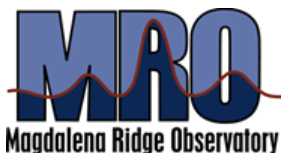


Calibration in Optical Interferometry

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Outline

- ▶ Key Differences Radio and Optical Interferometry affecting calibration
- ▶ Visibility Amplitude Calibration
- ▶ Phase Calibration
- ▶ Examples of data and practical considerations

Key Similarities/Differences

Same

- ▶ Measurement of the complex visibility, V_{ij}
- ▶ Need to coherently combine signals from separated collectors
- ▶ Imperfect collectors and detectors that “affect” the signal and result in lower visibility than the true source

Different

- ▶ Wavelengths (obviously)
- ▶ Timescales/spatial scales for atmosphere’s behavior to “change”
- ▶ Somewhat different angular scales on the sky - optical is in the mas to submas regime (more like VLBI) while radio can go up to 10’s of arcseconds

What we are NOT talking about with *Calibration*: throughput, individual telescope performance, optical coatings, delay line design, detectors or their readout methods. These ALL have a bearing on how the data is taken, but are not part of this conversation.



- ▶ In order to “freeze” the atmosphere over the telescopes we need to use very short observations
- ▶ Our typical measurement is about 10ms
- ▶ **Two effects:**
 - ▶ Spatial fluctuations across the telescope aperture - V_{ij} is not 1
 - ▶ Temporal fluctuations in 10ms even for a small telescope may still mean V_{ij} on a point source is not 1

Fried
parameters
and
Seeing

Work Fast - It's changing!

- ▶ Integrations/samples/interferograms measured quickly

- ▶ Try to “freeze out” the temporal/spatial effects

$$V_{ij\text{-measured-10ms}} = G * V_{ij\text{-true}}$$

- ▶ G is a complex gain factor with an amplitude of 1 and an unknown phase
 - ▶ One could factor the phase terms between each telescope in pairs of i and j
 - ▶ Atmosphere above each telescope is slightly different and continuously changing
→ piston fluctuations

Let's try again for a better outcome

- ▶ You can always separate a complex quantity into its real and imaginary components
- ▶ Let's rewrite this:

$$V_{ij\text{-measured-10ms}} = G * G_{ij} * V_{ij\text{-true}}$$

- ▶ G can be factored into G_i and G_j for each combined telescopes you are using
- ▶ G_{ij} is for each pair, together and it now contains the separate gain which is less than 1, but *no phase*
- ▶ We have now “decoupled” the errors into factorizable amplitude and phase terms

Statistics to the Rescue!

- ▶ The G_{ij} is an amplitude gain error
 - ▶ Combine this statistically as we have lots of data samples
 - ▶ Average a few thousand (low) SNR estimates of V_{ij} on the source
 - ▶ We typically work with $|V_{ij}|^2$ which we call sometimes call “visibility” - **Caution!**
- ▶ The “Calibration” part of the visibility amplitude is accomplished by comparing this interferometer response between the unresolved “calibrator” and the resolved “target”
- ▶ Use: Square root of the (Calibrated- V^2) = $|V_{ij}|_{\text{true}}$
- ▶ Interleave the observations between calibrator and targets on few to 10’s of minutes.
- ▶ **BUT, Remember we had to assume the spatial and temporal atmospheric fluctuations were frozen out!**

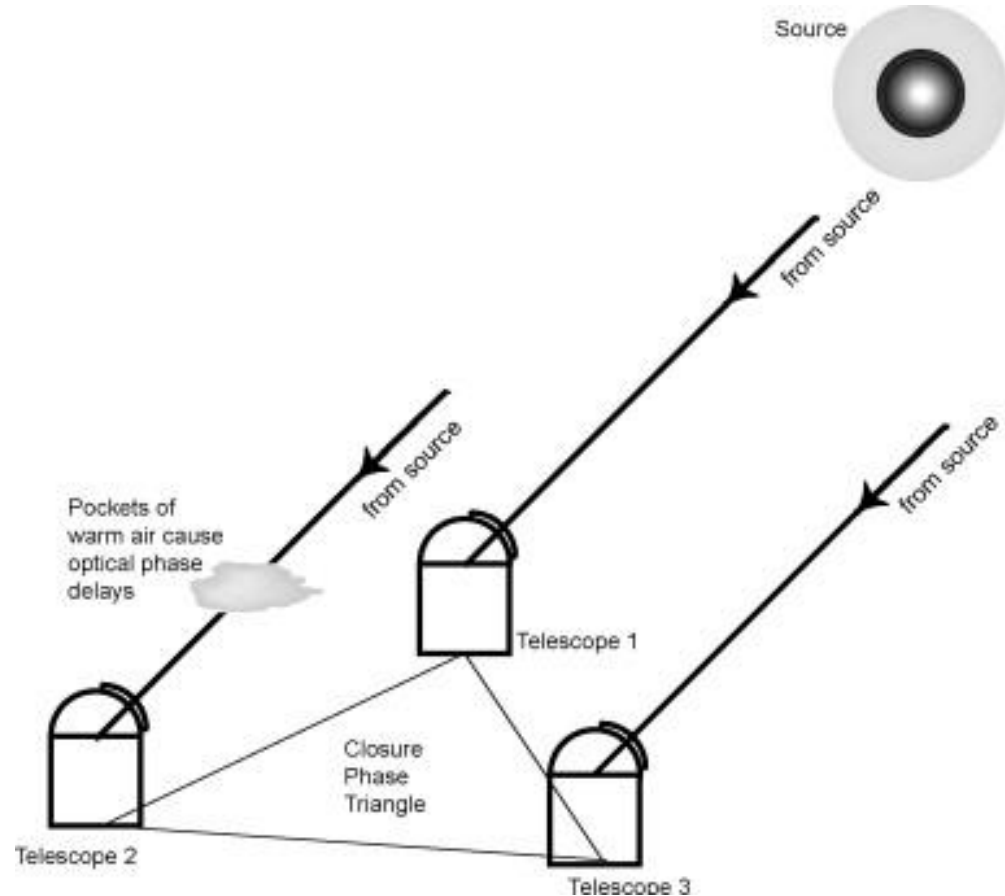
What about the Phase?

- ▶ Remember the phase over *each* telescope is different and changing about every 10 ms - so how do we get the *complex* visibility component measurement out of the data?
- ▶ **Crazy Solution:** Add another telescope!
 - ▶ Use something called the Bispectrum

Cornwell and Wilkinson (1981)
Cornwell (1987)

How does the Bispectrum work?

Monnier (2007)



- ▶ Measure V_{12} , V_{13} and V_{23} simultaneously
- ▶ We get a noisy estimate of the complex visibilities on each baseline in 10 ms
- ▶ Multiply these measurements together

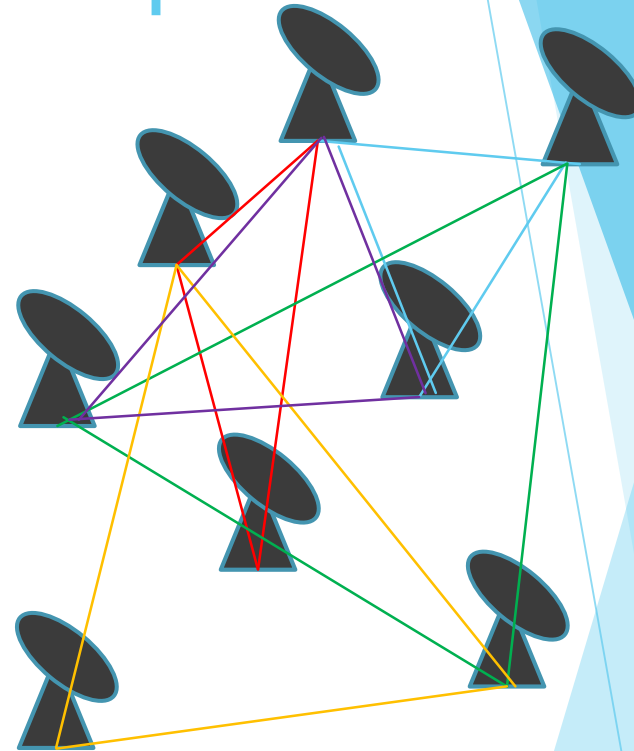
$$\text{Bispectrum} = \langle V_{12} V_{13} V_{23} \rangle$$

- ▶ The argument of the bispectrum is the *closure phase* and it is unaffected by telescope-based piston errors
- ▶ Do the same thing on your “calibrator” and “target” in interleaved observations

“Wash, Rinse, Repeat” with all Scopes

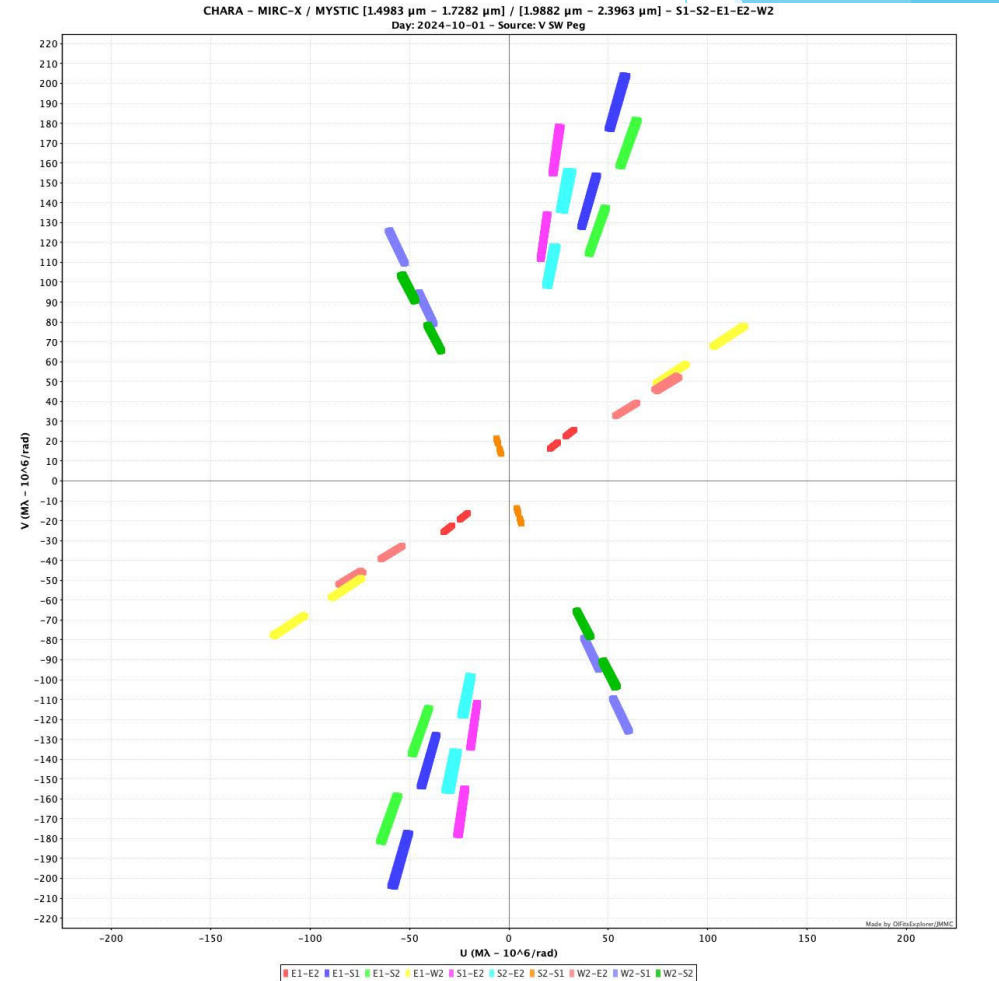
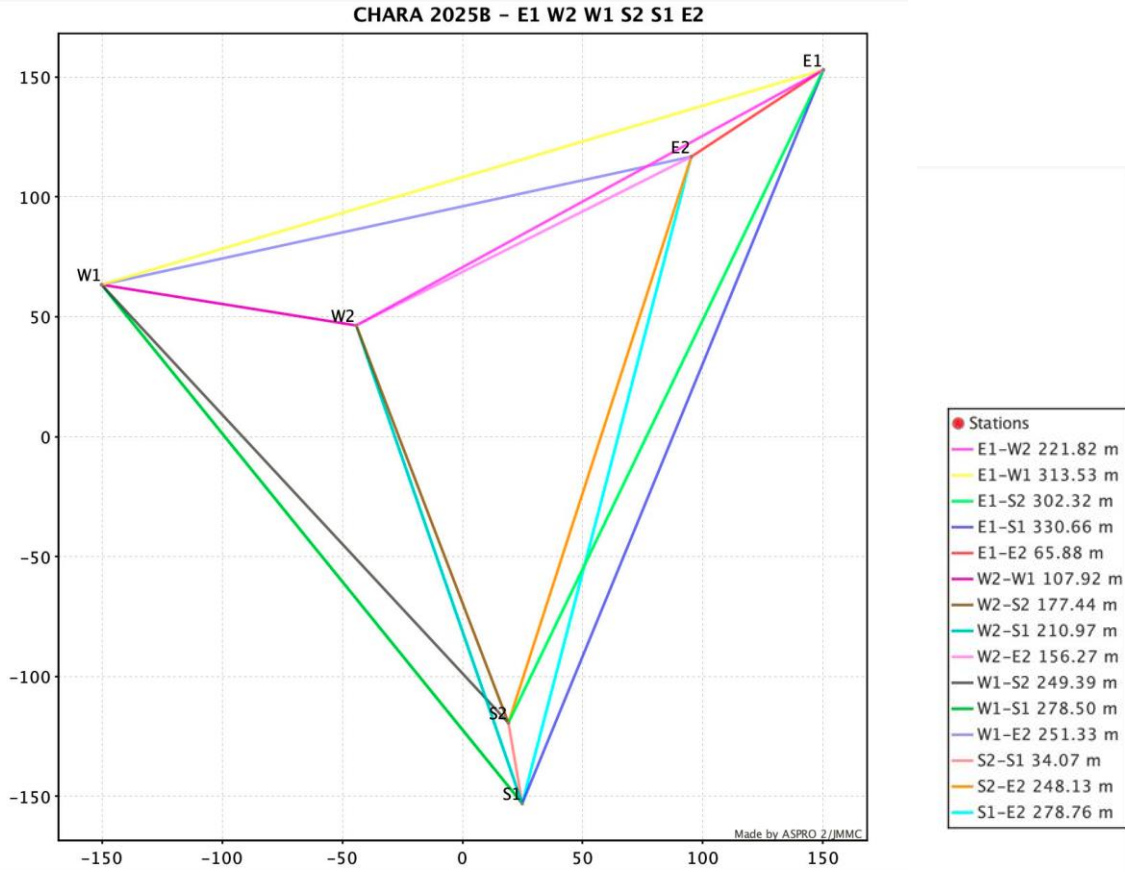
- ▶ We now have a bispectrum measurement every 10 ms for every telescope triangle combination in the array
- ▶ We can measure on the “target”, and on the “calibrator”, and divide each one if we wish
- ▶ Statistics come to the rescue yet again to help us win the race and build up SNR

- ▶ → AND now we can make an Image!

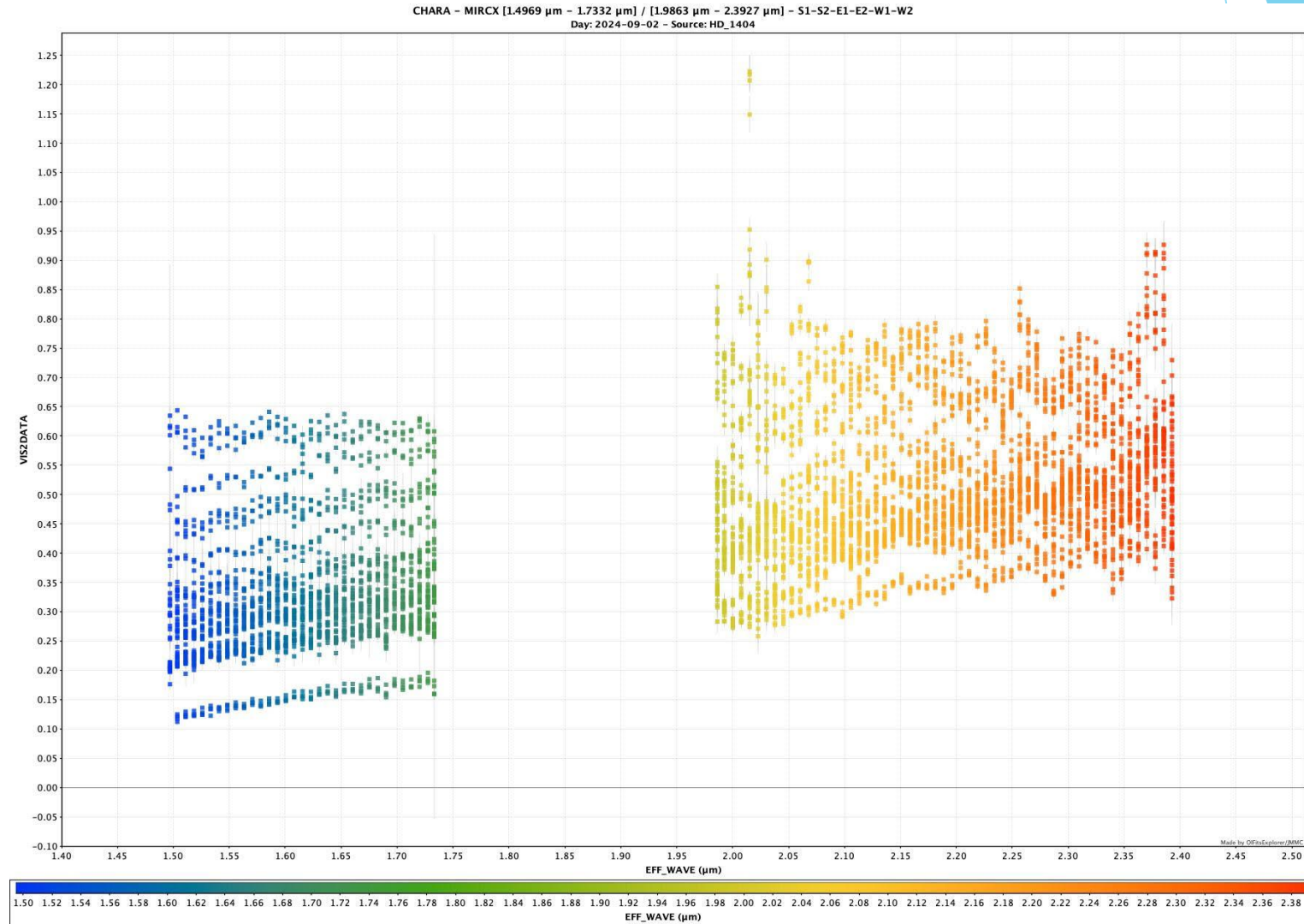


Real Data - CHARA Program on Miras

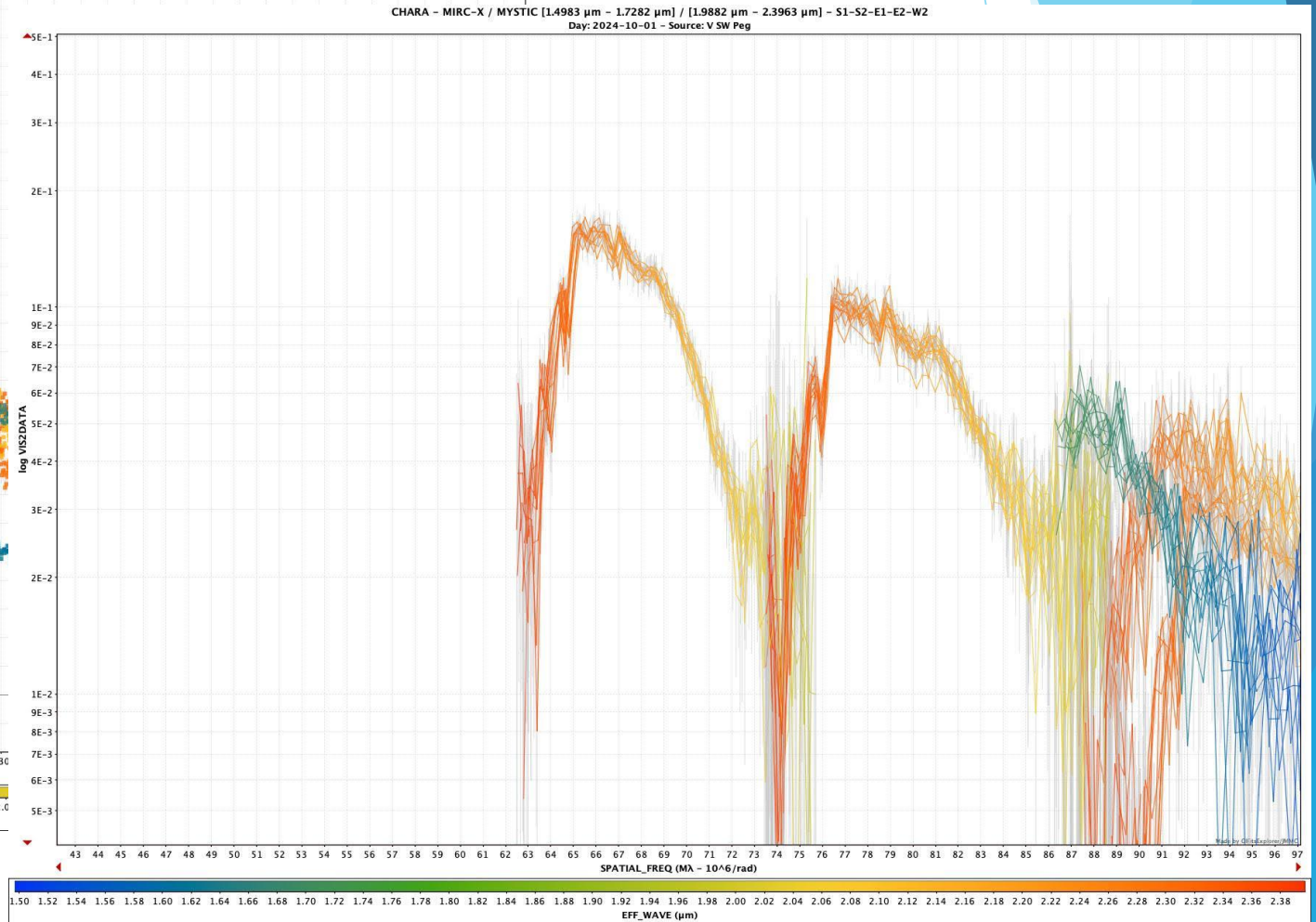
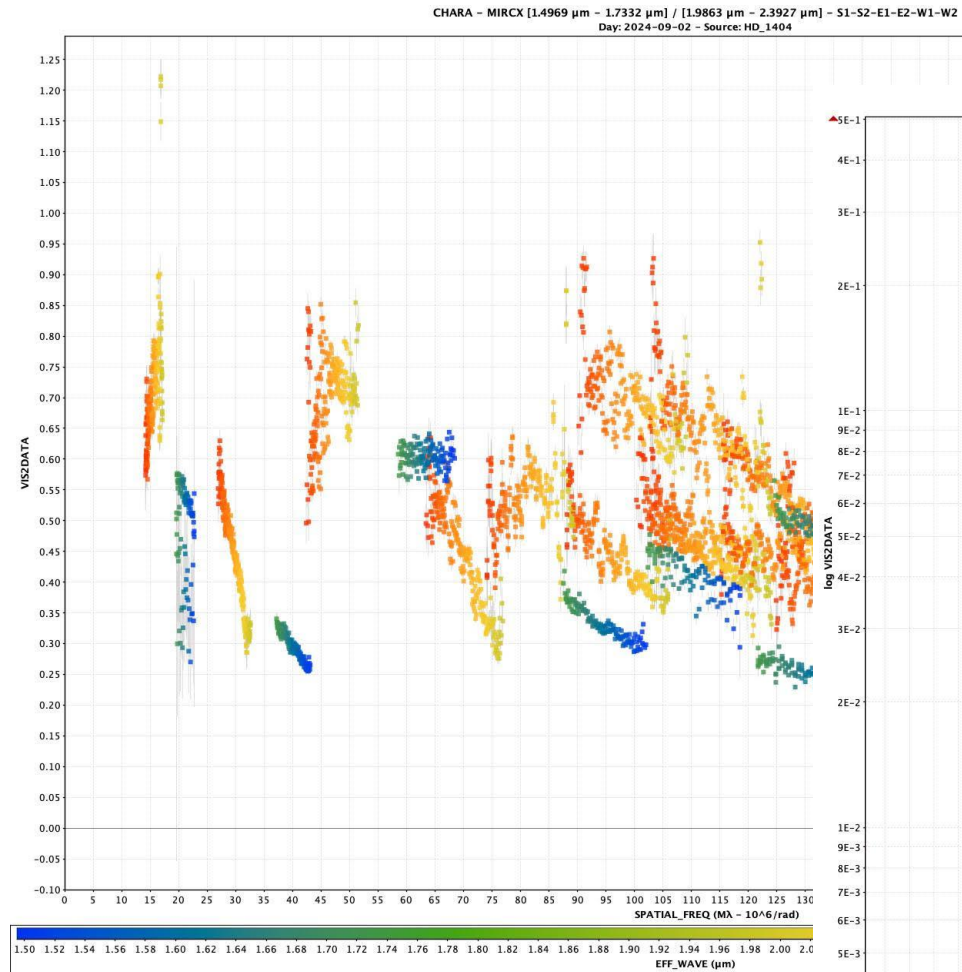
(Baylis-Aguirre in prep.)



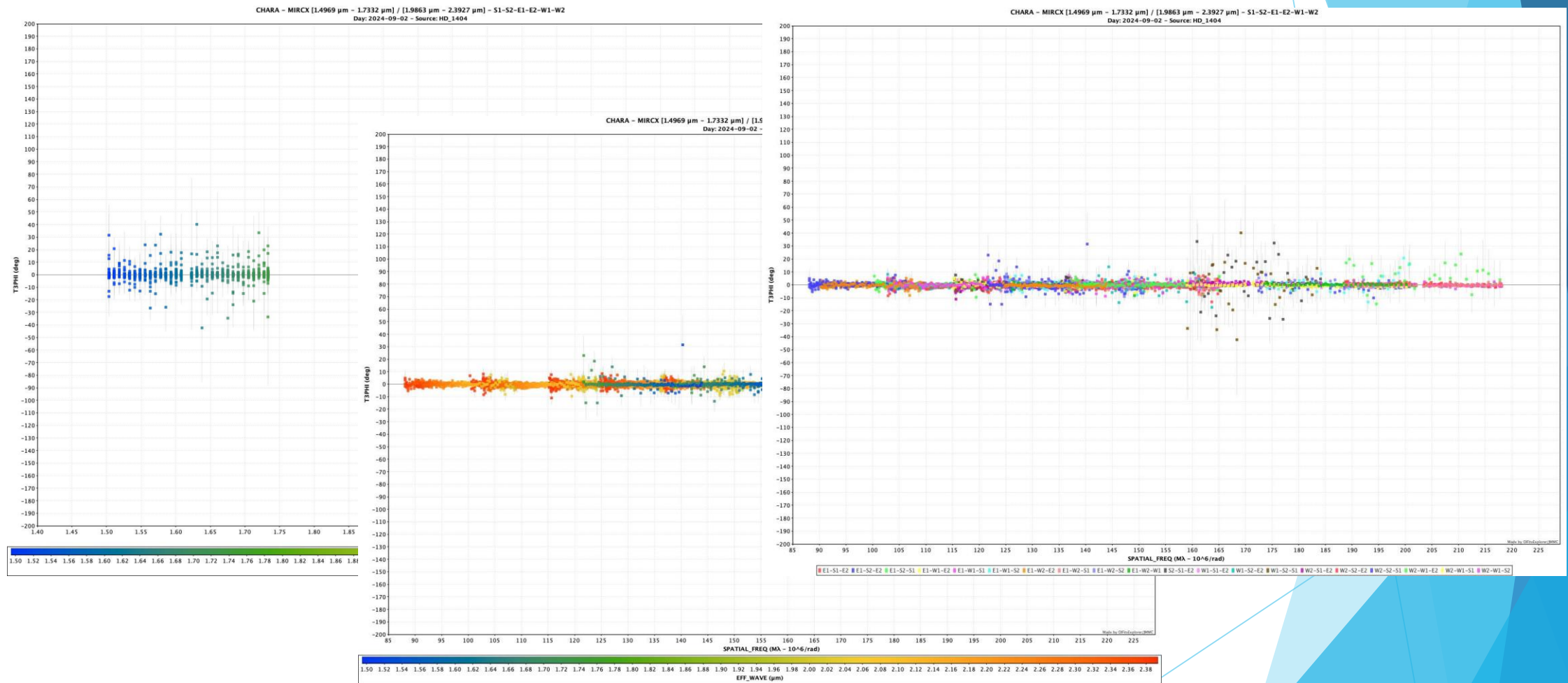
Calibrator Visibilities



Target Visibilities



Calibrator Triple Products/Bispectra



Practical Considerations

- ▶ Calibration objects should be BORING
 - ▶ Unresolved objects - pay attention to the baseline (0.25mas stars are hard to find at the right mag)
 - ▶ Usually single stars - *unless you need binaries*
 - ▶ Close in the sky to target
 - ▶ Similar magnitude
 - ▶ Without any spectral features - *unless you need them*
 - ▶ We don't worry about polarization calibration - yet!
- ▶ Use a model for the calibrator
 - ▶ Assume unresolved uniform disk
 - ▶ Use parametric/atmospheres models plus spectra energy distribution fits for the flux and angular diameter estimates
 - ▶ If you have RV and you know a binary orbit very well this can be a powerful calibration target
 - ▶ Calibrators depend on the wavelength you need - spectral lines might help

You can use whatever data reduction package you like for extracting the image from the data.

Parting Comments....

- ▶ Process of recording the interferometric data with radio and optical arrays is somewhat different (technology)
- ▶ The calibration is fairly dissimilar but the outcome is basically the same (atmospheric timescales)
- ▶ Imaging can be done with any data (radio/submm/infrared/optical/UV) and just about any imaging packages once you have your calibrated complex visibilities

Questions?

Special thanks to the organizers of the NRAO Summer School and to Professor Chris Haniff for valuable discussions about this material.

Thank you for your attention!