Map-Making and Signal Estimation with Bolocam

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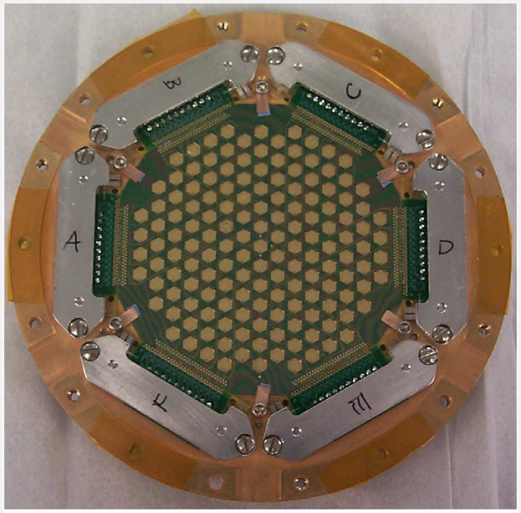
Overview

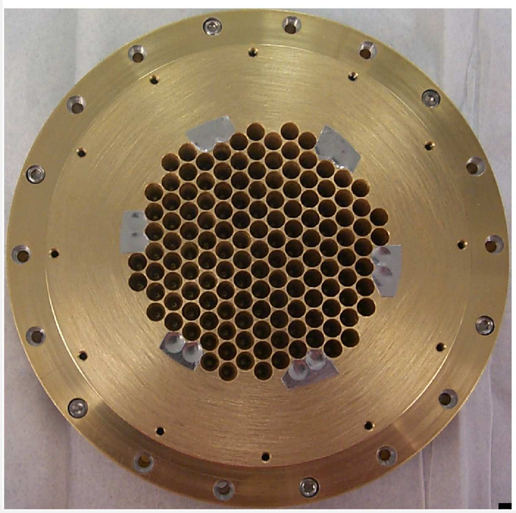
- Introduction to the Bolocam instrument
  - Bonus "quick look" at Bolocam's successor, MUSIC

- Bolocam noise properties and noise filtering algorithms

- Specific examples of map-making and signal estimation for different science observations with Bolocam
  - Isolated unresolved sources
  - CMB fluctuations
  - Bolocam galactic plane survey
  - Large-angular-scale galaxy cluster SZ emission

Bolocam Overview

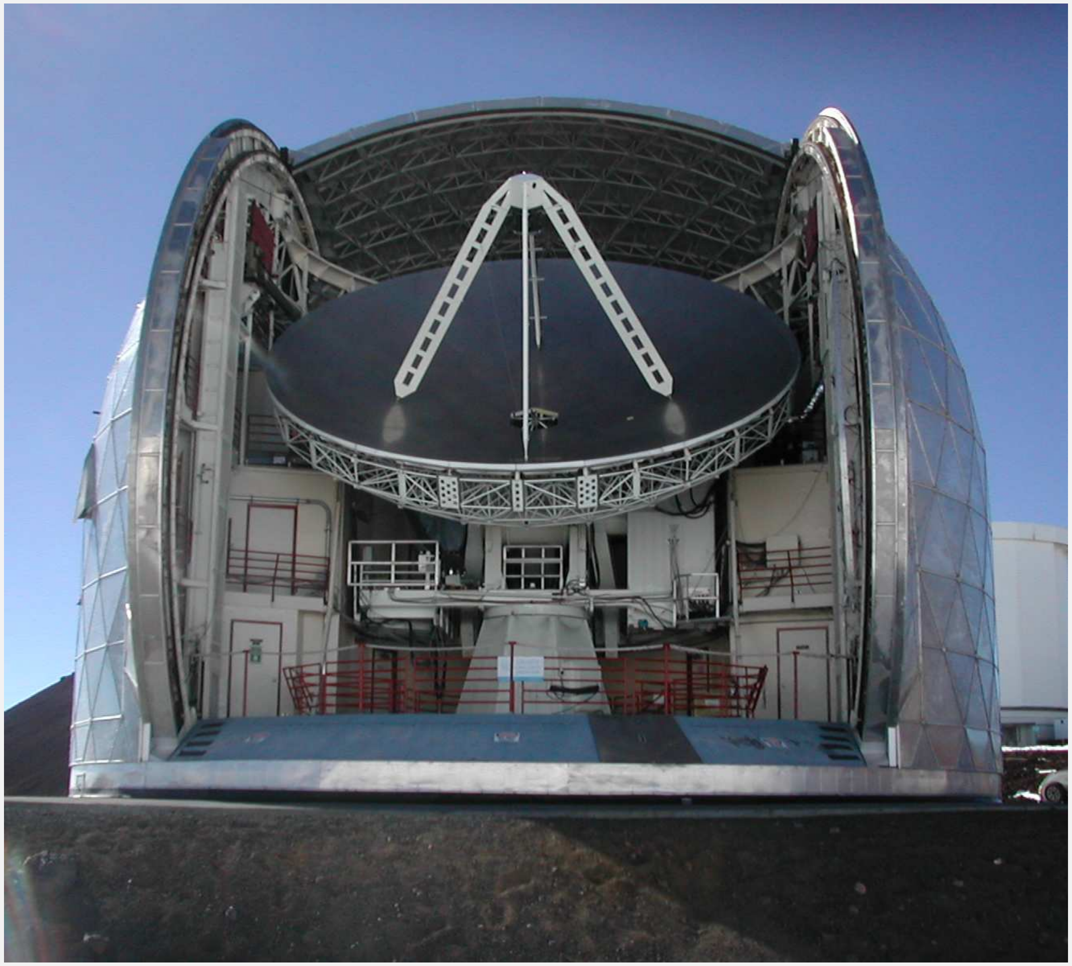




- 144-pixel NTD-Ge spiderweb bolometer array
- 2 non-simultaneous observing bands, 1.1 mm (dusty sources), 2.1 mm (SZ)
- Beams defined by smooth-walled conical feed-horns
- Array is operated at 250 mK
- Essentially identical to SPIRE!

Caltech Submillimeter Observatory

- 10.4 m telescope on summit of Mauna Kea
- Lat: 19° N
- Elev: 4087 m
- Median 1.75 mm column depth of precipitable water
- Median τ of 0.05 at 2.1 mm,
  0.13 at 1.1 mm

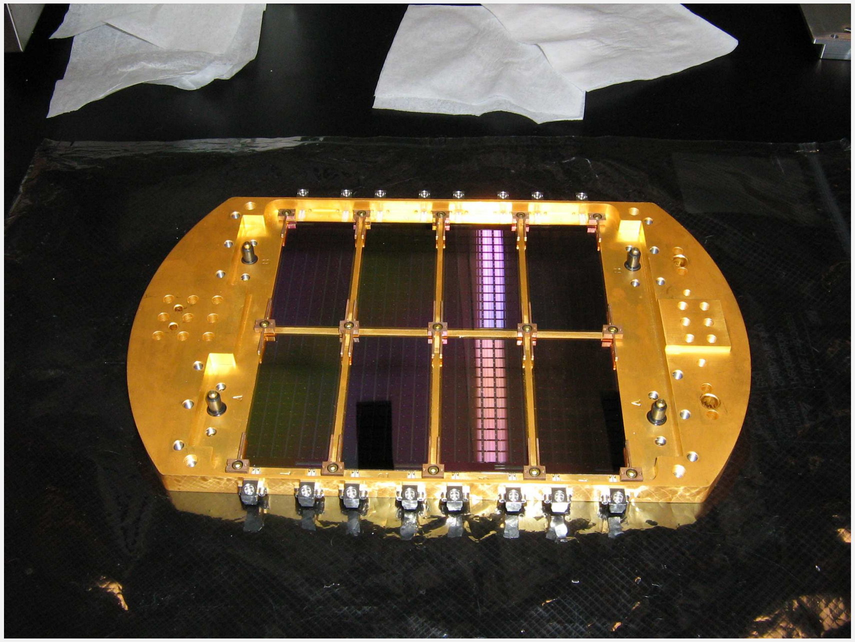


Bolocam Optics

- Use the same reimiging optics at both 1.1 and 2.1 mm (modulo AR coatings)
- Achieve an approximately circular FOV with a diameter of 8 arcmin (identical FOV at both wavelengths)
- PSFs with FWHM of 31 arcsec at 1.1 mm and 58 arcsec at 2.1 mm
- Pixel-to-pixel spacing of $\simeq 40$ arcsec $\longrightarrow$ nearly Nyquist sampling at 2.1 mm

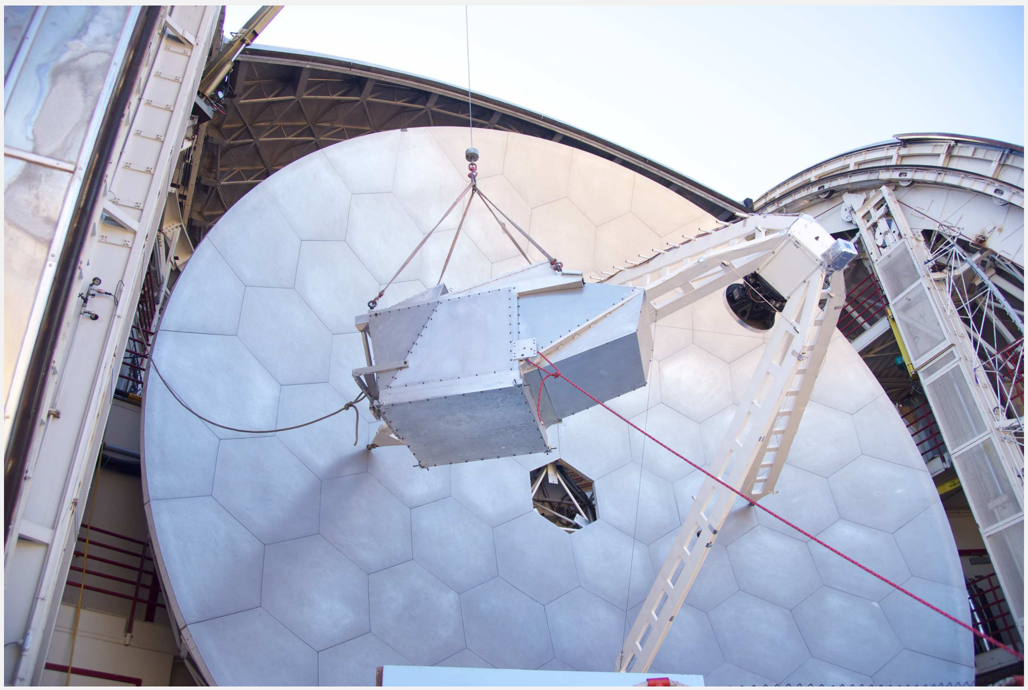
MUSIC

- MUSIC is replacing Bolocam at the CSO
- Square 14 arcmin FOV with 576 (24x24) pixels
- Four bands for each pixel (2.00, 1.33, 1.02, 0.86 mm)
- PSFs with FWHM of 45, 31, 25, 22 arcsec
- $\simeq 2400$ microwave kinetic inductance detectors (MKIDs)

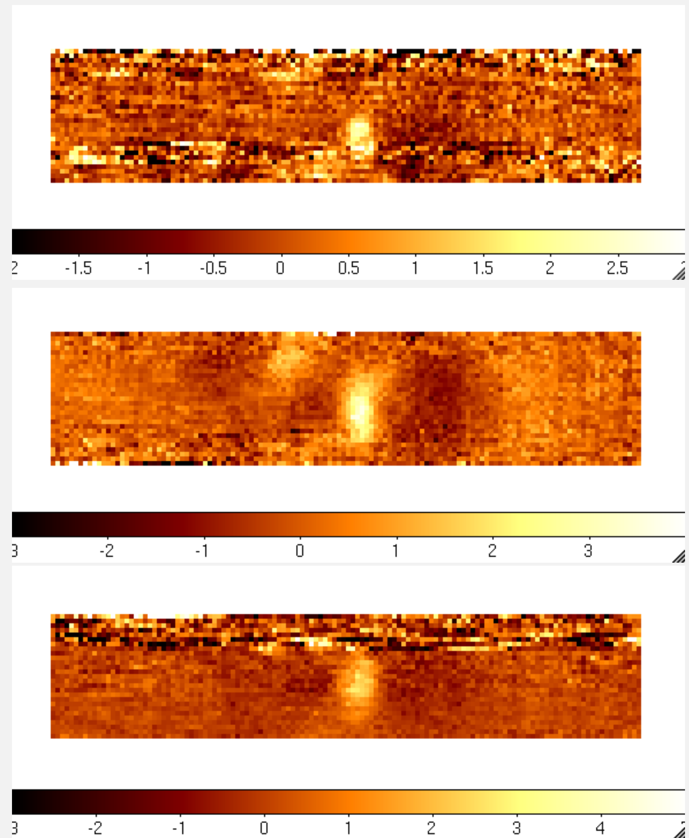


The Current Status of MUSIC

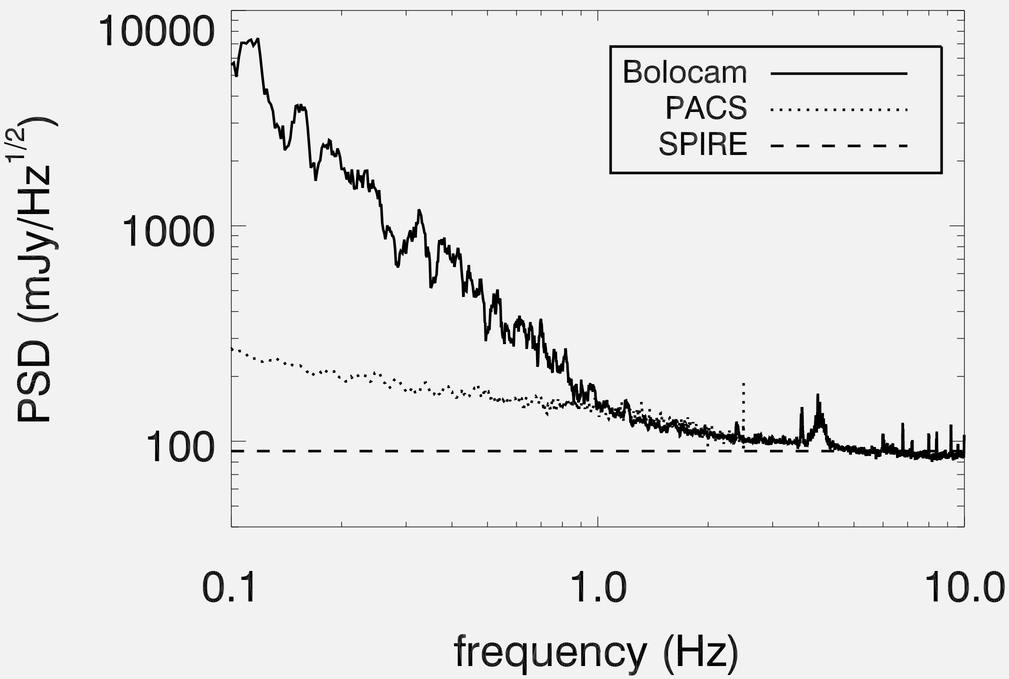
- We installed MUSIC at the CSO in April 2012
- We have had three short engineering runs since then
- Not quite "science-grade" yet → hopefully mid 2013



3-color SGR A image from 2-minute integration!! →



Typical Bolocam Noise PSD

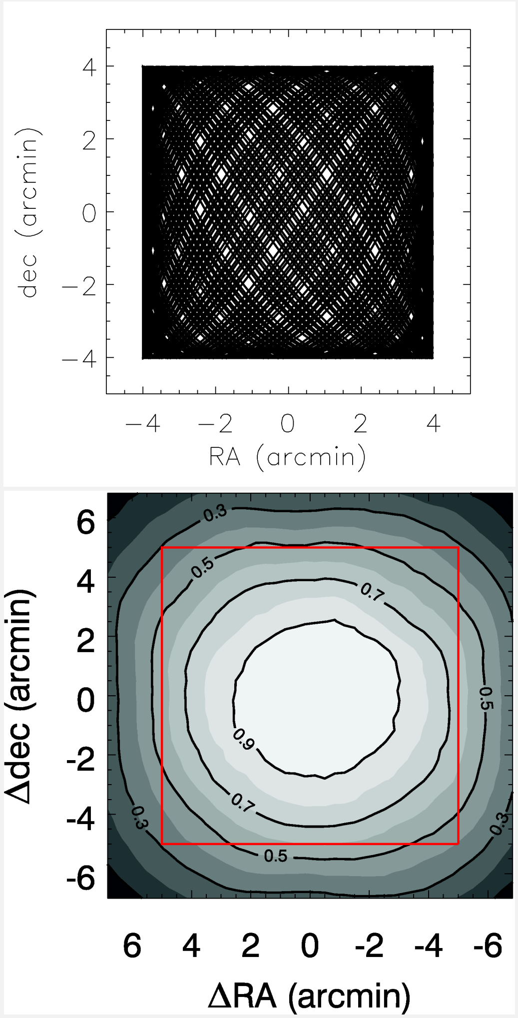


Typical Bolocam noise PSD, overplotted with PACS and SPIRE PSDs normalized to the same white level (SPIRE PSD is an artistic rendering meant to emphasize spectral features not easily seen in the true measurements)

- White noise of $\simeq 100$ mJy/$\sqrt{\text{Hz}}$ in both Bolocam bands
  - Approximately independent of atmospheric conditions
- Atmospheric fluctuations dominate at $f \lesssim 1 - 2$ Hz and are $\propto f^{-4/3}$
  - Amplitude roughly proportional to opacity, but with large scatter

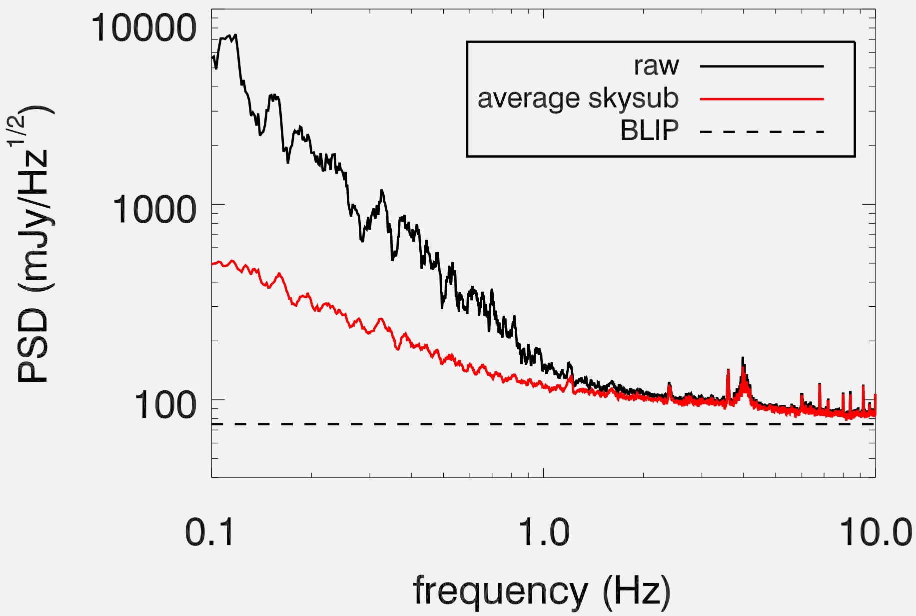
Bolocam Scanning

- Scan at CSO maximum of $2 - 4$ arcmin/sec to modulate cluster signal above low-frequency atmospheric noise
  - Typical drift speed of atmosphere is 30 arcmin/sec, so even relatively fast scans will not modulate atmospheric signal
- All large fields observed with stepped rasters evenly split between two orthogonal raster directions (RA/DEC or AZ/EL)
- Compact sources observed with Lissajous pattern



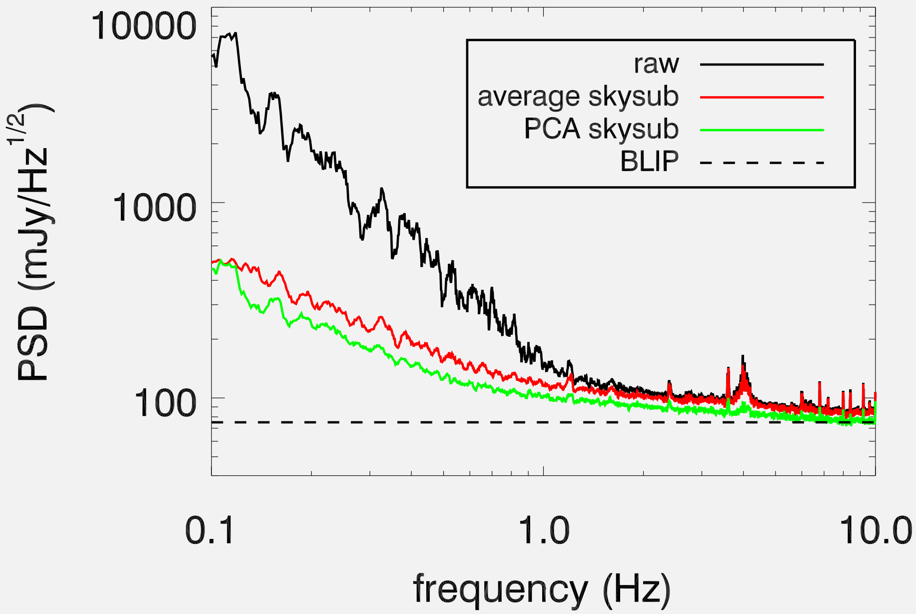
Top: Lissajous scan trace
Bottom: resulting coverage

FOV-Average Subtraction



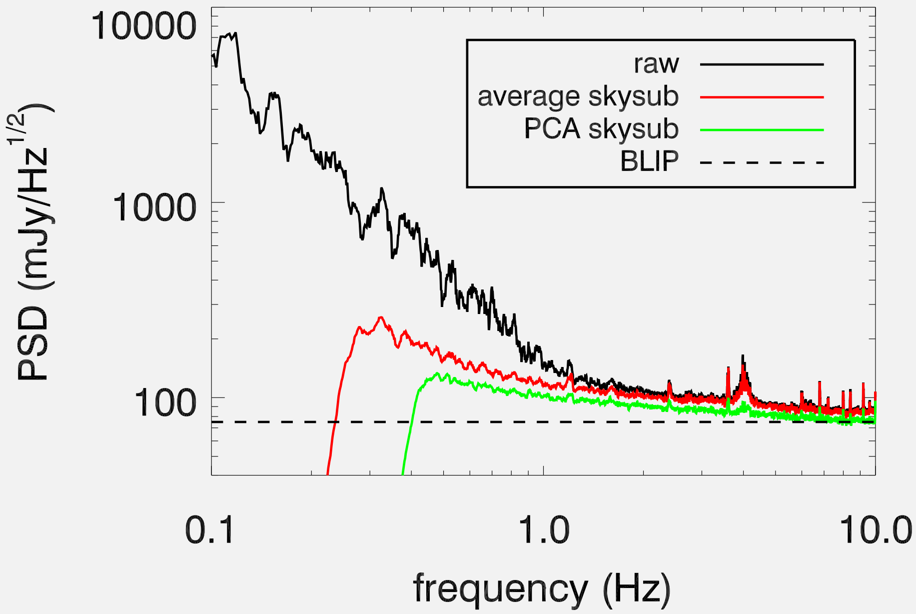
- Telescope far-field is 10s of km $\longrightarrow$ all beams overlap to high degree through atmosphere
- Atm fluctuations produce signal that is approx common to all bolometers at each time sample
- Removing FOV-average signal at each sample subtracts $\simeq 90\%$ of atmospheric signal
- Modest improvements from allowing linear/quadratic variation over FOV

FOV-PCA Subtraction



- Also use principal component analysis (PCA)
- Decompose a chunk of $N_{bolos} \times N_{samples}$ time-stream data into a set of N_{bolos} orthogonal basis vectors, each with $N_{samples}$
- Cut the vectors with the highest eigenvalues, either iteratively or by specifying a fixed number of vectors to cut
- Better noise removal than FOV-average, but non-linear wrt signal shape $\longrightarrow$ behaves like an "unpredictable black box"

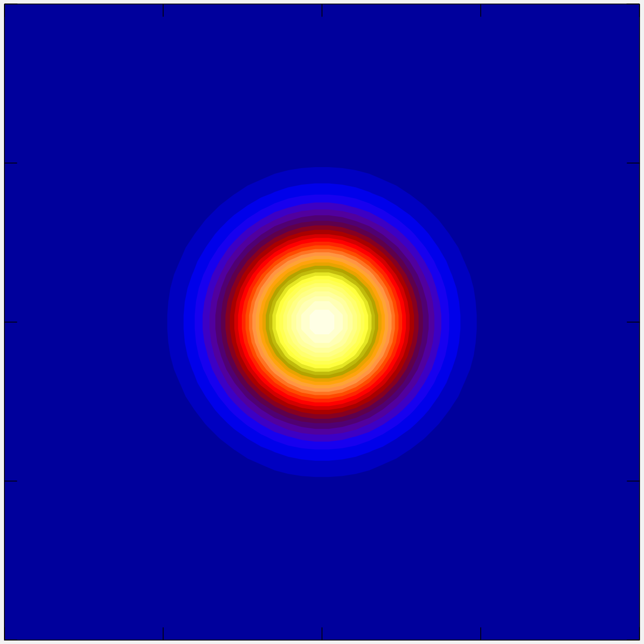
Time-Stream High-Pass Filter



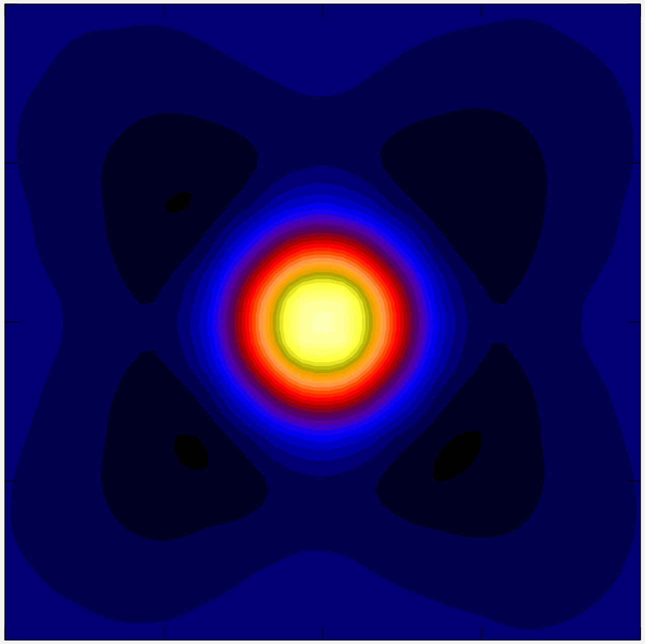
- Both PCA and average Subtraction leave significant noise at very low frequencies $\longrightarrow$ both methods have also attenuated most of the astronomical signal at these frequencies

- For short raster scans, remove this noise by subtracting mean of each raster (typically 5-10 seconds in length)
- For longer rasters and continuous scans (e.g., Lissajous), apply HPF directly to time-streams at $250 - 500$ mHz

Map-Making for Point Source Photometry



Left: True Bolocam PSF Right: Bolocam PSF filtered by PCA

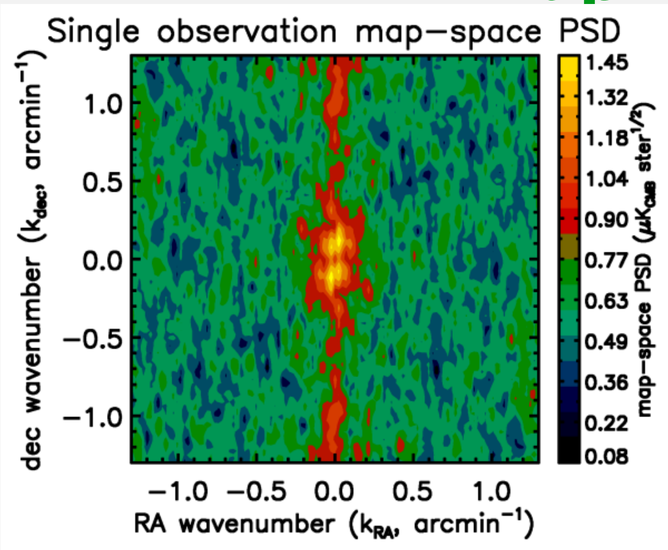


- PCA + HPF is the best option for isolated unresolved sources
- PCA is well behaved (and linear with signal strength) for these sources, and produces the lowest noise
- Only penalty is $\simeq 15\%$ reduction in source peak
- PSF photometry is obtained by fitting "PCA beam" to image

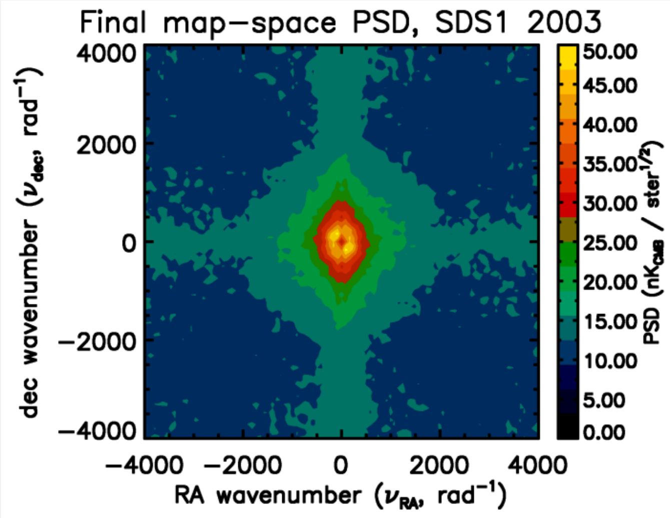
Map-Making for CMB

- $m = (p^T wp)^{-1} p^T wd$ is least squares optimal map estimate
  - m is map, p is pointing matrix, w is inverse of time-stream noise covariance, d is time-stream data
- Noise is stationary+circulant, so FT of w is diagonal and noise can be described by a PSD (e.g., SANEPIC)
- Our scans are strictly in RA or dec and there is roughly one time sample per map pixel $\longrightarrow p \simeq 1 \longrightarrow$ time-stream noise can be described by map-space PSD
- All correlations between bolos due to atmospheric noise $\longrightarrow$ instantaneous and constant over observation so correlated noise is stationary $\longrightarrow$ FT of w still diagonal
- Relative bolometer positions also constant over observation $\longrightarrow$ map-space PSD still describes time-stream noise

Map-Making for CMB



Left: MAP PSD for single set of RA scans
Right: Optimal map PSD from $\simeq$ 200 sets each of RA and dec scans

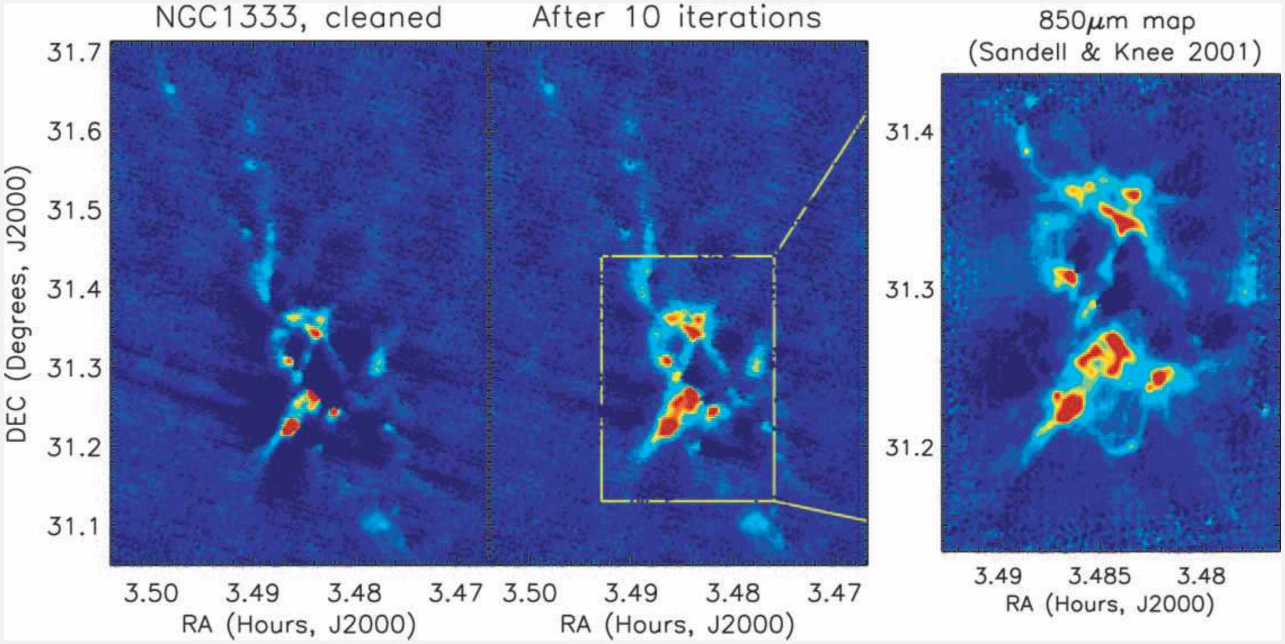


- $m = (p^T wp)^{-1} p^T wd \rightarrow M = (\sum_i 1/P_i)^{-1} (\sum_i (1/P_i) M_i)$
  – M is FT of naive map of observation i, P is noise PSD of map
- Extremely fast compared to typical GLS $\rightarrow$ no inversions and only requires N_{obs} FFTs of maps with N_{pix} elements
- Approximately optimal if: 1) parallel raster scans, 2) constant noise properties for each set of scans that covers the full map 3) many sets of scans (observations)

Map-Making for the Galactic Plane Survey

- Return to GLS equation ($d = ps + n$), but $N_{scans} = 1, 2$
- Split n into multiple components, each solved for separately (atmosphere, correlated electronics, long timescale drift, Gaussian photon/detector)
- Iteratively fit for all noise components (plus astronomical signal), going in sequence from largest to smallest amplitude signal within each iteration
- Use PCA for atmospheric subtraction, with fixed number of discarded vectors
- Build "true" sky model using CLEAN algorithm on data map with a kernel size of $\simeq 1/2$ FWHM

Map-Making for the Galactic Plane Survey

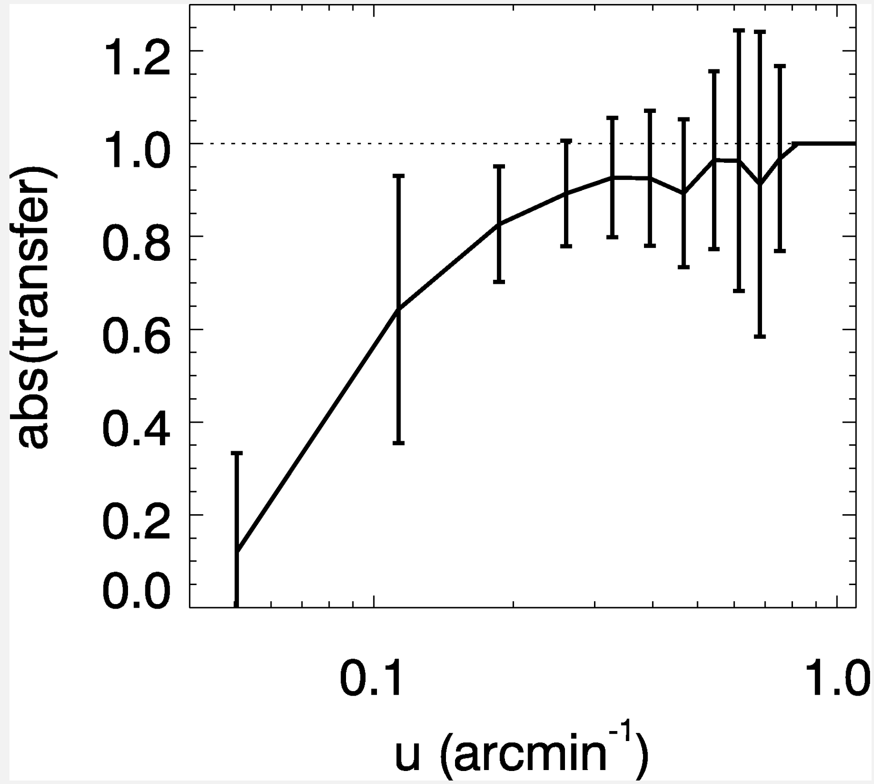


Left: original Bolocam map with deep negative rings around the sources, Right: after 10 iterations of the iterative map-maker, Far Right: SCUBA map of same field

- Results in a map with accurate photometry for sources with Gaussian FWHMs less than $\simeq 100$ arcsec
- Still heavy attenuation on FOV and larger scales (> 8 arcmin) due to atmospheric subtraction

Map-Making for Resolved SZ Clusters

- Map clusters using Lissajous scans, tapered coverage to $\simeq 10$ arcmin in radius
- Quasi-random scan direction $\longrightarrow$ can't use CMB GLS
- Care more about unbiased signal estimate than minimum noise $\longrightarrow$ can't use iterative GLS

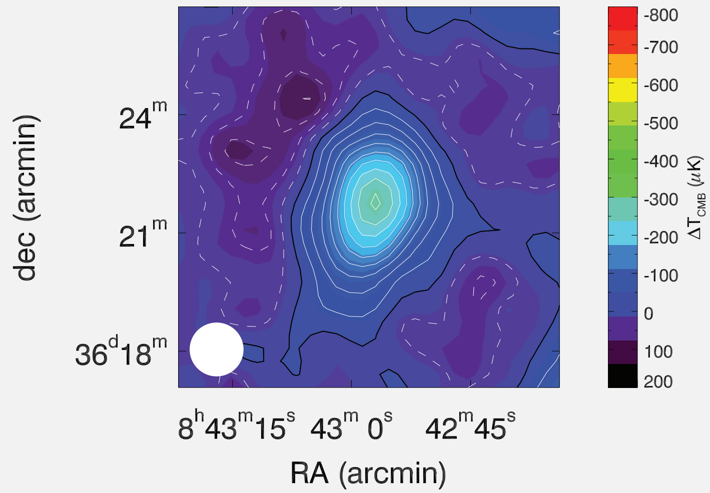


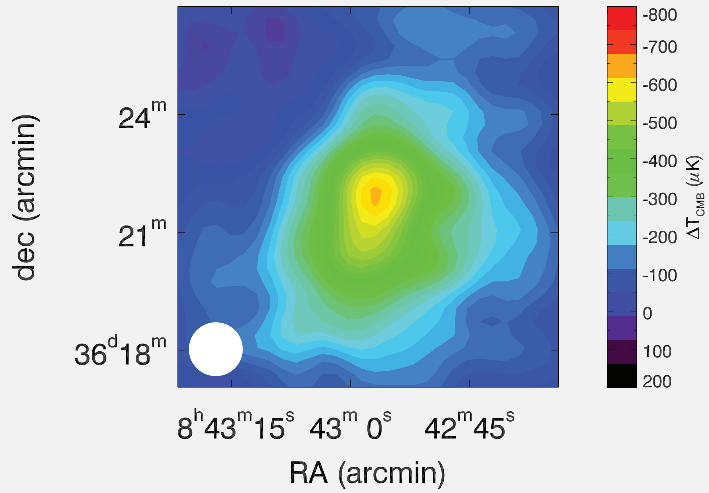
- Make naive map using FOV-average plus HPF to produce a repeatable and approximately linear signal transfer function at all angular scales $\longrightarrow$ allows for reliable deconvolution

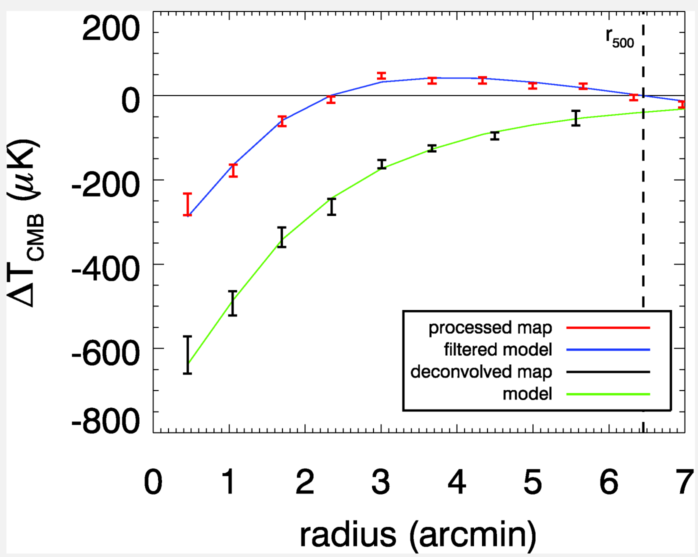
Map-Making for Resolved SZ Clusters

- Can deconvolve filtering to obtain unbiased estimate of signal at all angular scales in map $\longrightarrow$ except "DC" signal
- Sunyaev-Zel'dovich signal from galaxy clusters has radial profile that goes roughly like R^{-1}
  - Significant emission on scales larger than the 4 arcmin FOV radius (and even the 10 arcmin radius of our maps) $\longrightarrow$ how to set zero-point of the image?
- Constrain image "DC" signal as follows
  - Constrain parametric SZ model using the data and transfer function
  - Add offset to image so that average map value outside some radius (e.g., 5 arcmin) matches parametric SZ model
  - Allows quasi-model-independent photometry inside that radius

Abell 697 ($z = 0.28$)







Summary

- Bolocam has been used to image a variety of astronomical sources, and we have developed approximately optimal map-making routines to constrain the photometry (and morphology) of these sources
- Aggressive filtering (PCA + HPF) is optimal for unresolved sources
- To recover large scale emission for maps with repeated orthogonal rasters a "fast" GLS method is best
- Optimal recovery of extended emission in sparse coverage maps is obtained via iterative GLS map-making
- Linear map-making (e.g., not PCA or anything iterative) is best for unbiased signal recovery for quasi-random scans

The CSO and Herschel

- The 10.4 m Caltech Submm Observatory (CSO) provides an ideal ground-based long-wavelength complement to Herschel
- Bolocam/MUSIC provide imaging at 850, 1000, 1300, and 2000 μm at $22 - 45$ arcsec resolution
- SHARC II provides imaging at 350 and 450 μm at $9 - 11$ arcsec resolution
- ZSpec provides moderate resolution spectroscopy ($R \simeq 300$) with instantaneous coverage from $1000 - 1600$ μm (HCN, CN, CS, SO)
- ZEUS II provides moderate resolution ($R \simeq 1000$) large bandwidth ($\Delta\lambda/\lambda \simeq 0.05$) spectroscopy simultaneously at 350 and 450 μm in 9-element slit (CO $7 \rightarrow 6$, $6 \rightarrow 5$, CI)
- Heterodyne receivers covering 180-920 GHz

The CSO and Herschel

- As you may know, the NSF discontinued funding for the CSO, but....
- The CSO *is still available!*
- We have developed partnerships with the plan of extending operations through 2016, and we welcome additional partners
- Contact
  - Sunil Golwala (golwala at astro.catlech.edu)
  - Darek Lis (dcl at caltech.edu)
  - Tom Phillips (tgp at caltech.edu)