



Advantages of a wide Field-of-view camera for galaxy survey and its data reduction techniques.

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30/11/2020



I. Introduction

II. Data reduction pipeline and image synthesis

III. Sky removal

IV. Introducing new ChunkPCA algorithm

V. Beam characteristics of the MKID camera

VI. Advantages of the pipeline

VII. Conclusion

Introduction

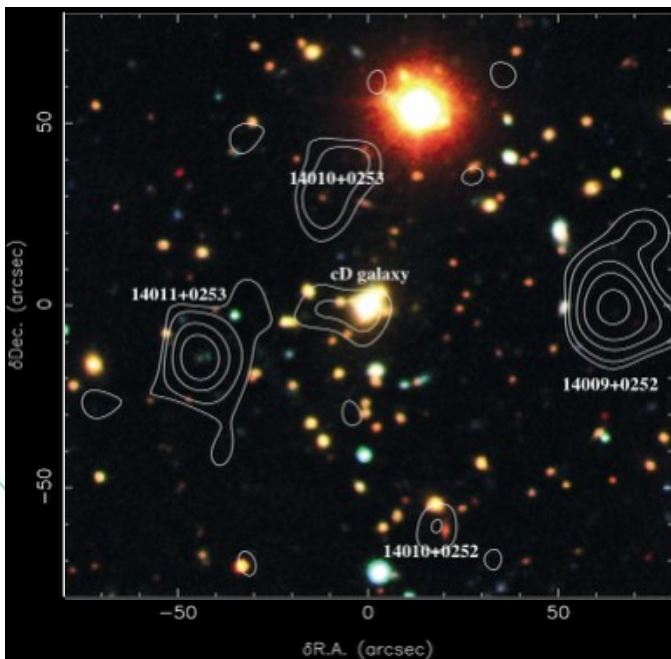


MKID camera: A superconducting based on microwave kinetic inductance detectors to observe 100 GHz bands with Nobeyama 45-m camera.

Objective -

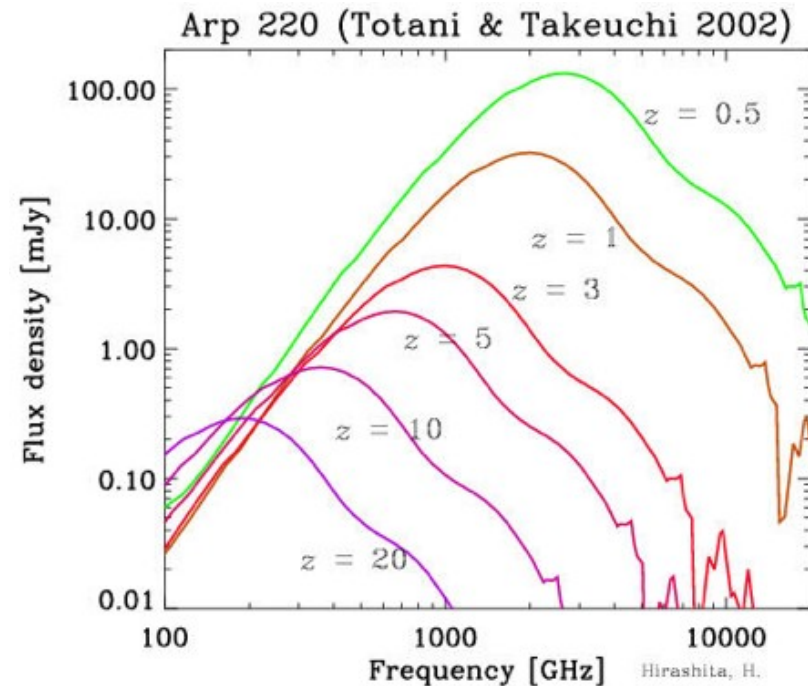
- Survey the massive star forming regions of the Galactic plane in 100 GHz.
- Distant galaxy survey to understand the star-formation, history and evolution process of galaxies.

Optical (color) : near galaxy
350 GHz : distant galaxy



Blain et al. 2001

Peak freq. Of BB emission (from dust) is shifted for high redshift.
100 GHz is good freq for high Z



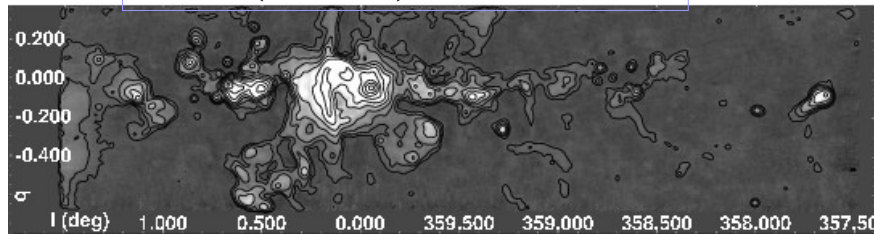
Introduction



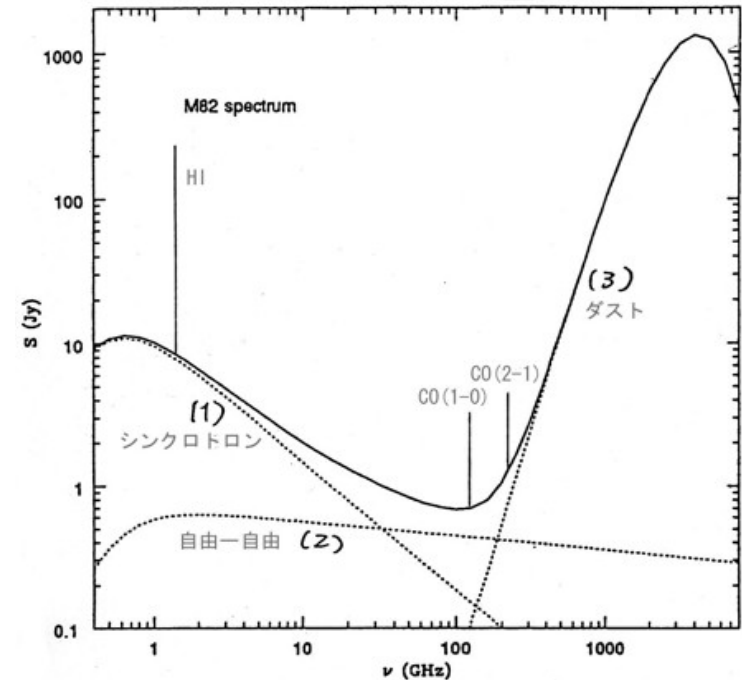
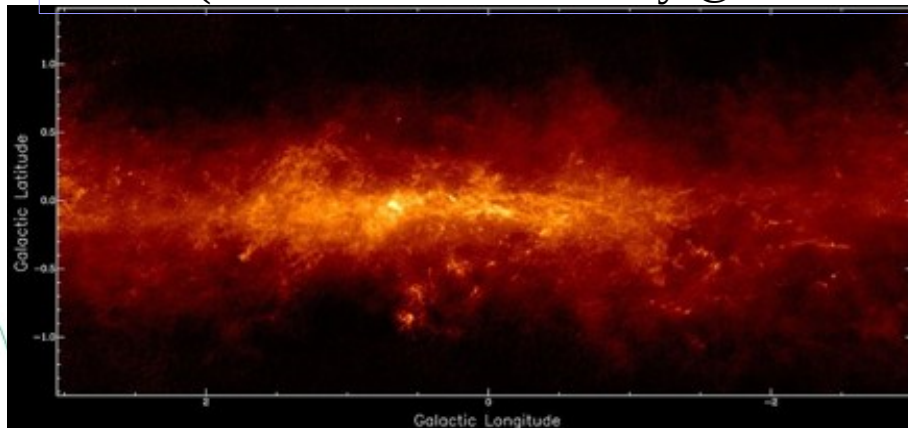
Objective Galactic plane survey

- Observation of massive star forming region with large FoV and high spatial resolution.
- Free-free emission is dominant at the the 100-GHz continuum observation
 - Good tracer of the massive star forming region (HII region)
- Physical properties will be determined by comparing the synchrotron and dust emissions

GBT (3.5cm), Law + 2014



APEX (The ATLASGAL survey @ 350 GHz)



Credit: Csengeri+2016

Nobeyama 45m telescope



Altitude	1350 m
Diameter of antenna	45 m
Surface accuracy	0.1mm
Frequency	20 ~ 150 GHz
Angular resolution	0.004°/14.4"
Weight	700 tons



Photo by Atsushi Nakazawa

Camera Optics

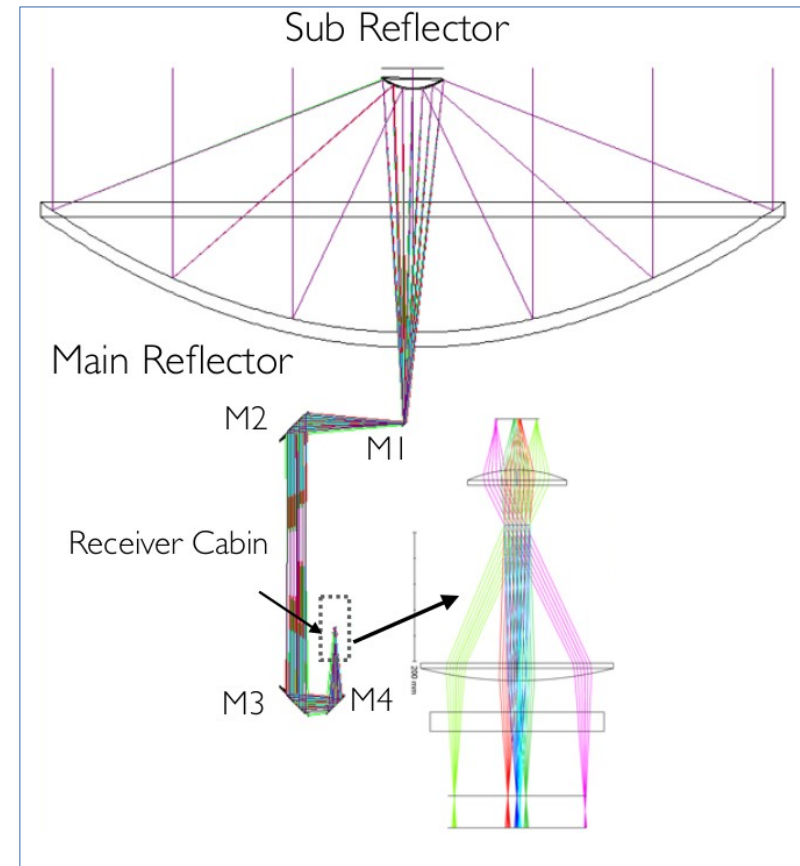


Camera was installed in the Nobeyama 45-m telescope from 10th May to 1st June, 2018.

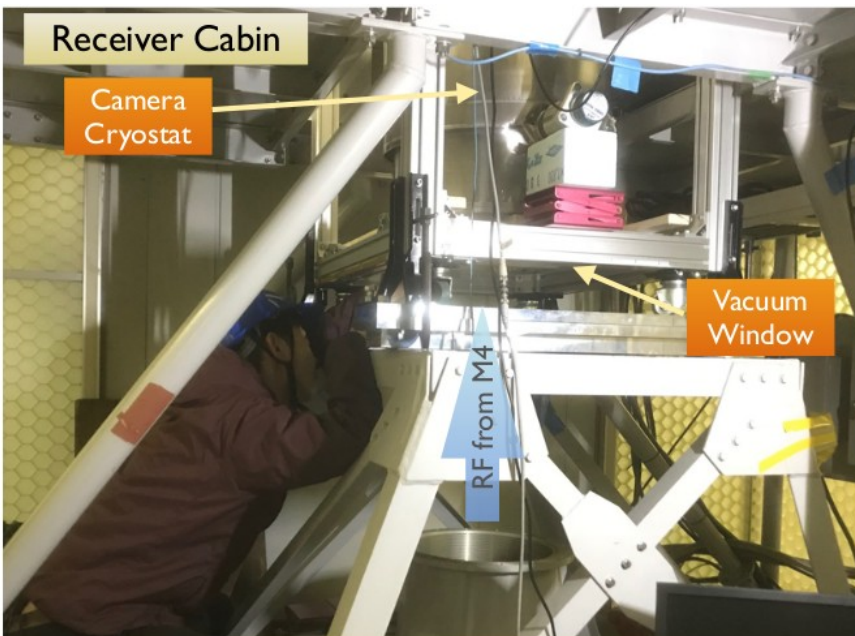
The Nobeyama 45-m telescope has an optics leading the beam to the camera.

Works by raster scan

Optics of 45-m telescope & MKID camera



T. Nitta et al., 2018



T. Nitta et al., 2018

Camera cryostat at the Receiver Cabin

Cryostat and Focal Plane Array

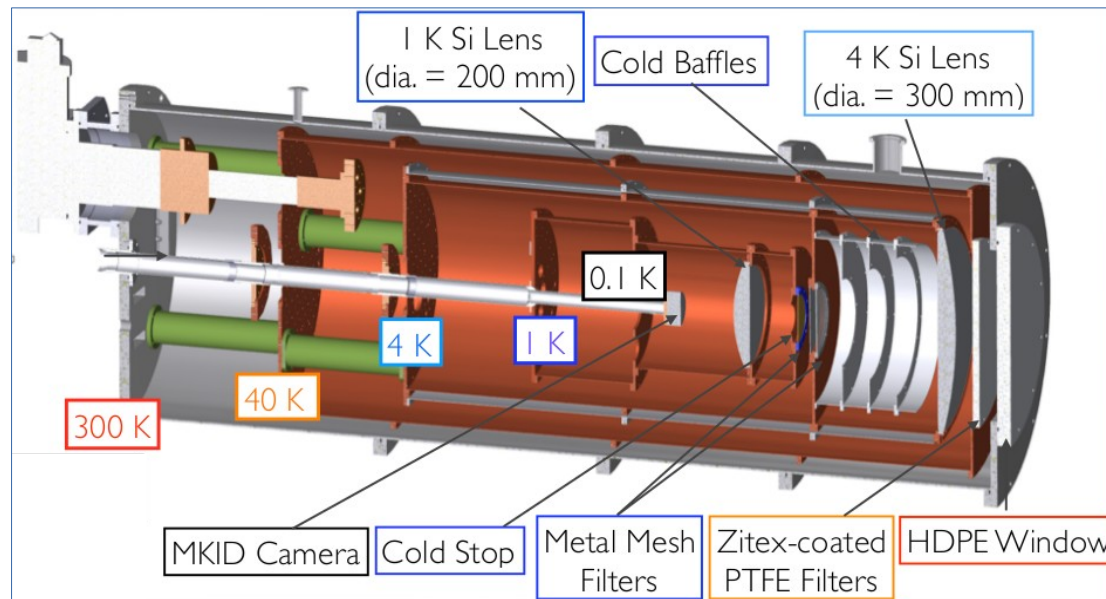


The refractive type cold re-imaging optics has two silicon lenses.

Purpose- Coupling from a telescope focus of $F/5.6$ to a focal plane of $F/2$. Field of view (FoV) of the camera is around $3'$, which is limited by the telescope optics.

The cold optics is composed of -

- Two Si lenses 154mm(1K) and 300mm(4K),
- Zitex coated PTFE and Nylon filters,
- Cold baffle for reducing the stray light
- Metal-mesh filters with 120 and 300GHz cutoff
- 1K cold stop



T. Nitta et al., 2018

Camera cryostat

Cryostat and Focal Plane Array



The focal plane array of the camera

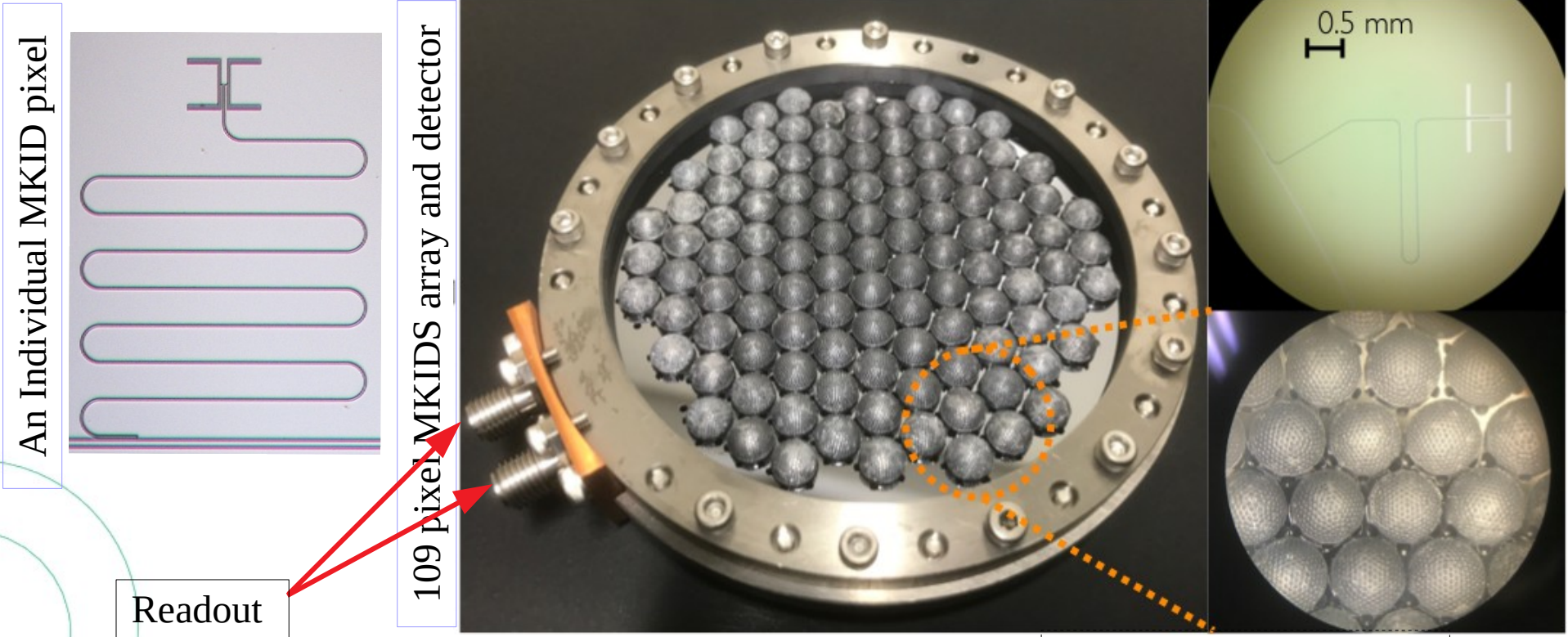
- 109 pixels antenna-coupled Microwave Kinetic Inductance Detectors (MKID) array and the glass-beads coated silicon (Si) lens array. 3 inch area.

MKID consists of

- coplanar-waveguide $\lambda/4$ resonator
- double-slot antenna.
- 150nm Al film is deposited on the Si wafer

Si lens array – diameter - 5.7mm, glass beads coating anti-reflection coating. (30% reflect)

Purpose - to produce low side-lobe beam pattern..



An Individual MKID pixel

109 pixel MKIDS array and detector

Readout

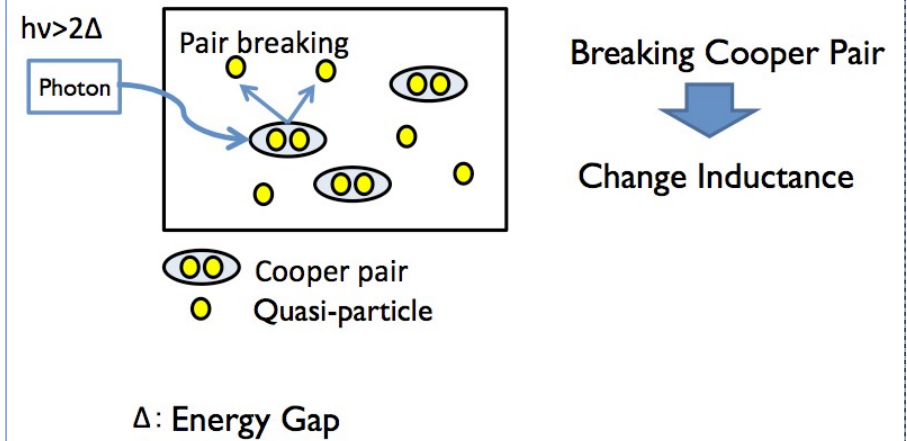
MKID Working Principle



The Microwave Kinetic Inductance Detector (MKIDs) consists of:

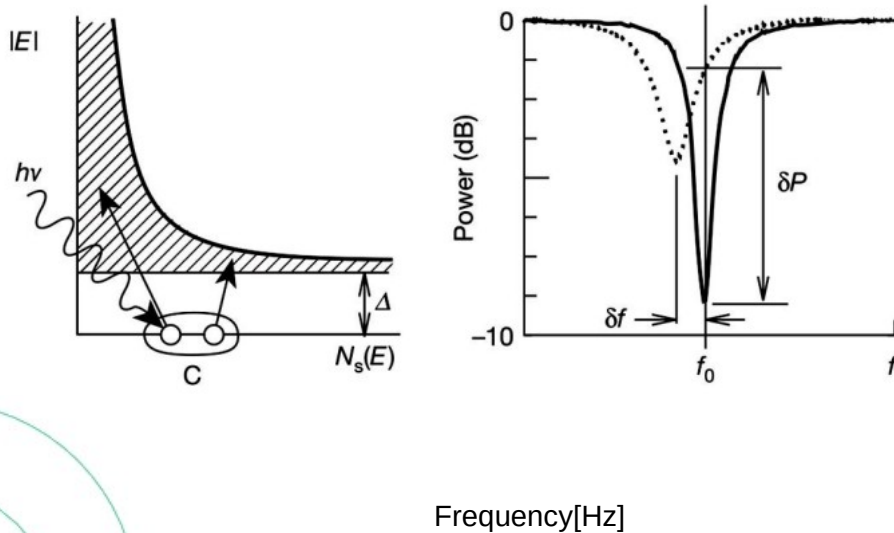
- A feedline,
- Several resonators (specific resonant frequency)

Resonators fed with resonant frequency through a capacitive coupling with the feed line.

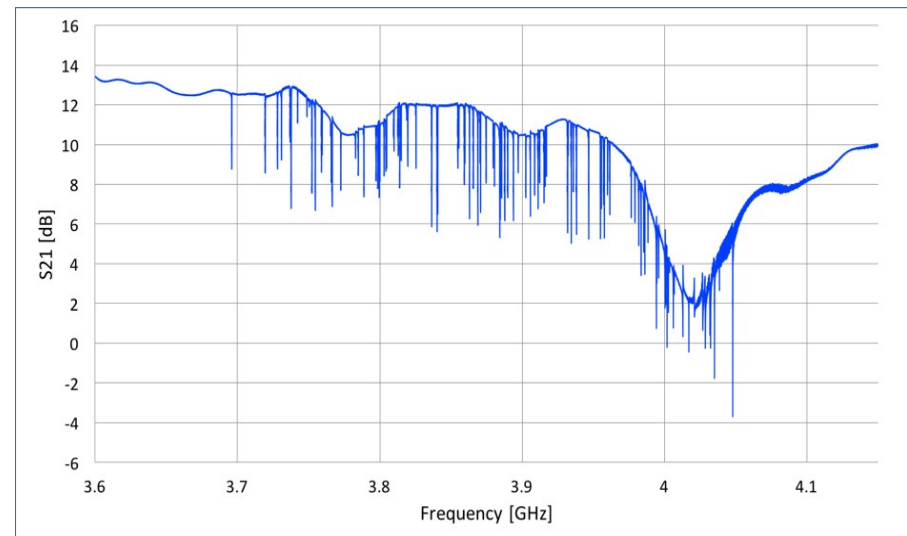


K. Hattori et al., 2013

P.K. Day et al., 2003



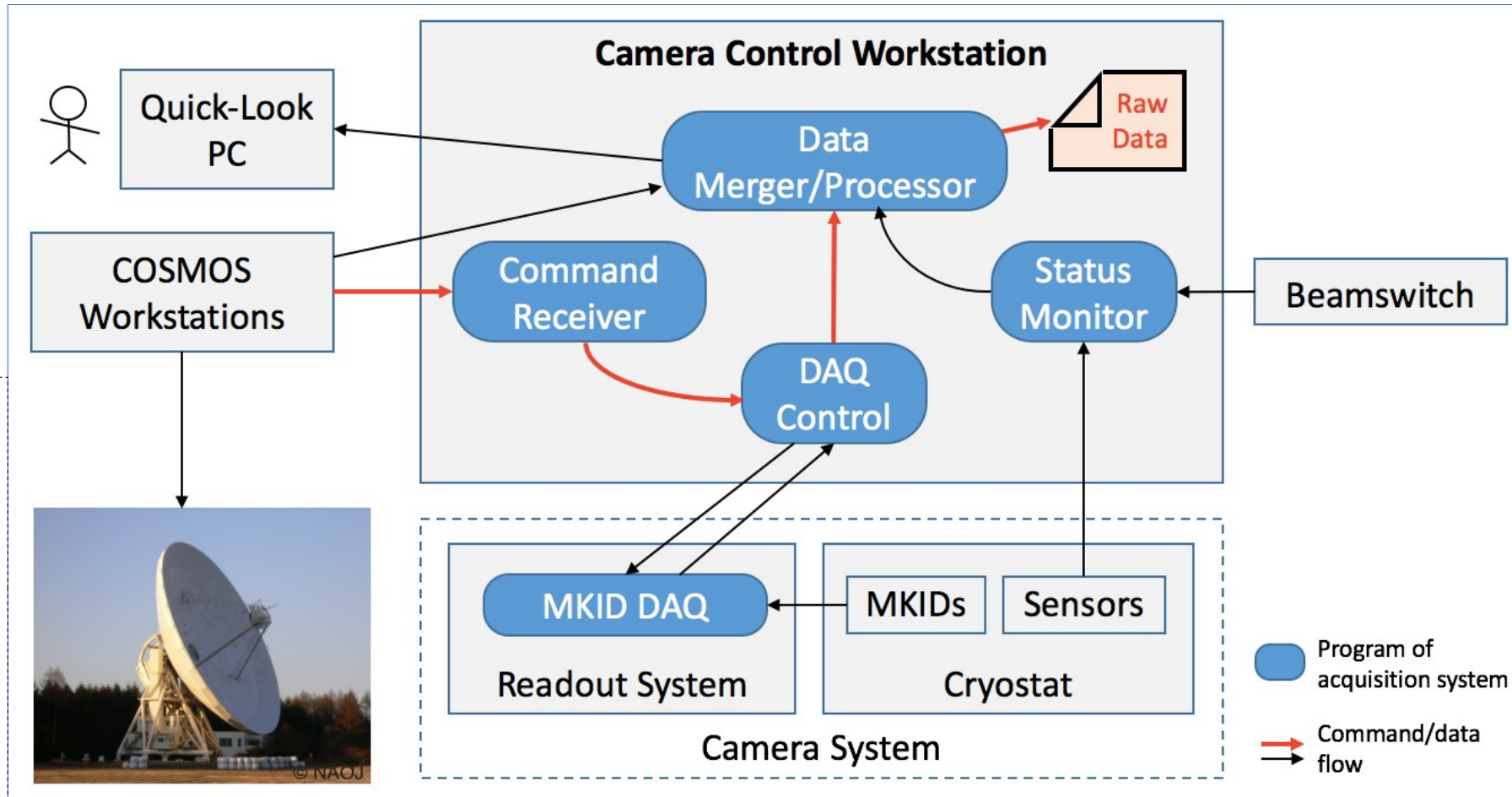
Temperature dependence on frequency



T. Nitta et al., 2018

A typical S21 from a MKID readout.

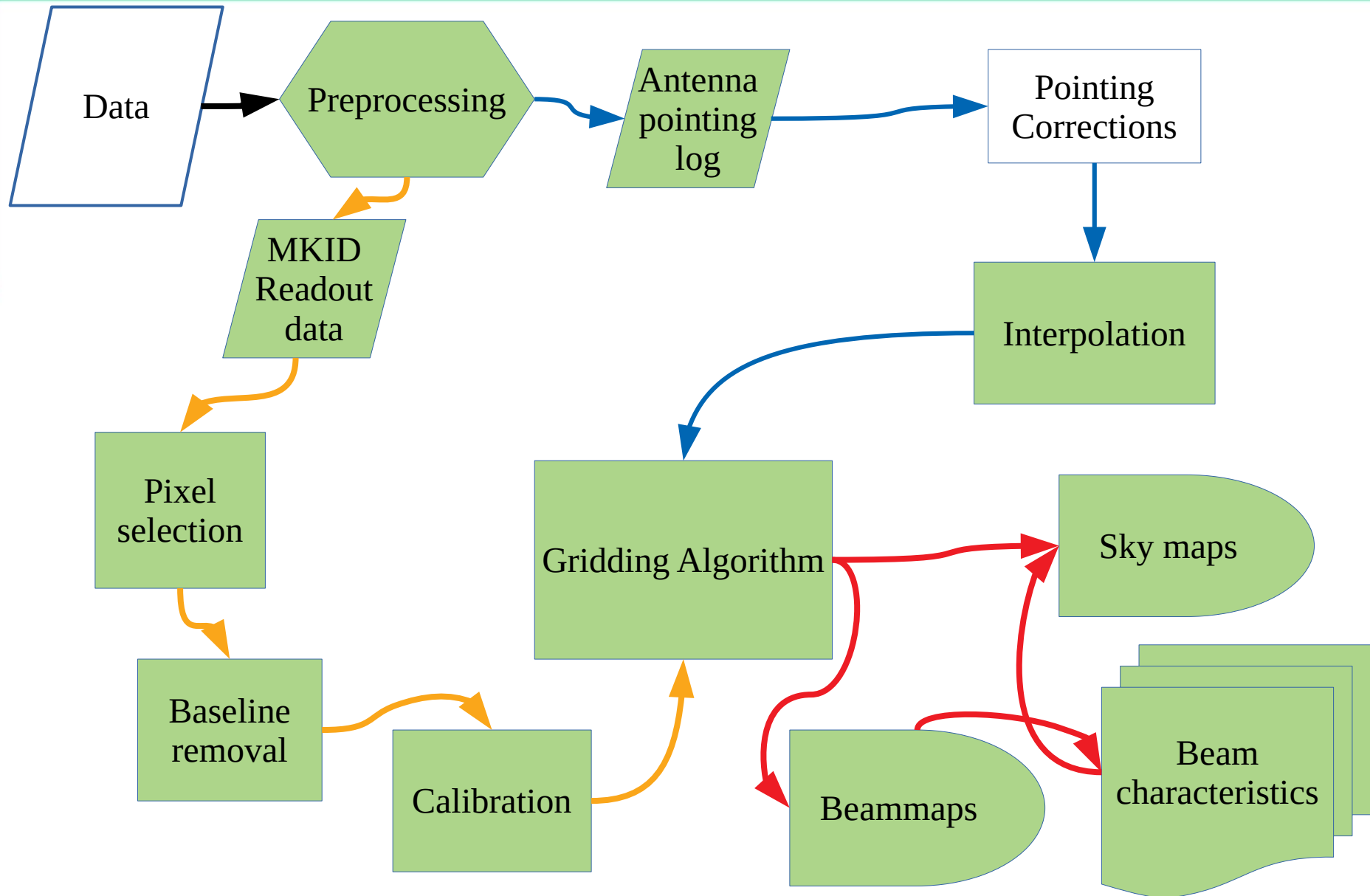
Data Acquisition System



T. Nitta et al., 2018



II). Pipeline Workflow



This thesis presents all the work that has been done shown in Green here.



a). Baseline Removal

Fluctuations in observed data caused by variations in Sky due to weather and atmospheric changes, as well as variation in the electronic readout system.

Baseline removal using **median filter**:

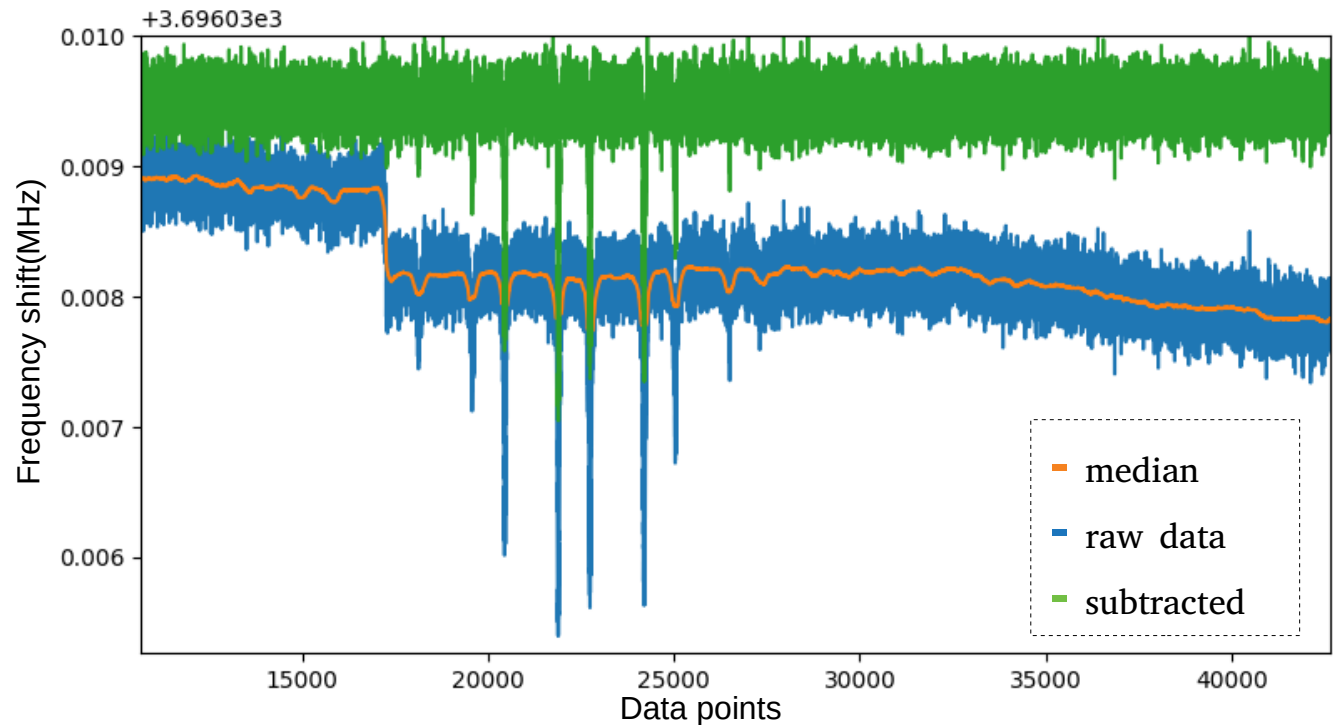
- A median filter is a method where a 'window' is defined and the median is calculated for the window.
- Extensively used for denoising. Being a very fast method to implement, it is used to preview the data in some cases.

Pros:

Easy and fast to use.

Cons:

Not enough control on baseline determination.
(low-high freq. noise)



PCA



Principal Component Analysis(PCA) is a method of transforming correlated dataset of observations **into linearly uncorrelated variables**. The uncorrelated variables are then used on the observations to **represent the dataset in reduced dimensions**.

Explanation:

Step 1: Arrange the dataset.

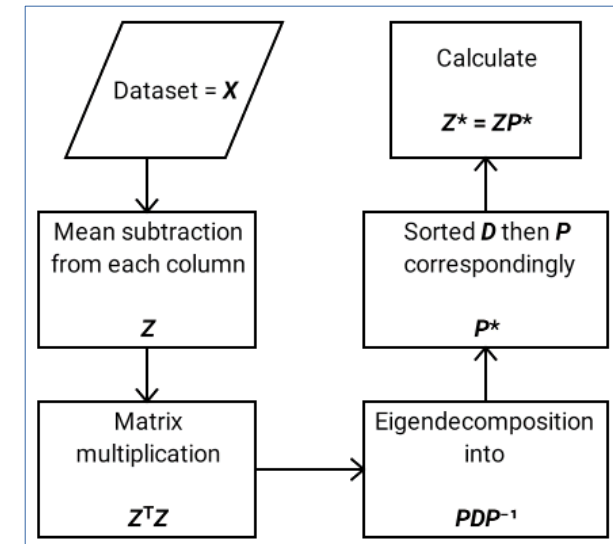
n: data points per sample(number = length of observation * sampling rate)

p: Time Order Data(number = number of pixels)

$$X = \begin{bmatrix} 1 & \cdot & \cdot & p \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ n & \cdot & \cdot & \cdot \end{bmatrix}^{n \times p}$$

elements

Time order data



Step 2: The mean of each column is subtracted from all the values in that column such that every column has a mean of 0. (**Z**)

$$\Sigma = Z^T Z$$

Covariance matrix:

$$\sigma(x, y) = \frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})$$

$$\Sigma = \begin{pmatrix} \sigma(x, x) & \sigma(x, y) \\ \sigma(y, x) & \sigma(y, y) \end{pmatrix}$$

Then the **covariance**, Σ is calculated

PCA



Step 3: Eigen decomposition of Σ .

$$\Sigma = PDP^{-1}$$

P is the Matrix of Eigen vectors.

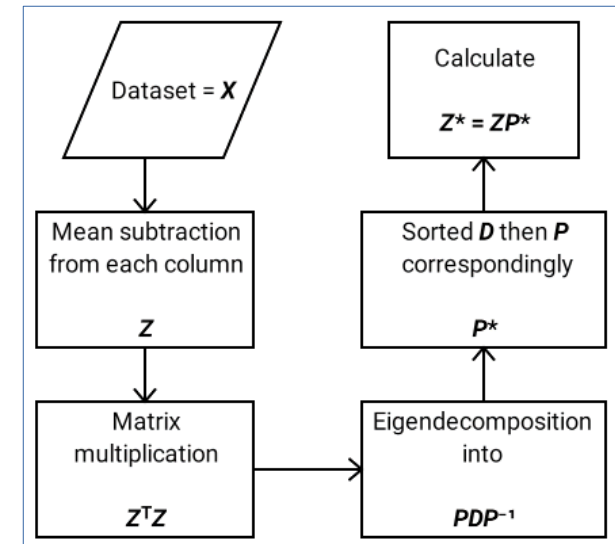
D is the diagonal matrix of corresponding eigen values. (**eigen vectors are independent of one another**)

Step 4: D , the diagonal matrix is then sorted according to the eigen value from highest to lowest. And P is also modified accordingly to give P^* .

Step 5: Z^* , is calculated.

Z^* is a standardized, centered version of X , with the **weights determined by the eigenvectors**.

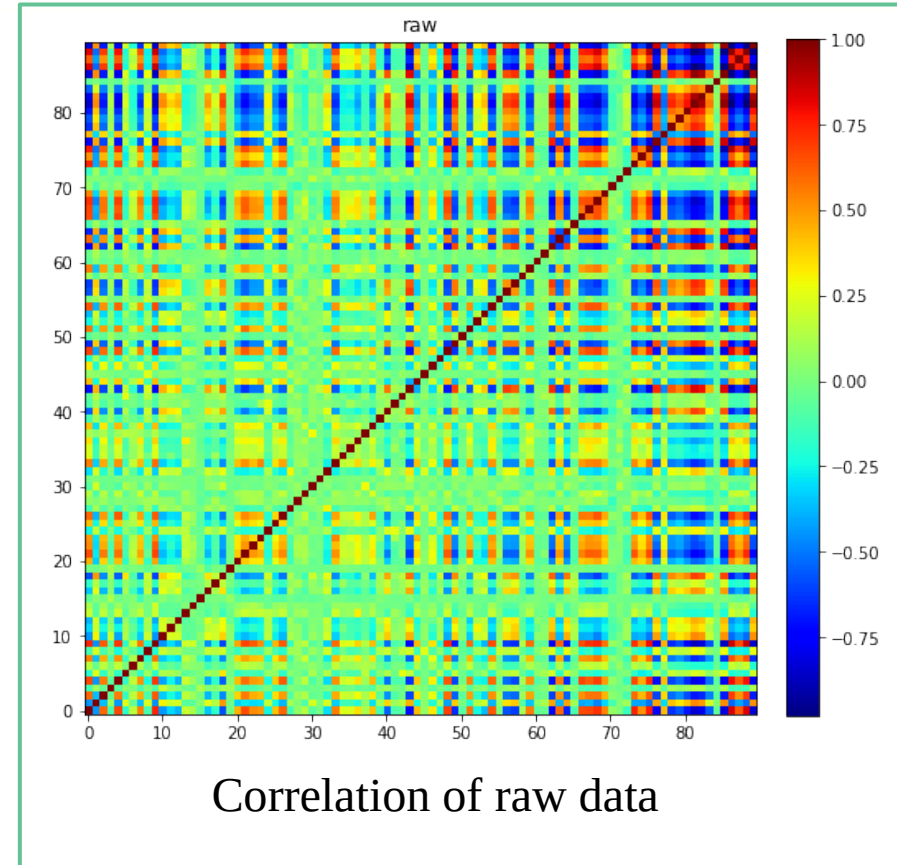
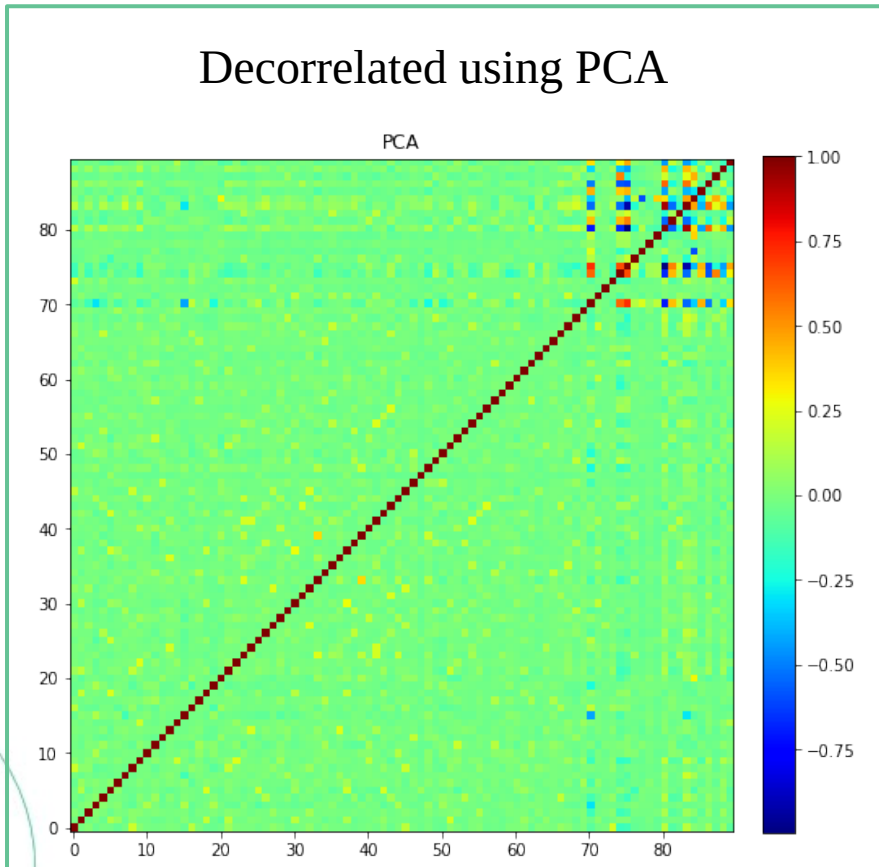
(Since P^* is independent of one another, Z^* will also be independent of one another)



PCA Decorrelation



Mars observation



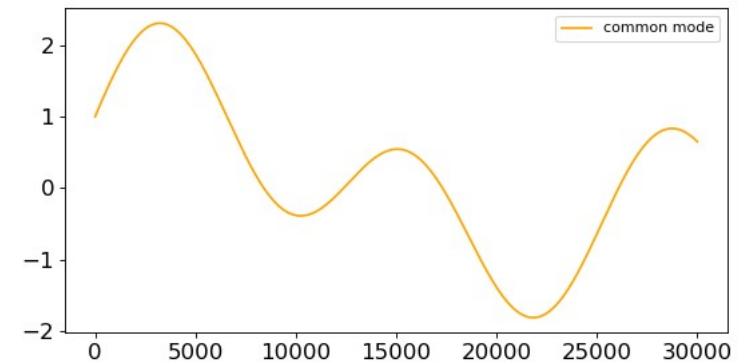
Simulation data



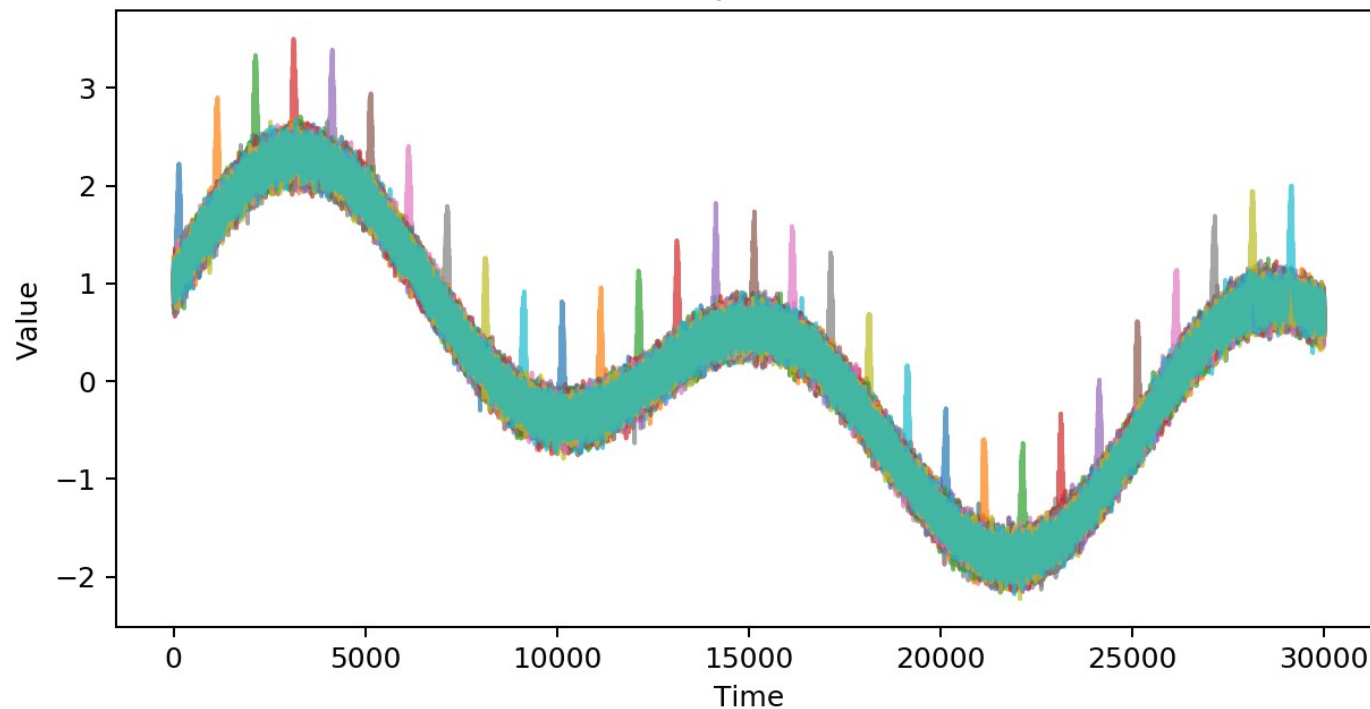
To test and demonstrate the behavior of the decorrelation algorithm, a dataset is generated.

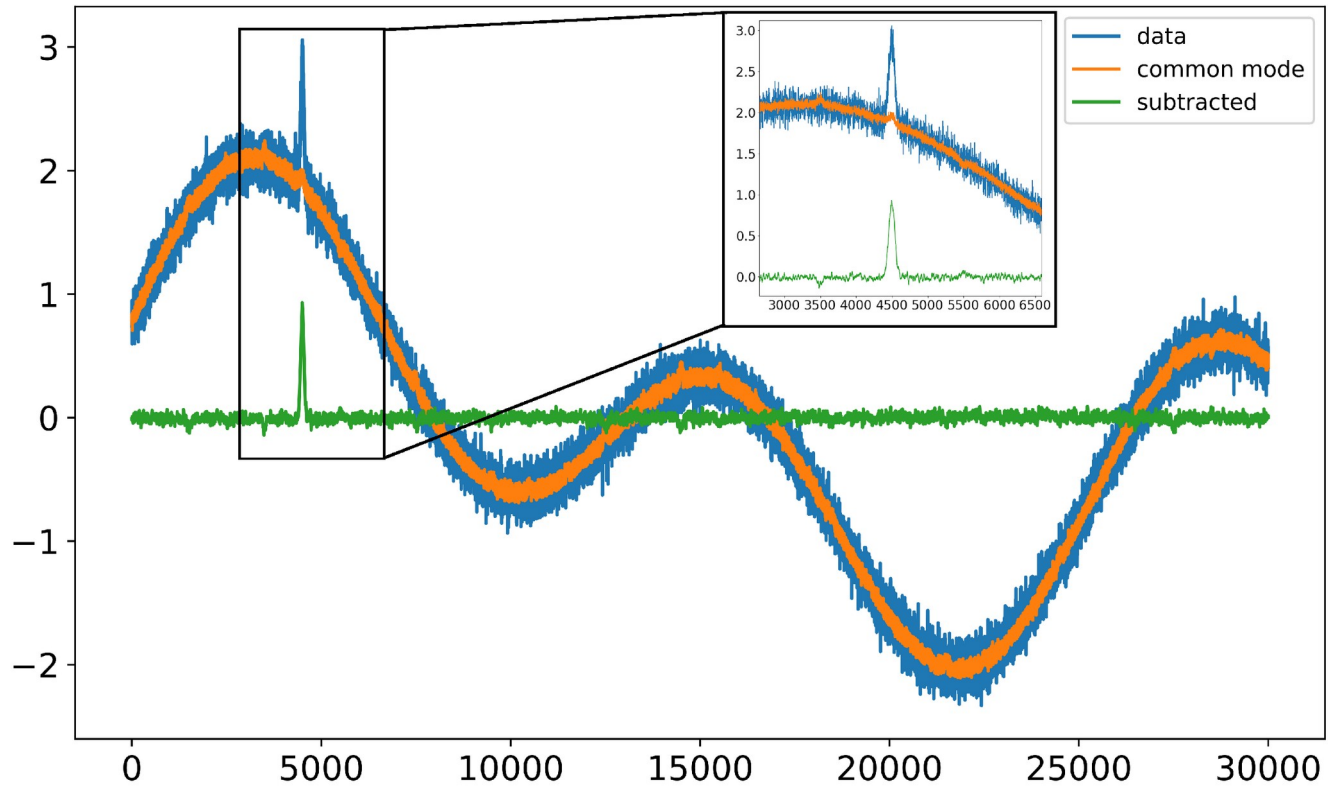
Process:

- A common mode is first defined
- Gaussian signal peaks added at intervals
- Random noise is added.



Sample Data



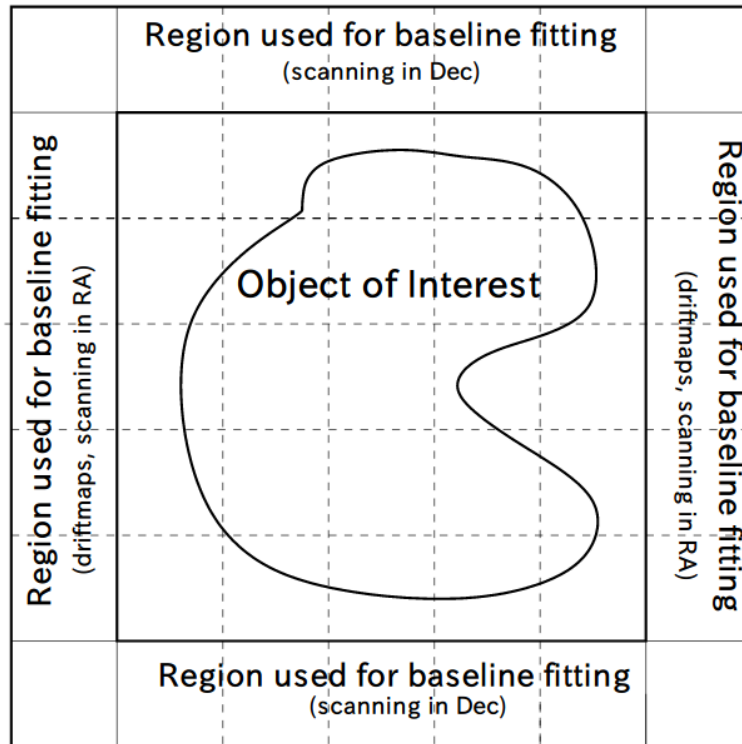


Loss of amplitude by using PCA

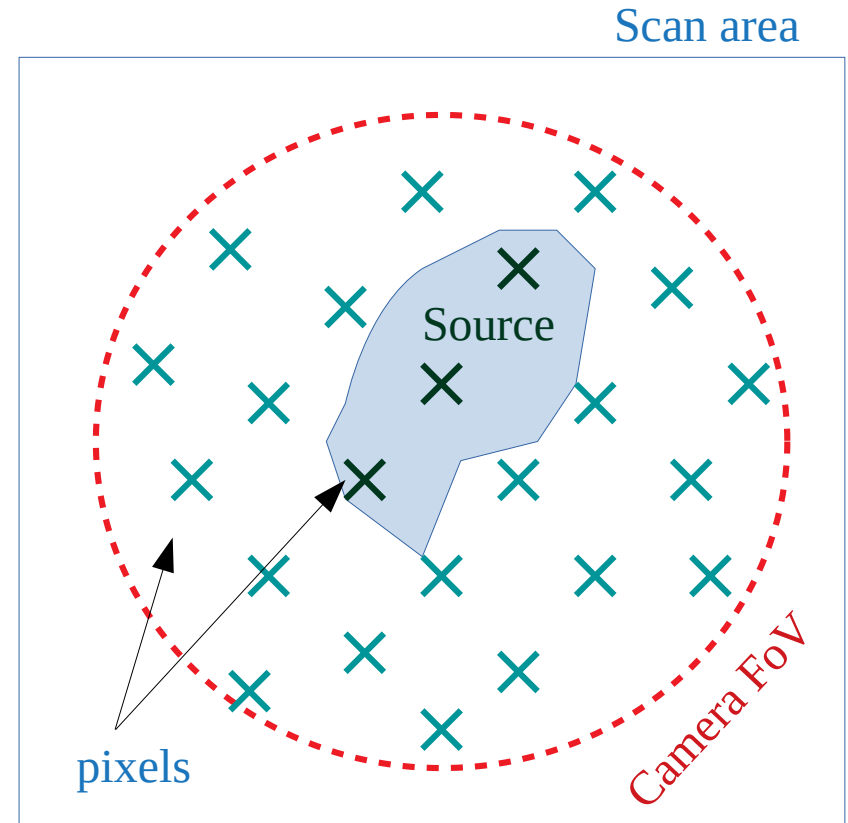
Pros: Decorrelates data. Better method than median filter.

Cons: For astronomical TODs, it inherits artifacts

New ChunkPCA algorithm



Typical Radio telescope sky removal



Advantage of Multiarray large Field of View camera

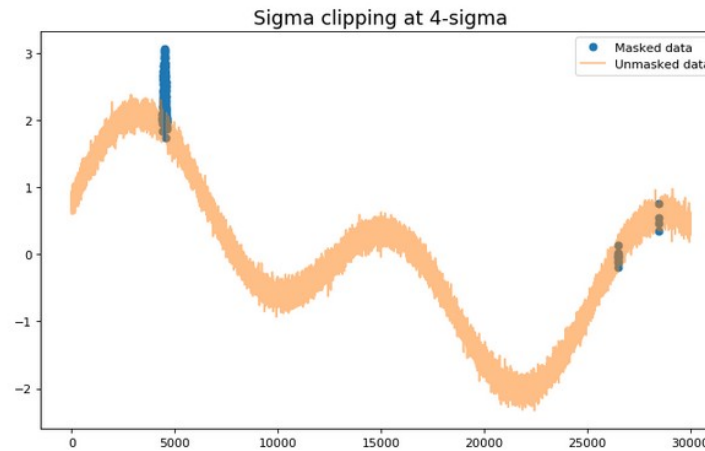
A new algorithm is created to take advantage of the large FoV of the MKID camera.

Uses off-source pixels only for baseline calculation using PCA.

Masking on-source signal

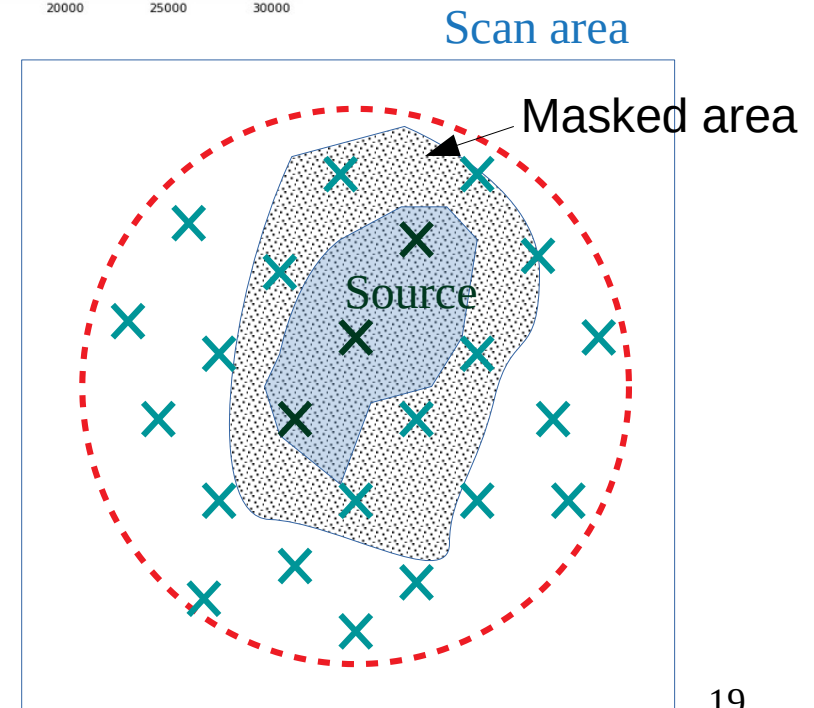


1). source detection using sigma clipping



An `astropy` method called '`sigma_clip`' is used to do the sigma clipping.

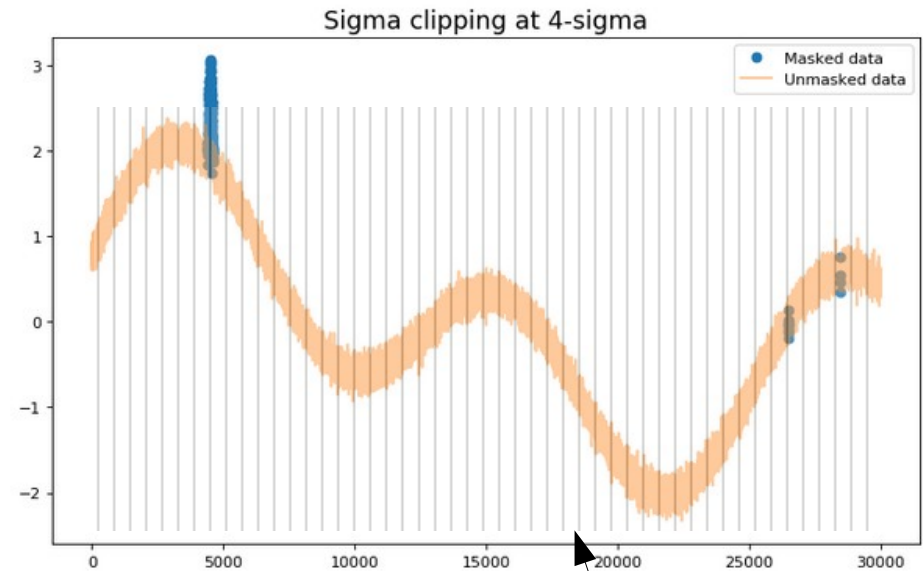
2). Predefining a mask when the source is expected.



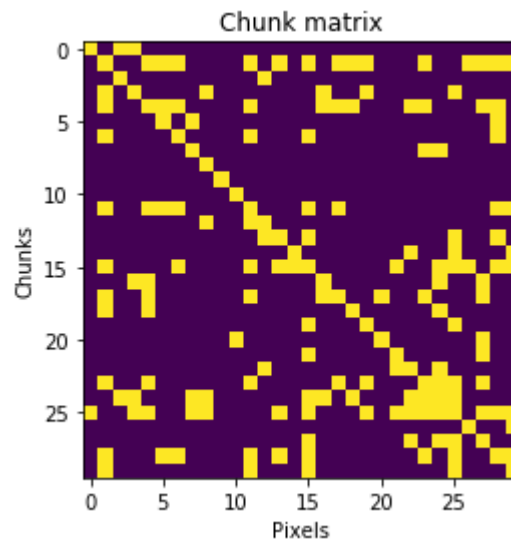
Chunk Matrix



- Divide the data into chunks.
- Create the chunk matrix



Chunks

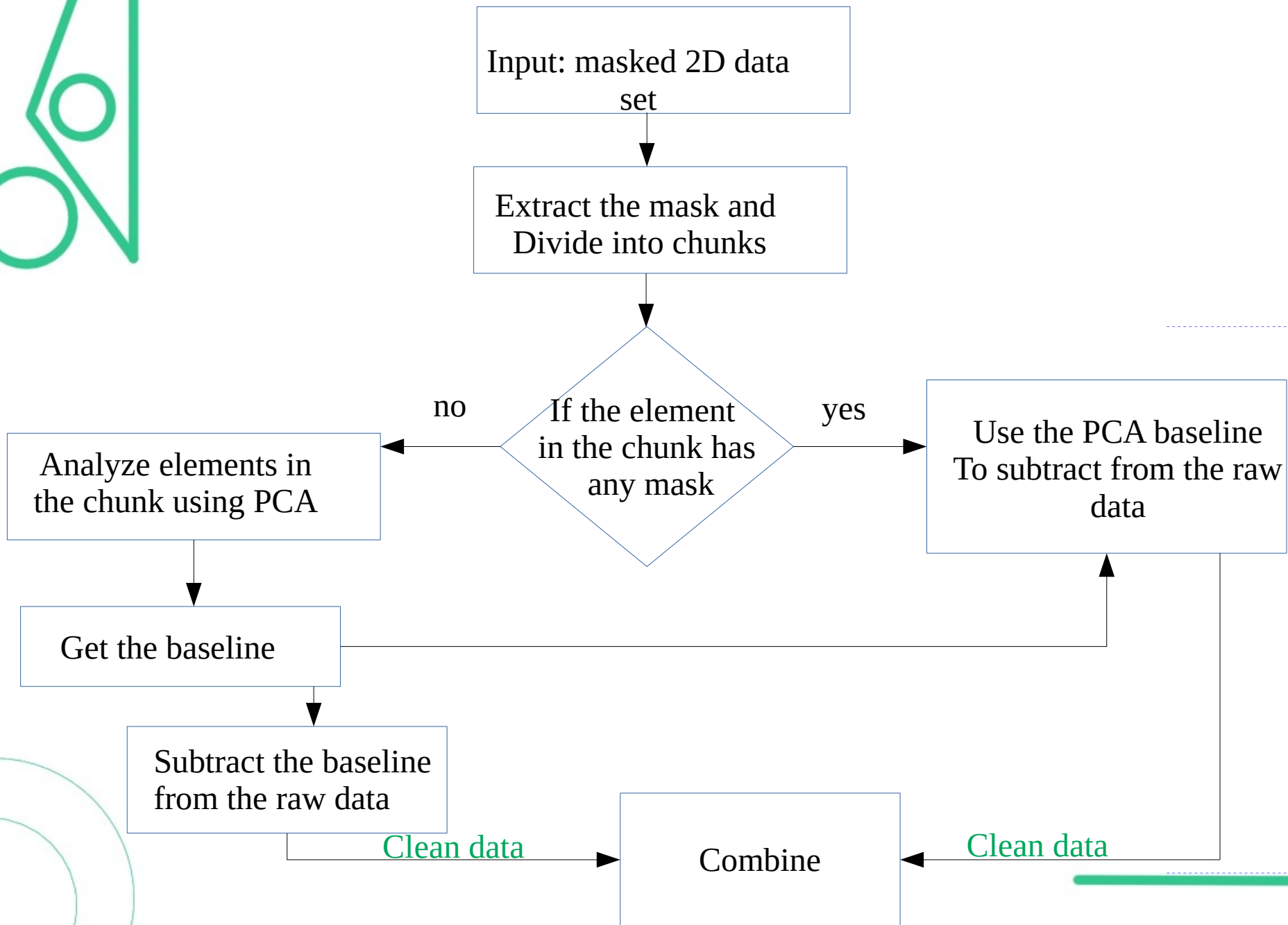


If it has mask, chunk matrix value = 1.

If no mask, then 0.

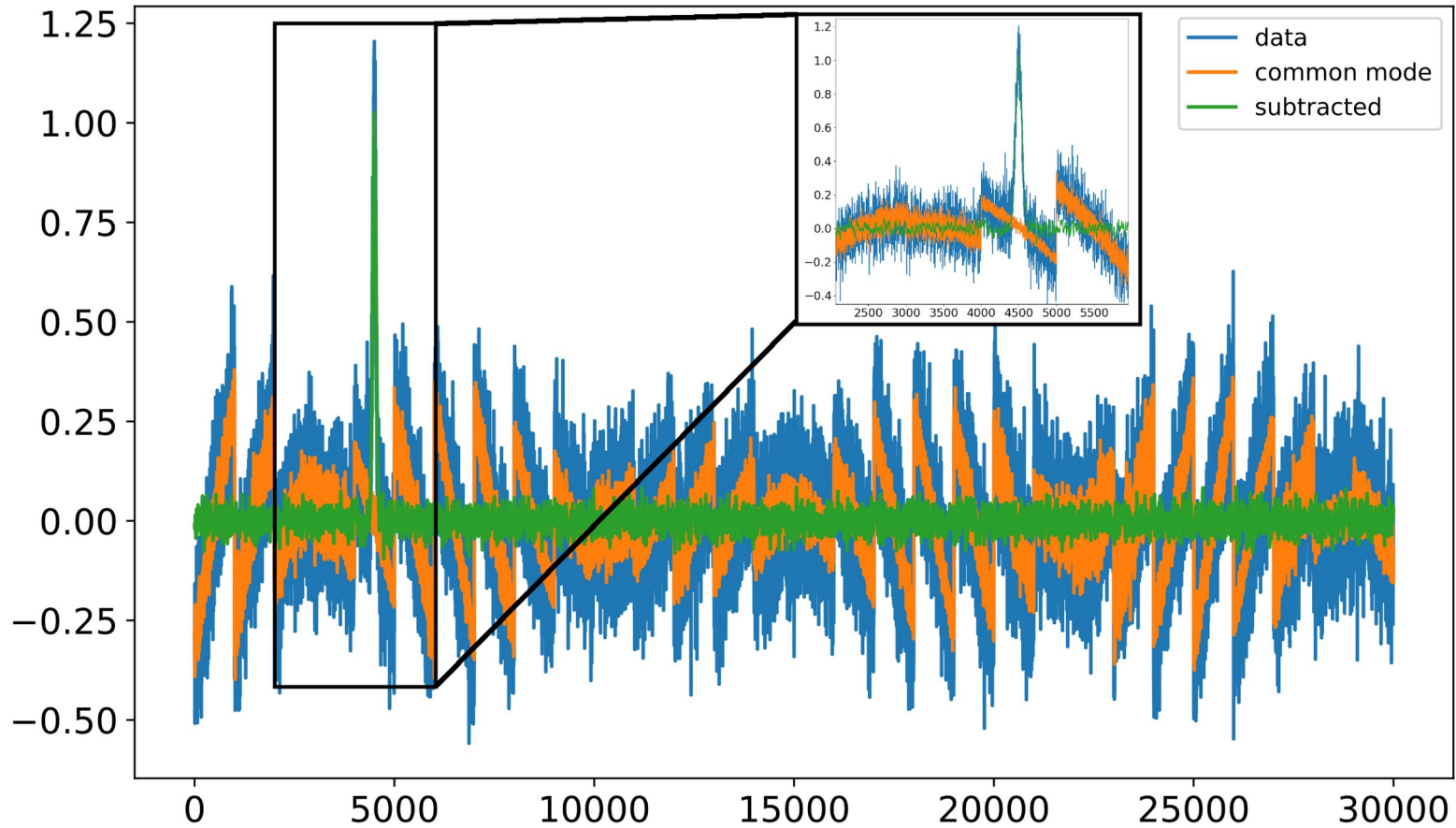


ChunkPCA Algorithm



repeated over all chunks

ChunkPCA Result

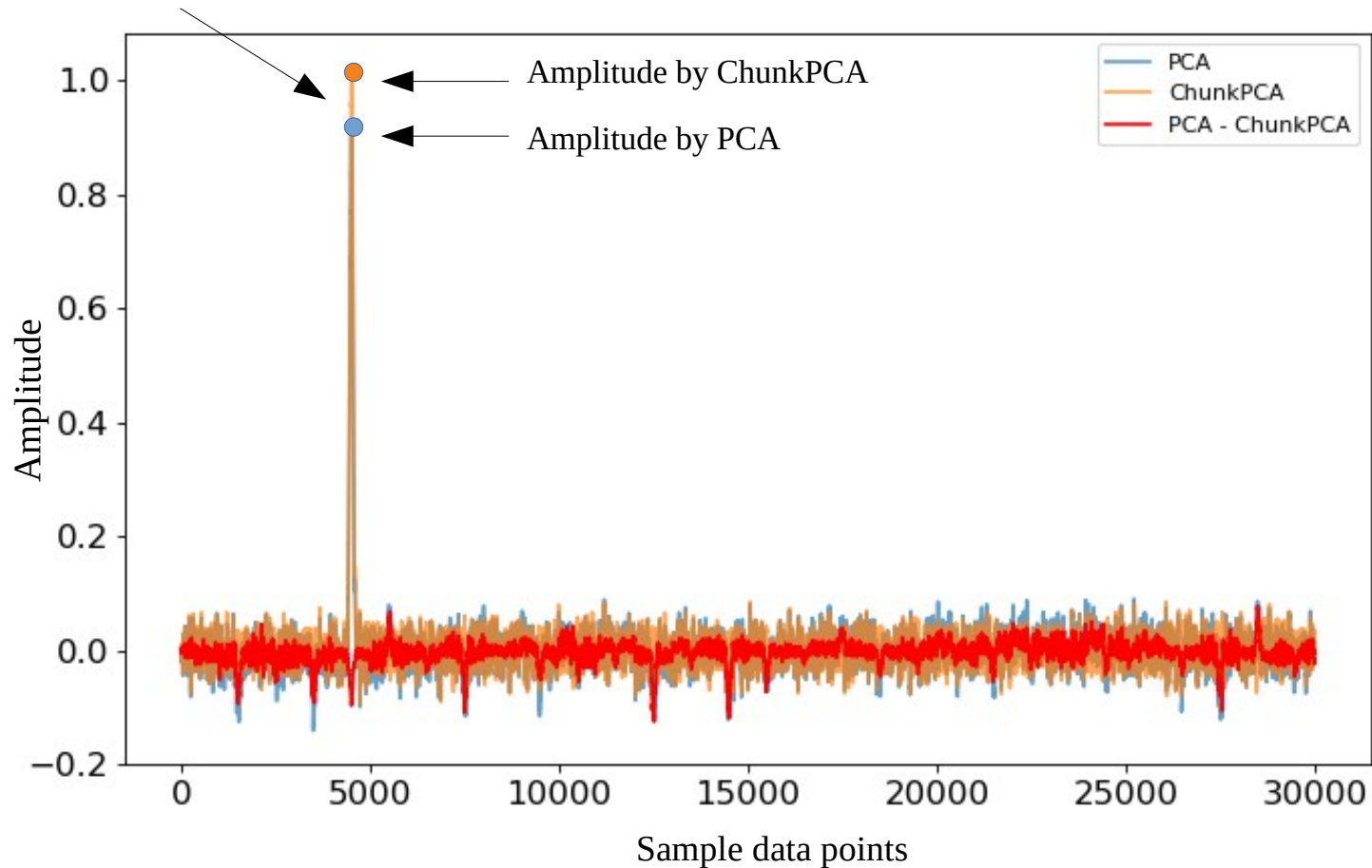


No loss of amplitude by using ChunkPCA

PCA - ChunkPCA Compare



Preservation of signal amplitude



Baseline obtained by ChunkPCA compared with Conventional PCA.

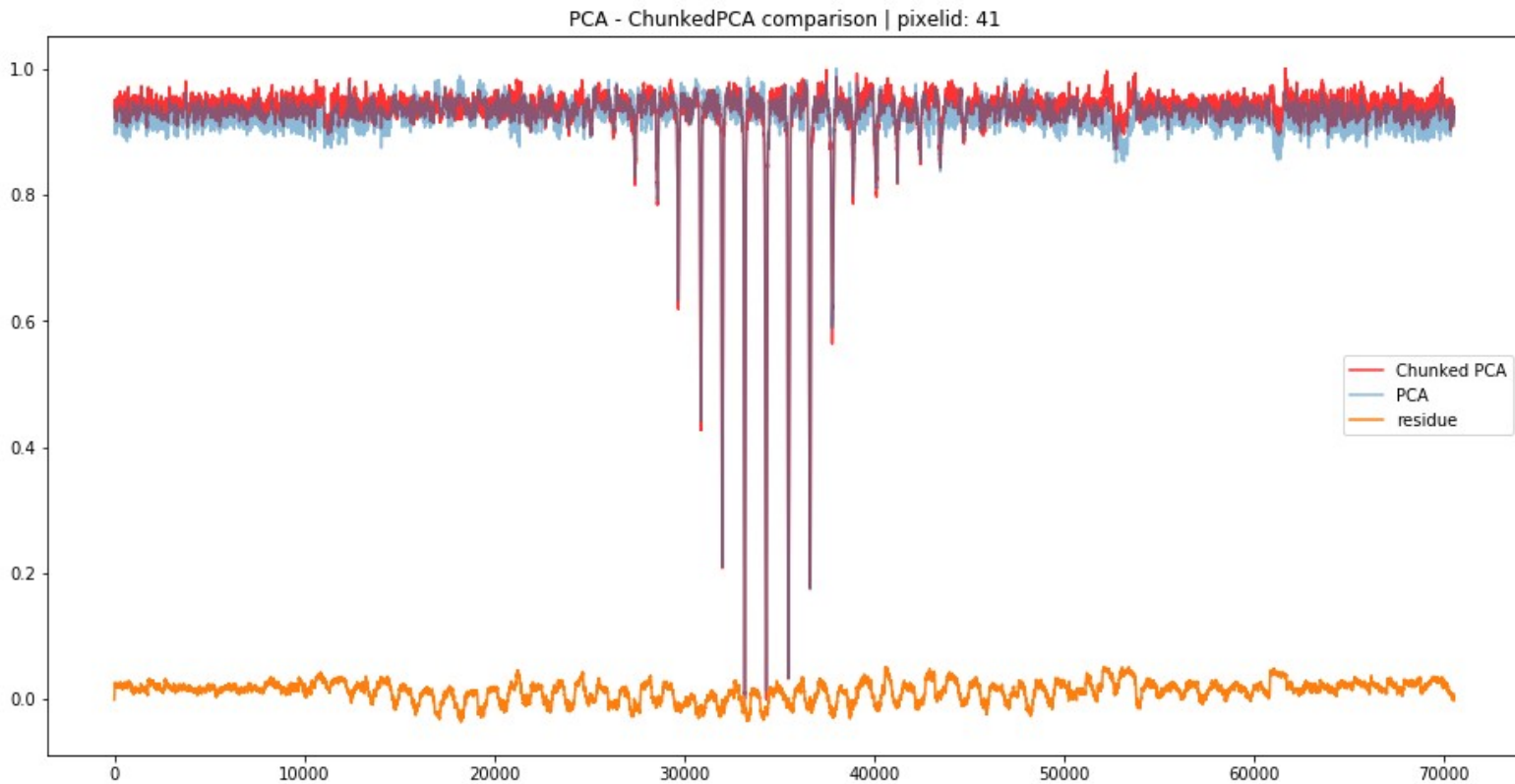
The residue (shown in red) shows the improvement in baseline.

PCA - ChunkPCA Compare



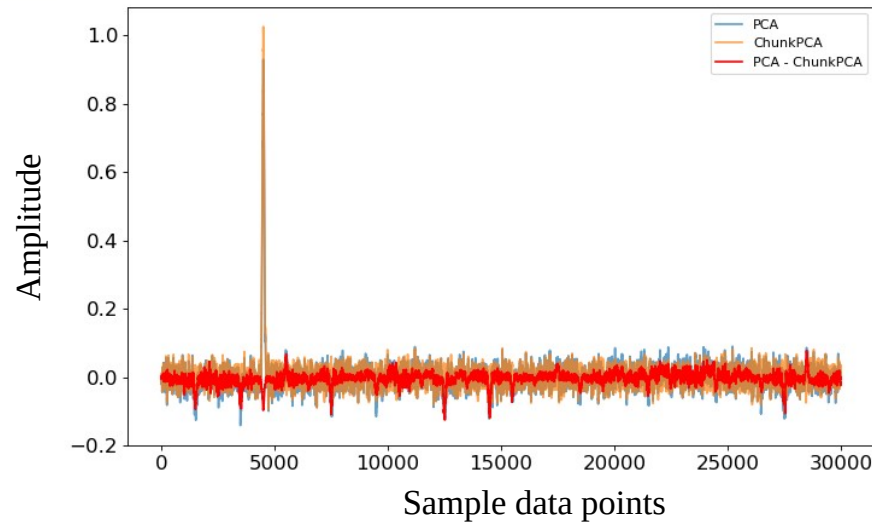
The algorithms are implemented on a real observation data of Mars observation.

The same TOD has been used for both the PCA, and Chunk-PCA analysis.
Subtracting the two, the residue shows the rippling artifact caused by the signals has been removed



The “rippling” artifacts in the baseline are successfully removed.

RMS with amplitude



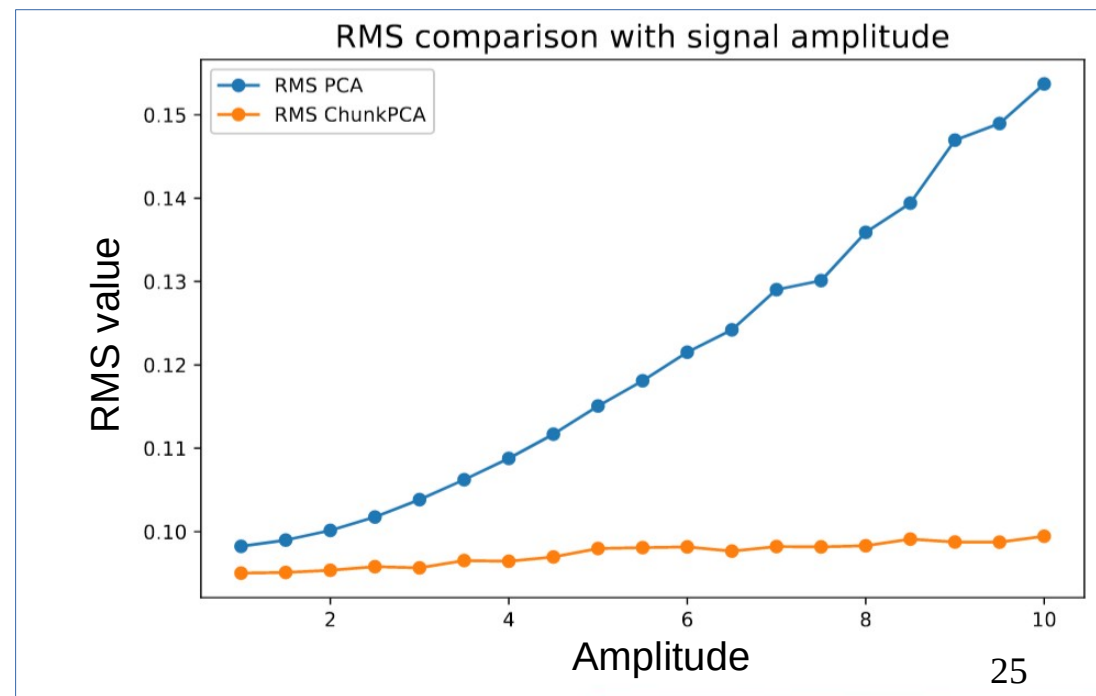
Amplitude of signal is 1 as shown here

This amplitude in the sample data is increased step by step upto 10.

The RMS of the subtracted data is calculated.

As expected, higher the amplitude, higher the ripples in the baseline for PCA.

ChunkPCA shows lower RMS



Intensity calculation



- To calculate the temperature of observed region we calibrate the data with
 - Load measurement (f_{load} / f_{ref})
 - On source measurement (f_{on})
 - Off source measurement/empty sky measurement (f_{off})

As a special case for doing Radio Astronomy with MKID data, we need to calculate T_{a^*} from the frequency shift data.

$$f_{new} = -HP_{in} + f_{res}$$

$$f(T) = -CT + f_{res}$$

where $C = k_B B G H$ is a constant for a single MKID detector

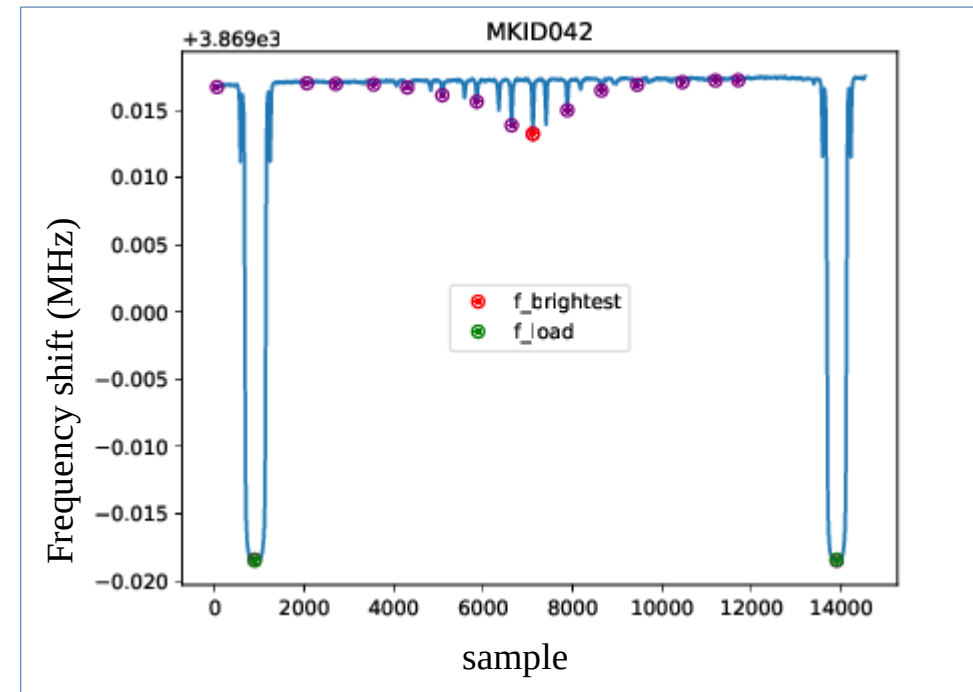
$$f_{ref} = -C(T_{amb} + T_{rx}) + f_{res}$$

$$f(T) = -CT + f_{res}$$

$$f_{load} = -C(T_{amb} + T_{rx}) + f_{res}$$

$$f_{on} = -C(T_{sky_{on}} + T_{rx}) + f_{res}$$

$$f_{off} = -C(T_{sky_{off}} + T_{rx}) + f_{res}$$



Chopper wheel temperature calculation



$$T_{sky_{on}} = T_b e^{-\tau} + T_{atm} (1 - e^{-\tau})$$

$$T_{sky_{off}} = T_{atm} (1 - e^{-\tau})$$

$$\frac{f_{on} - f_{off}}{f_{load} - f_{off}} = \frac{T_a^*}{T_{atm}}$$

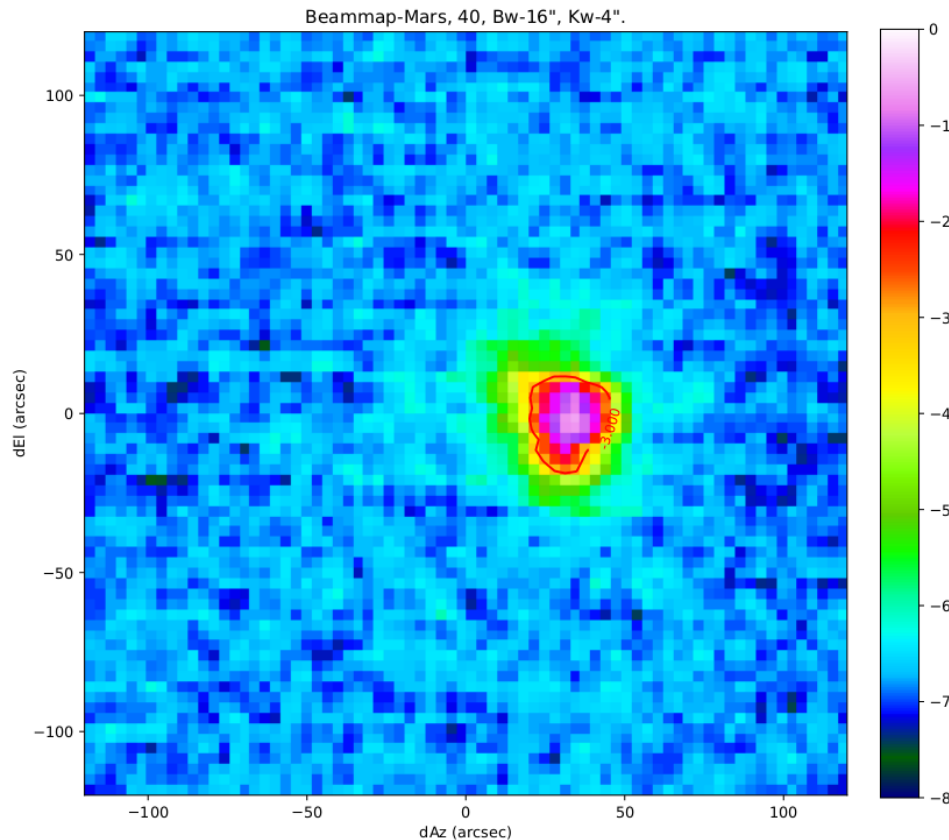
$$T_a^* = T_{atm} \times \frac{f_{on} - f_{off}}{f_{load} - f_{off}}$$

Making Beam maps



I have developed A gridding system to work with the Nobeyama antenna pointing log files and MKID readout files for generating several kinds of maps.

It's based on an algorithm called Cygrid.



A single element Beammap

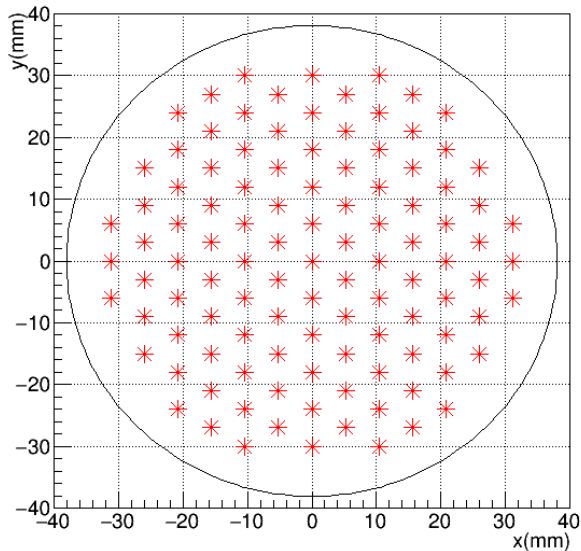
Beam shape and position



- Identifying the low noise readouts.
- Syncing signal with antenna-log during observation.
- Define the Beamwidth(bw), kernelsize(\sim bw/2-3), and pixelsize(bw/4-5)
- Offsets are noted from these beam positions.

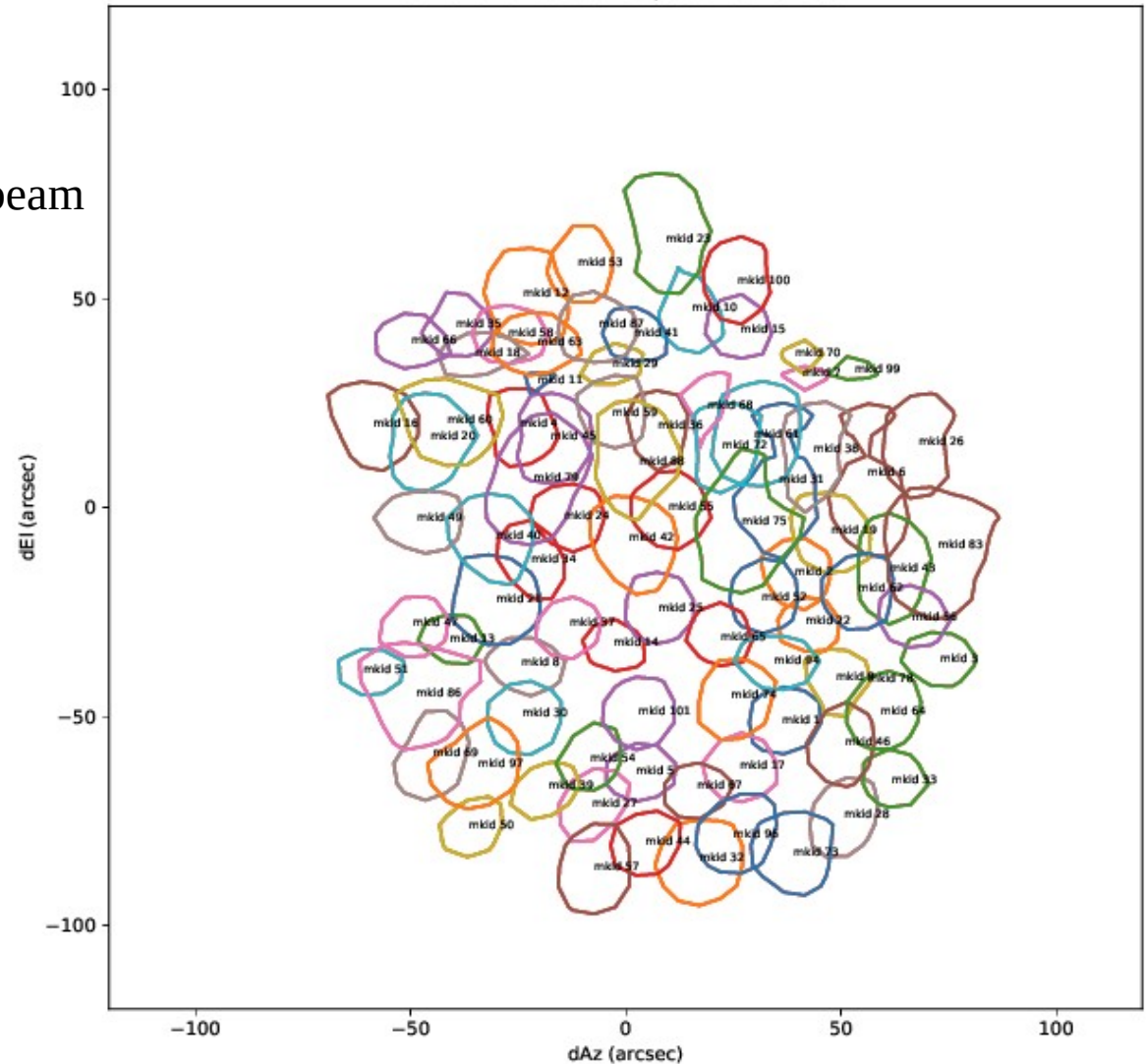
Manufactured positions of MKID Array

LensArrayPosition



Beam position

combination of beams | contour at -3dB

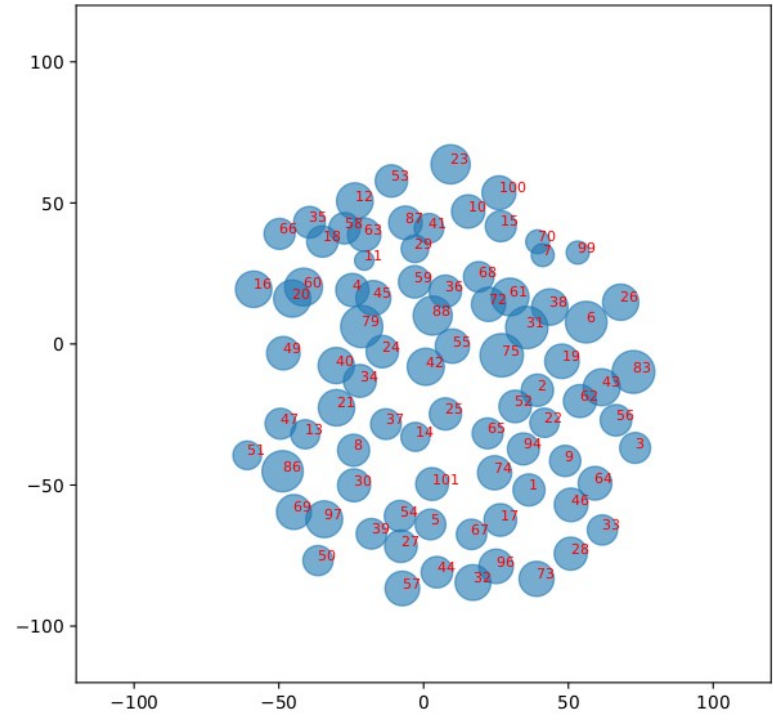
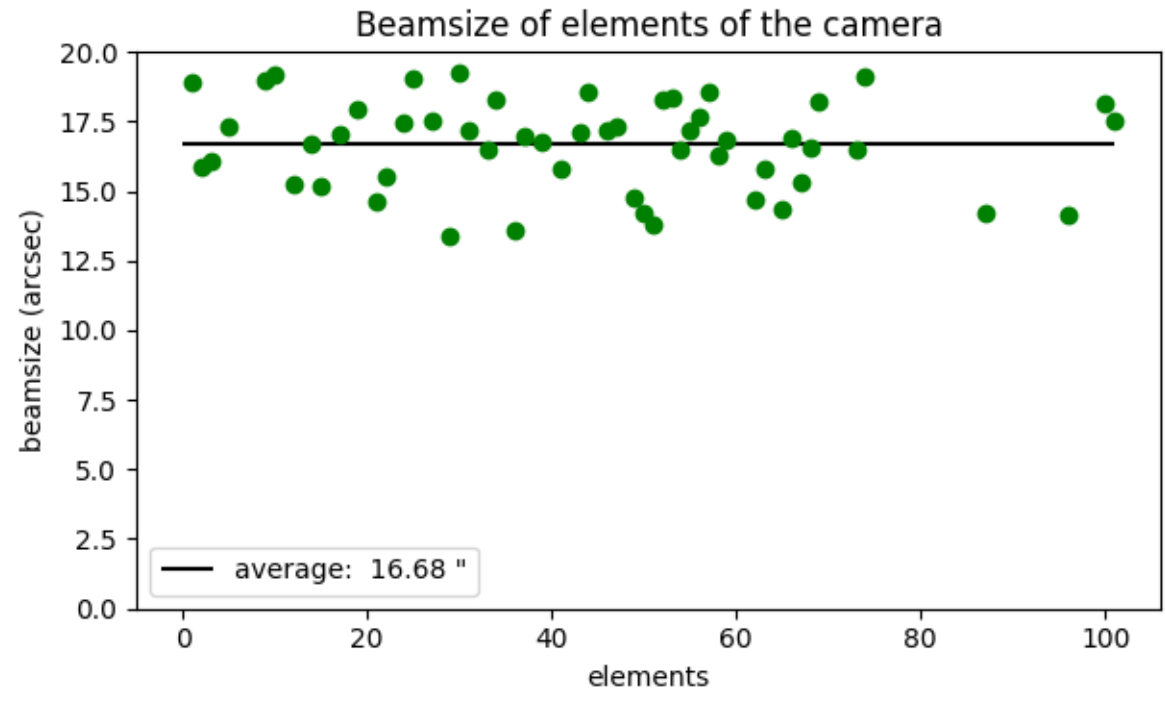


Beam size



Beam size from individual element beammap

Beam position from individual element beammap

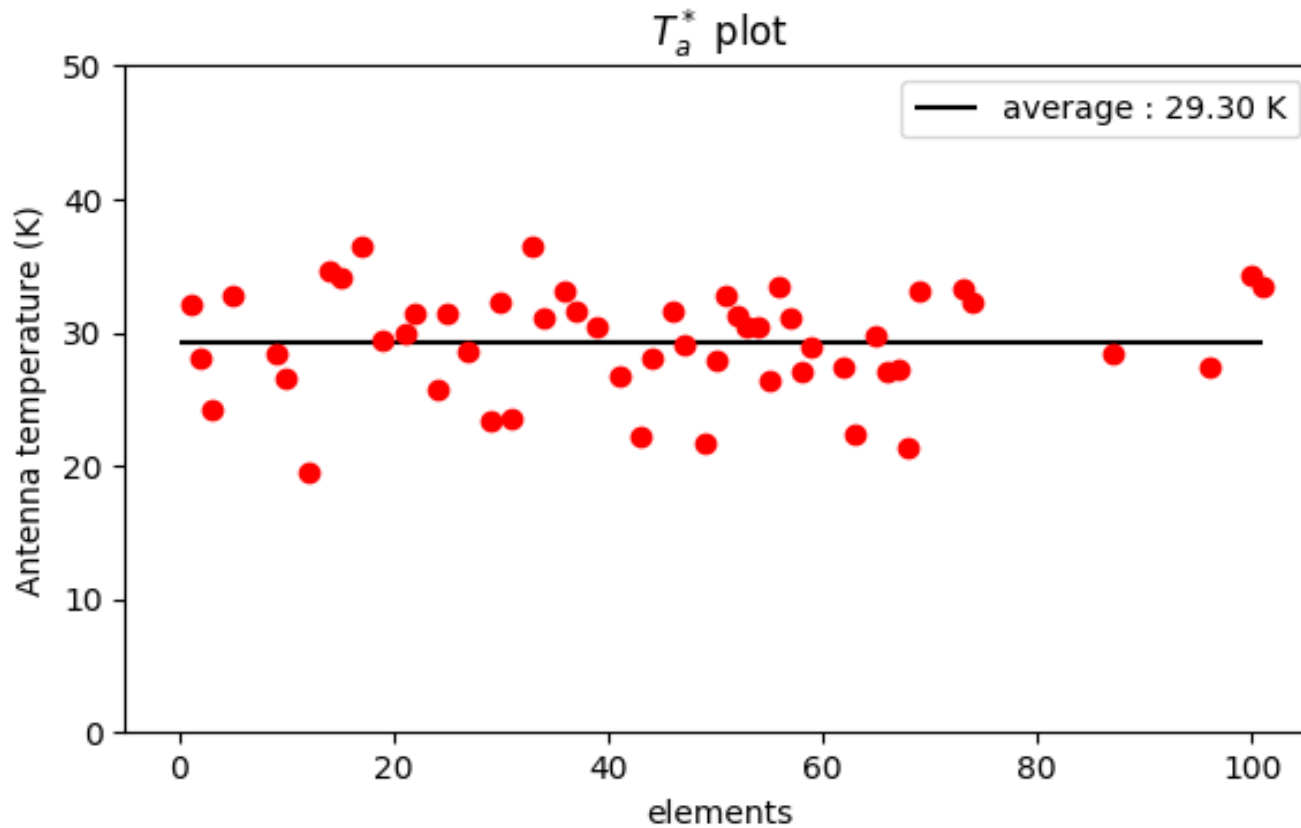


The Beam size averaged, is very closed to the expected value.

Antenna temperature (Mars)



Antenna temperature calculated plotted using the pipeline commands





Main beam efficiency

$$\eta_{\text{mb}} = \frac{T_a^*(\text{source})}{T_b} \times \left[1 - \exp \left(- (\ln 2) \left(\frac{\theta_s}{\theta_{\text{mb}}} \right)^2 \right) \right]^{-1}$$

Main beam temperature

$$T_{\text{mb}} = \frac{T_a^*}{\eta_{\text{mb}}}$$

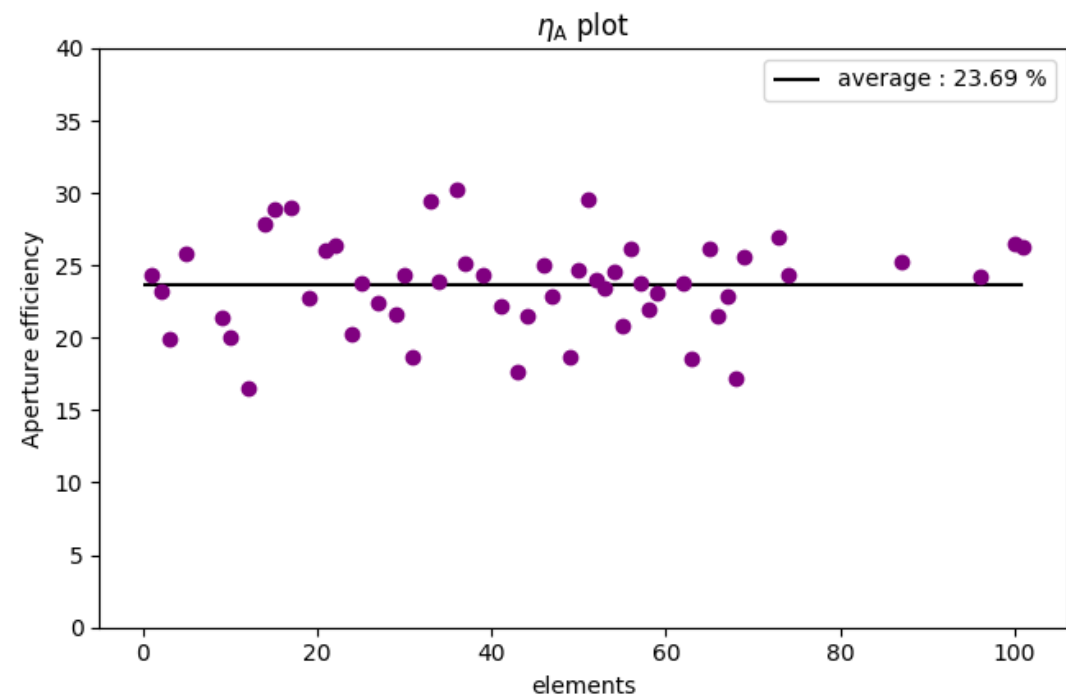
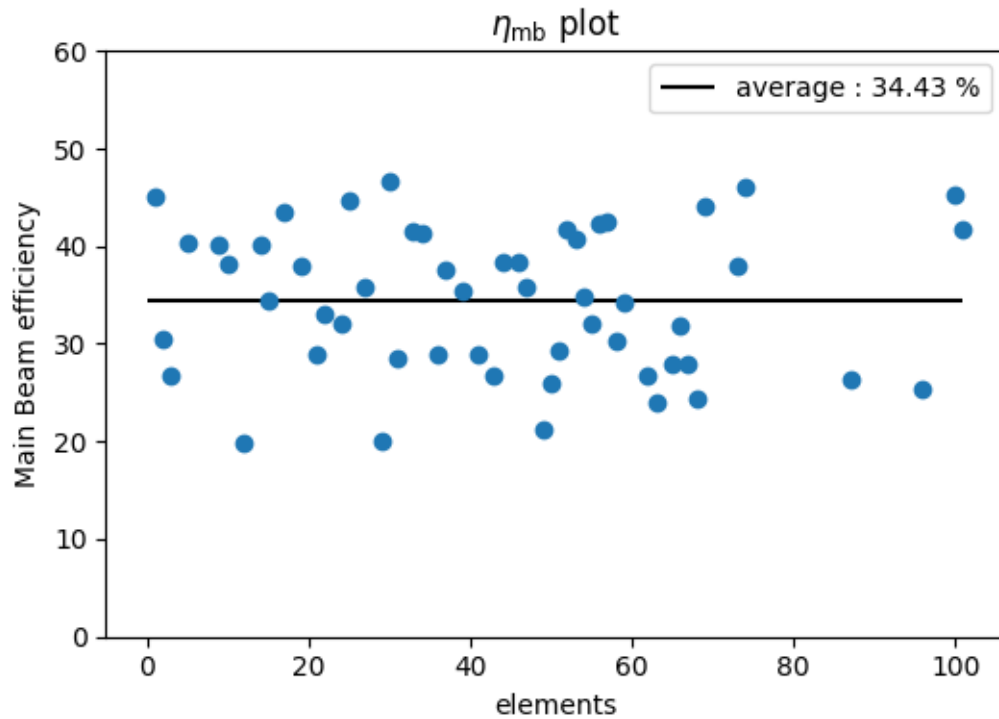
Aperture efficiency

$$\eta_{\text{MB}} / \eta_A \approx \frac{\pi}{4 \ln 2} \cdot \theta_X^{\text{FWHM}} \cdot \theta_Y^{\text{FWHM}} \cdot \frac{\pi D^2}{4 \eta_R \lambda^2} = 0.8899 \cdot \theta_X^{\text{FWHM}} \cdot \theta_Y^{\text{FWHM}} \cdot \frac{D^2}{\eta_R \lambda^2}$$

Efficiencies (Mars)



Efficiencies calculated plotted using the pipeline commands

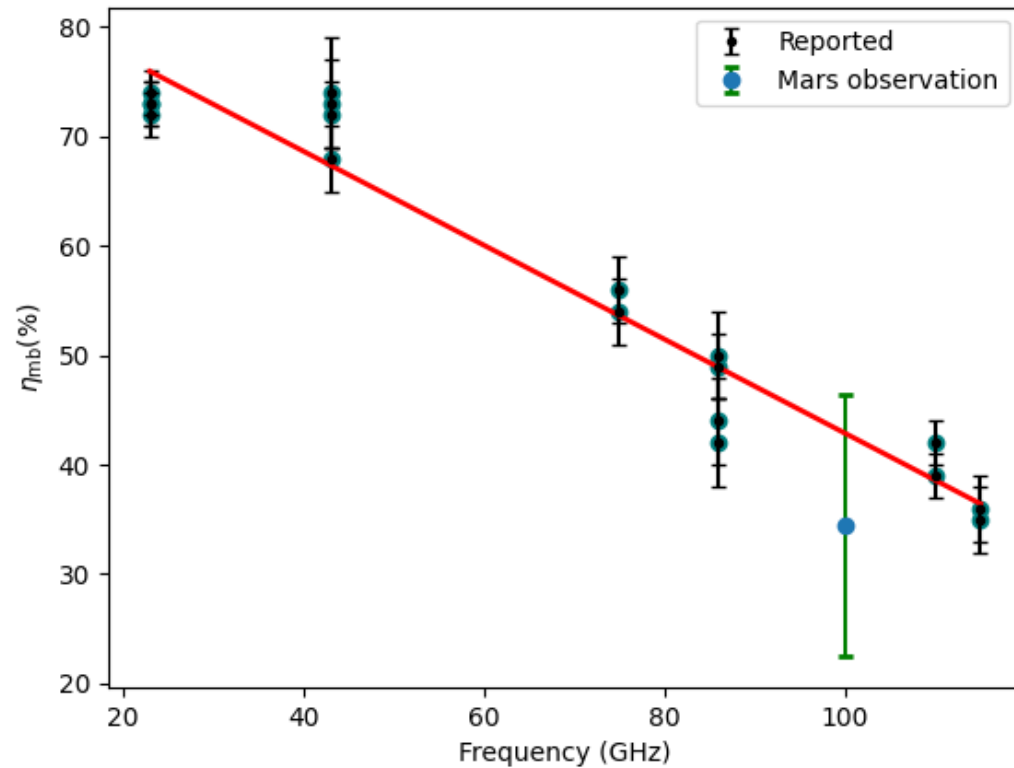


Efficiencies (Mars)

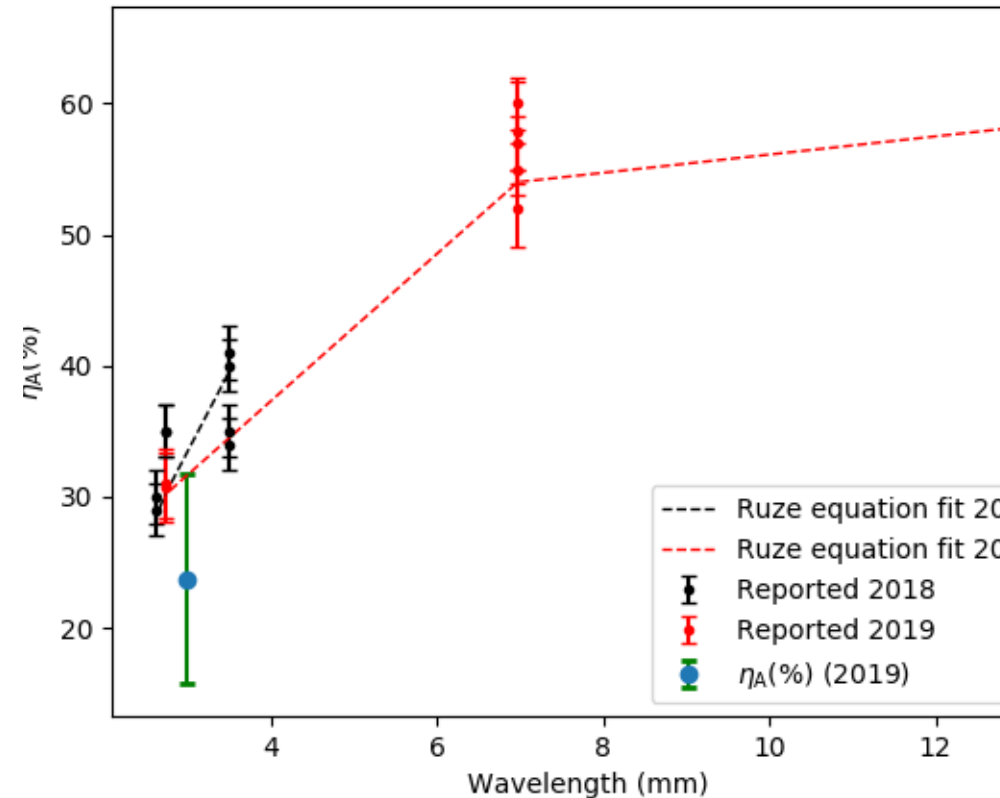


Efficiencies compared to reported data.

$\eta_{mb}(\%)$ from NRO 45m observations in 2018-2019



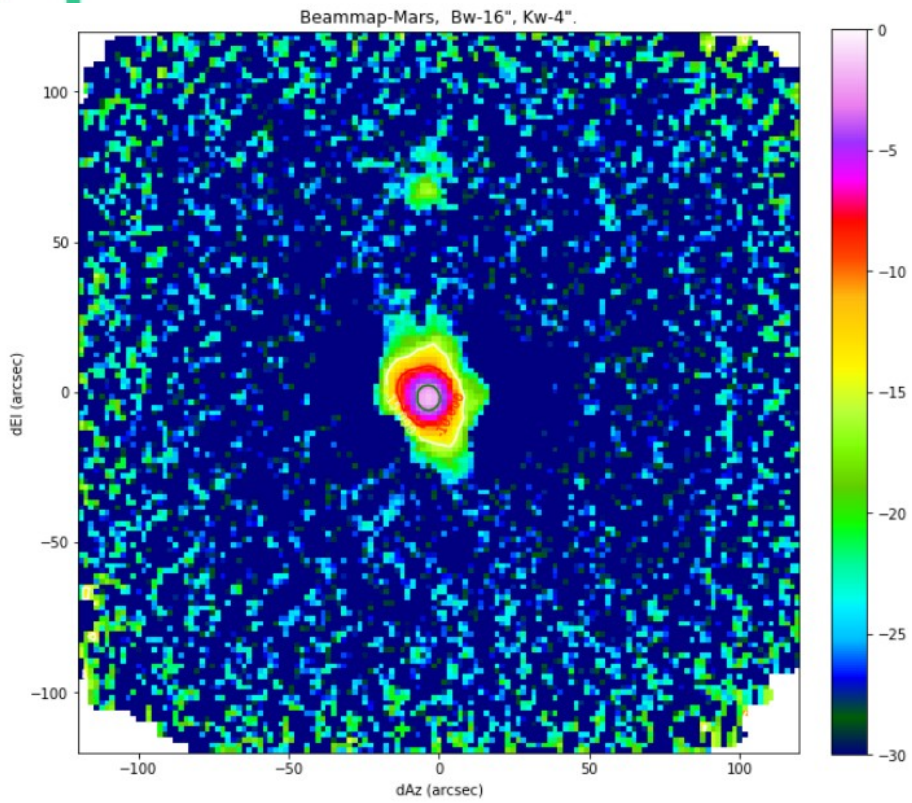
$\eta_A(\%)$ from NRO 45m observations in 2018-2019



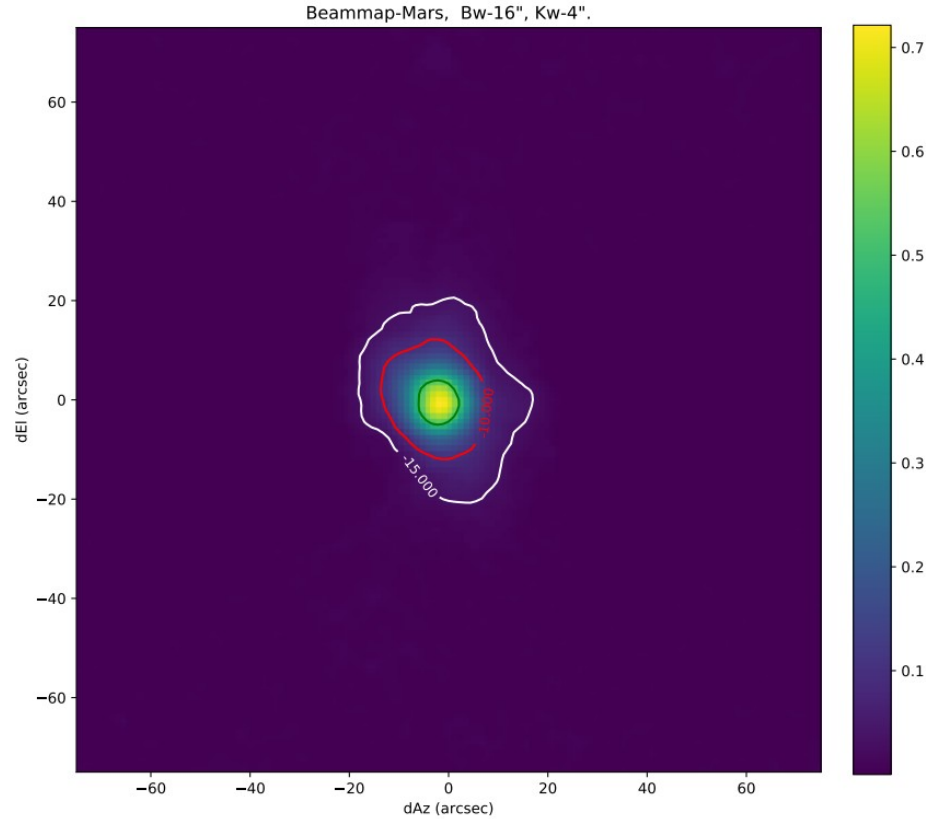
Combined Beammmaps



The offset of each Beam from the central pixel is corrected to get a Combined Beammmap

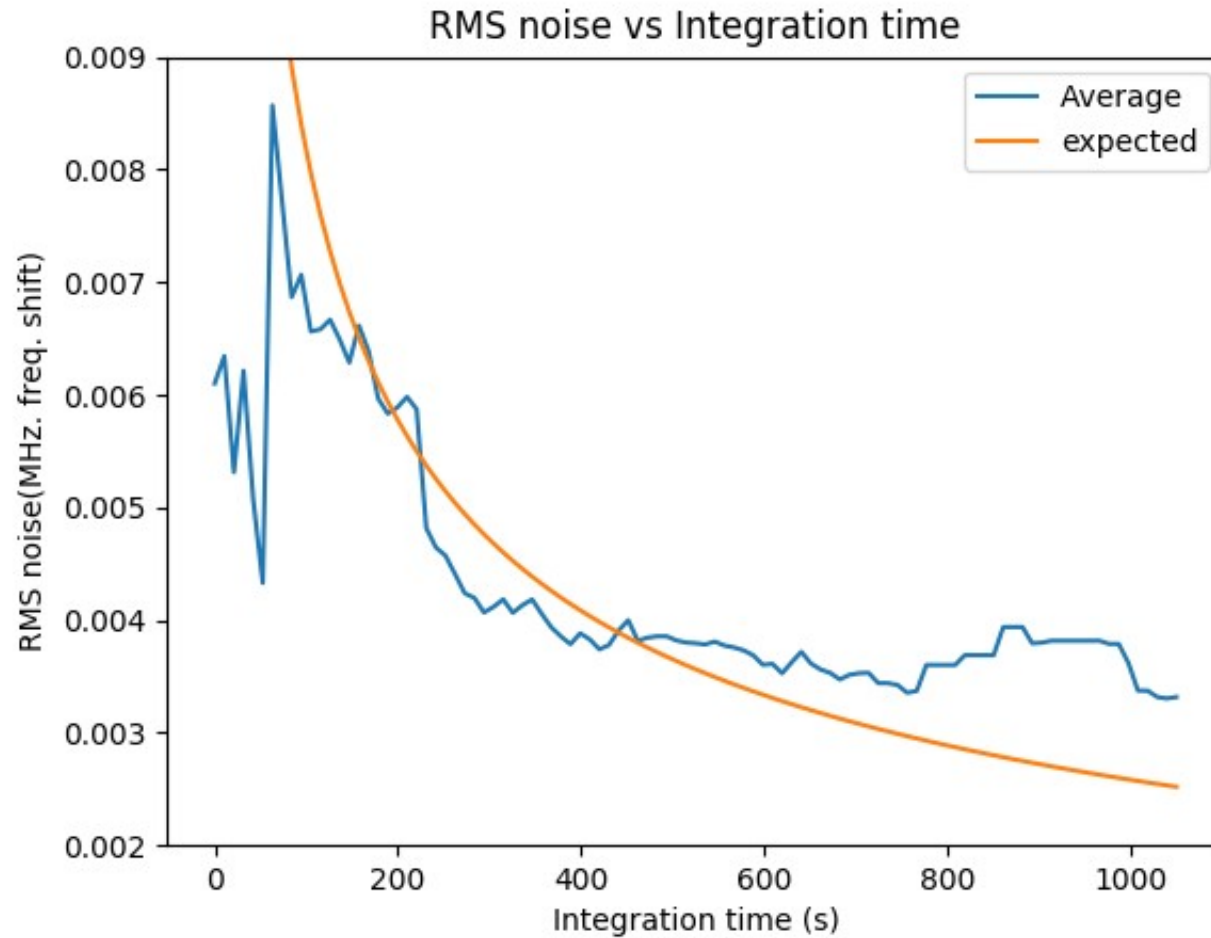


Combined BeamMap in dB of the Mars observation



Combined BeamMap of the Mars observation

Reduction in RMS by combininng

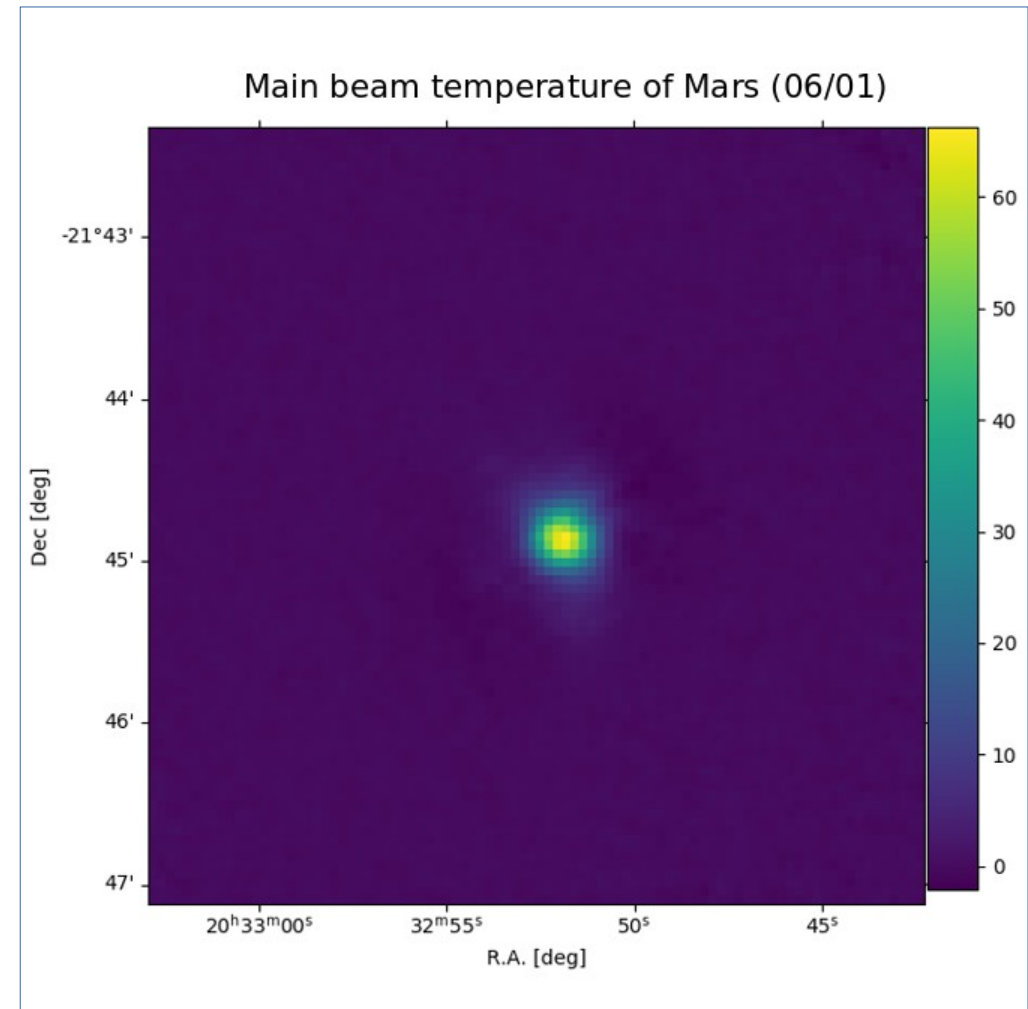


As more maps are combined, the RMS value followed an expected decline.

Skymap



- The antenna log is used to extract the RA-Dec coordinates.
- Cygrid can handle World Coordinate System very well, hence gridding becomes very easy.
- The coordinates calculated matches the original position of Mars in the sky during observation.



Skymap in RA-Dec coordinates.
Colorbar is Main-beam temperature (K)

Conclusion



- With the wide FoV, larger areas can be scanned relatively quicker with less noise.
- Baseline removal can utilize larger FoV for decorrelation.
- A new pipeline developed for data reduction of MKID 45m 100GHz camera.



筑波大学
University of Tsukuba



Thank you





extra

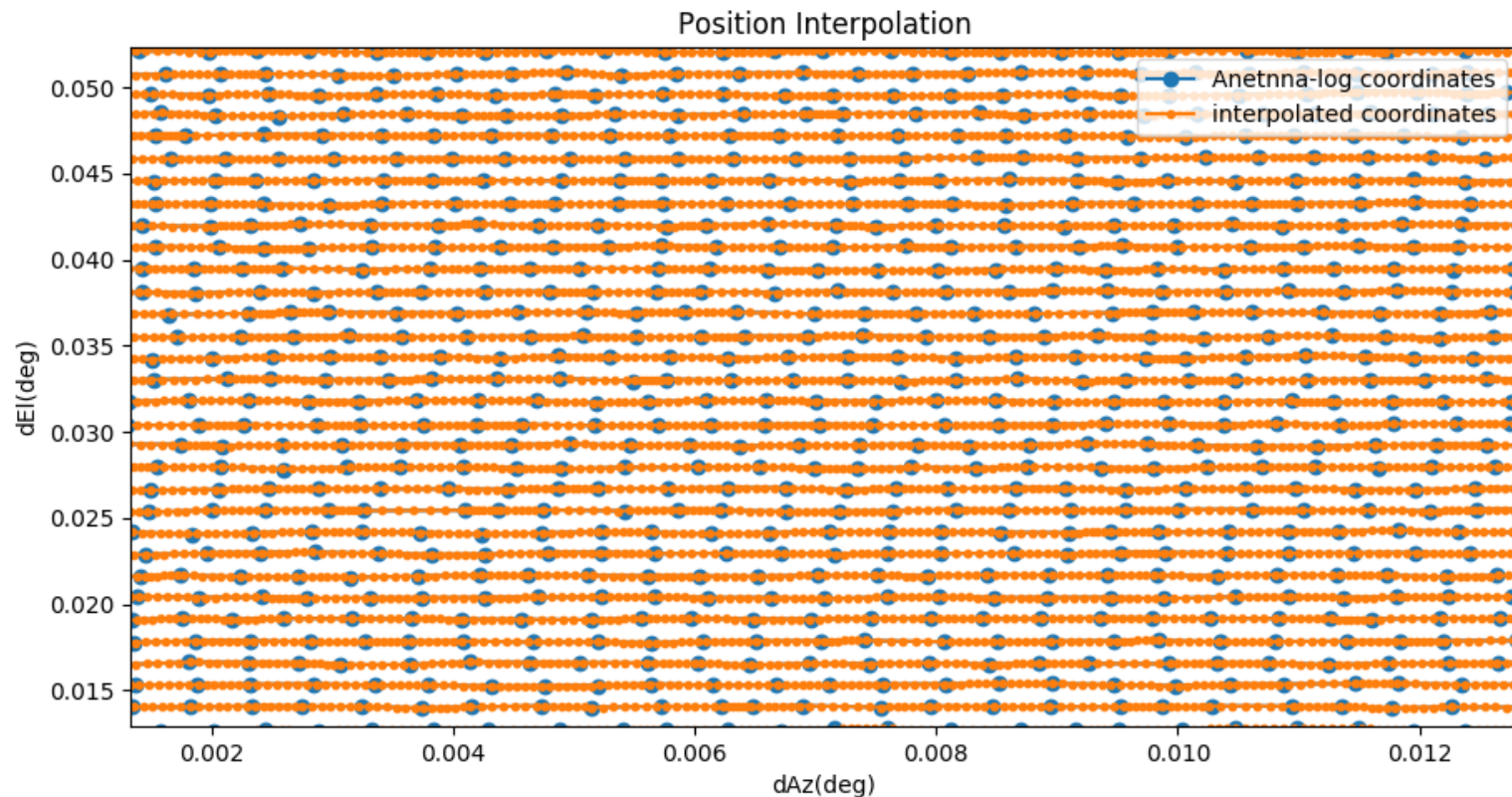


Interpolation of coordinates



Interpolation of coordinates:

- **Difference in sampling rate** of the Antenna pointing log file and intensity log files.
- Interpolated **using linear interpolation** to get the values to match in number of data points.





Objectives:

- Intensity – antenna pointing coordinate relation.
- Intensity integration management.
- To manage different projections properly
- Survey observation data management.

HEALPix gridding:

Pros and cons of using HEALPIX

Pros:

One step solution for positioning and intensity averaging of multiple observations, including rotation of the camera
Merging different observations is convenient

Cons:

Resolution goes up in discrete steps, it could create problems in finding the optimum resolution in which the data is processed.

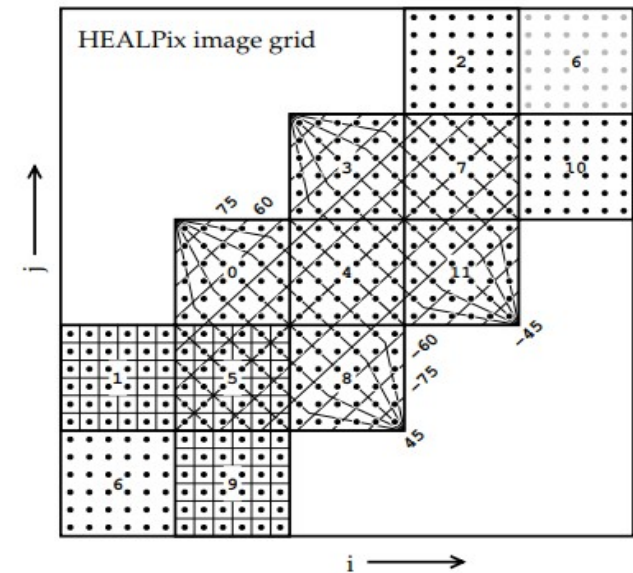


Figure 4. The HEALPix pixelisation for $N = 6$ on the HEALPix projection for $H = 4$ projected with a 45° rotation onto the mapping grid showing the twelve facets with standard numbering. The graticule of the HEALPix projection is shown in the seven facets adjacent to $(\phi, \theta) = (0, 0)$, and those at lower left show the pixel boundaries for $N = 6$ as defined by the HEALPix pixelisation.

Credit: Mark R. Calabretta et al.