Astrometry

Amy Mioduszewski (NRAO)

What is Astrometry?

Precise measurement of position

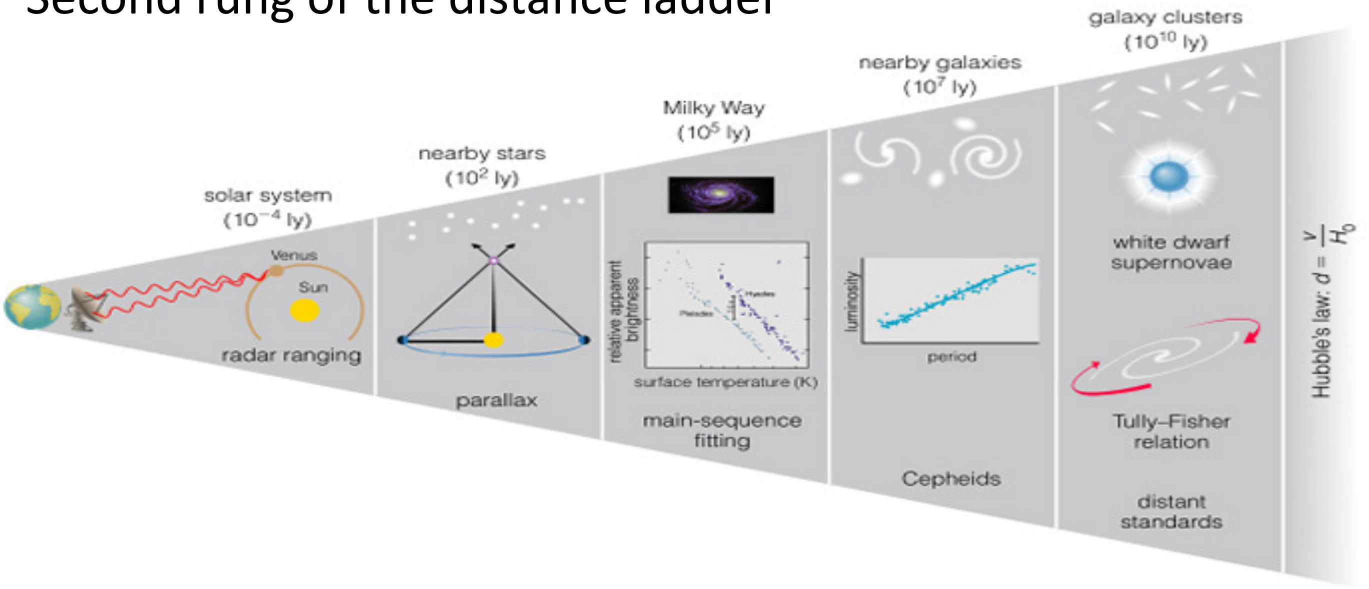
- Since ancient times people have been measuring the heavens – fundamental for agriculture, navigation and was key to the scientific revolution.
  - Brahe's precise positions of the planets → Kepler's Laws of Planetary Motion → Newton's Theory of Universal Gravitation.
- The motion of the Sun and planets were commonly measured using alignments
  - Relative Astrometry!
- Measuring the precise position of the Sun to predict the solstices and equinoxes.
- Ancient sites of astrometric measurement can be found all over the world, and on every continent (except Antarctica).
  - Australia, Brazil, Canada, China, Germany, Ecuador, Egypt, Finland, Honduras, India, Italy, Mexico, Netherlands, Portugal, Russia, South Korea, Spain, Sweden, UK…and New Mexico (Chaco Canyon)

What is Astrometry

An aside: Chaco Canyon (Part of Chaco Culture UNSCO Word Heritage Site)

Why is Astrometry important today

- Need to know where source are in relation to other sources, including the Earth
  - E.g. the International Celestial Reference Frame (ICRF)
- Need to know where objects are in relation to observations of same object from different date or different wavelength/energy.
  - Proper motions, orbits…
- Distances using geometric parallax – only direct method of obtaining distance outside solar system
  - Second rung of the distance ladder



Why use VLBI for Astrometry

Phase referencing makes radio interferometry a natural astrometry machine and with the longer the baselines the lower the errors.

With VLBI, for a single observation:

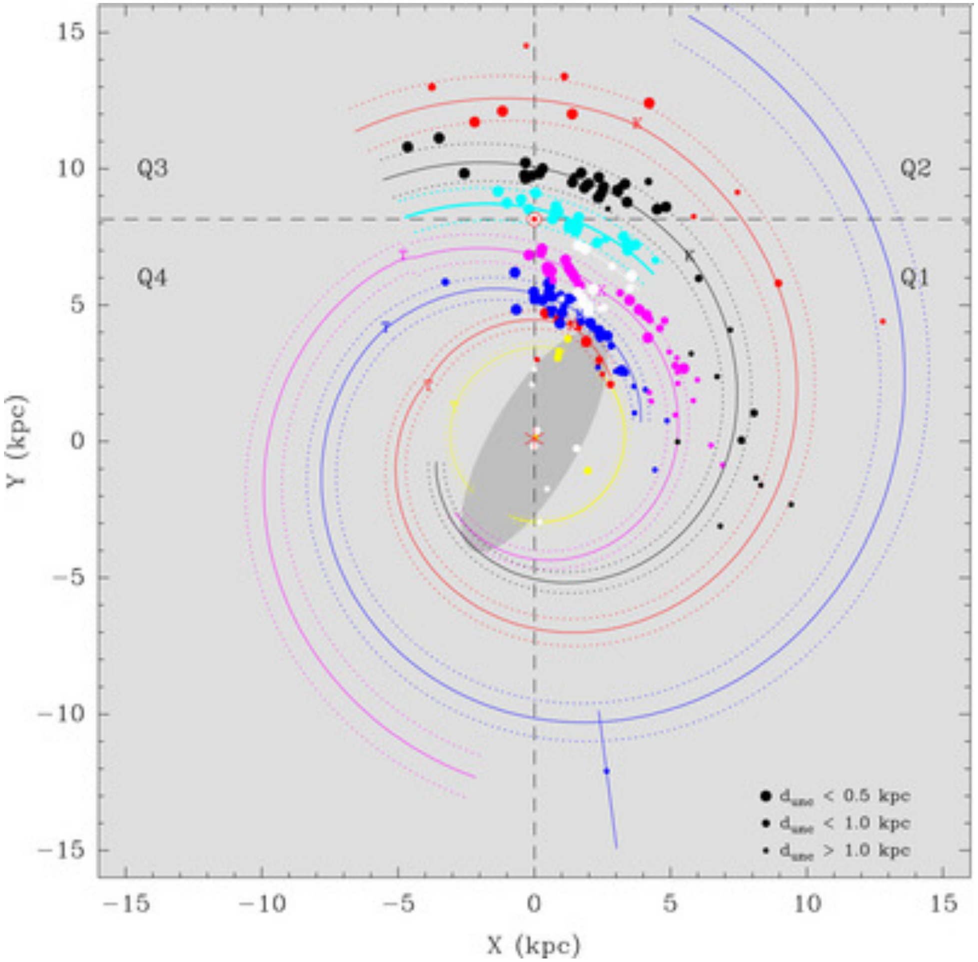
- 200μas precision easily obtained
- 10-20μas precision with effort
- Fundamental reference frame
- As a check for Gaia and other optical methods
- Can do astrometry to obscured regions (star forming regions, through the galactic plane…)

With 6 observations the VLBA can obtain:

Parallax (π)	Δπ	Distance	Error
5 mas	± 0.02	200 pc	0.4%
1 mas	± 0.02	1 kpc	2%
0.5 mas	± 0.02	2 kpc	4%

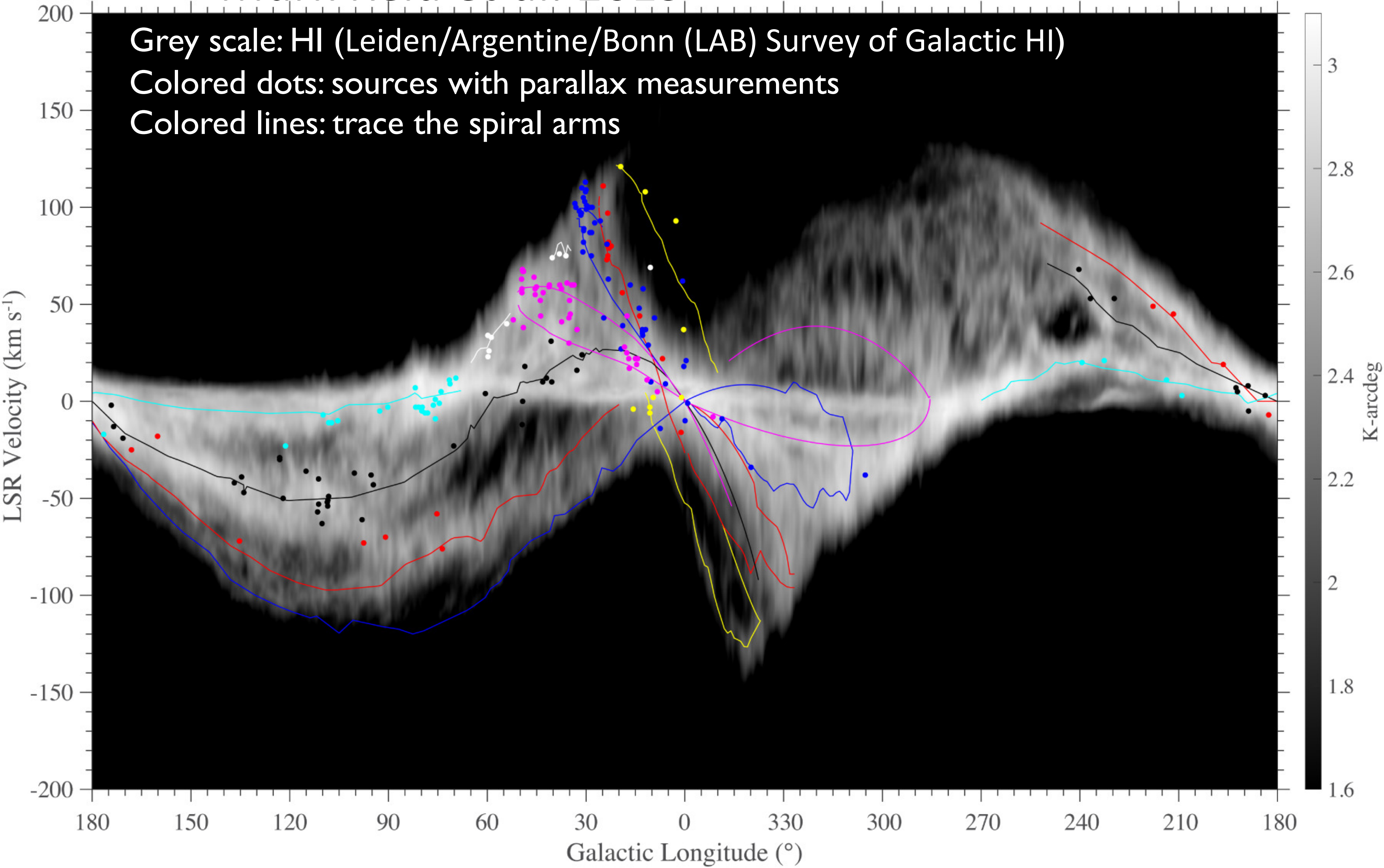
Bar and spiral structure legacy survey (BeSSeL) *Mark Reid et al.*

- Goal: determine structure and kinematics of the Milky Way Galaxy
- Perform astrometry on masers in star forming regions
    - Water masers at 22 GHz
    - Methanol at 11 and (soon) 6.7 GHz
- Results have improved measurements of the distance to the Galactic Center and rotational velocity
    - $R_0 = 8.15 \pm 0.15$ kpc
    - $\Theta_0 = 236 \pm 7$ km/s



Bar and spiral structure legacy survey (BeSSeL)

Mark Reid et al. 2019



Grey scale: HI (Leiden/Argentine/Bonn (LAB) Survey of Galactic HI)

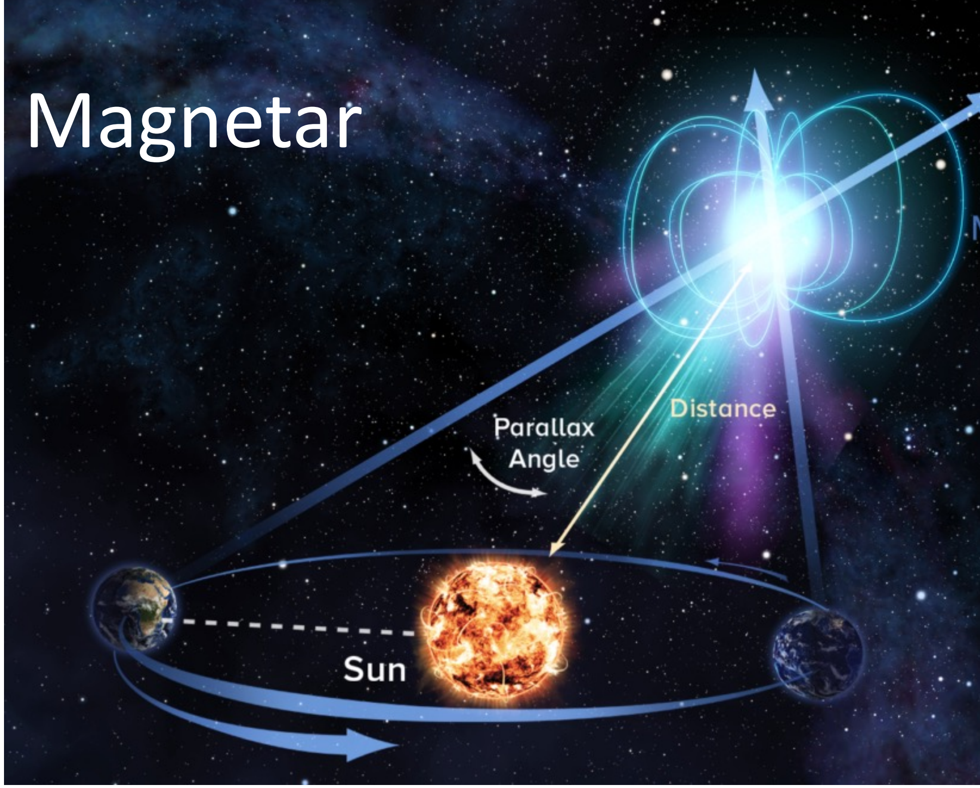
Colored dots: sources with parallax measurements

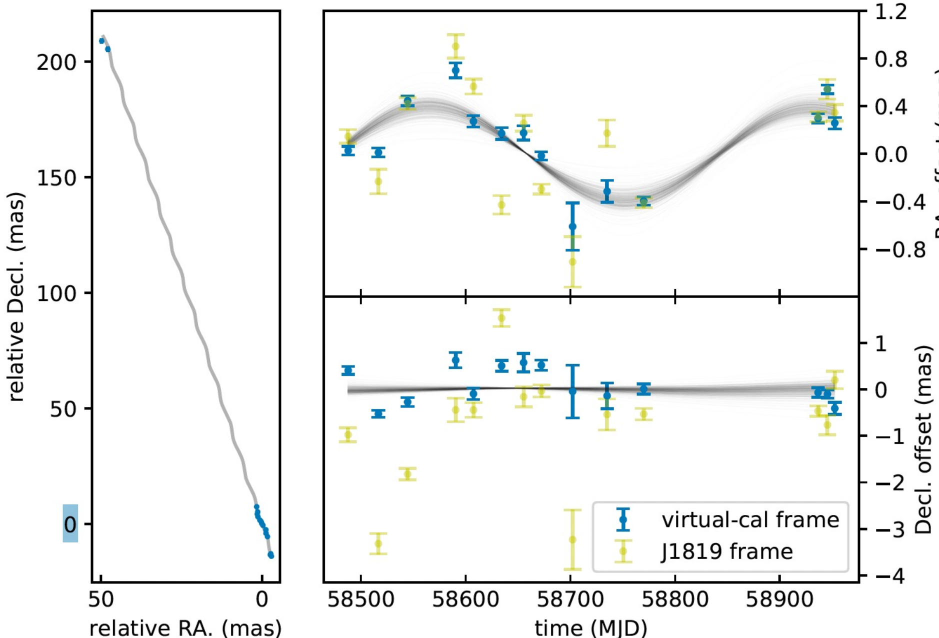
Colored lines: trace the spiral arms

First direct distance to a Magnetar

Ding et al. 2020

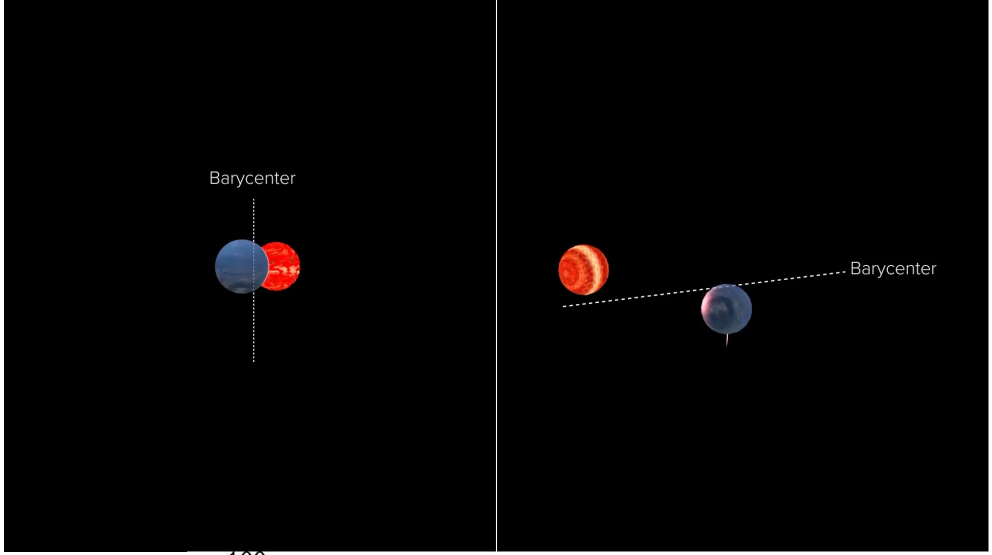
- Magnetar are highly magnetic neutron stars and may be the progenitors of Fast Radio Bursts (FRBs).
- Distances are very important to study the physics of a source
- Used 2 calibrators almost colinear with target so used "virtual calibrator" vey near target (blue points).
- Observed at ~6 GHz.
- Distance is $2.5 \pm_{0.3}^{0.4}$ kpc

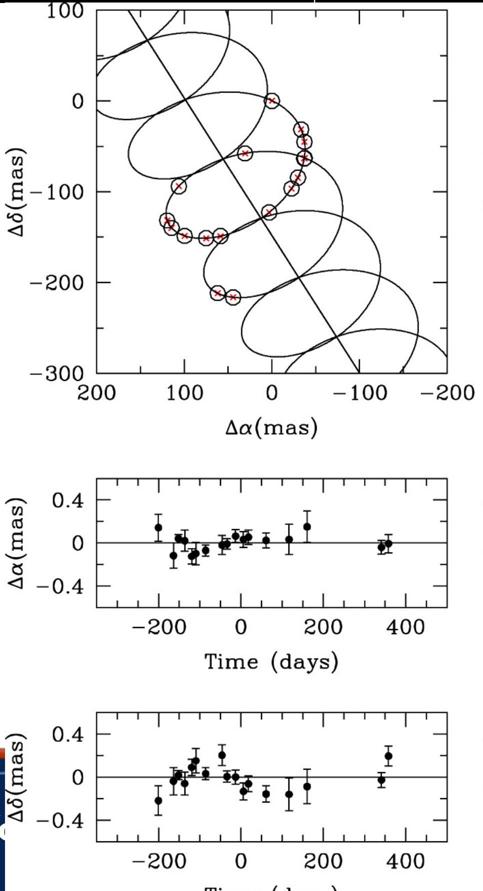




Planet Detection
Curiel et al. 2021

- Planet detected using VLBA astrometry
  - The motion that the planet induces in the star
- M9 dwarf star at a distance of 10.762 ± 0.027 pc
- Planet discovered has a mass of 0.35−0.42 M_J (~ mass of Saturn)
- Planet in a ~221 day orbit at ~0.3 AU from the star
- Figure at right shows the parallax and proper motion fit at the top and the residuals at the bottom
  - The shifts seen in the residuals (particularly in $\Delta\delta$) is caused by the pull on the star by the planet.

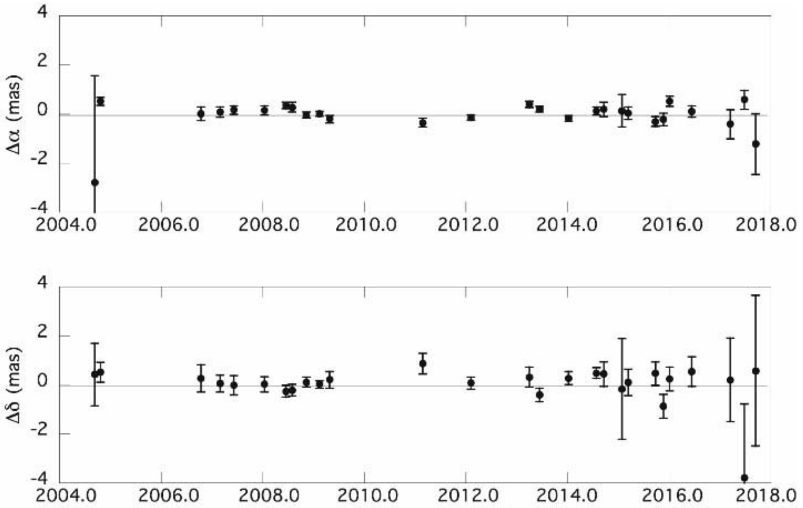




Orbit of Saturn

Jones et al. (2020)

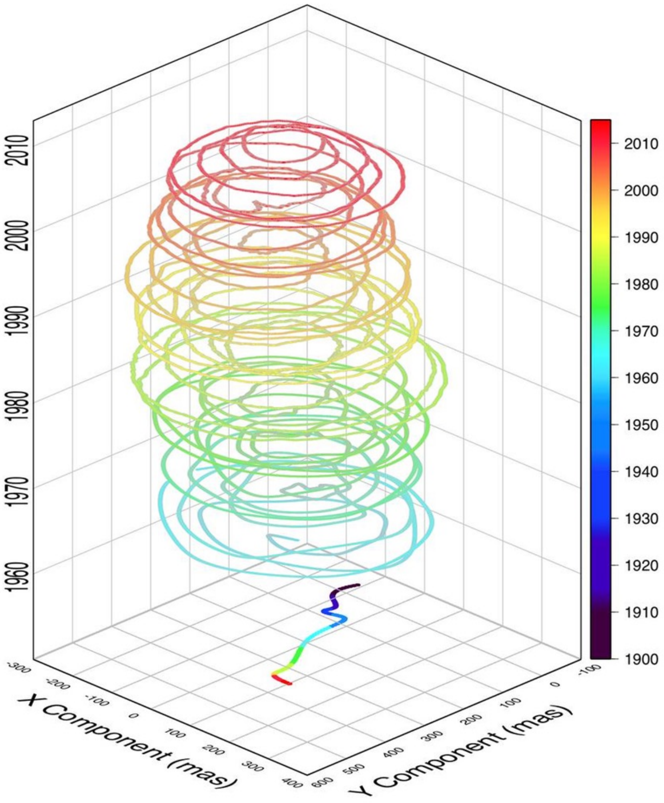
- The satellite Cassini orbited Saturn from 2004-2017
- VLBA astrometric observed Cassini’s 8.4 GHz downlink the entire time it orbited Saturn and phase referenced to background ICRF source.
- These data were combined with spacecraft ranging to improve the ephemeris of Saturn by an order of magnitude.
- Mars orbiters were used in a similar way and Juno is being observed currently around Jupiter
  - Improve the ephemeris of solar system objects



Geodesy

Science of measuring and understanding Earth's geometric shape, size, orientation in space, and gravity

- Earth Orientation Parameters (EOPs) and UT1-UTC must be measured with VLBI.
- UT1-UTC
  - UT1 (Universal Time 1) – time based on the Earth's rotation with respect to the ICRF (International Celestial Reference Frame)
  - UTC (Coordinated Universal Time) – time base on International Atomic Time
  - UT1-UTC is used to add leap seconds to UTC to keep UTC within 0.8 seconds of UT1
- EOPs – Describes irregularities in the rotation of the Earth
  - Earths rotational velocity and rotation axis are not constant
  - Effected by tides, ocean currents, earthquakes etc
- These measurements are done by observing QSOs (used to create the ICRF) all over the sky with known positions and solving for the geometric delay (more later)
- Plot to the right shows the orientation of the Earth's polar since 1964.

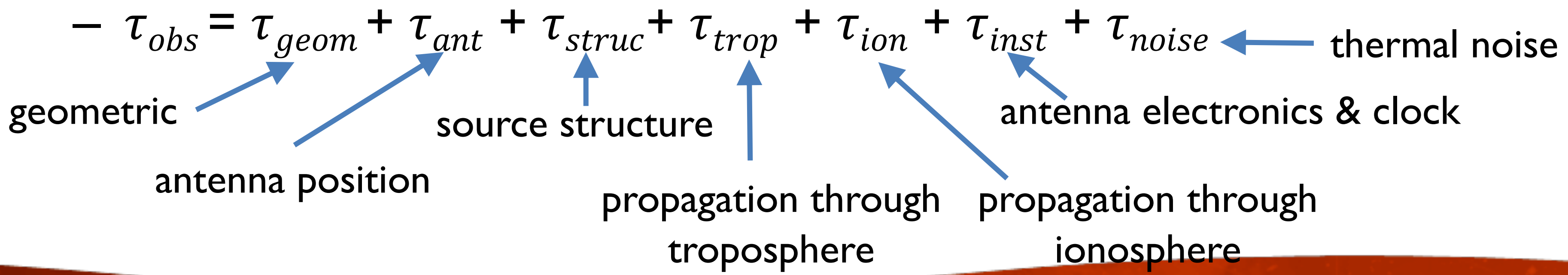


Pavlis et al. (2015)

Fundamentals of Astrometry

(based mostly on Reid & Honma 2014 and Campbell 1999)

- Ideally the delay (τ_{obs}) in an observation is simply:
  - $\tau_{obs} = \frac{\vec{s}\ \vec{B}}{c}$; where $\vec{s}$ is the position of the source; $\vec{B}$ is the baseline length and c is the speed of light.
- Therefore the error in the position is:
  - $\Delta s \approx \frac{c\Delta\tau}{|B|}$; so the longer the baseline and the smaller $\Delta\tau$ the the smaller the error
- The delay is a combination of many things



  - $\tau_{obs} = \tau_{geom} + \tau_{ant} + \tau_{struc} + \tau_{trop} + \tau_{ion} + \tau_{inst} + \tau_{noise}$ ← thermal noise

geometric

antenna position

source structure

propagation through troposphere

propagation through ionosphere

antenna electronics & clock

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- The delay is a combination of many things
  - $\tau_{obs} = \tau_{geom} + \tau_{ant} + \tau_{struc} + \tau_{trop} + \tau_{ion} + \tau_{inst} + \tau_{noise}$
- Note that when the observation is correlated a model for most of these things are included so a majority of these delays are removed.
  - What is left is the error that must be minimized

Fundamentals of Astrometry

An aside: *Absolute* Astrometry

- Ideally the delay (τ_{obs}) in an observation is simply:
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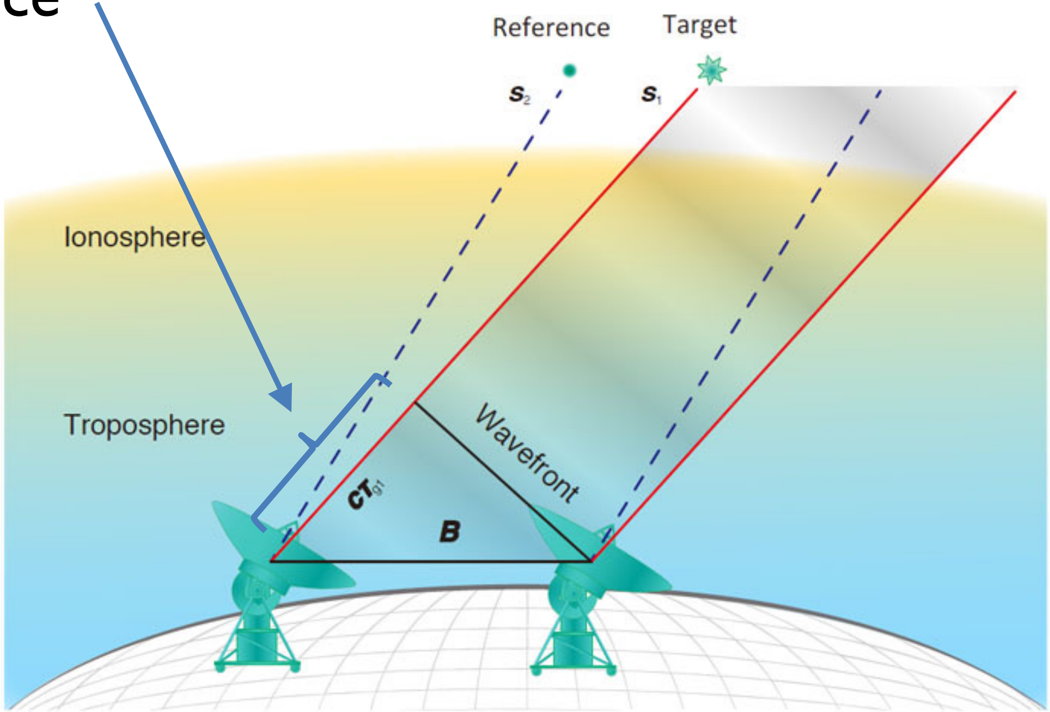
- Therefore the error in the position is:
  - $\Delta s \approx \frac{c\Delta\tau}{|B|}$; so the longer the baseline and the smaller $\Delta\tau$ the the smaller the error
  - For earth length baselines of ~10,000km (MK-EB) and typical delay errors of 2cm ($c\Delta\tau$):
  - $\Delta s = \Delta\theta \approx \frac{c\Delta\tau}{|B|} = \frac{2\times10^{-2}}{1\times10^{7}} = 2\times10^{-9}\,radians = 0.4\,mas$
  - **Not good enough for galaxy scale distances, where the parallax at only 2kpc is 0.5 mas**

Minimizing the position error

Baseline length is already maximized, so it comes down to minimizing the delay error – $\Delta\tau$

- $\Delta\tau_{obs} = \Delta\,\tau_{geom} + \Delta\tau_{ant} + \Delta\tau_{struc} + \Delta\,\tau_{trop} + \Delta\tau_{ion} + \Delta\tau_{inst} + \Delta\,\tau_{noise}$
- $\Delta\tau_{geom}$ – arrival time difference with respect to the line-of-sight to the source



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- $\Delta\tau_{ant}$ – antenna position error, incudes earth orientation parameters (EOPs), and UT1-UTC
- $\Delta\tau_{struc}$ – structure of the target if not a point source
- $\Delta\,\tau_{inst}$ – delay from electronics in antenna and clock at different ant.
- $\Delta\tau_{noise}$ – thermal noise which cannot be calibrated and removed *but* is random so can be reduced by averaging long observation. Due to thermal noise the centroid can be localized with an error of

$$\Delta\theta = 0.5\,\frac{\theta_{beam}}{SNR}$$

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Note: For Geodesy this is what they are solving for

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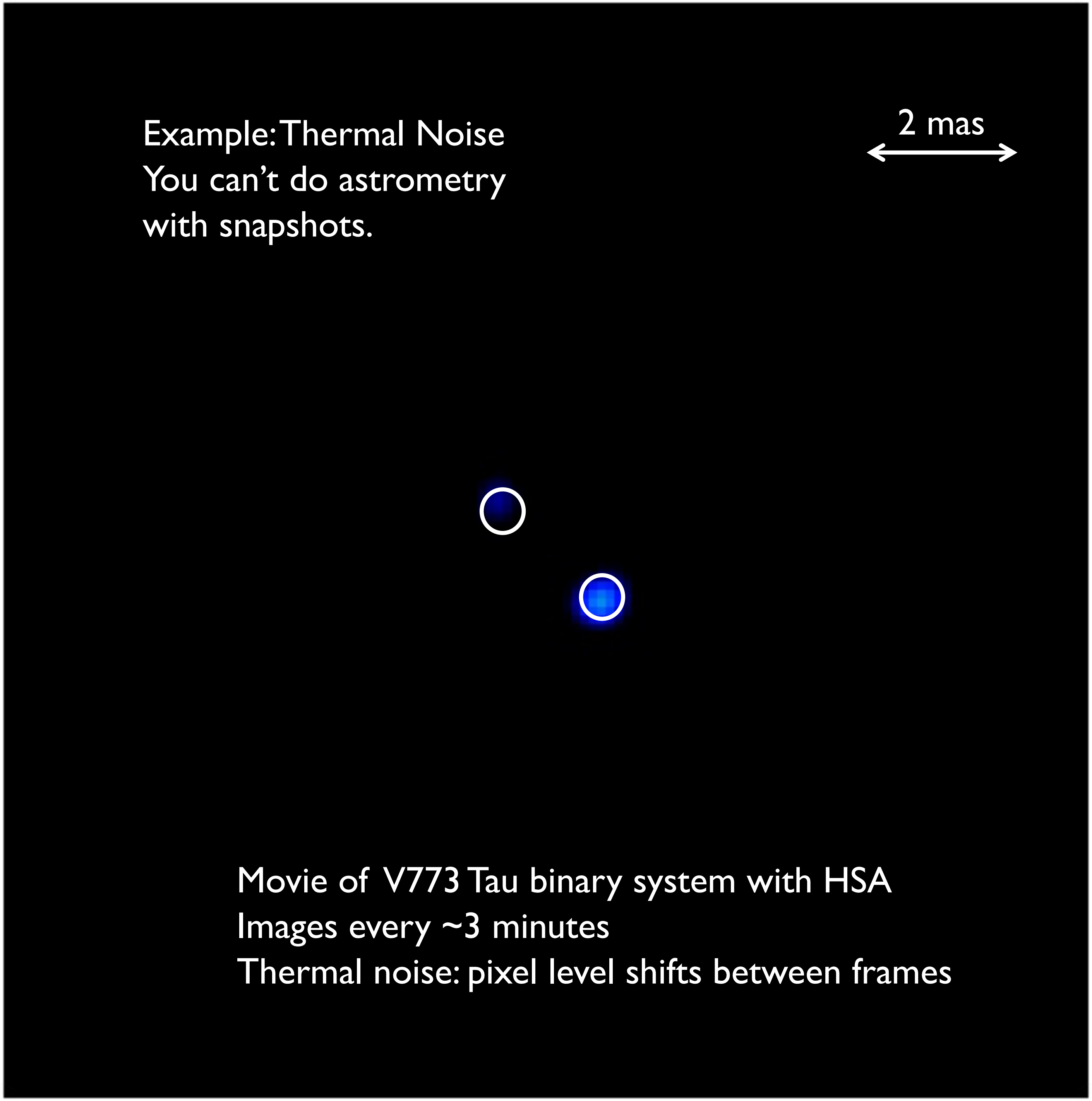

Example: Thermal Noise
You can't do astrometry
with snapshots.

Movie of V773 Tau binary system with HSA
Images every ~3 minutes
Thermal noise: pixel level shifts between frames

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- $\Delta\tau_{geom}$ the source

Position of calibrators and antennas known so minimal

- $\Delta\tau_{ant}$ (EOPs

Errors pretty small for most antennas (geodesy) and small if using measured EOPs & UT1-UTC. (Note this means that corrections must be done *after* obs.)

- $\Delta\tau_{struc}$ – st

Phase referenced image of target or calibrator, if needed

- $\Delta\,\tau_{inst}$ nics in ant

Removed in calibration

Reduced by observing geodetic blocks

- $\Delta\tau_{noise}$ s random thermal noise the centroid can be localized with an error of

Not a problem if SNR high enough and observation averaged over a many samples.

$$\Delta\theta = 0.5\,\frac{\theta_{beam}}{SNR}$$

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Caveat: This is very simplified, these errors are not gone but are just much smaller than the atmospheric errors, τ_{trop} & τ_{ion}

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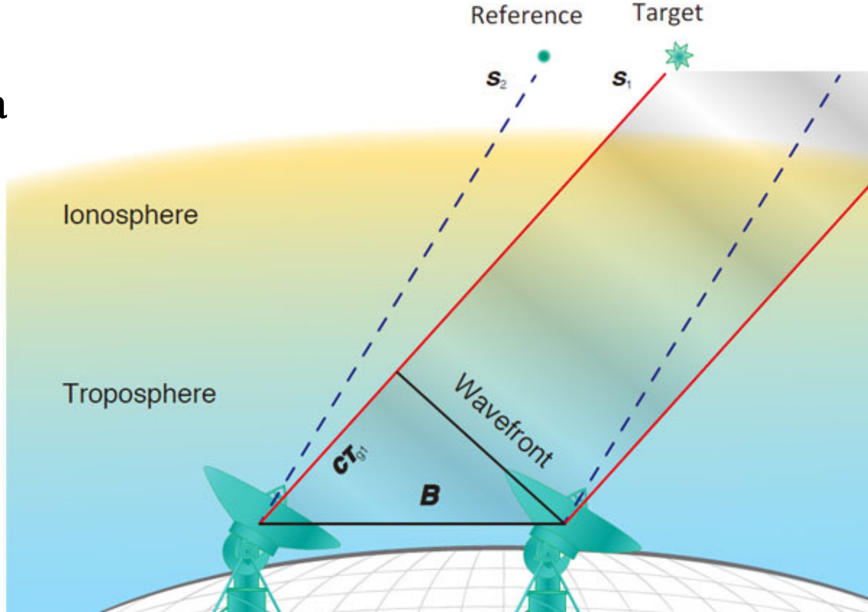
Relative Astrometry: Phase referencing

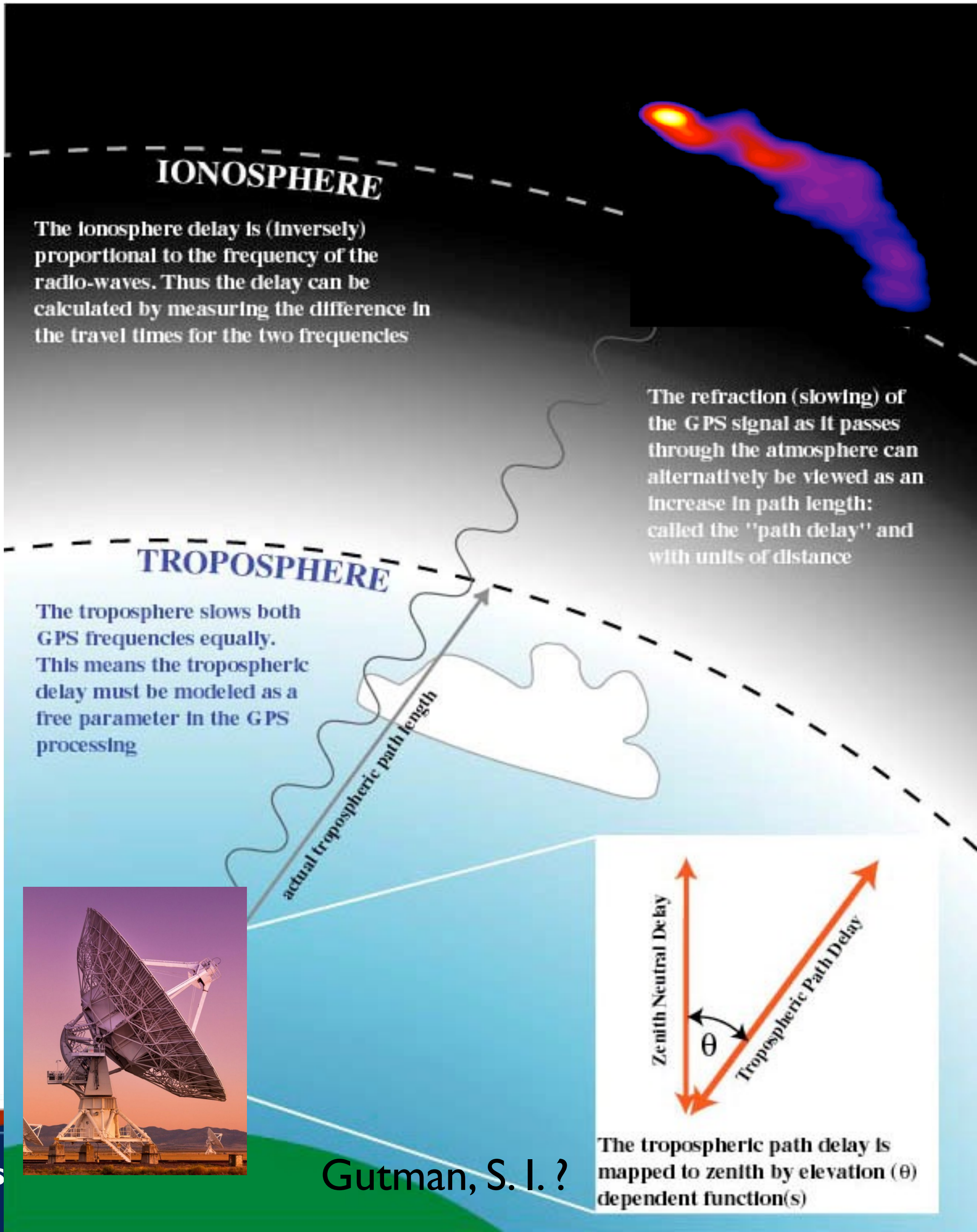
Minimizing atmospheric (and other) delay errors

- Observe a calibrator at about the same time and about the same position as target.
- Minimizes many of the errors because looking through nearly the same atmosphere and through the same electronics and antennas
  - **You are left with the biggest source of error being the difference in the atmosphere between calibrator and target**
- This is usually done by fast switching (seconds to minutes) between target and calibrator
  - There are VLBI arrays (e.g., VERA) where there are two beams that you can put one on the target and one on the calibrator so there can be simultaneous observations of target and calibrator.
- Advice: closer is always better. If you can get a calibrator close enough (≪ 1° for cm wavelengths) then errors from atmosphere will be very small additional calibration will not be needed.



The Earth's Atmosphere

- Causes radio signals to refract (slow and bend)
- The main constituents of the atmosphere which cause delays are:
- Ionosphere – free electrons
- Troposphere – temperature, pressure, and water vapor



The ionosphere delay is (inversely) proportional to the frequency of the radio-waves. Thus the delay can be calculated by measuring the difference in the travel times for the two frequencies

The refraction (slowing) of the GPS signal as it passes through the atmosphere can alternatively be viewed as an increase in path length: called the "path delay" and with units of distance

The troposphere slows both GPS frequencies equally. This means the tropospheric delay must be modeled as a free parameter in the GPS processing

The tropospheric path delay is mapped to zenith by elevation (θ) dependent function(s)

Gutman, S. I. ?

Ionosphere

- Dispersive (frequency dependent) delay
  - Can be removed by observing at two different frequencies simultaneously.
- Varies based on the Sun ionizing the ionosphere during the day and differing Solar activity
- Worse at lower frequencies.
  - $\tau_{ion} \propto TEC * \nu^{-2}$
  - Observe at higher frequencies (~8 GHz and higher)
  - If cannot avoid lower frequencies then find very close calibrators (e.g., Pulsars)
- Various space agencies measure and model the Total Electron Content (TEC) based on GPS observations and these can be applied to data.
- So, avoid if possible and apply a TEC model

Credit: NASA. Video taken from the ISS
Red and green glow the ionospere

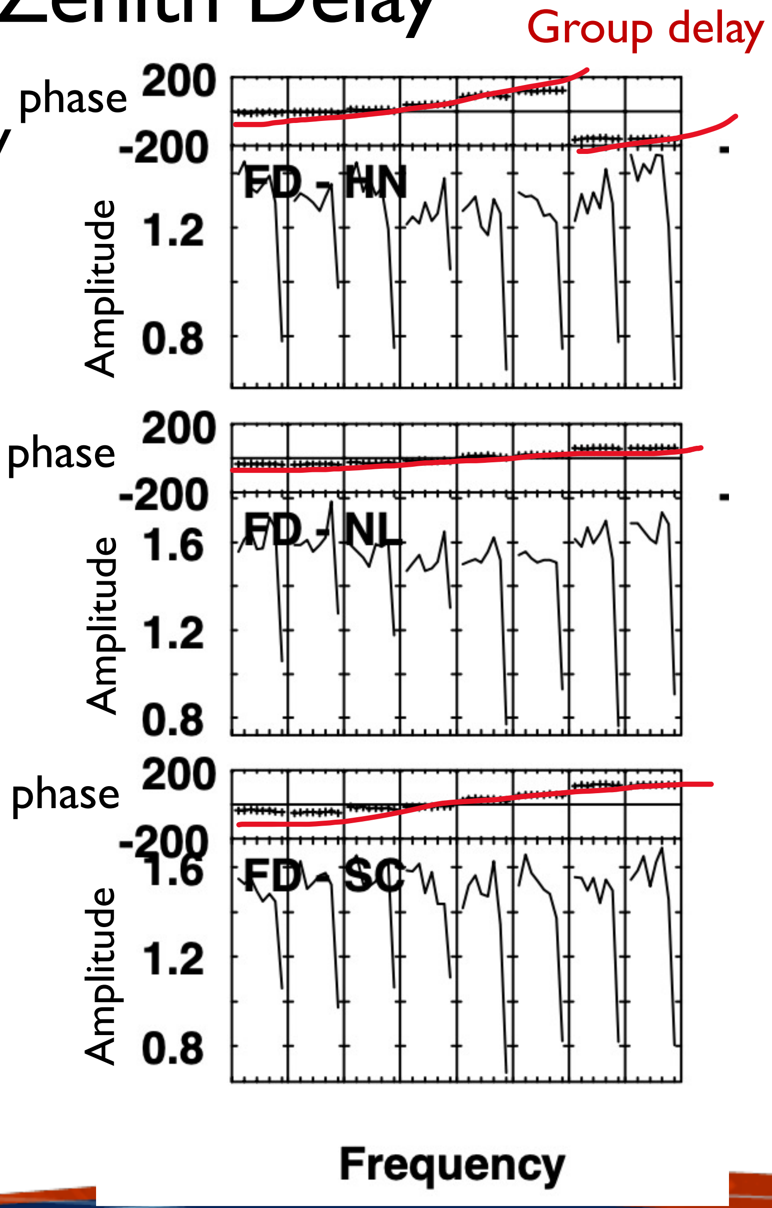
Troposphere

Where most weather happens

- Non-dispersive delay at radio frequencies
  - Worse at higher frequencies
- Can be separated into rapidly and slowly changing.
- Rapidly changing wet component is caused by small clouds of water vapor moving over antennas
  - Removed by switching between target and calibrator faster than the coherency time
  - Completely removed by in beam calibrator
- Slowly changing dry component
  - Can be estimated by elevation and latitude of antenna and can be removed
- Slowly changing wet component cannot be modeled and must be measured and removed to achieve μas astrometry
  - Geodetic Blocks!

Geodetic Blocks: Determining Zenith Delay

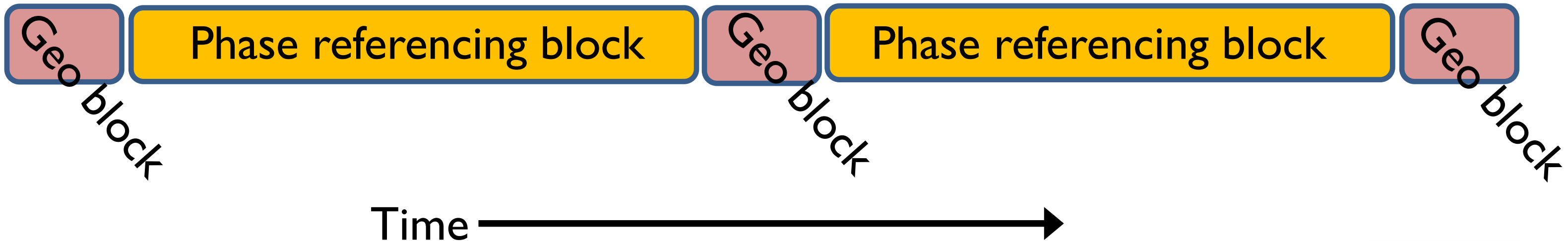
- Determine multiband (group) delay by observing QSOs with good positions
- This residual (remember a model including the EOPs, estimated atmospheric delays etc. has been applied during correlation) group delay will be dominated by the troposphere at $\nu \gtrsim 8 GHz$ and any antenna based clock delay.
- The group delay is then used to estimate and model the zenith delay above each antennas and the residual clock delay



Geodetic Blocks: Observing Stategy

- Observe with wide as possible band (currently 500 MHz for VLBA)
- Observe blocks of ~10 calibrators (usually QSOs with <1 mas astrometric positions) all over the sky
  - Remember to get low elevation observations at each antenna
  - Observe each calibrator for 1-3 minutes
  - Blocks will be 30-40 minutes long
  - Blocks should be at the beginning, end and every 2-3 hours in between
- SCHED (VLBA/VLBI scheduling software) can set up optimized geodetic blocks up automatically

Typical Observing Sequence



Geo block

Phase referencing block

Geo block

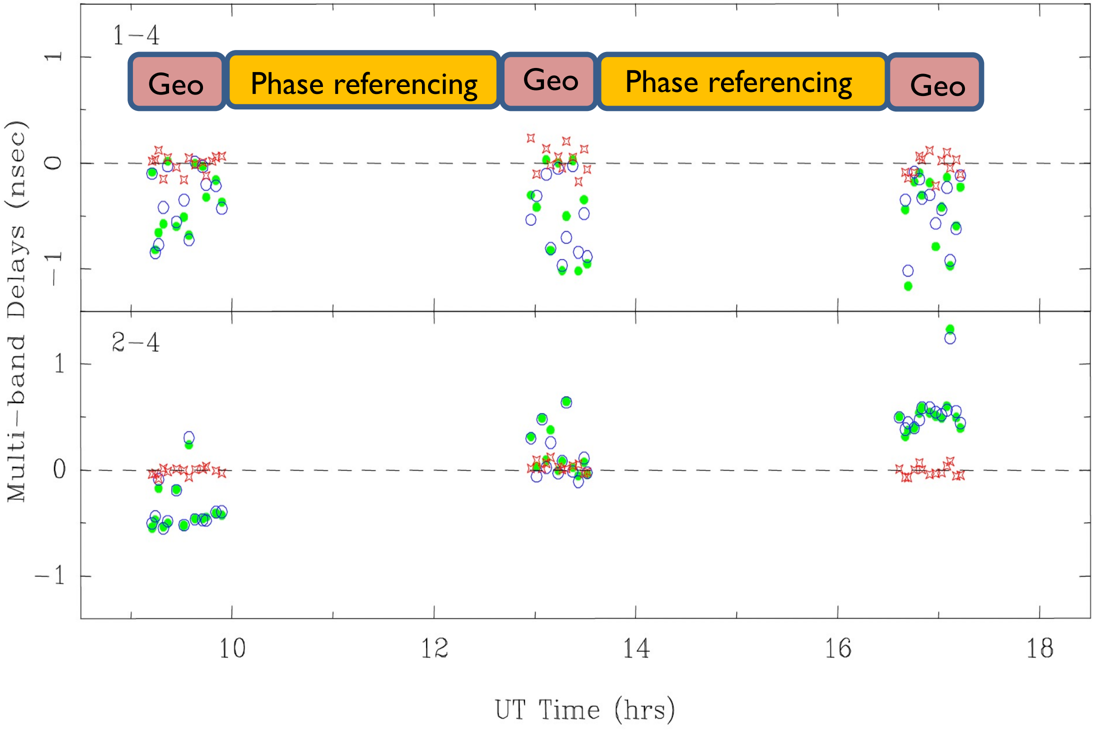
Phase referencing block

Geo block

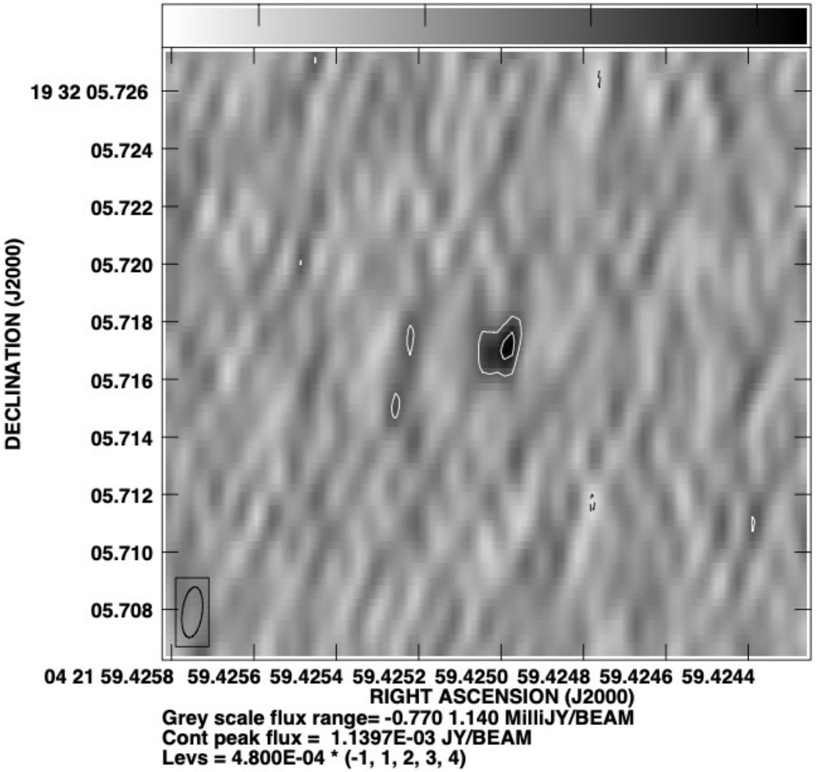
Time

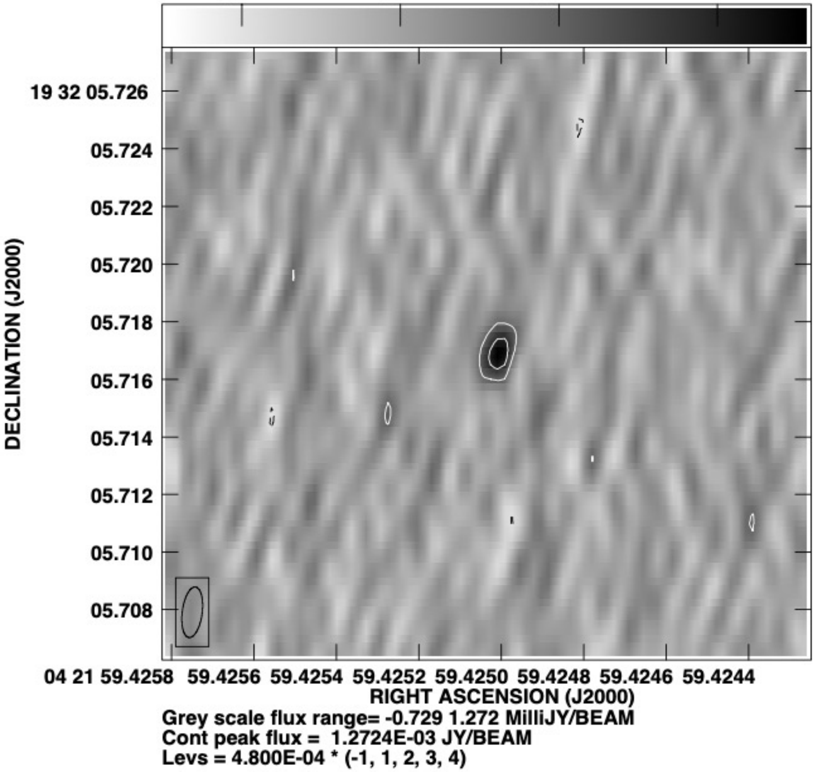
Example of Model Fitting

- The group (multiband) delays from the geodetic blocks is modeled (in AIPS use DELZN) and then applied to the data.
- One thing that is nice about this method is you can check if modeled the antenna based zenith and clock delays are reasonable. See plot at right.
- Then the antenna based zenith and clock delays are interpolated and applied to the phase referencing blocks.



DATA MODEL RESIDUALS


Before


After

- This is T Tauri star T Tau Sb. It is ~1 mJy and we obtained a 0.4% (Loinard et al.) distance to it with VLBA astrometry observations.
- Applying the Geodetic solutions made the source more compact and the peak brighter – which obviously improves the position of the T Tau Sb

More Information

- I glossed over so much stuff…for more in depth discussion see:
  - Reid & Homna *Annu. Rev. Astron. Astrophys. 2014. 54*
  - Campbell, So you want to do VLBI, 4th EVN VLBI School
- For description of data reduction procedure see:
  - Mioduszewski & Kogan, *Strategy for Removing Tropospheric and Clock Errors using DELZN, 2009*
  - Astrometry AIPS Spectral Line and Astrometry Tutorial

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Growth in VLBI Astrometry