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Turning the Haystack-37m Telescope into a Multi-User Research Instrument

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01 Background & Introduction

Background

Haystack 37m Telescope

- 37-meter, radome-enclosed radio dish first constructed in 1964

- Rebuilt in 2010–2014 to have a significantly-improved dish surface accuracy of <0.1 mm

- Slewing speed, surface precision, and pointing accuracy result in efficient, sensitive observations at frequencies up to ~230 GHz in the winter

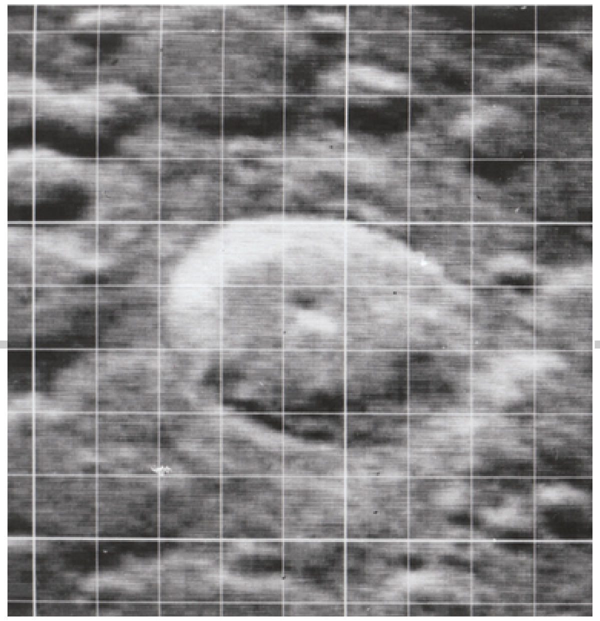
- Current work is focused on instrument characterization and demonstration of scientific capabilities

Haystack Telescope Radome | Credit: The Center for Land Use Interpretation

History of Astronomy with the 37m

Selected Astronomical Achievements

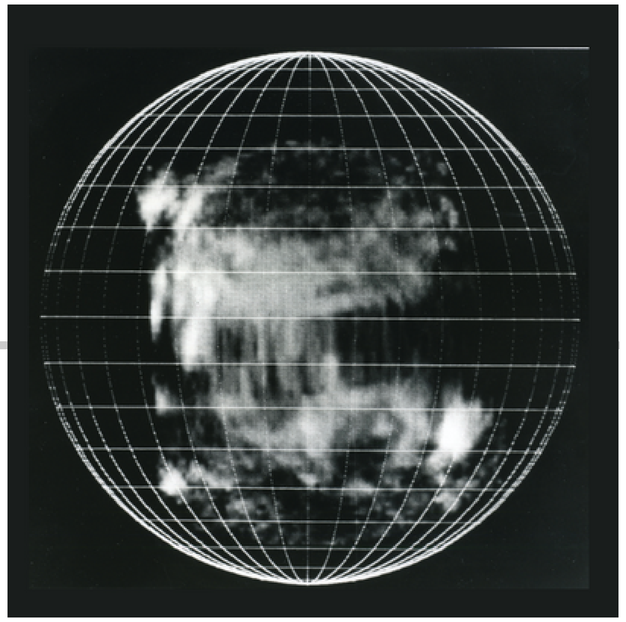
1964



Radar map of the lunar crater Tycho, published in 1974

1960s

Informed selection of Apollo landing sites



Venus's surface features from radar interferometry, 1966

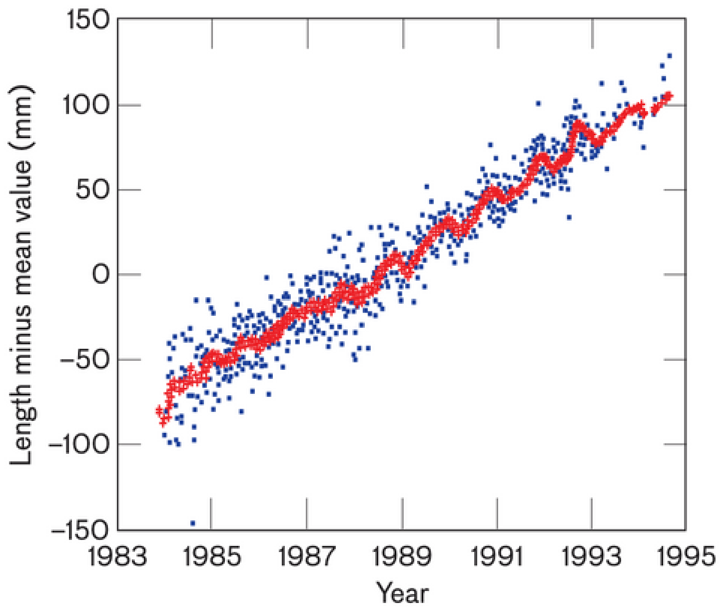
1960s

Created first radar maps of Venus' surface with separate northern and southern hemispheres

Early VLBI Recorder

1960s-70s

Leader in the establishment of Very Long Baseline Interferometry (VLBI)



Gradual opening of the Atlantic Ocean floor

1970s-90s

Creation and development of Geodetic VLBI

Figures taken from Whitney et al. 2014

Project Goals

Motivation

- If fully equipped, **the Haystack 37m Telescope would be one the two most sensitive millimeter wave instruments in the continental United States.**

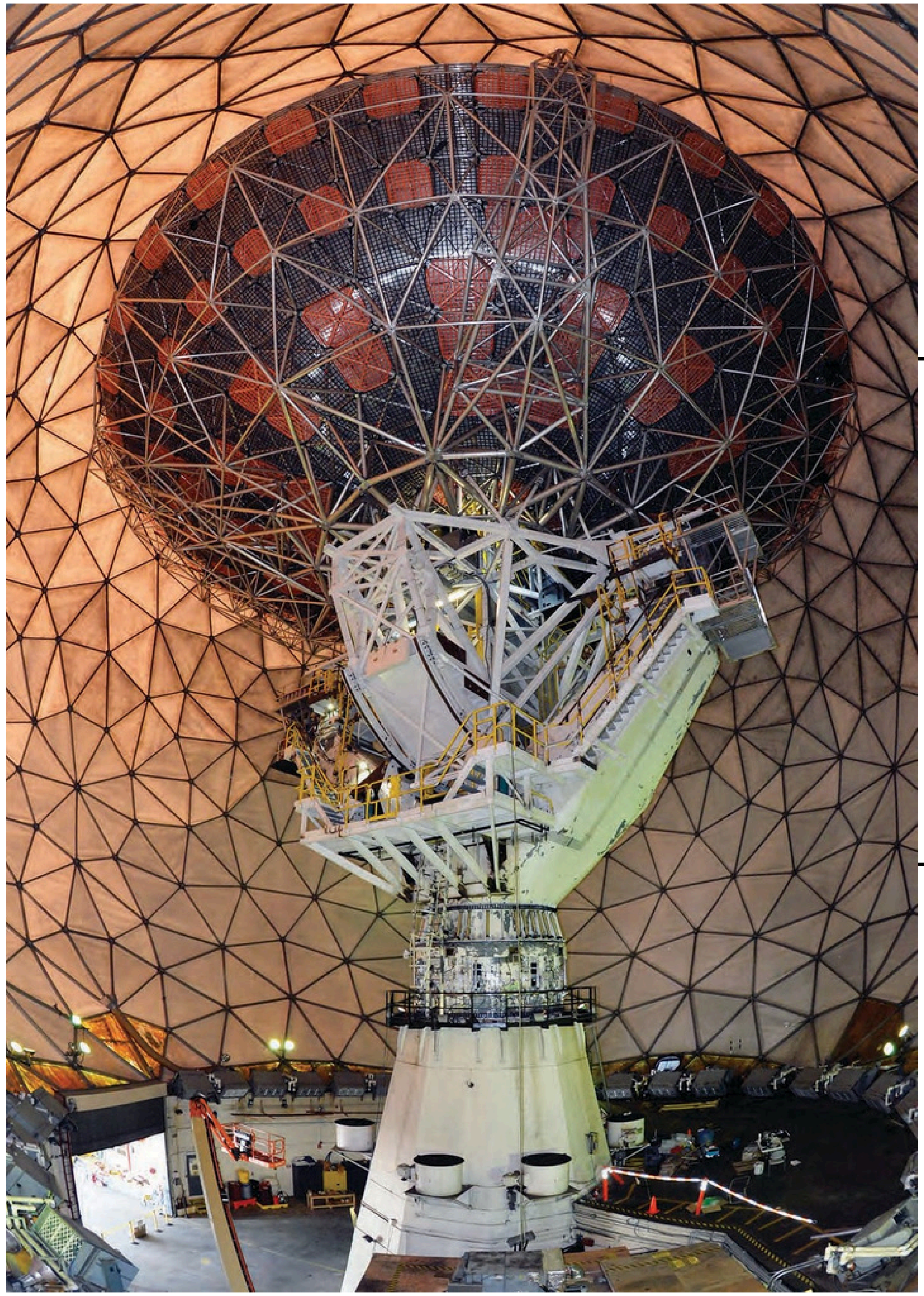
- Extremely useful instrument for a variety of different research fields

- Near-future goal is to make this telescope available for the astronomical community for research and education

- However, lacking a user friendly control system

Goal

Create a more capable system for the Haystack 37m Telescope to turn it into a multi-user research instrument

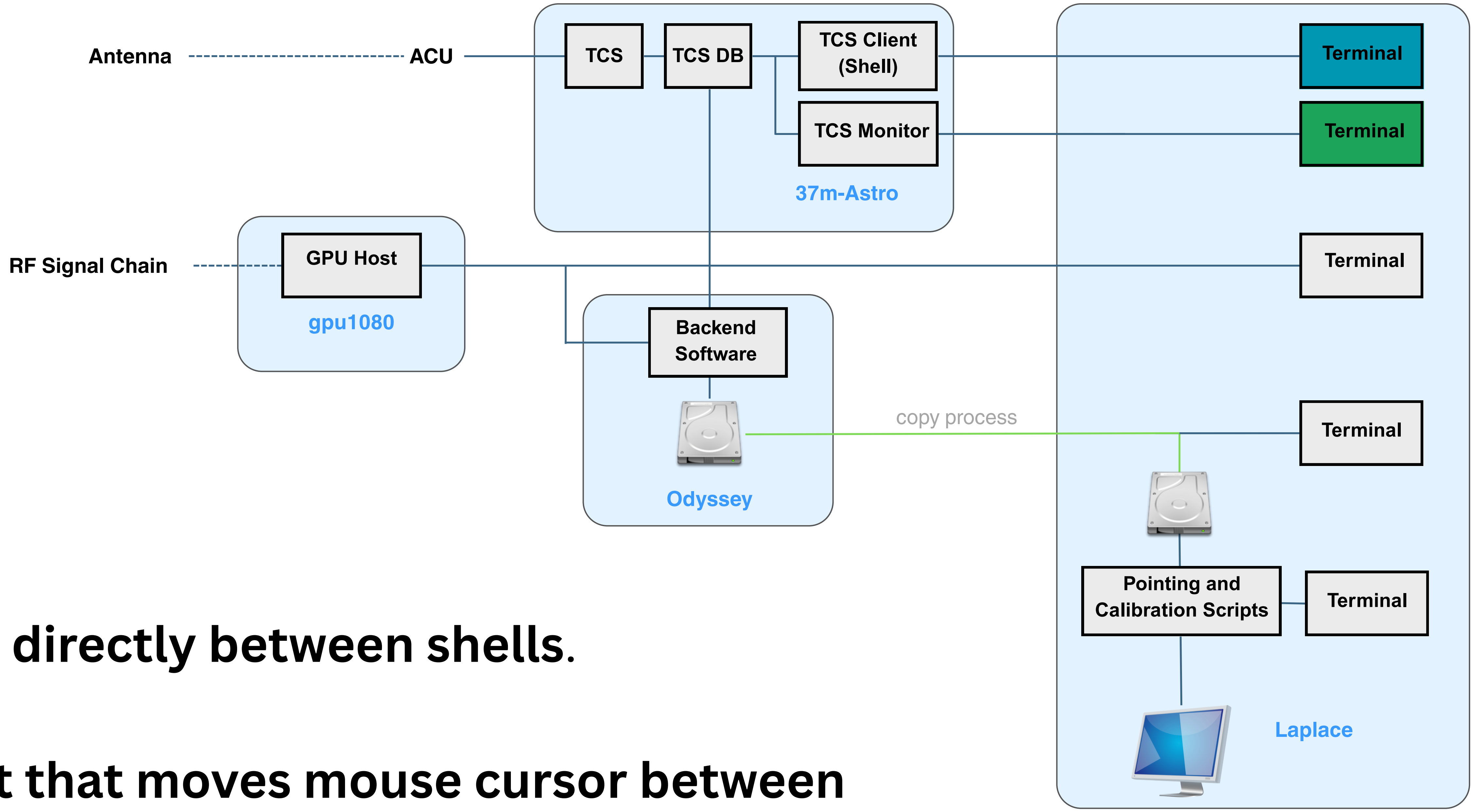


Haystack Ultrawideband Satellite Imaging Radar
Credit: Lincoln Laboratory Website

02 Old Control System & User Interface

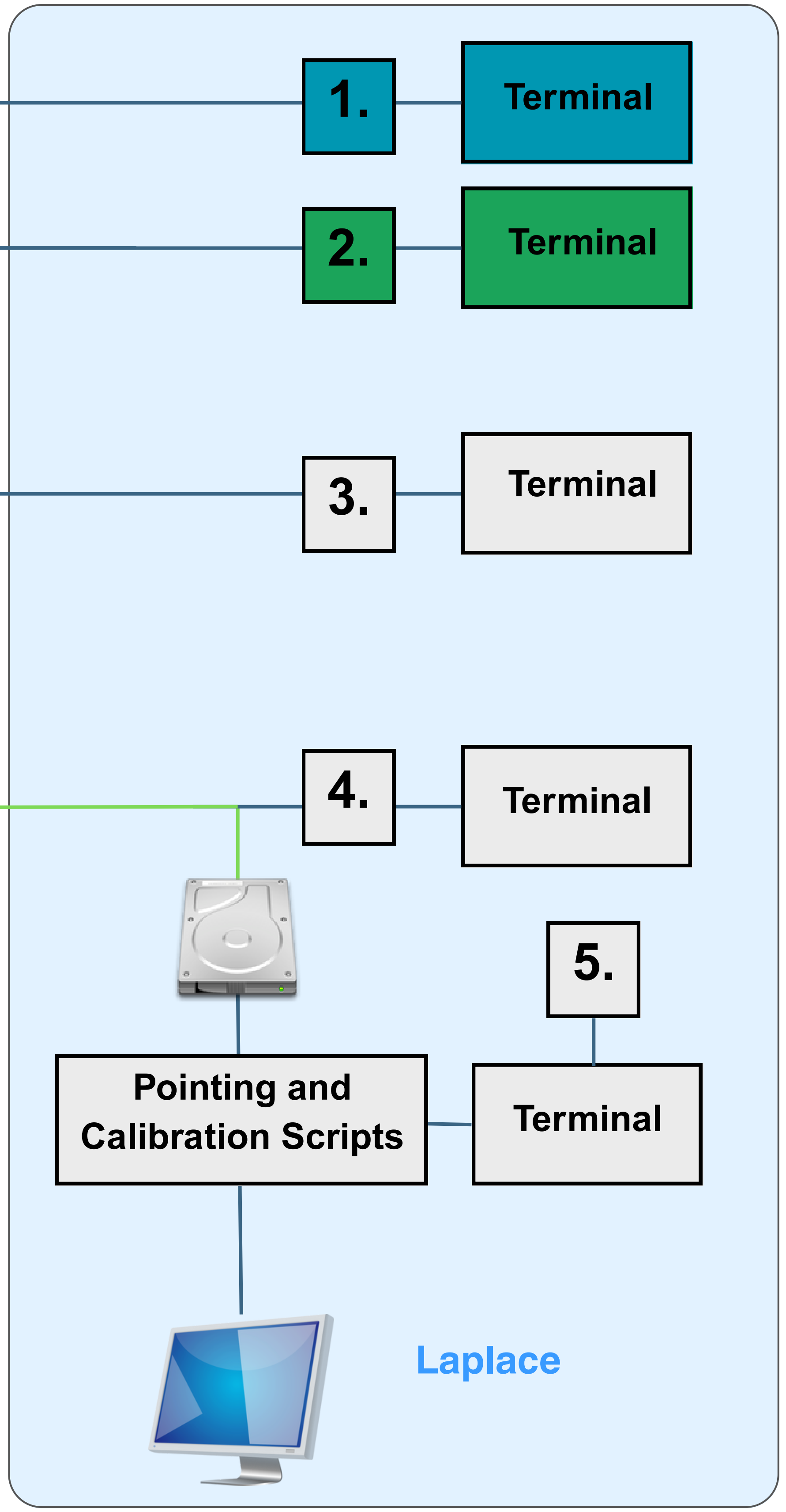
Old Control Signal Chain

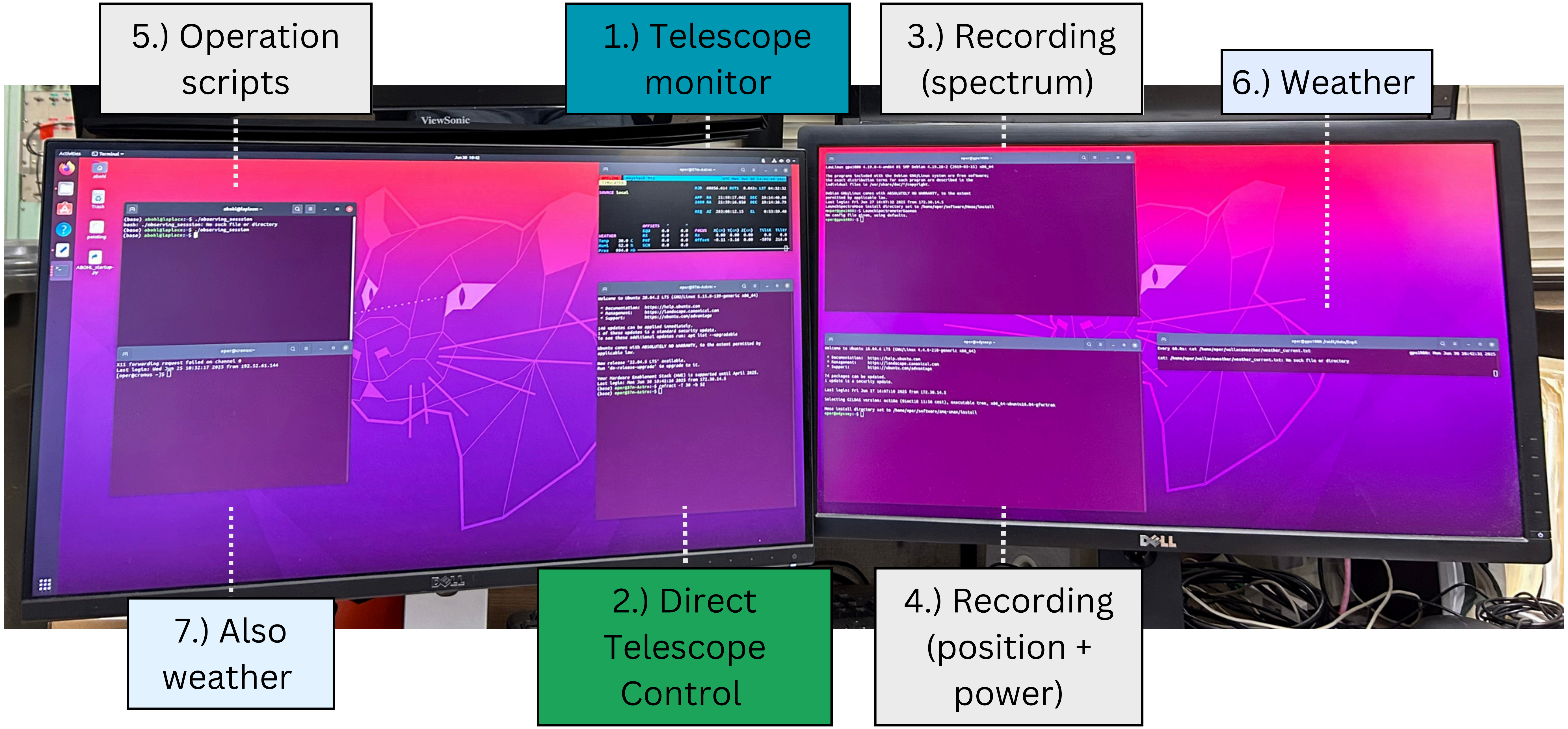
- Each blue box is a separate computer with distinct capabilities and roles within the signal chain
- Telescope operation requires that these computers share real time data
- However, **data cannot be shared directly between shells**.
- **Data coordinated via shell script that moves mouse cursor between different terminal windows**
- Cannot touch mouse during telescope operation!



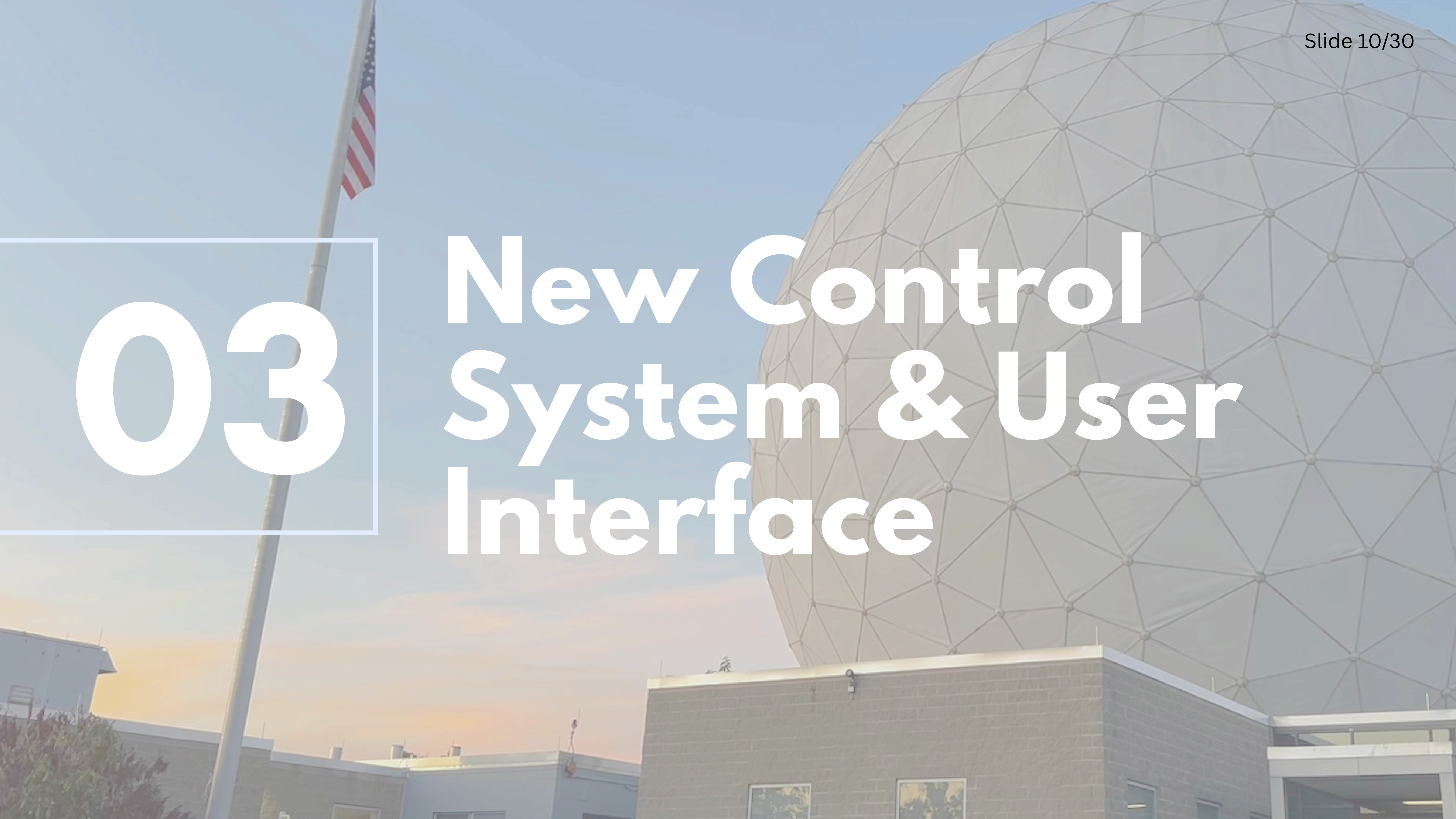
TCS: Telescope Control System

Old User Interface



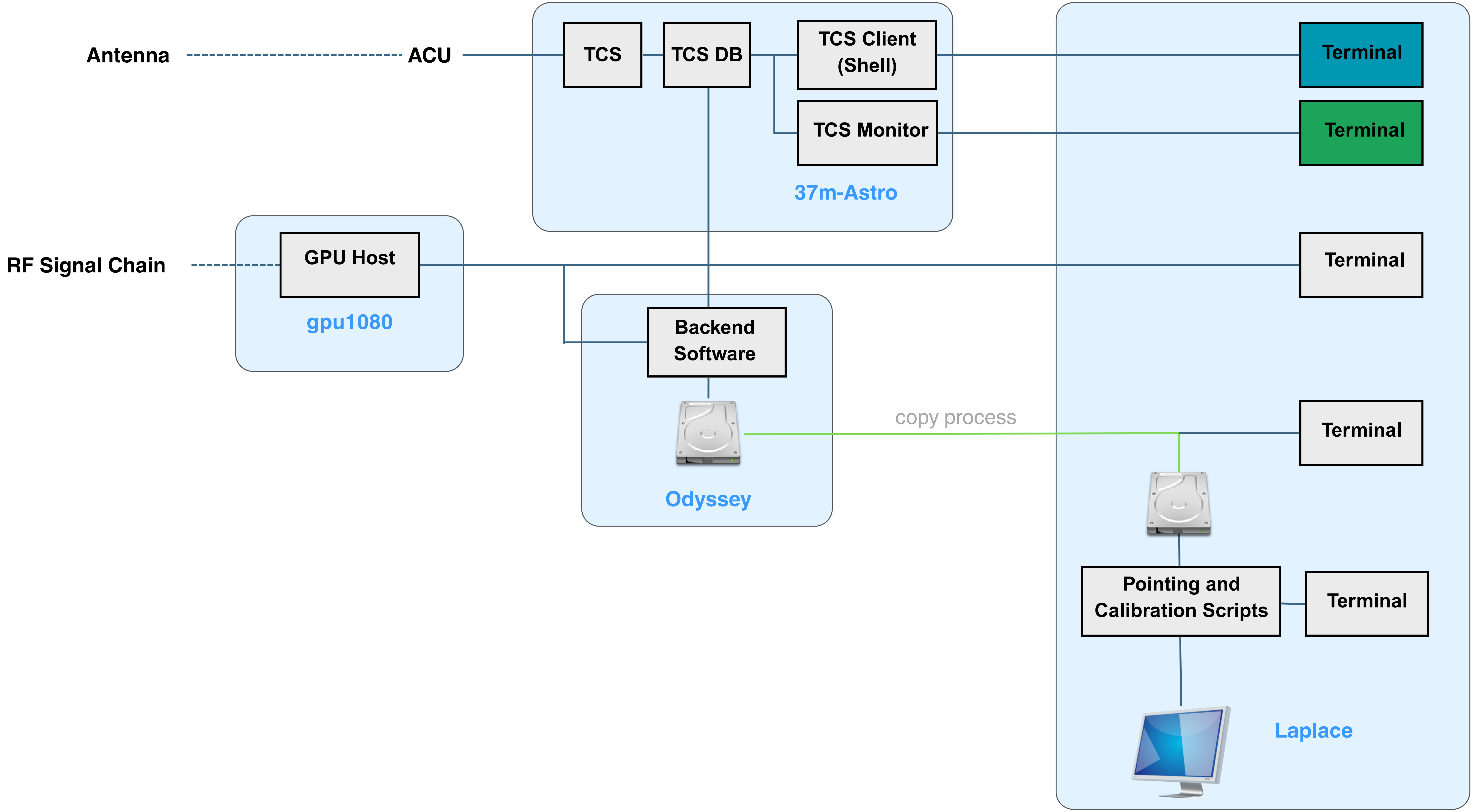


- Visually cluttered
- Shells not communicating
- Cannot touch mouse during operation.

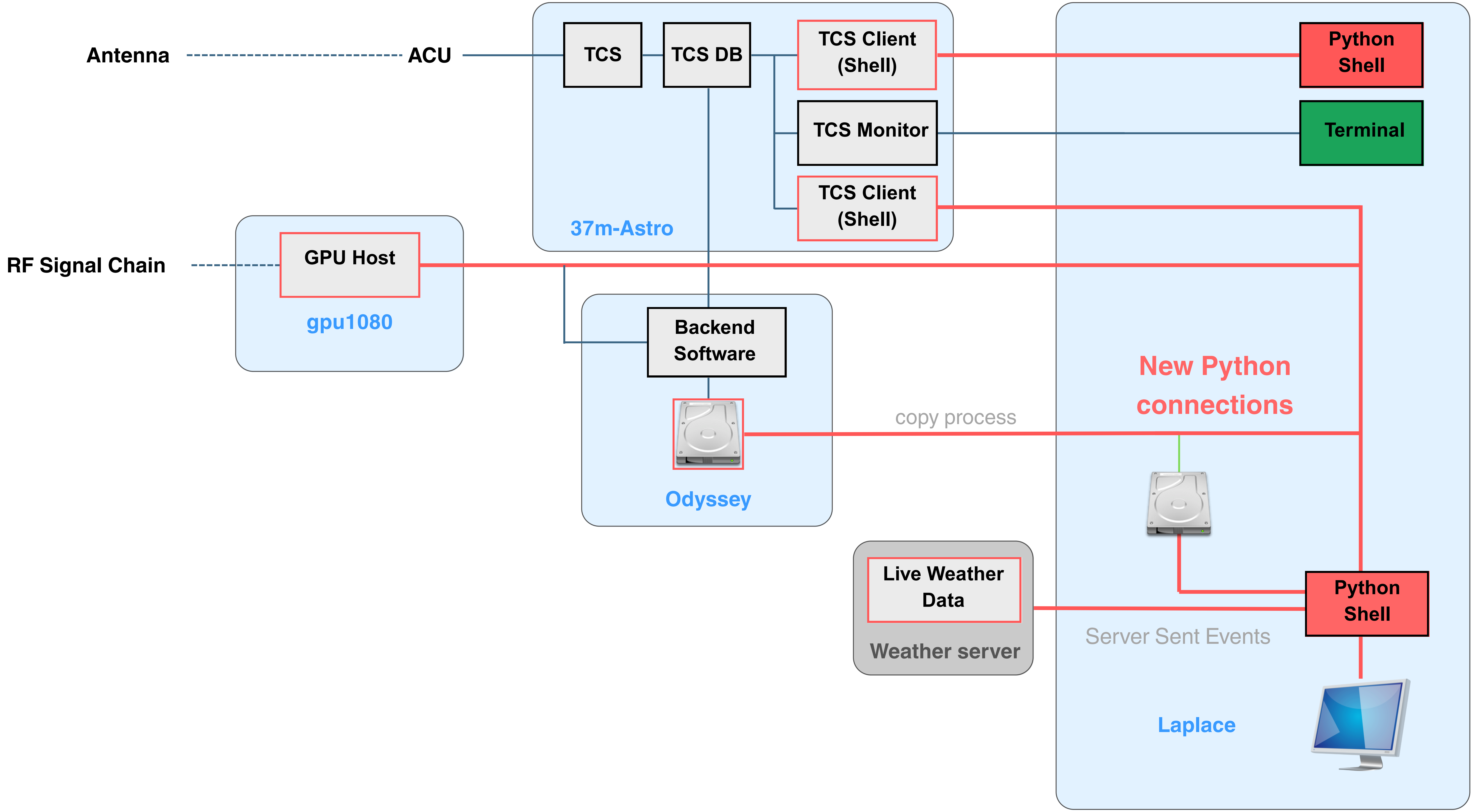


03 New Control System & User Interface

Old Telescope Control Signal Chain

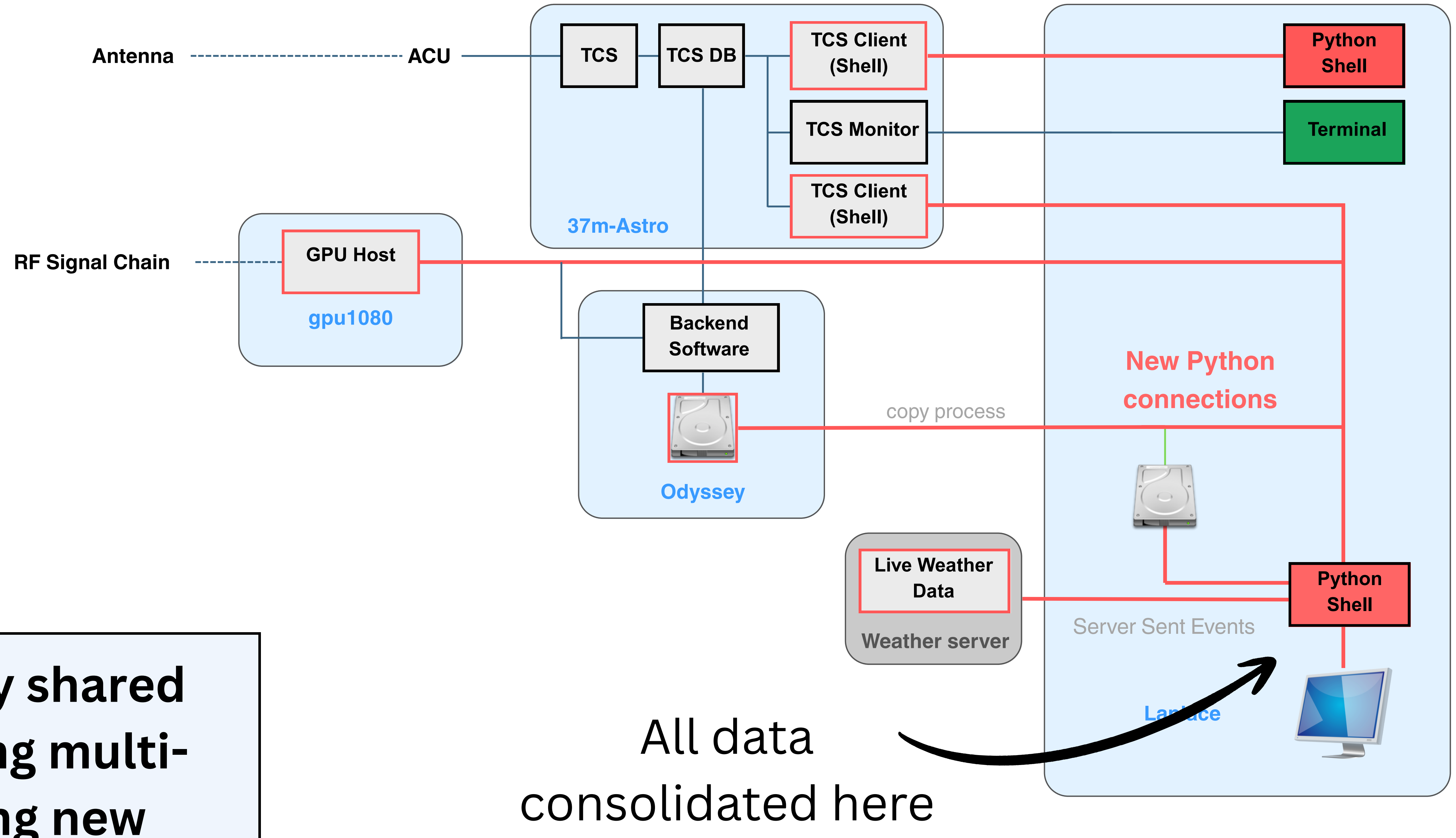


New Telescope Control Signal Chain



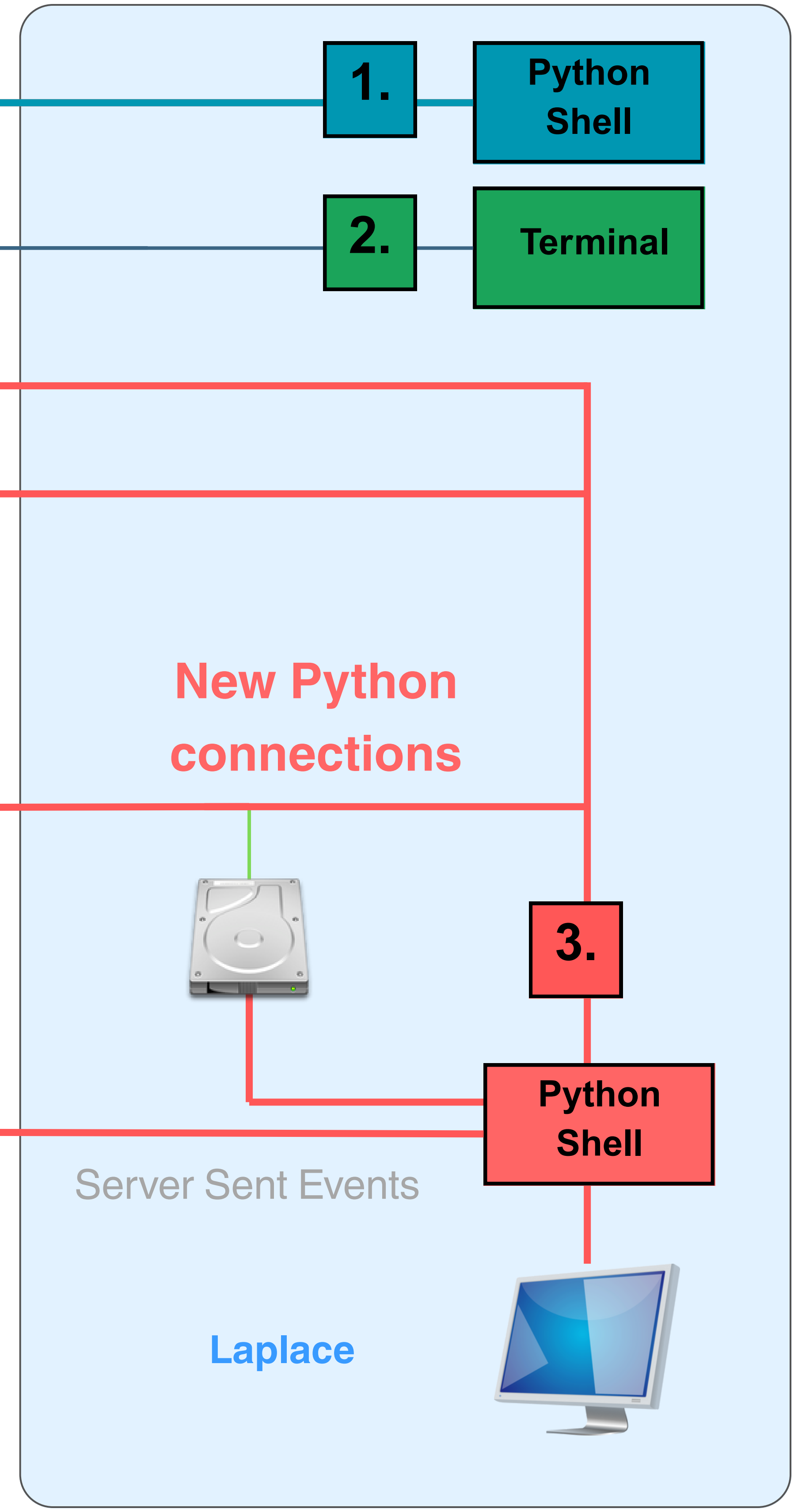
New Telescope Control Signal Chain

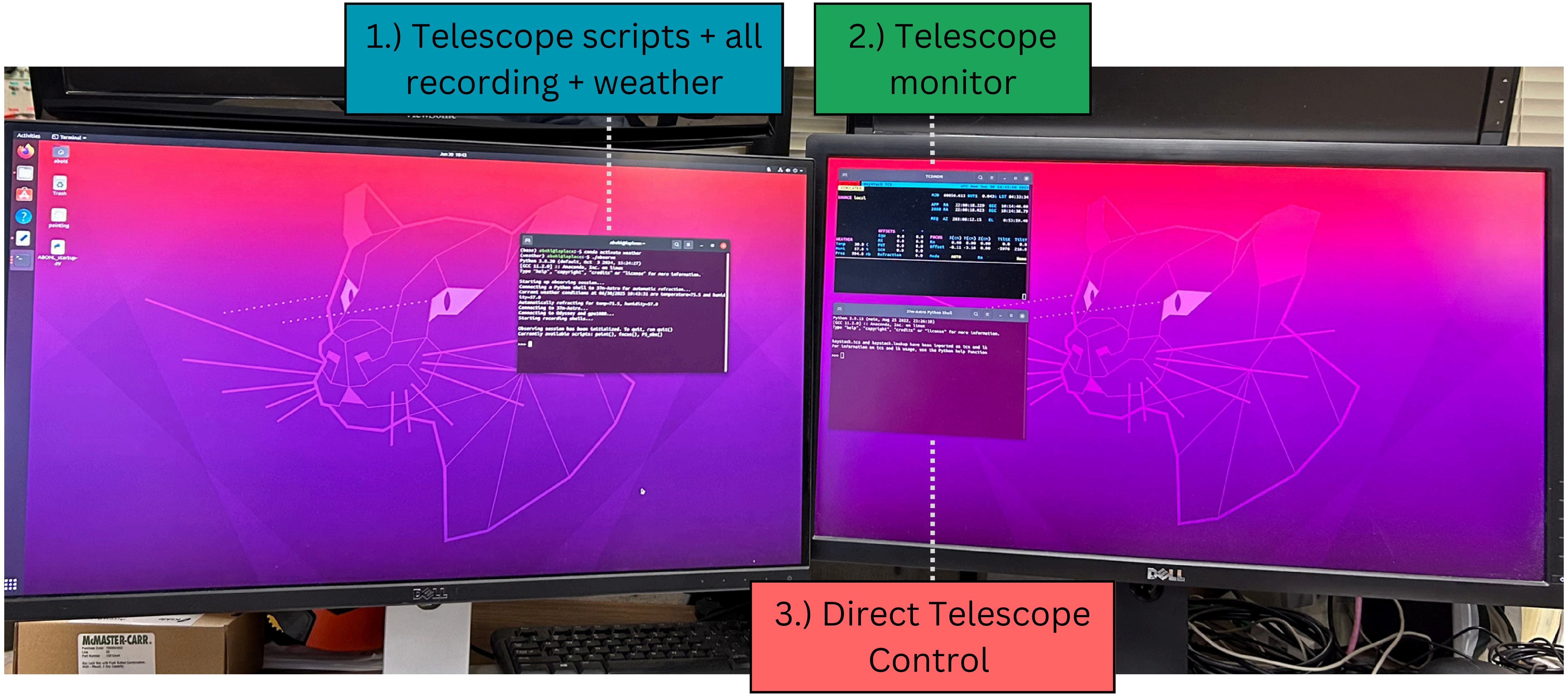
- Red represents a new Python connection
- One Python shell in Laplace communicates simultaneously with other three computers
- All data is now in one central location



- **Real-time data can now be easily shared between computers, streamlining multi-computer processes and enabling new metadata collection**

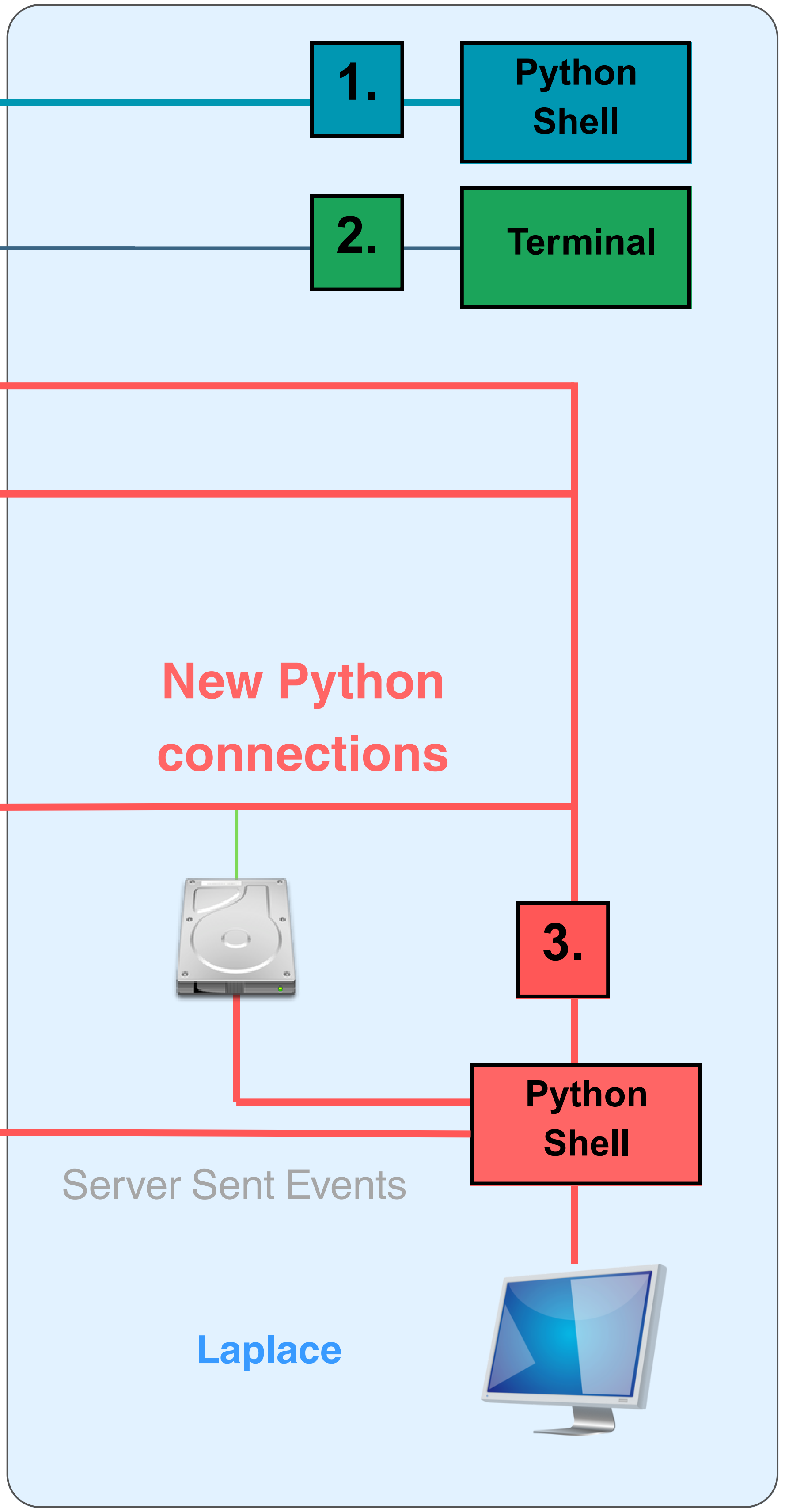
New User Interface

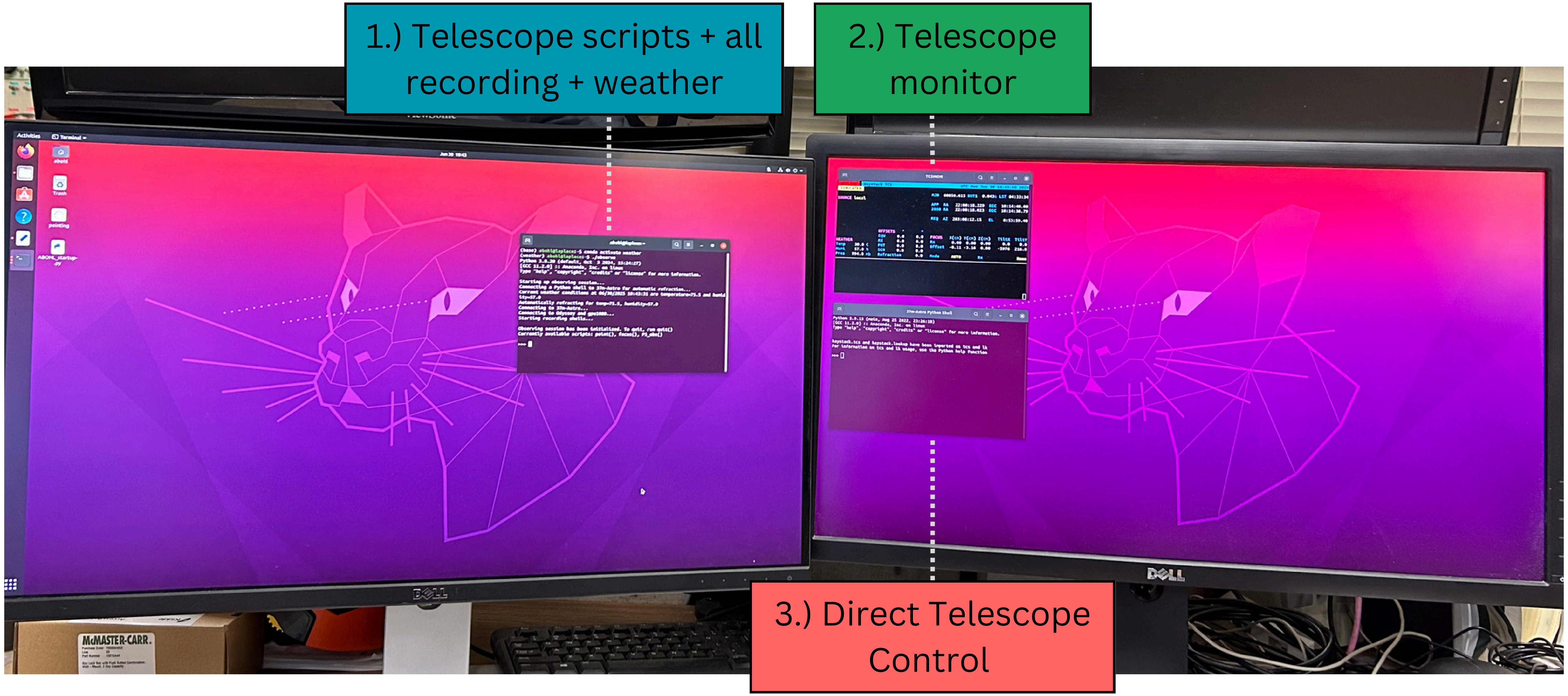




- Less visual clutter
- Real-time data sharing streamlines multi-computer scripts
- Allows for metadata collection

New User Interface

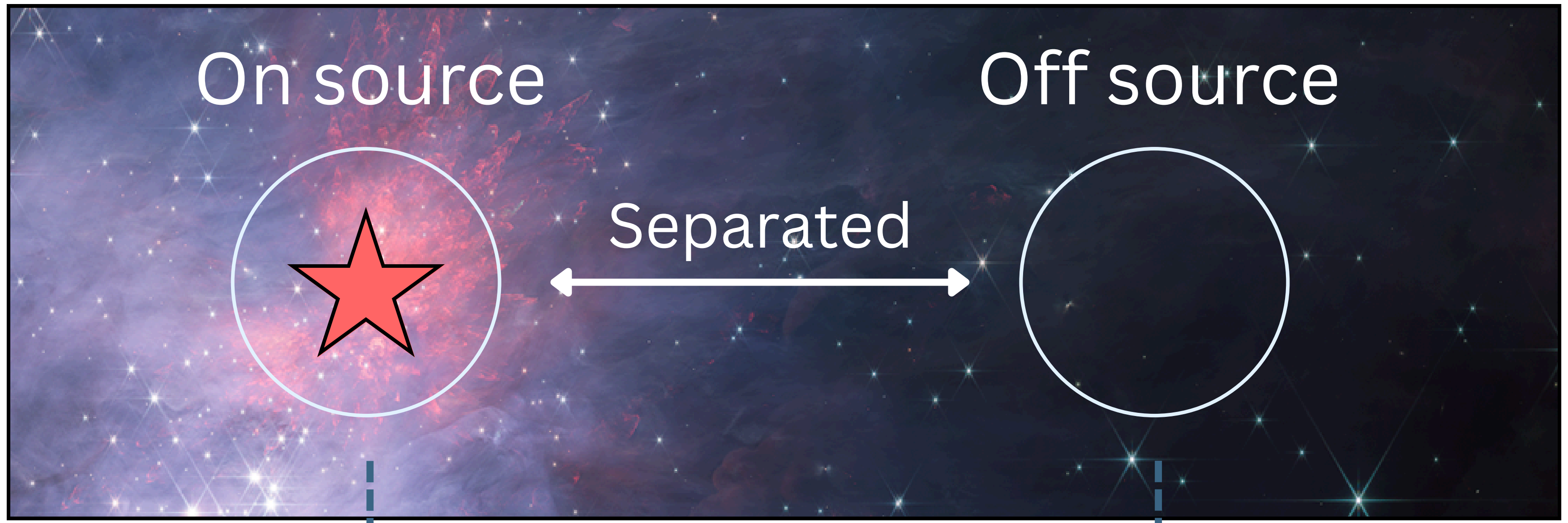


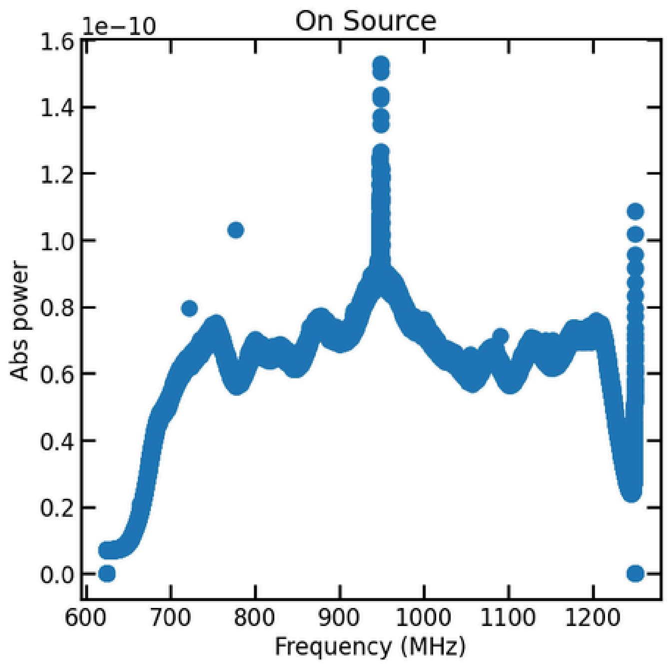


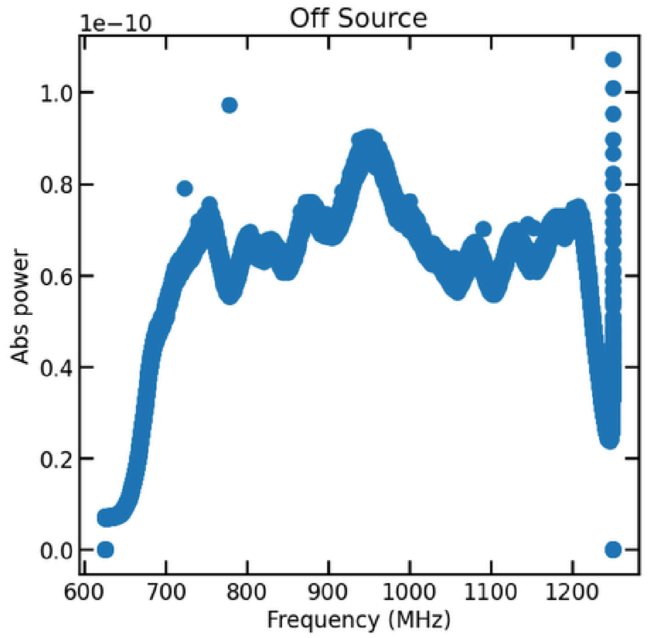
- Less visual clutter
- Real-time data sharing streamlines multi-computer scripts
- Allows for metadata collection

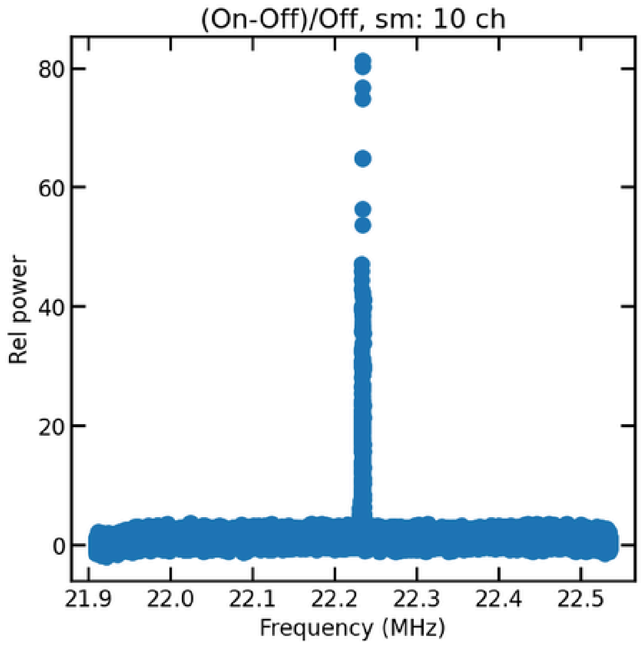
...And you can touch the mouse!

Computers Working Together: Raster Map









Subtract, normalize

Position Switching

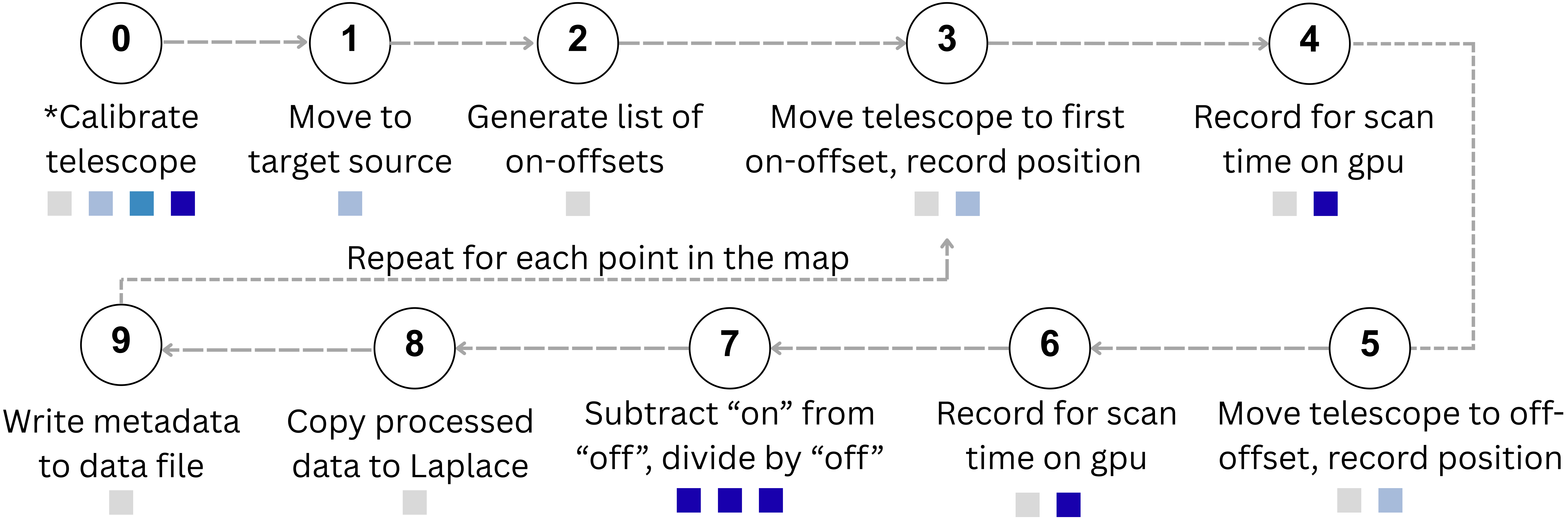
- To remove atmospheric contributions, take observations “on-source” and “off-source”
- This is called position switching
- Subtract the off-source from the on-source and normalize to obtain spectra

Image: Orion Nebula in NIRCam | Credit: ESA

Computers Working Together: Raster Map

Computer key:
Laplace
37m-Astro
Odyssey
gpu1080

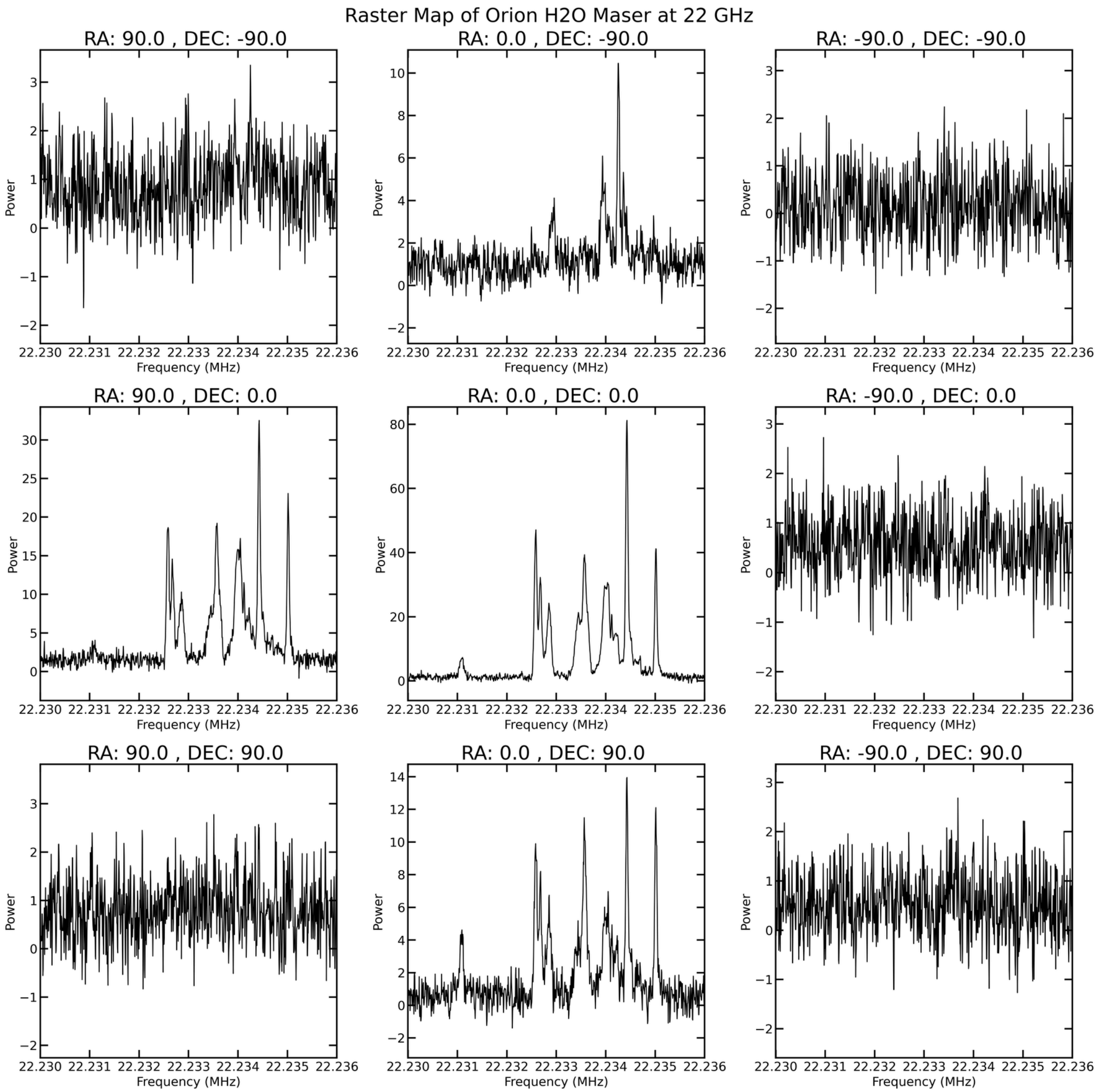
Parameters: target source, raster map dimensions, off-source offset, scan time, smoothing



Computers Working Together: Raster Map

Results:

- Result: spectra that can be processed to obtain a raster map
- **Metadata is required for such maps– need to know where on the sky each data-point was taken**
- **This functionality was not available prior to the creation of the new control system**



Python Libraries Created

Primary Observing Script

- **observing_session.py**: Creates an interactive observing session from which calibration and observing scripts can be run. Observing session maintains persistent connections with 37m-Astro, Odyssey, and gpu1080, sharing data between computers.

Haystack-Python Module

- **connections.py**: Facilitates rapid connections between computers; Continually updates a data log in the background of observing sessions

- **plotting.py**: Processes and plots data as it is taken by the telescope

- **tcs_functions.py**: Contains helper scripts for observing_session.py, including position tracking, file transfers, and data recording

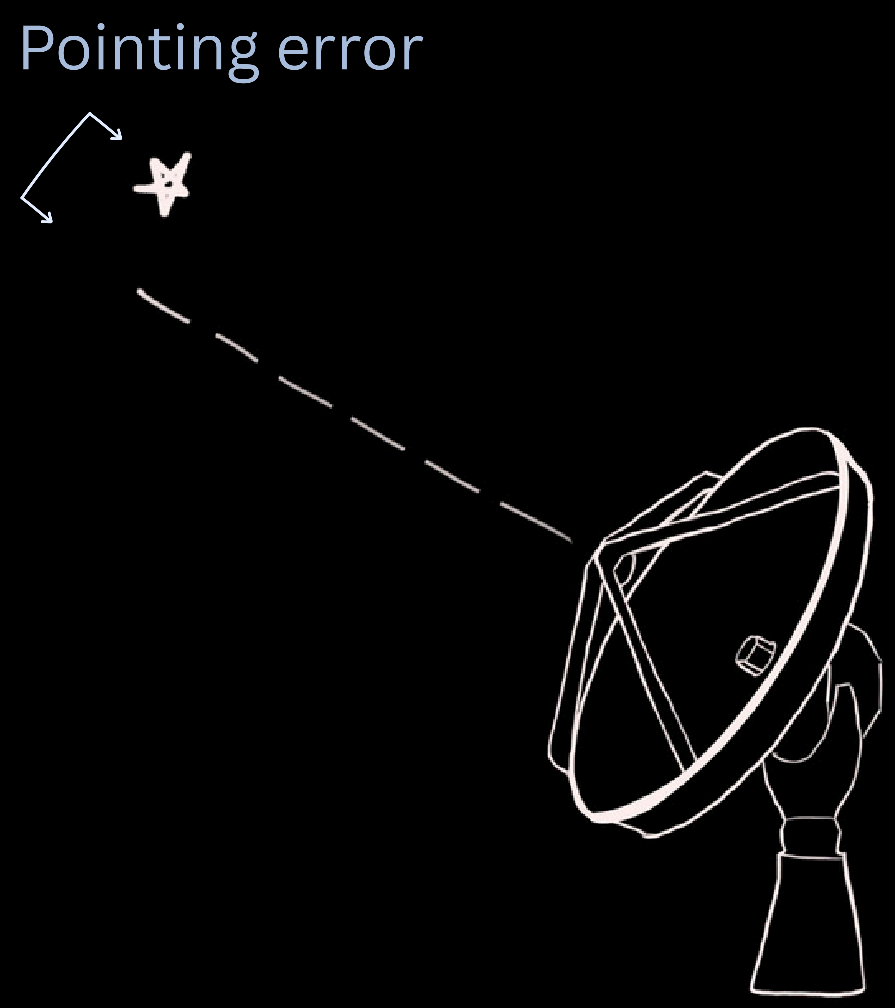
- **weather.py**: Constantly monitors live weather data in the background of observing sessions, adjusting telescope refraction when weather changes exceed a given threshold

04 Sample Projects

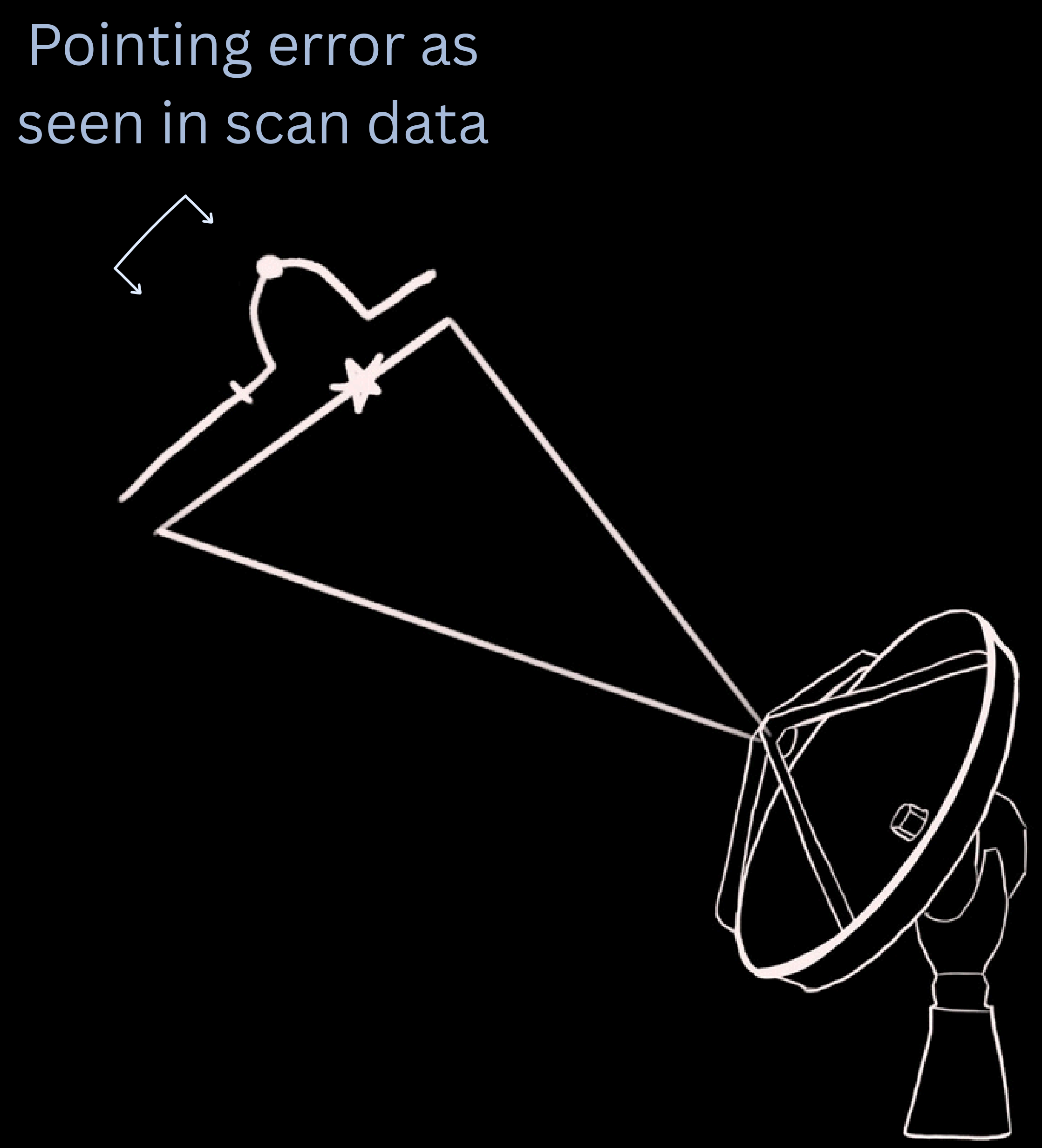
Pointing Scans: Background

What is a pointing scan?

- Telescope must be calibrated to ensure it is pointing exactly at the target source
- Pointing the telescope at a source, then scan across in azimuth and elevation
- Find the distance between the data peak and the center of the scan, adjust pointing

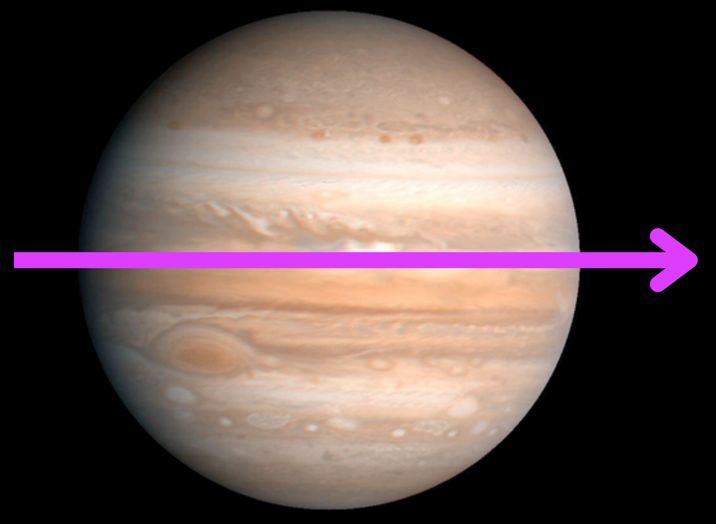


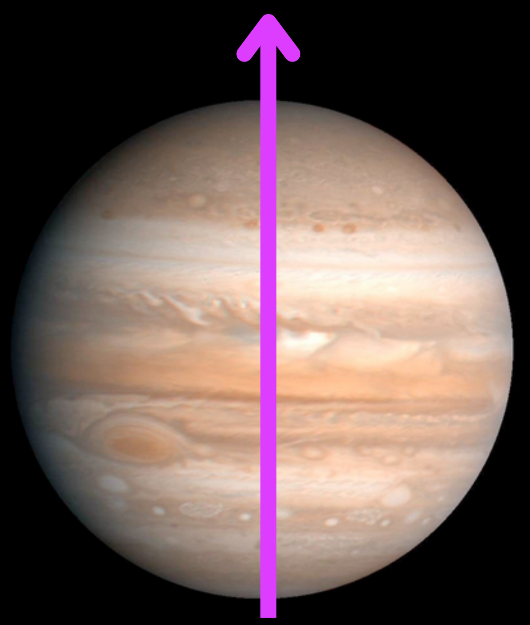
Un-calibrated telescope pointing

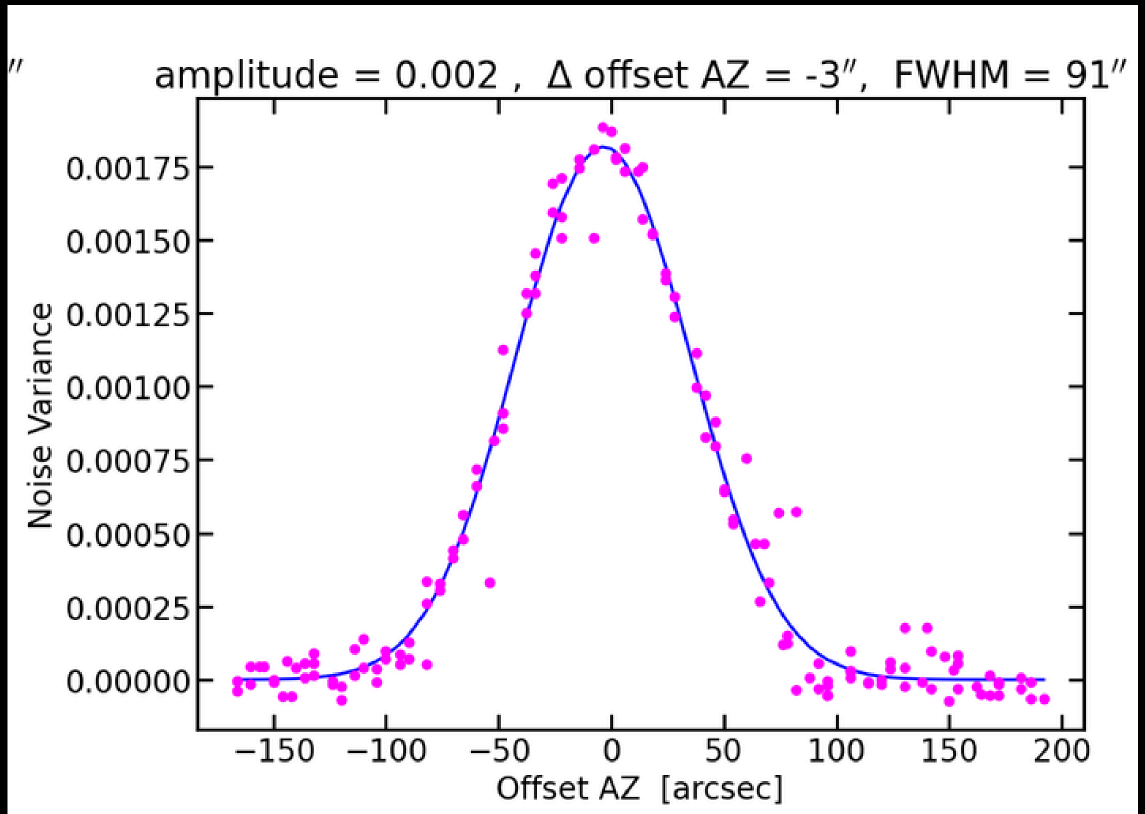


Scan across target source, adjust pointing

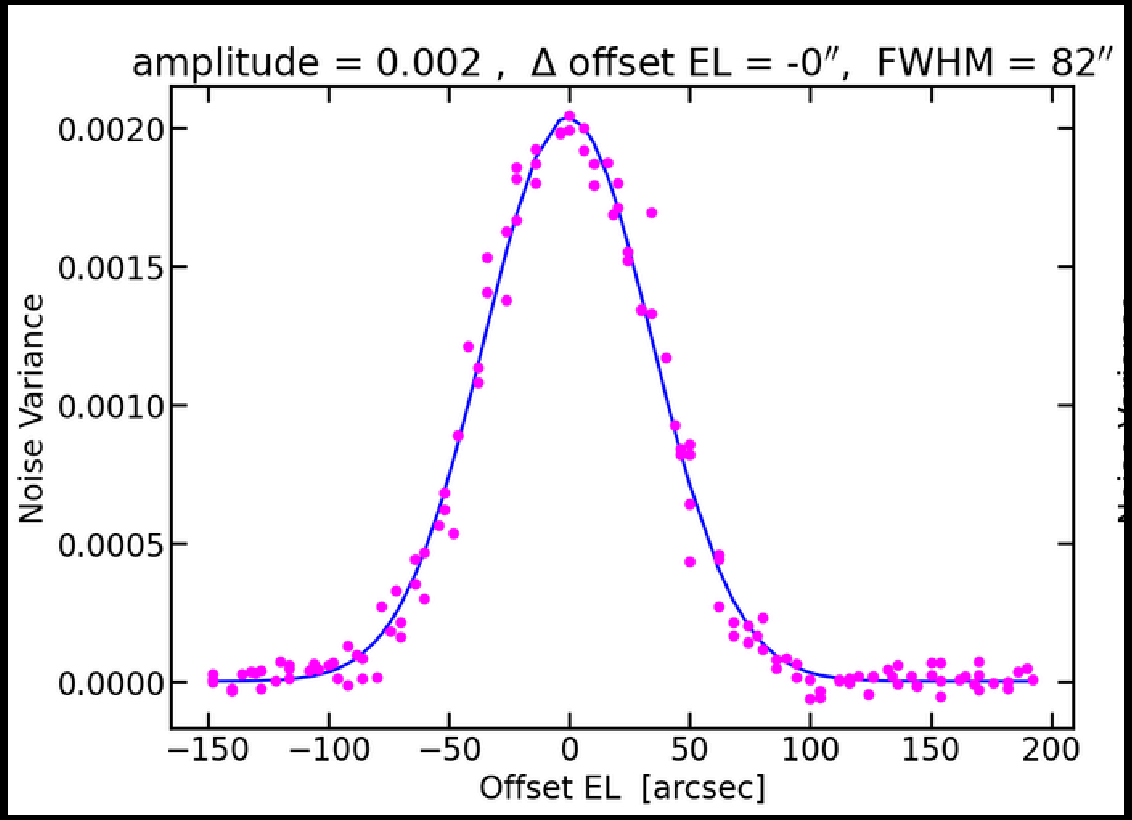
Pointing Scans: Jupiter







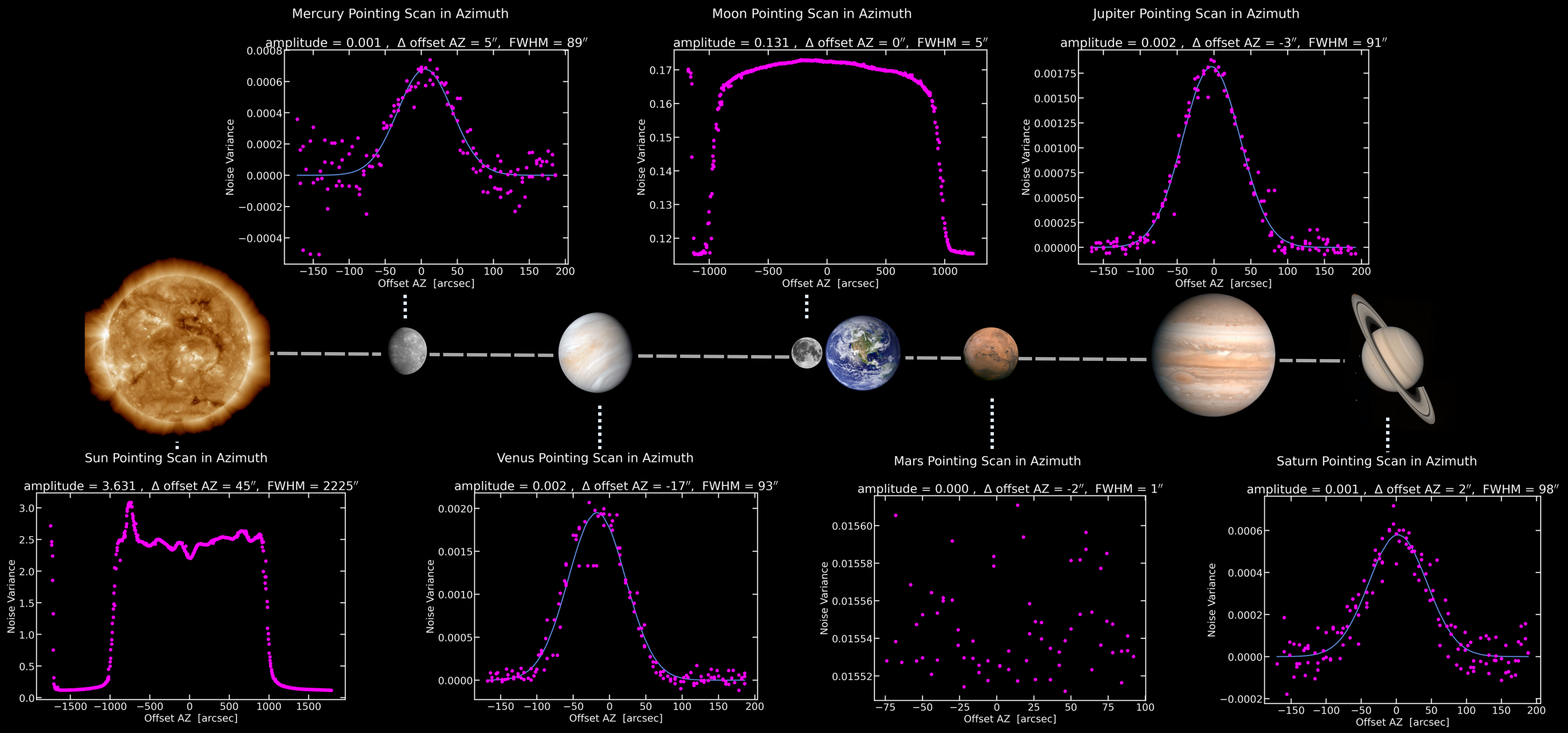
Scan in azimuth



Scan in elevation

- Example pointing scans of Jupiter
- Scans in both azimuth and elevation
- AZ Δ offset = -3 arcsec, EL offset = 0 arcsec
- Note, the delta offset is small in both scans, has been calibrated

Pointing Scans: Solar System Gallery

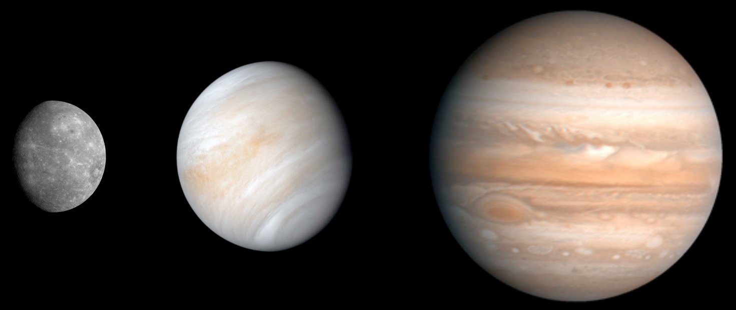


Pointing Scans: Temperature Ratios

Method

- Can easily calculate the relative temperature between planets using pointing scans by
    1. Calculate the signal amplitude of the pointing scans
    2. Calculate angular cross section of each planet using distance to Earth and planet radius
    3. Calculate relative temperature using

$$T_{sig,planet} = \frac{\Omega_{planet}}{\Omega_{beam}} T_{surf,planet} \longrightarrow \frac{T_{surf,planet1}}{T_{surf,planet2}} = \frac{T_{surf,planet1}}{T_{surf,planet2}} \frac{\Omega_{planet2}}{\Omega_{planet1}}$$

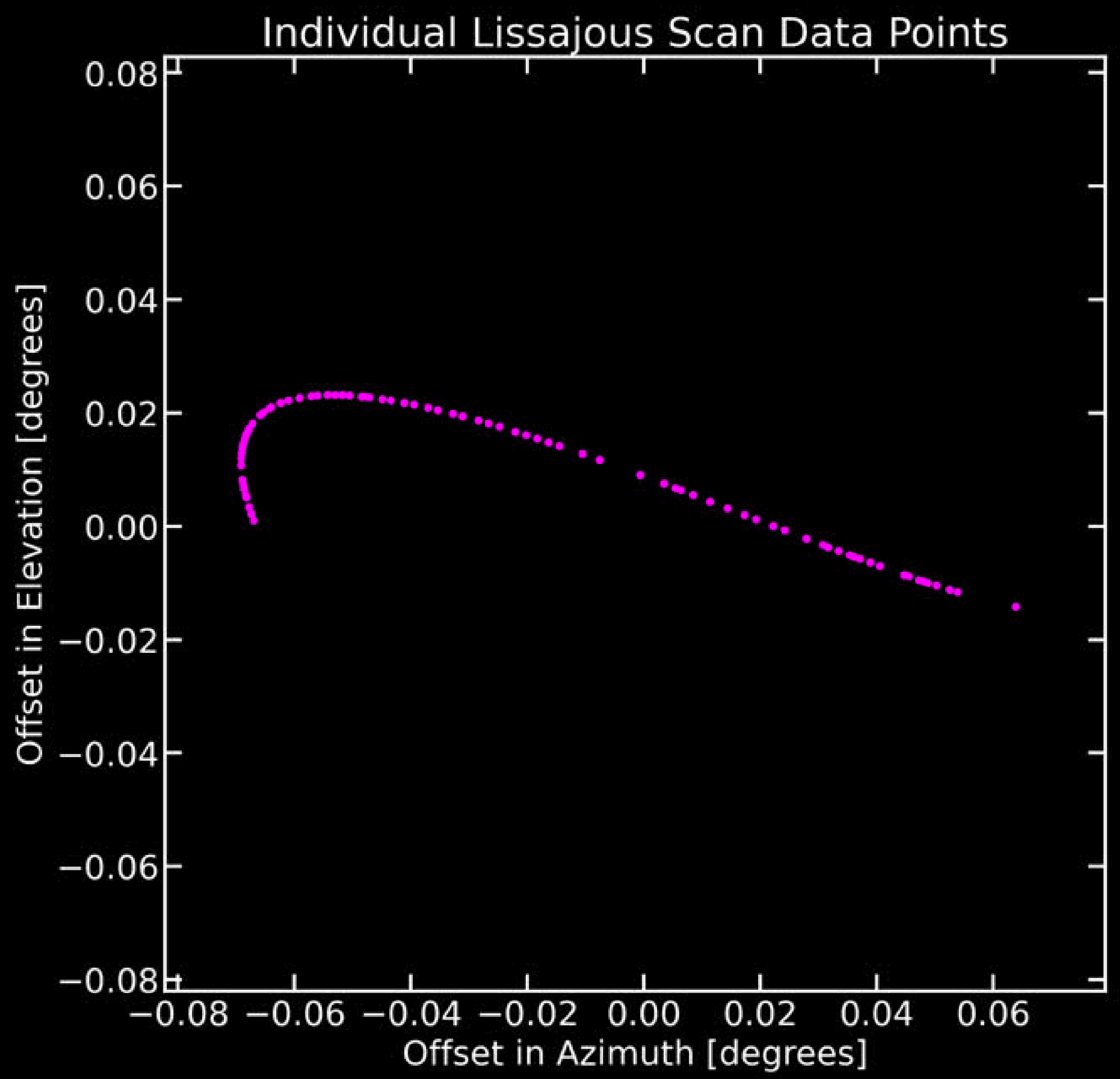


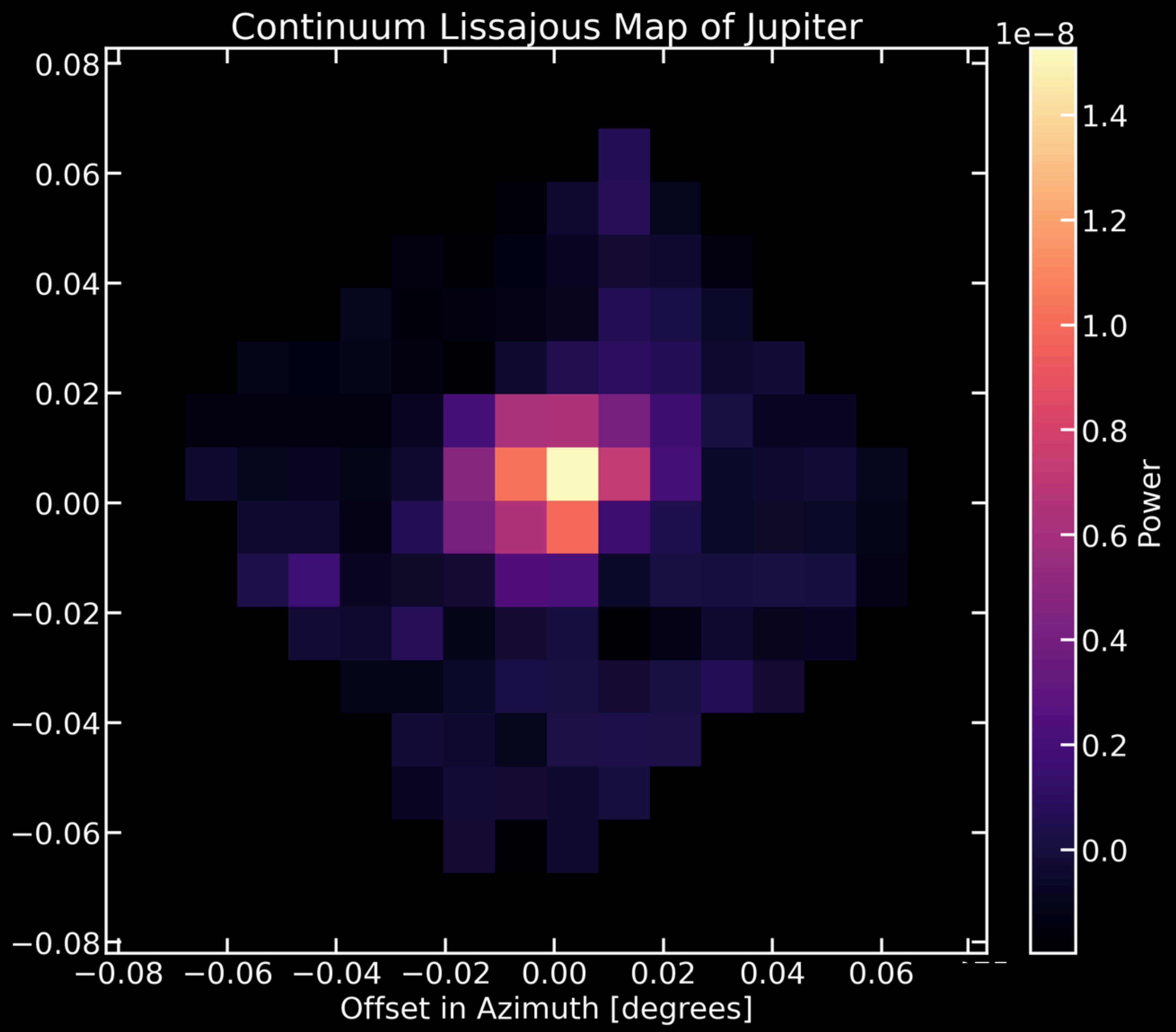
Takeaway: Straight-forward method that obtains results consistent with the literature

Results

Name	Temp Relative to Venus	Brightness Temp. (K)
Venus	AZ: 1.00 EL: 1.00	AZ: 480 EL: 480
Mercury	AZ: 0.407 EL:0.515	AZ: 196 EL: 247
Jupiter	AZ: 0.526 EL: 0.440	AZ: 252 EL: 211

Lissajous Raster Map





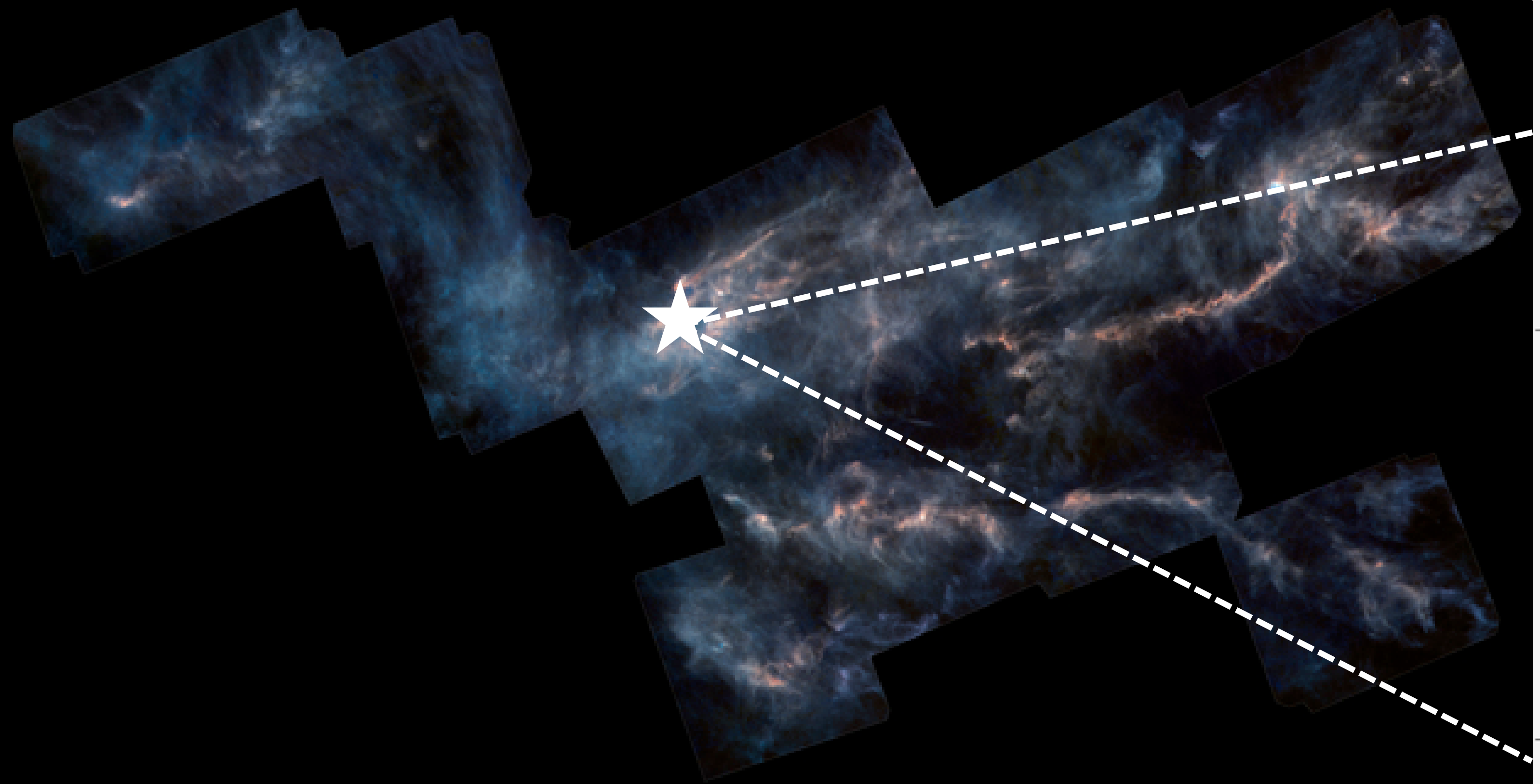
- Lissajous scans across target source in spirals
- Re-grid continuum data to obtain map

Ammonia Spectra from TMC 1

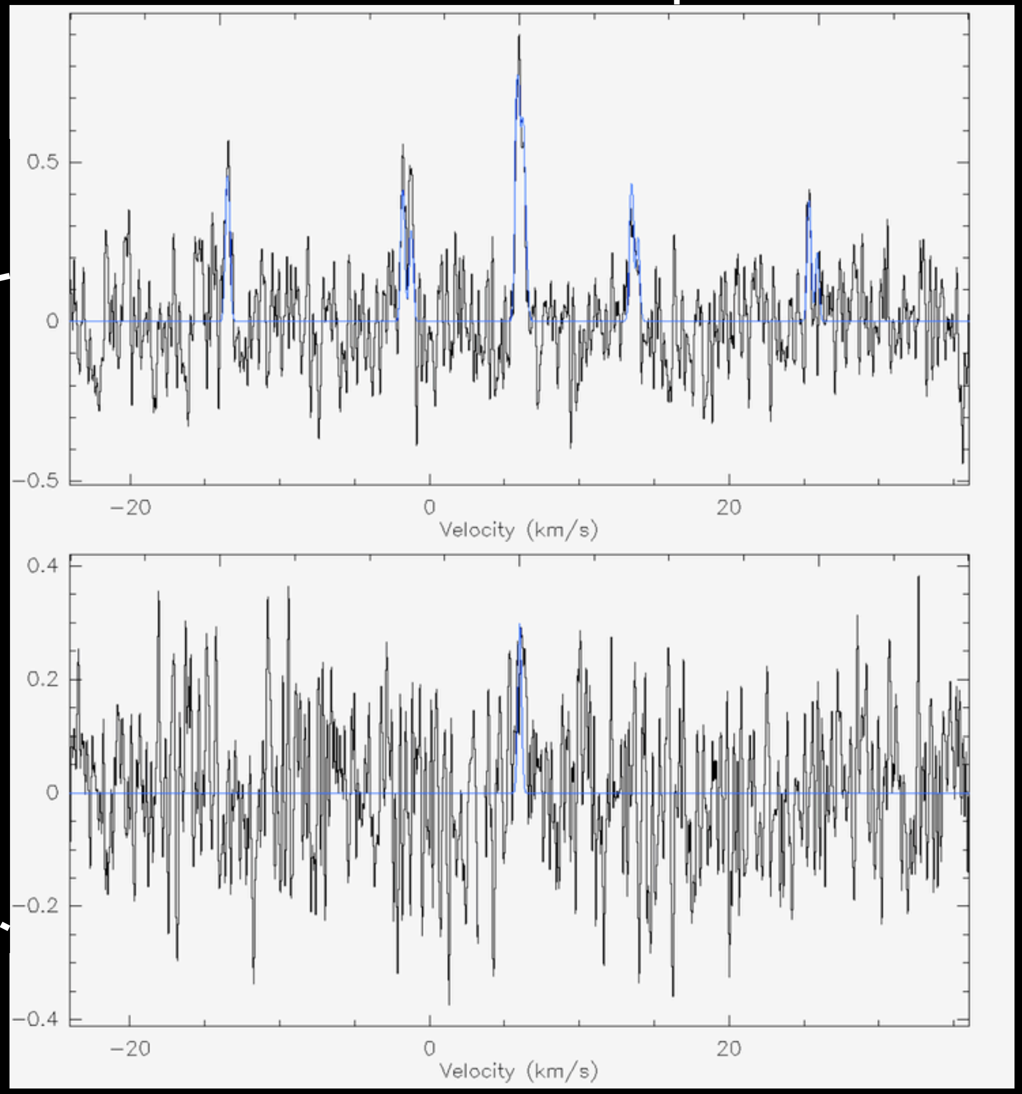
Astro-Chem

- Taurus Molecular Cloud 1: TMC1
- Site of current astrochemical research
- We observe ammonia spectra in TMC 1
- Proof of capability to contribute to modern astro-chemical research

Hershel Image of Taurus molecular cloud



Calibrated Ammonia Spectra



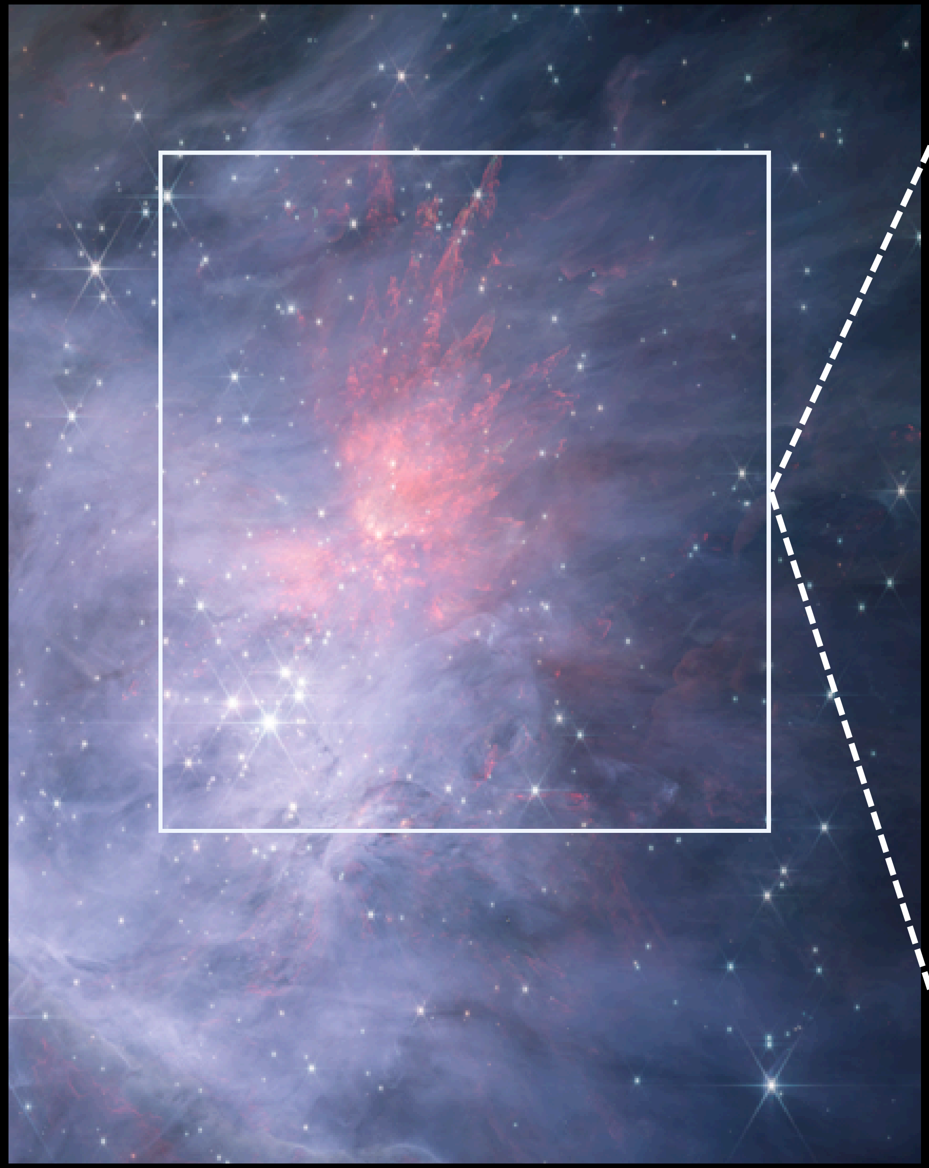
Cloud Parameters from Spectra

- From spectra, can obtain upper limit on the **gas temperature and ammonia column density** that agrees with the literature

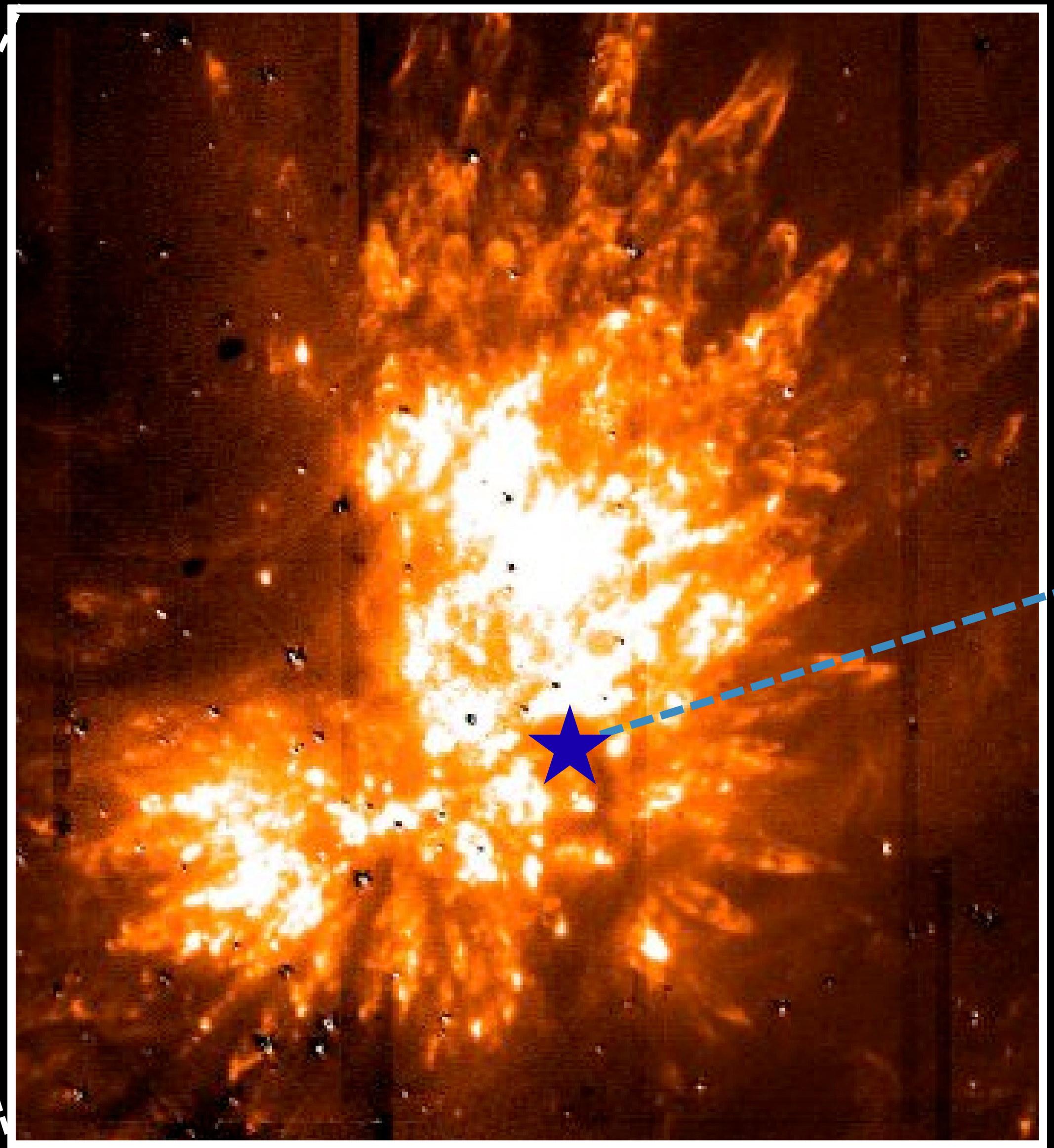
$$T_{\text{kinetic}} < 10.8\text{K} \qquad N_{\text{NH3}} < 4.5 \times 10^{14}\text{cm}^{-2}$$

Water Maser Spectrum in Orion-KL

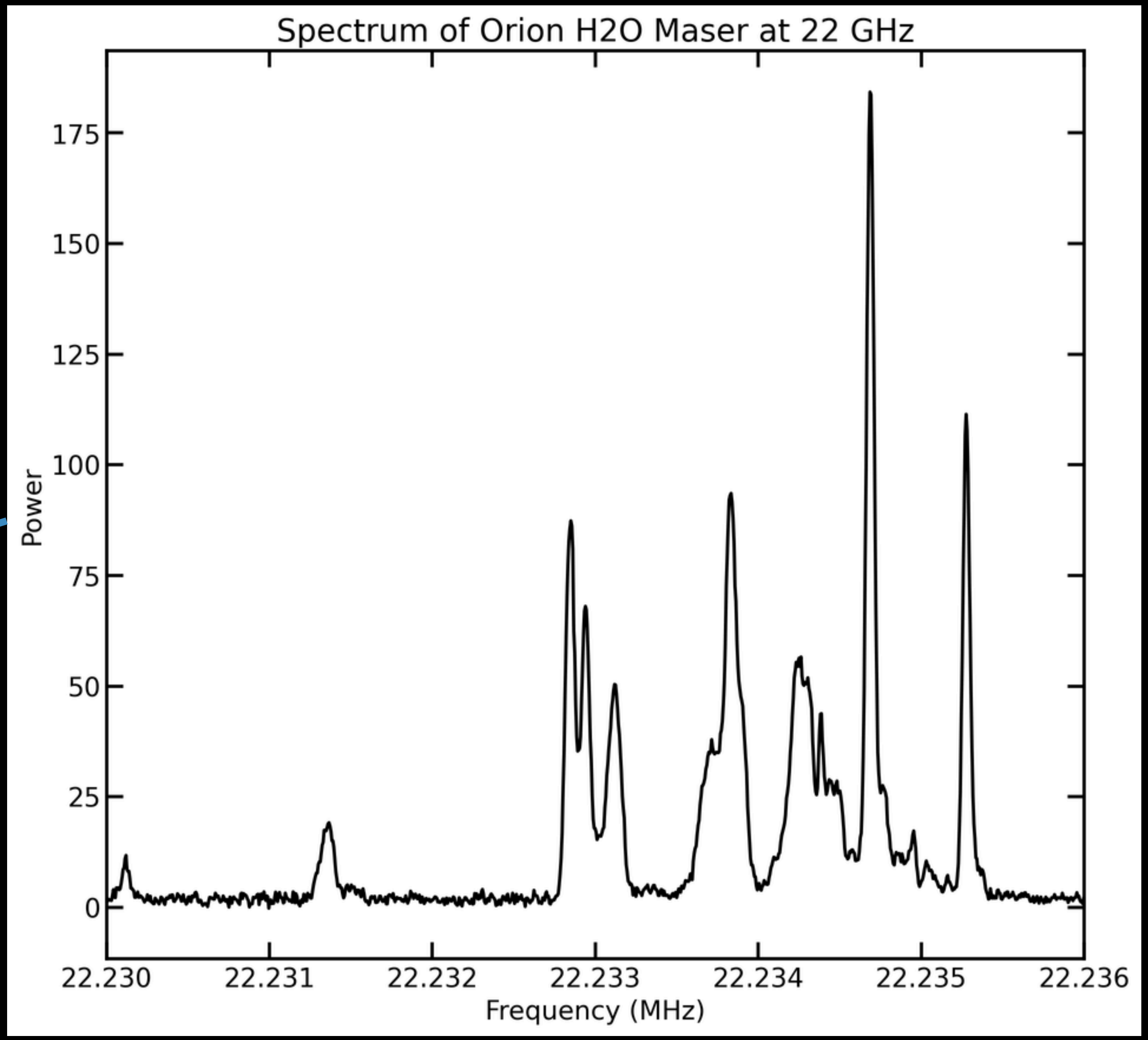
Orion KL Nebula from JWST



Orion KL Nebula from Subaru Telescope



H2O Spectra at 22 GHz



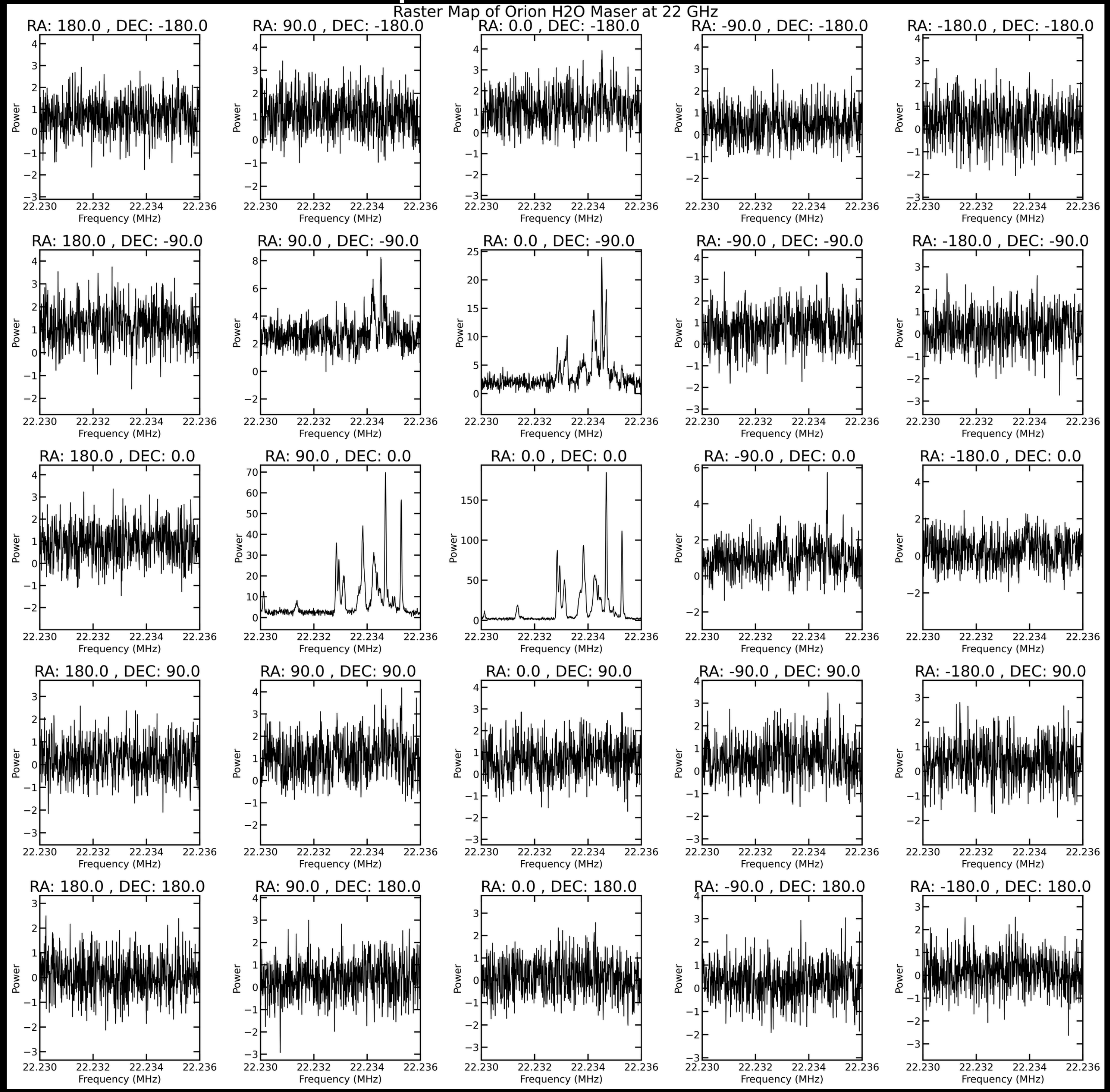
- Kleinmann-Low or Orion-KL nebula
- Active star forming region, location of past explosion event
- Contains extremely strong water maser at 22 GHz, which we observe

Water Maser Raster Map of Orion-KL

- Create raster map around center source
- Each spectrum is spaced 90 arcsec in RA and/or Dec from the others
- Demonstrates functionality through metadata that was not possible prior to the new user interface.

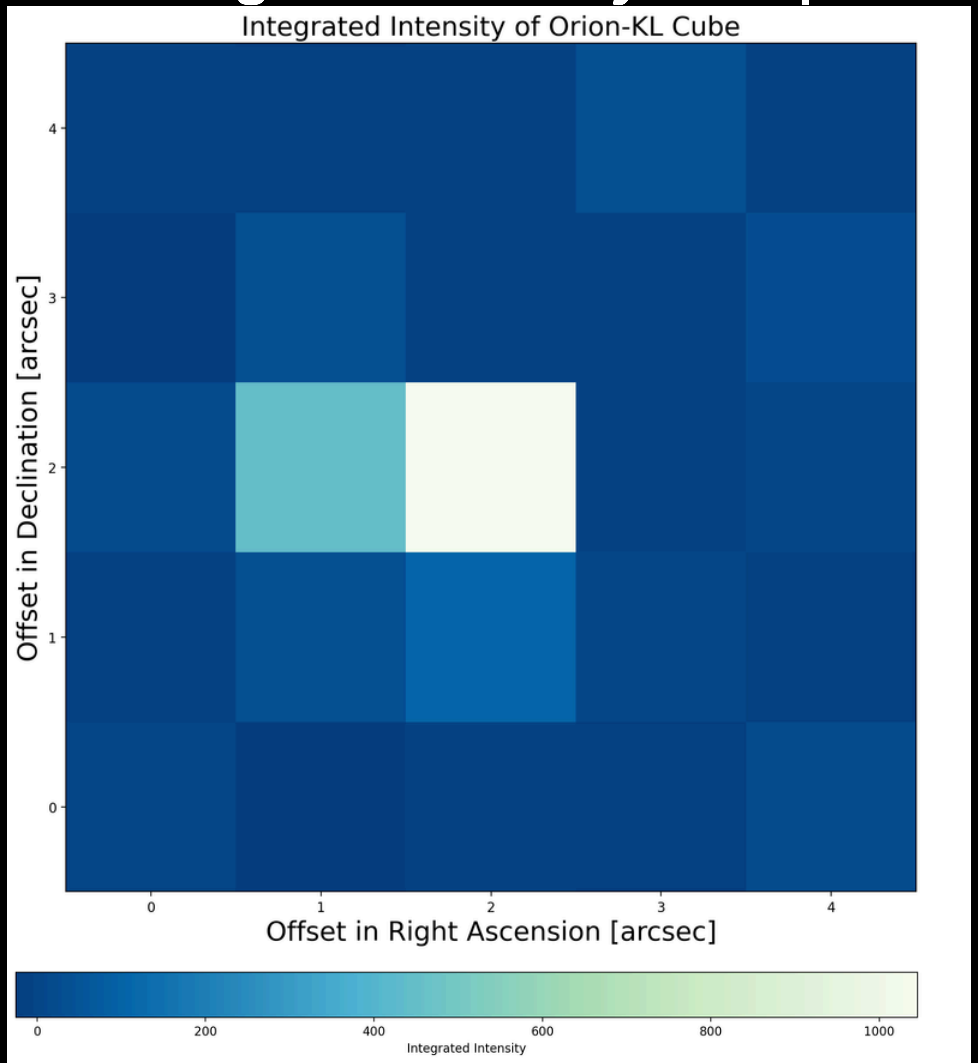
Raster Map of Orion H2O Maser at 22 GHz

Power



Frequency

Integrated Intensity of Map



Conclusion

- Telescope closer to becoming a multi-user system
- New, **user-friendly interface** allows computers to **easily share data** within an observing session
- New Python connections **allow for the collection of metadata**, enabling the creation of data maps
- Variety of straightforward experiments can be conducted using the new system

Acknowledgements

I would like to thank my mentors for their guidance and support throughout the REU program. I've really enjoyed working on this project and appreciated all the help and feedback along the way.

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