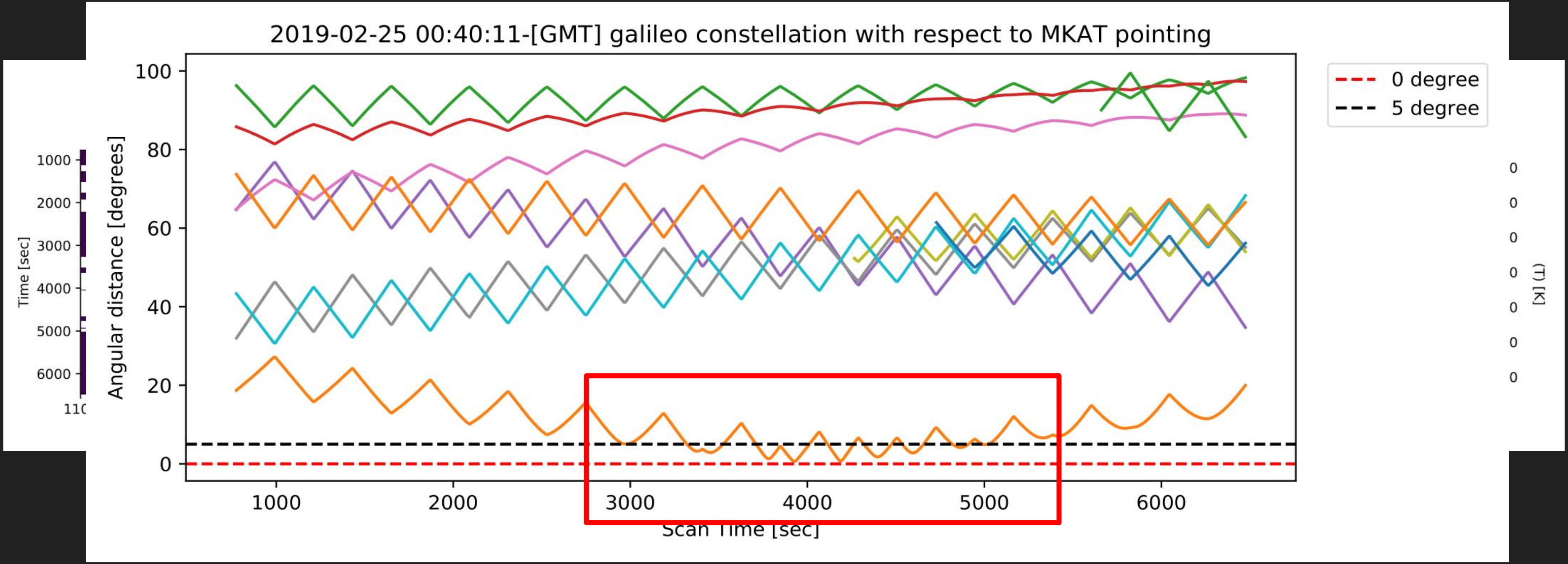
Constellation estimation: Masking data



Constellation estimation: Masking data in degrees

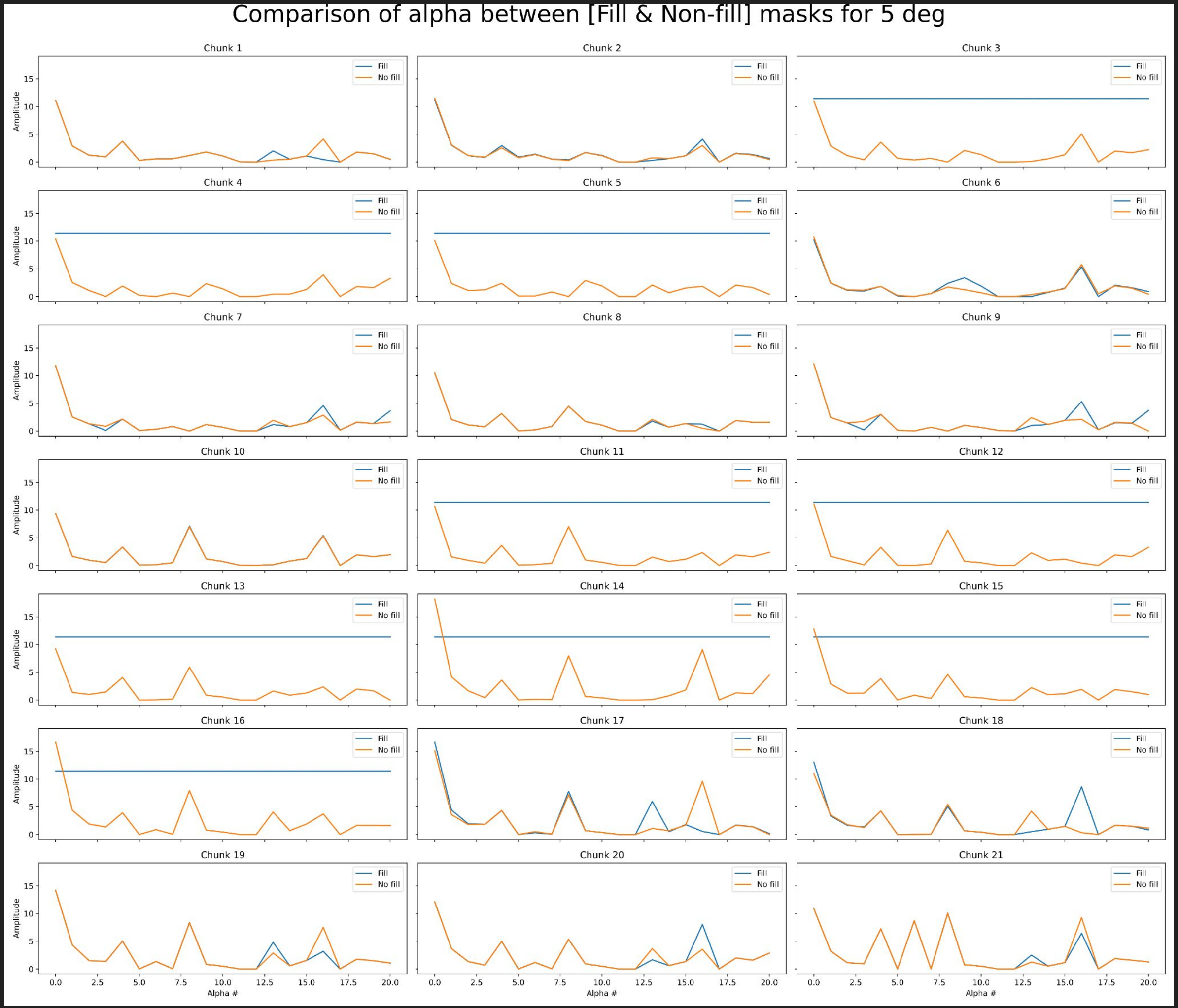


Constellation estimation: Masking data in degrees



Comparing the fitting parameter

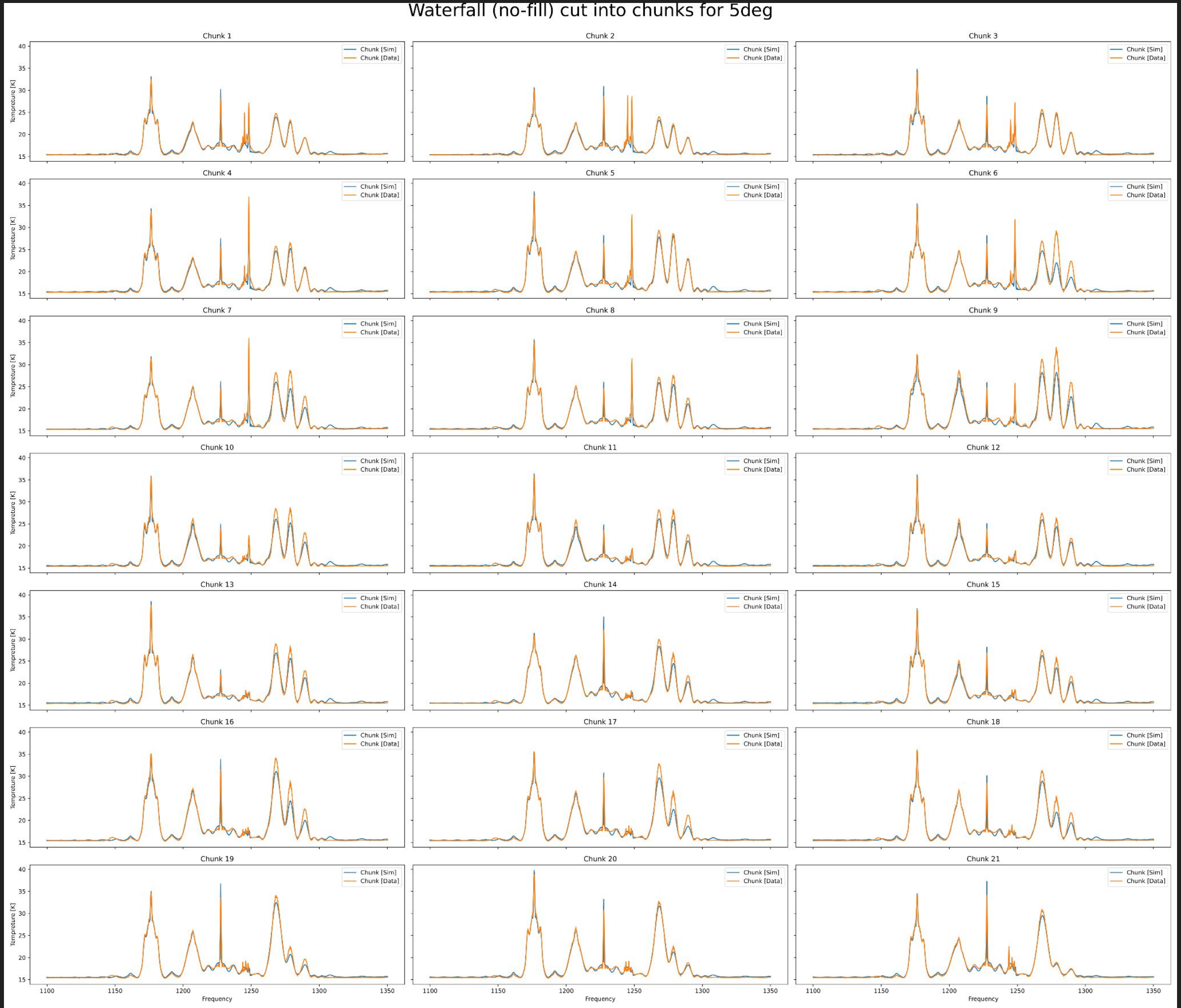
We looked at shuffling the parameters



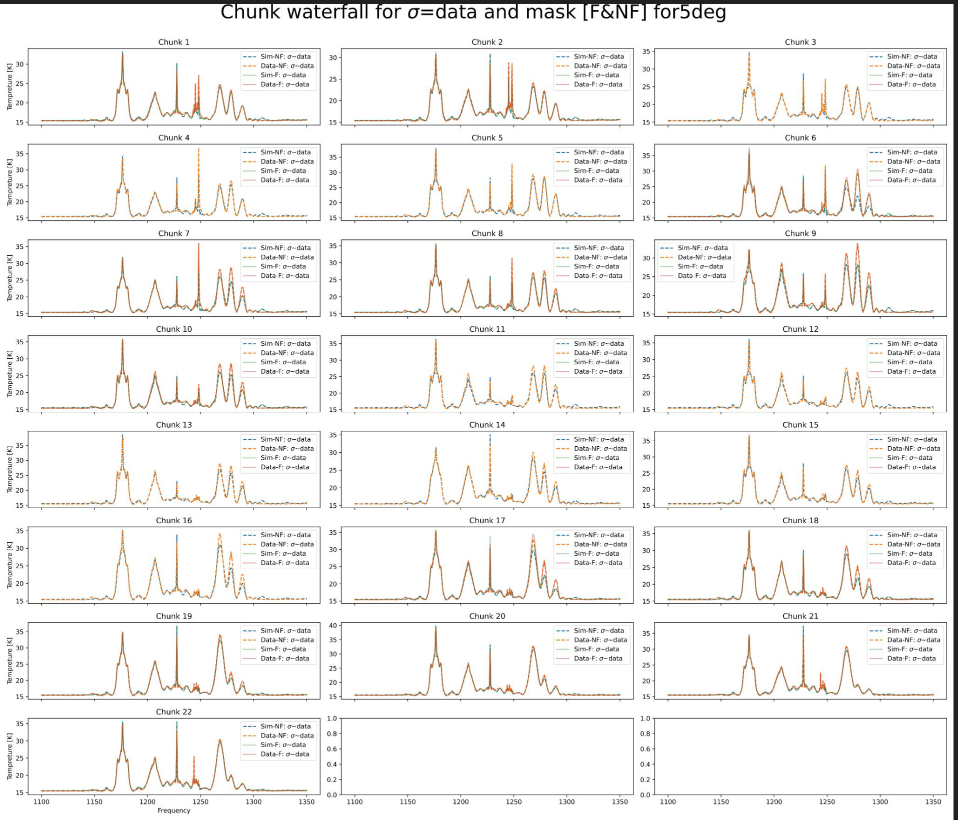
Comparing the non-fill mask

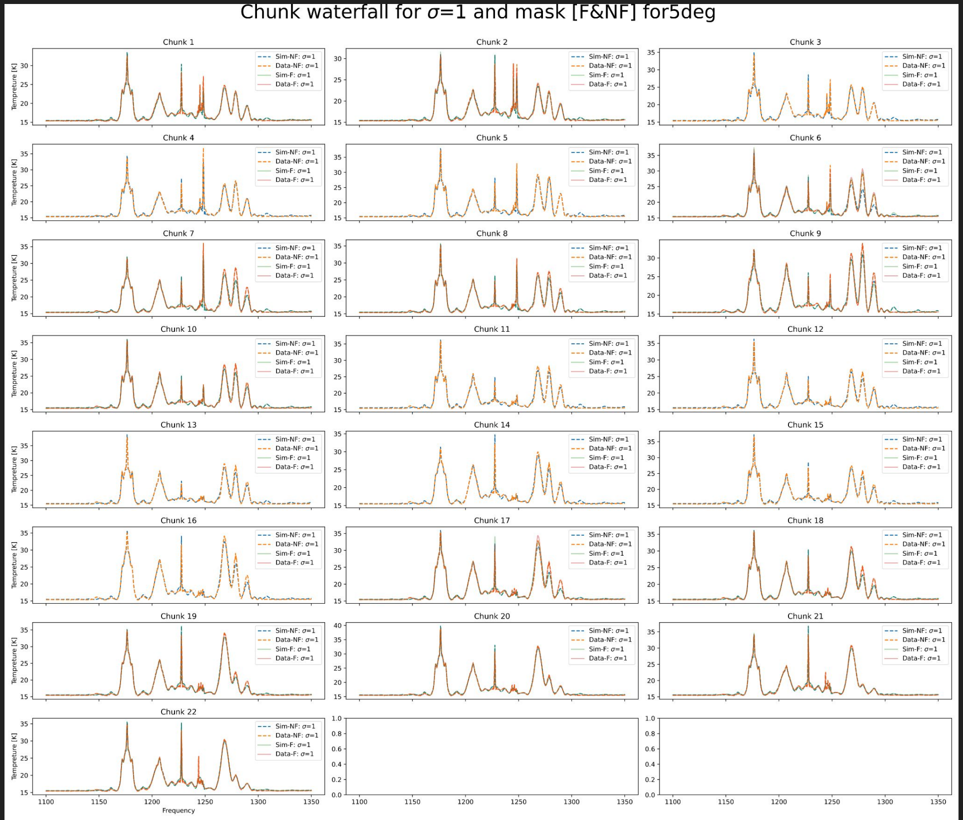
Structure overlay is present

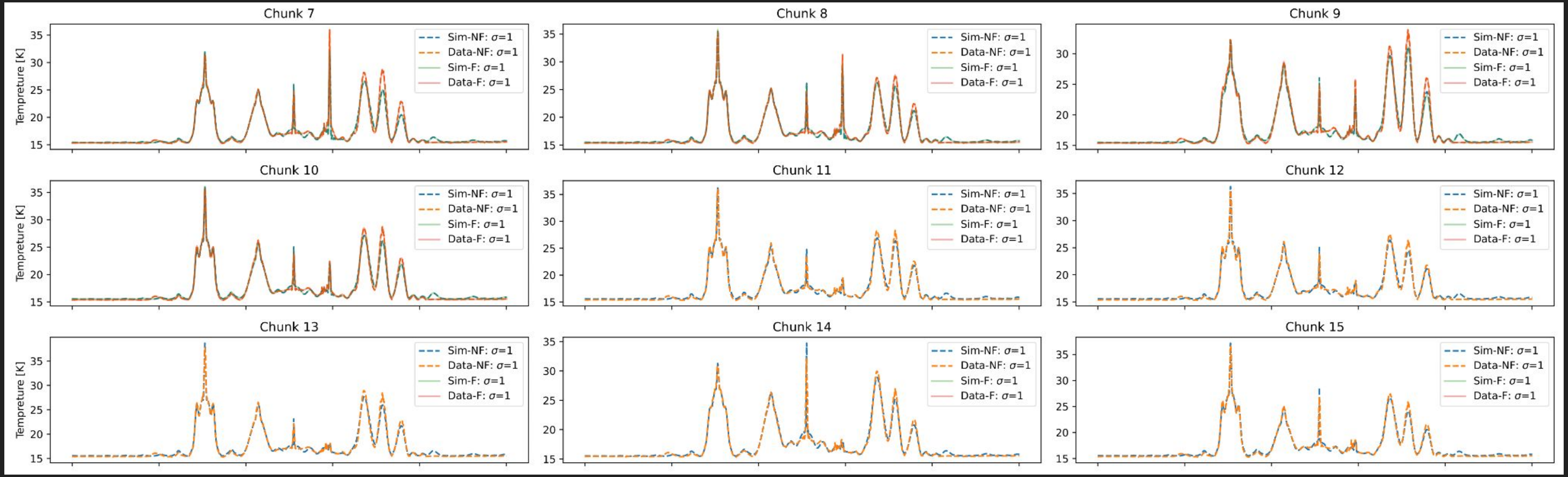
Amplitude offset at the peaks



Constellation estimation: Varying the radiometer eq

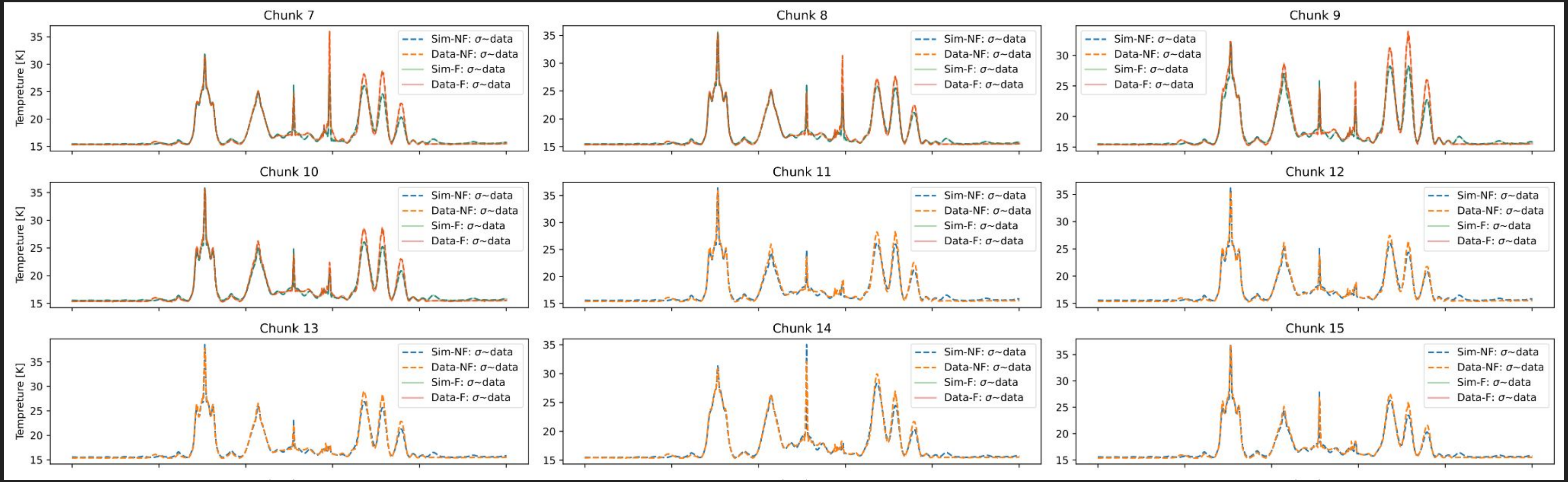






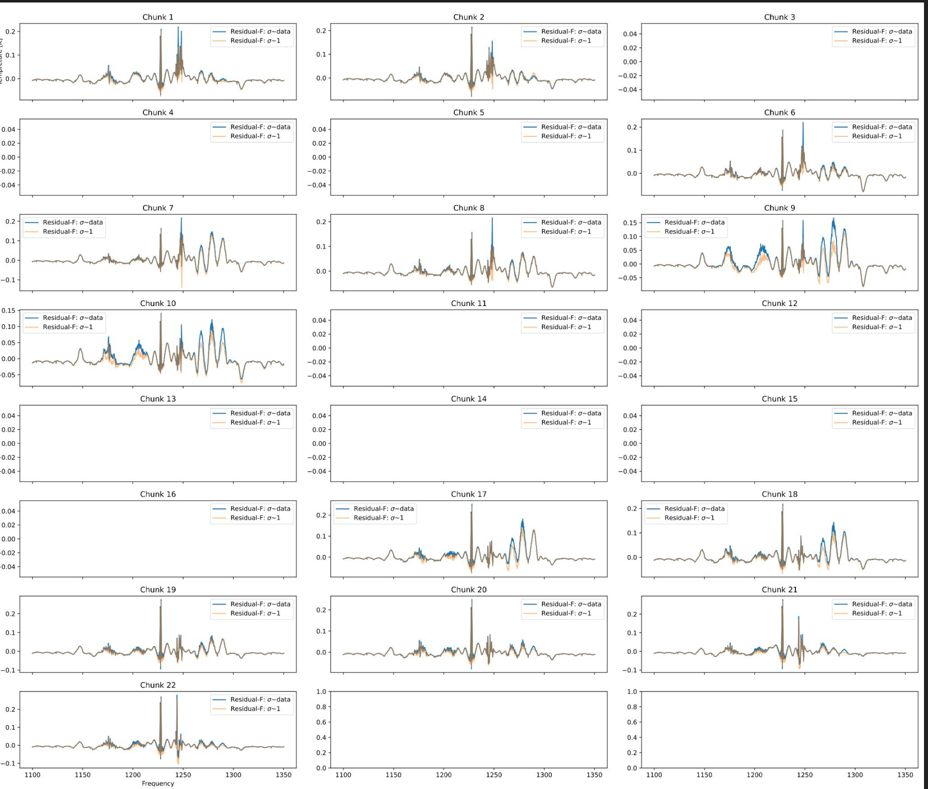
sigma=1

sigma=data

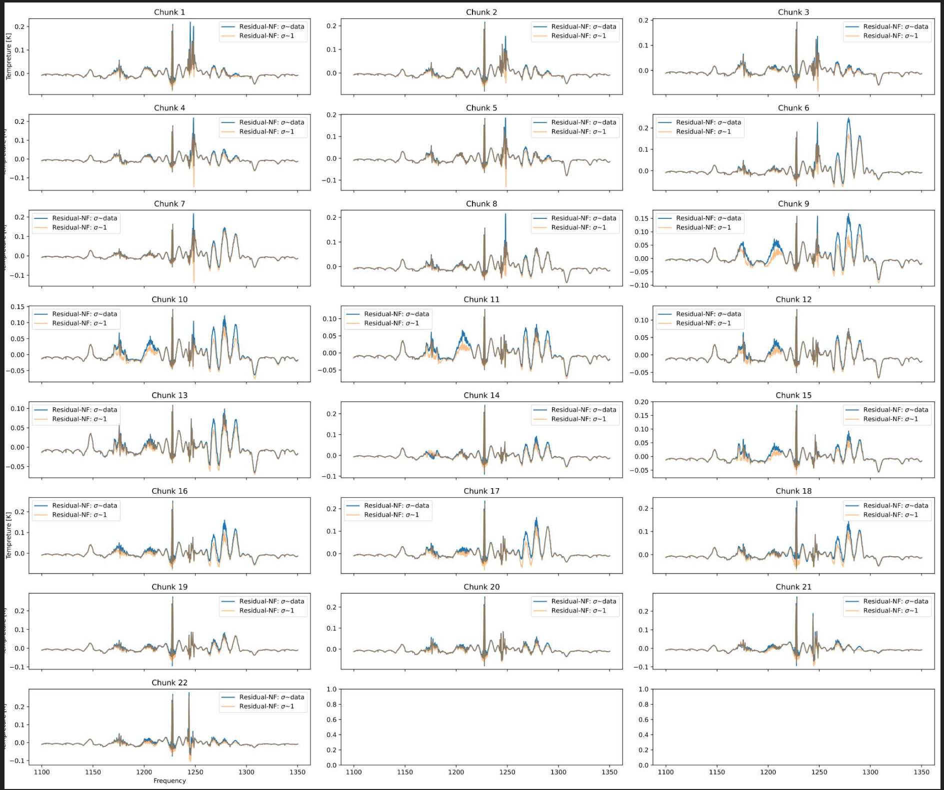


Constellation estimation: Residuals of variation

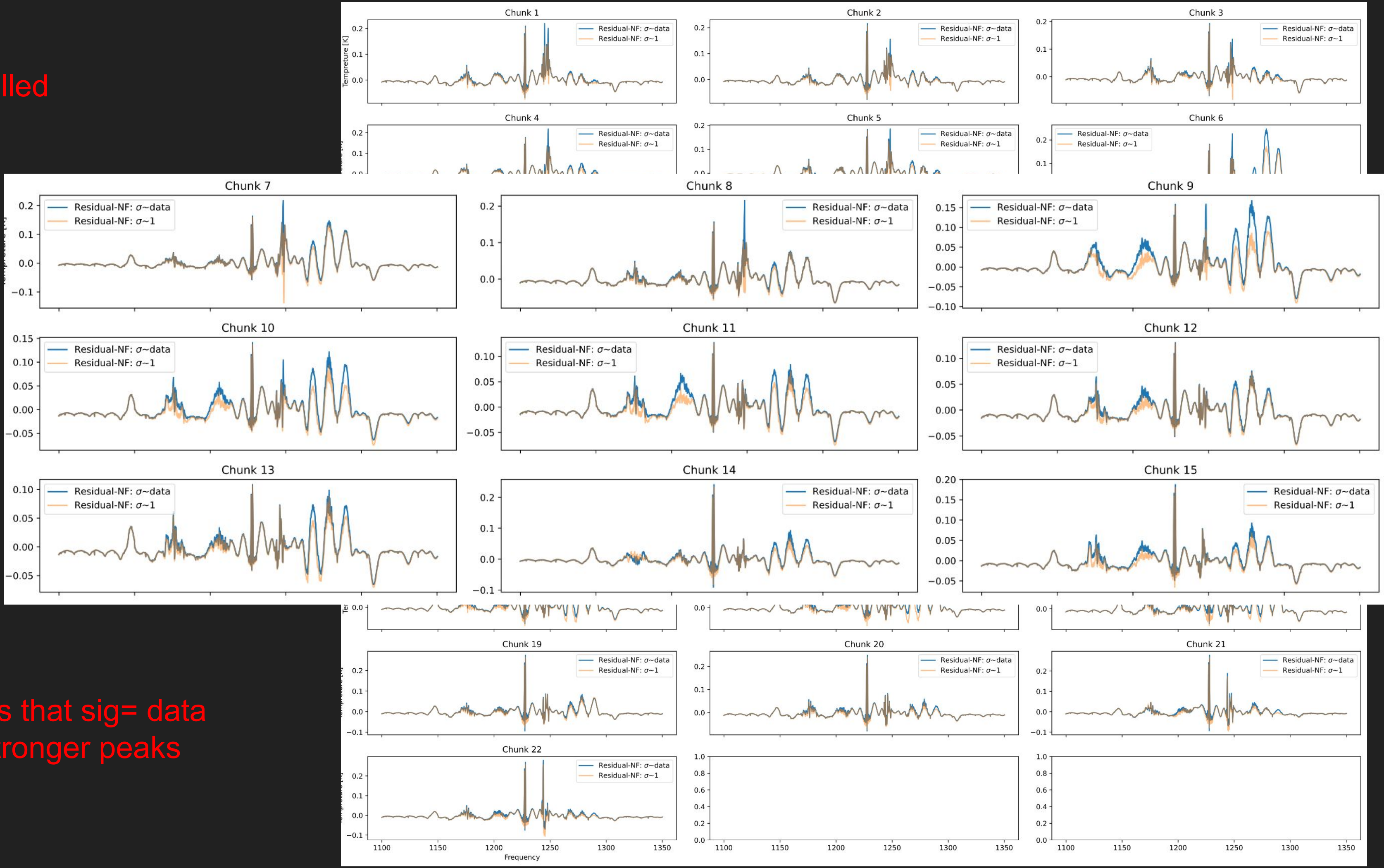
Mask is filled out



Mask is **not** filled out



Mask non-filled



sig=1 shows that sig= data dampens stronger peaks

Discussion

- Alpha parameters partially fit the simulation to the data.
- When satellites cross the pointing, the simulation cannot fit well to the data.
- Masking
- Chi-square with sig=1 resulted in a small improvement over all chunks
- Possible concerns:
  - Delay timing between the satellite position in the simulations versus in the data might have an offset.
  - The alphas are fitting more than the satellite power, fitting for the background level as well.
  - Out of band emission.
- Looking at applying a new frequency bandpass.

The other method…..