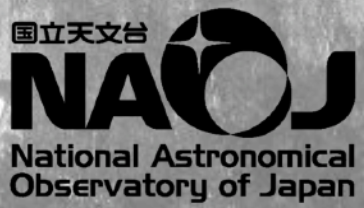
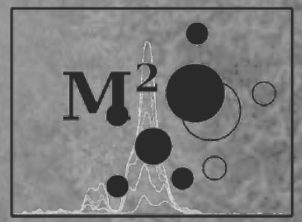
Astrometry

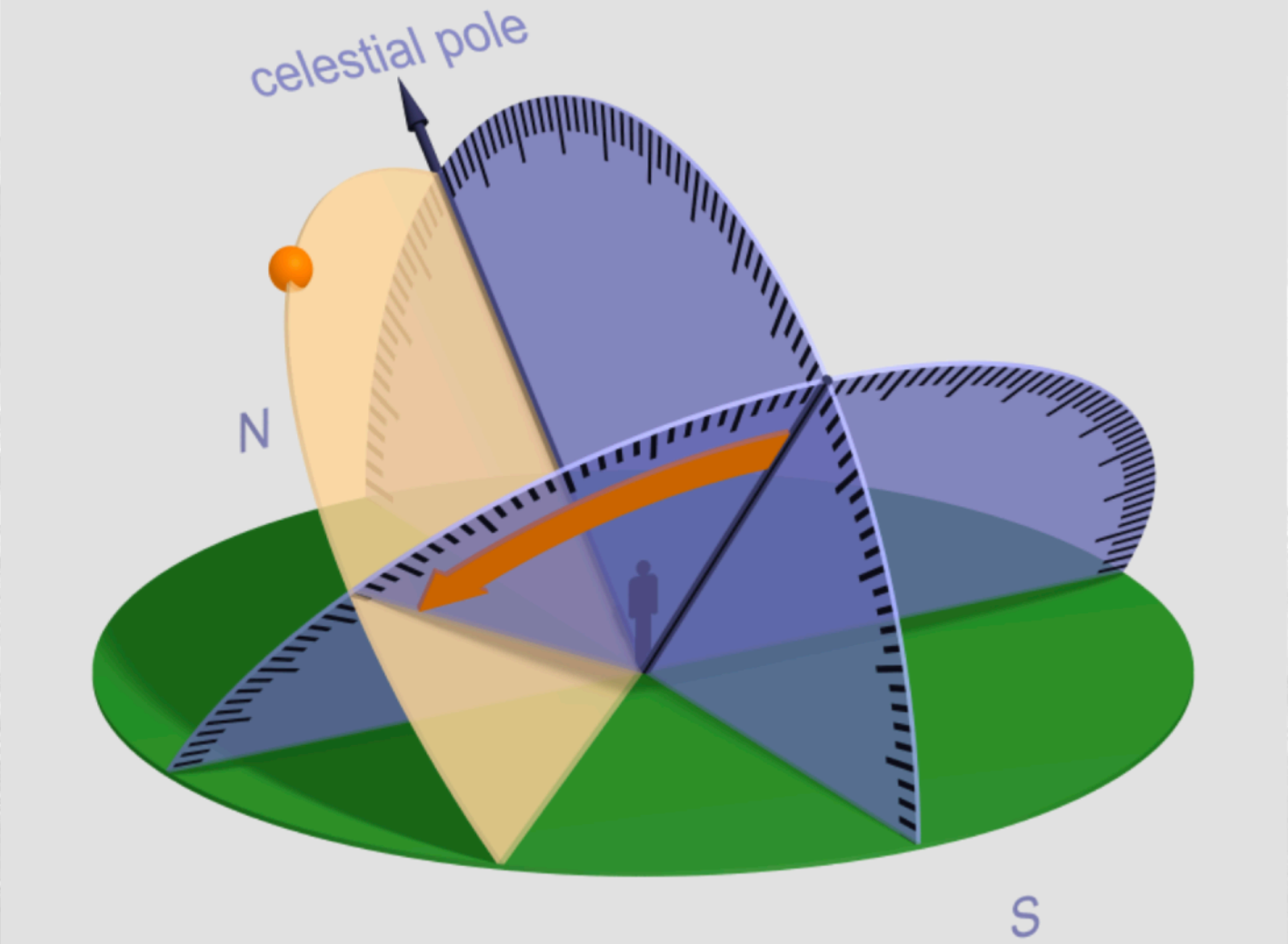
Ross Burns

DARA training, June 2021





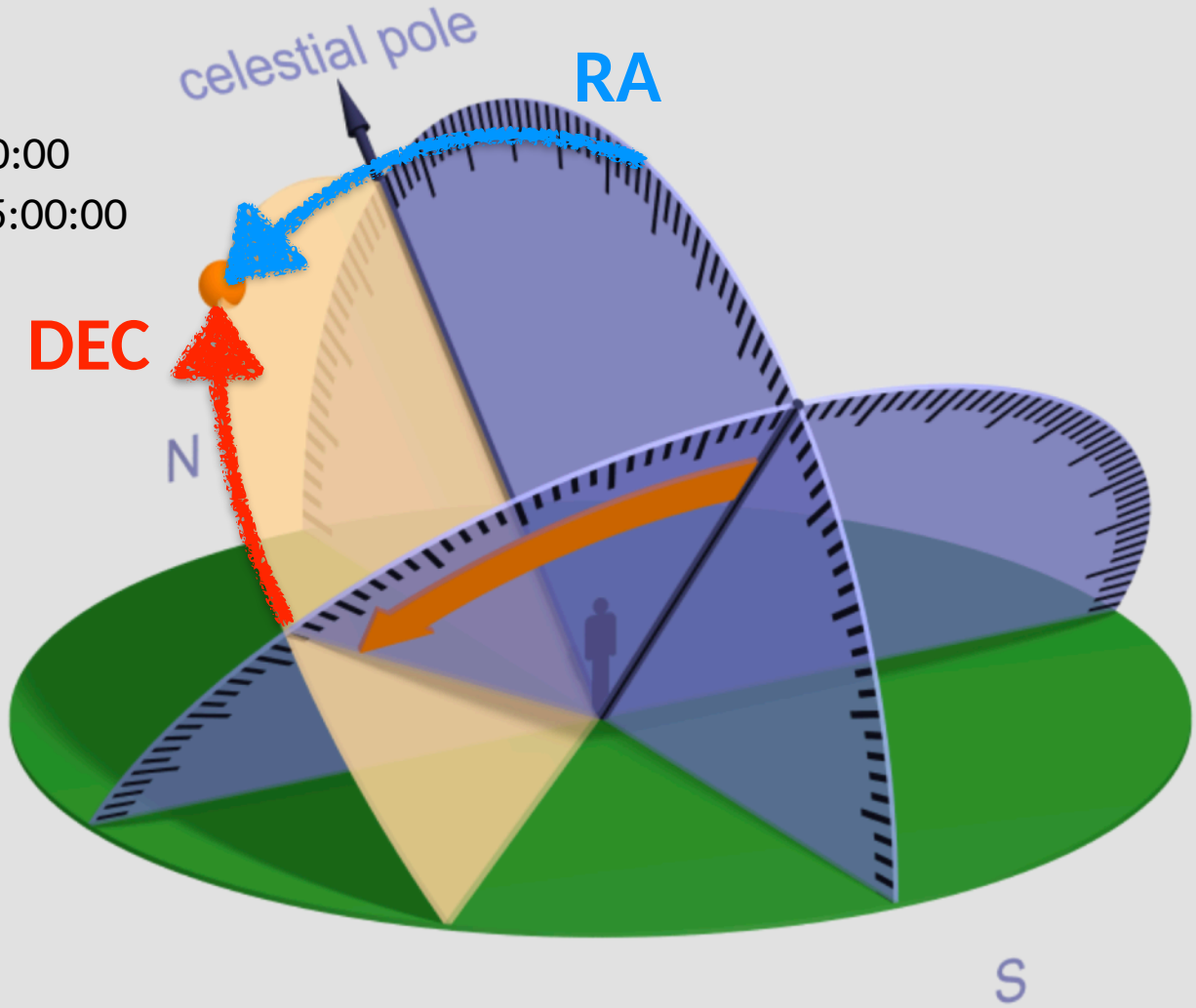
Using the coordinate system of RA and DEC, we define a celestial reference frame



https://commons.wikimedia.org/wiki/File:HourAngle_Observer_en.png

Using the coordinate system of RA and DEC, we define a celestial reference frame

Object 1
RA= 02:00:00
DEC= + 45:00:00



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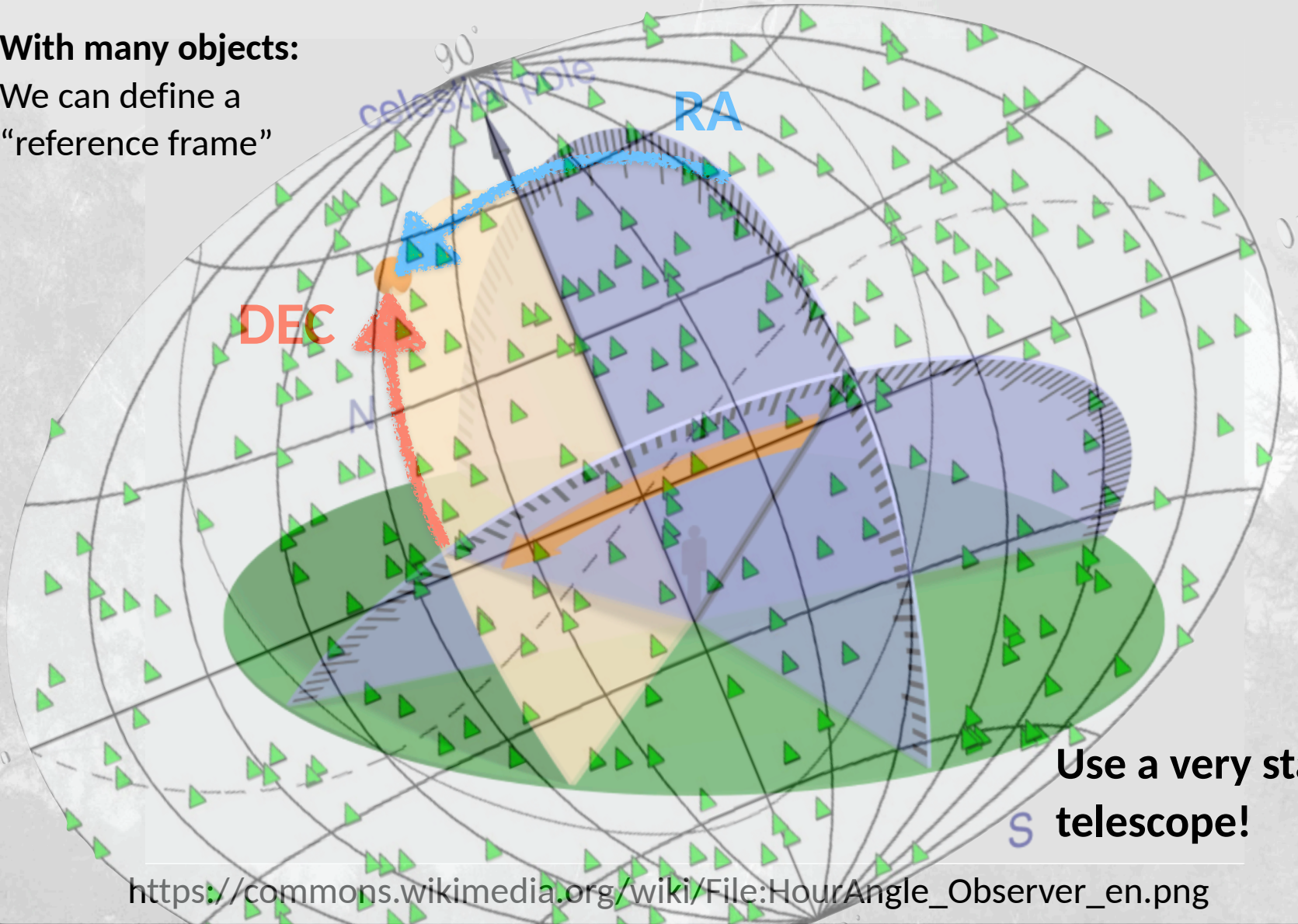
Using the coordinate system of RA and DEC, we define a celestial reference frame

This is the first step for navigating the sky

With many objects:
We can define a
“reference frame”



Use a very stable telescope!

https://www.nasa.gov/centers/goddard/news/topstory/2009/icrf2.html

https://commons.wikimedia.org/wiki/File:HourAngle_Observer_en.png

Astrometry

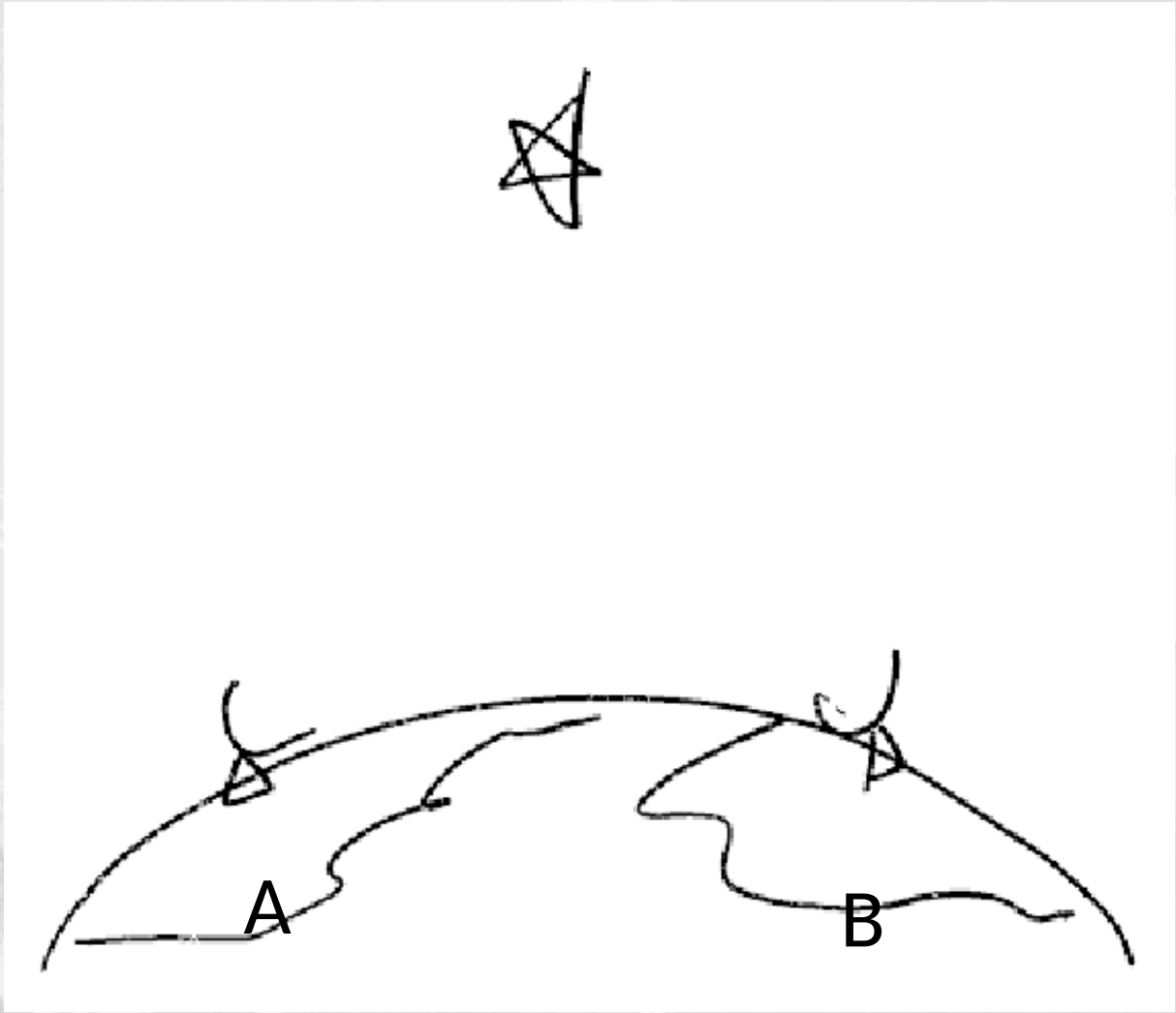
Astrometry is the measure of the positions of things on the sky

(with respect to a coordinate system)

How to get astrometry with a radio interferometer?

(not a very "stable telescope")

In interferometry, the target's location is determined by the signal's arrival time at each antenna



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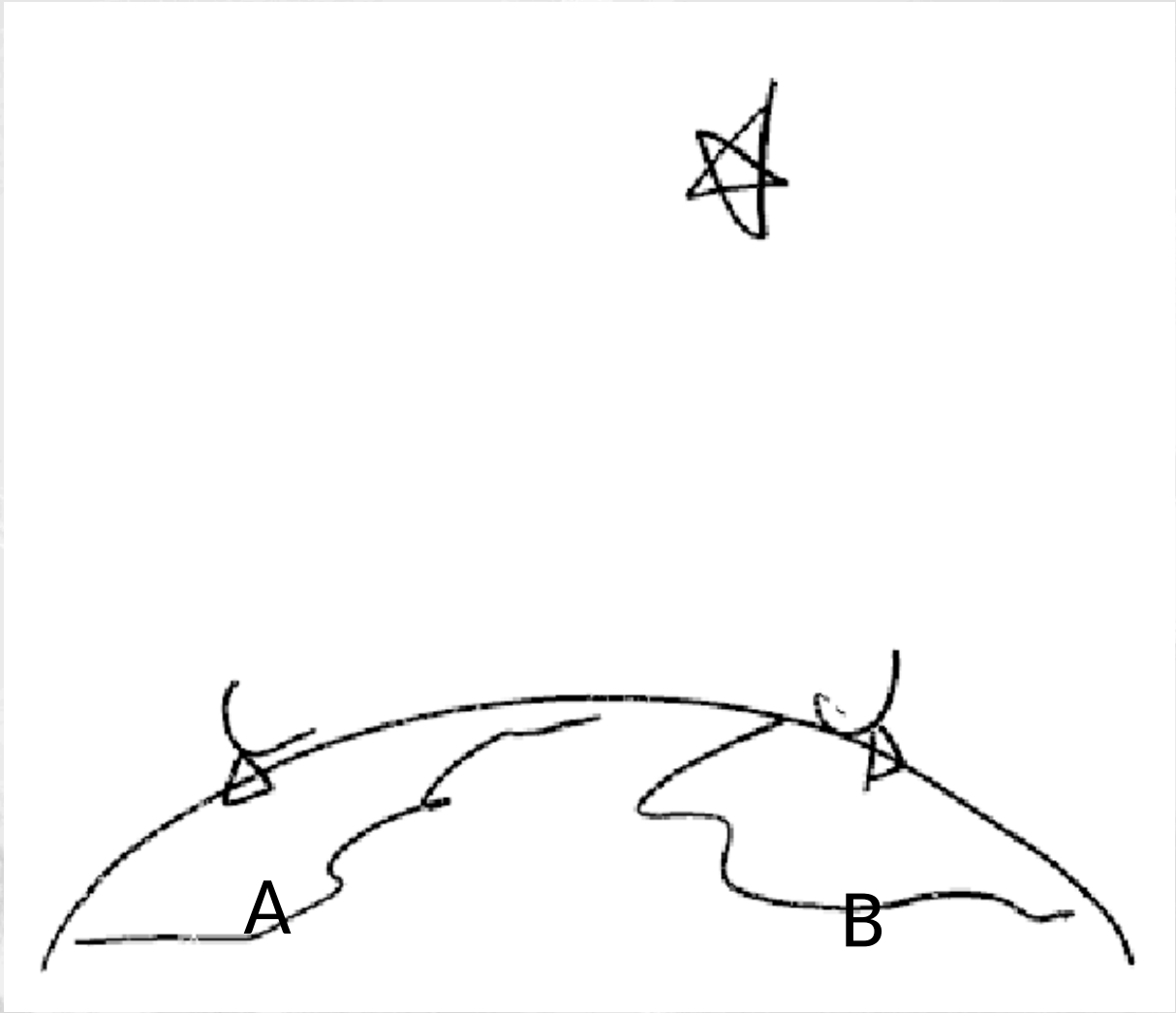

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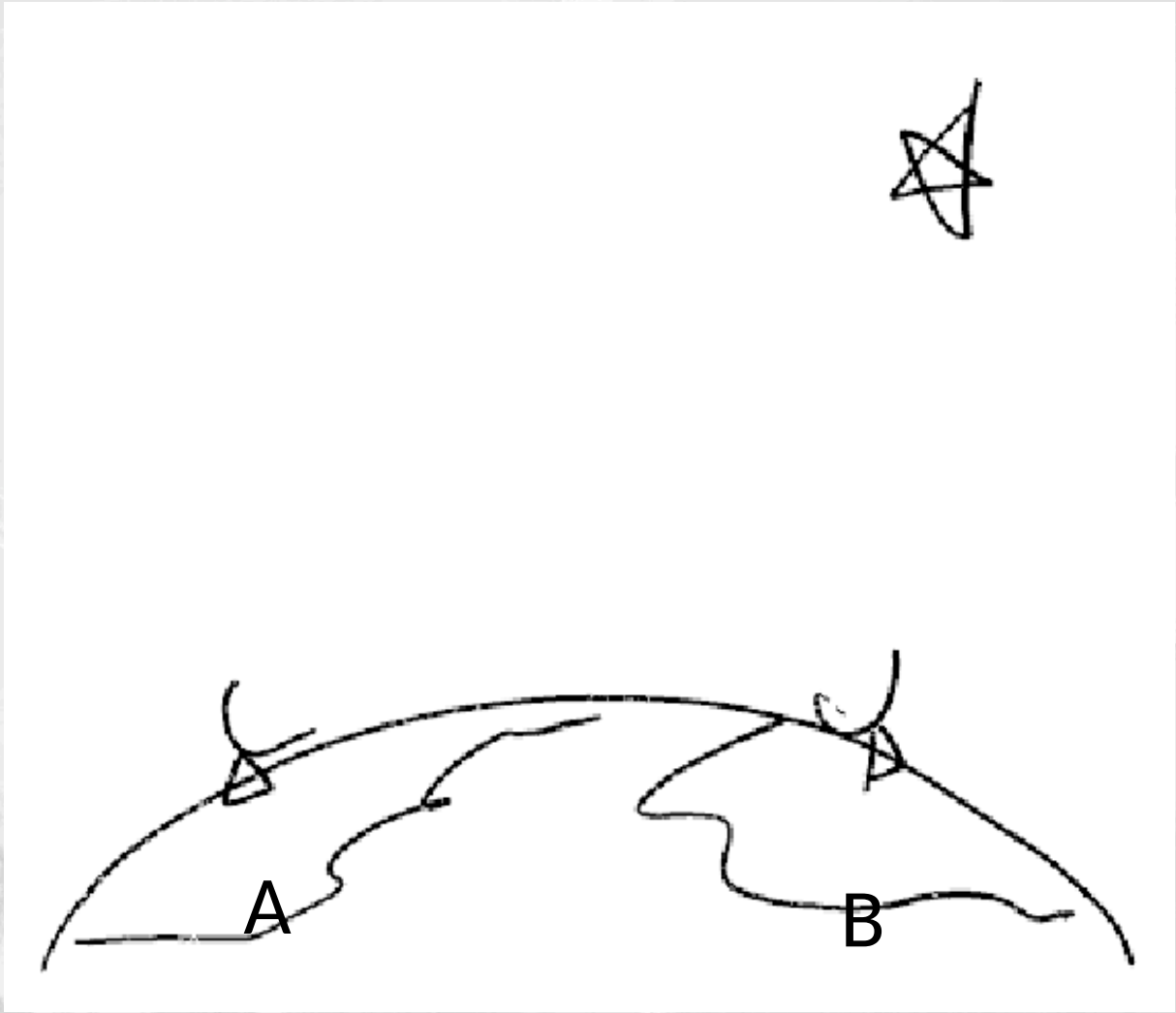

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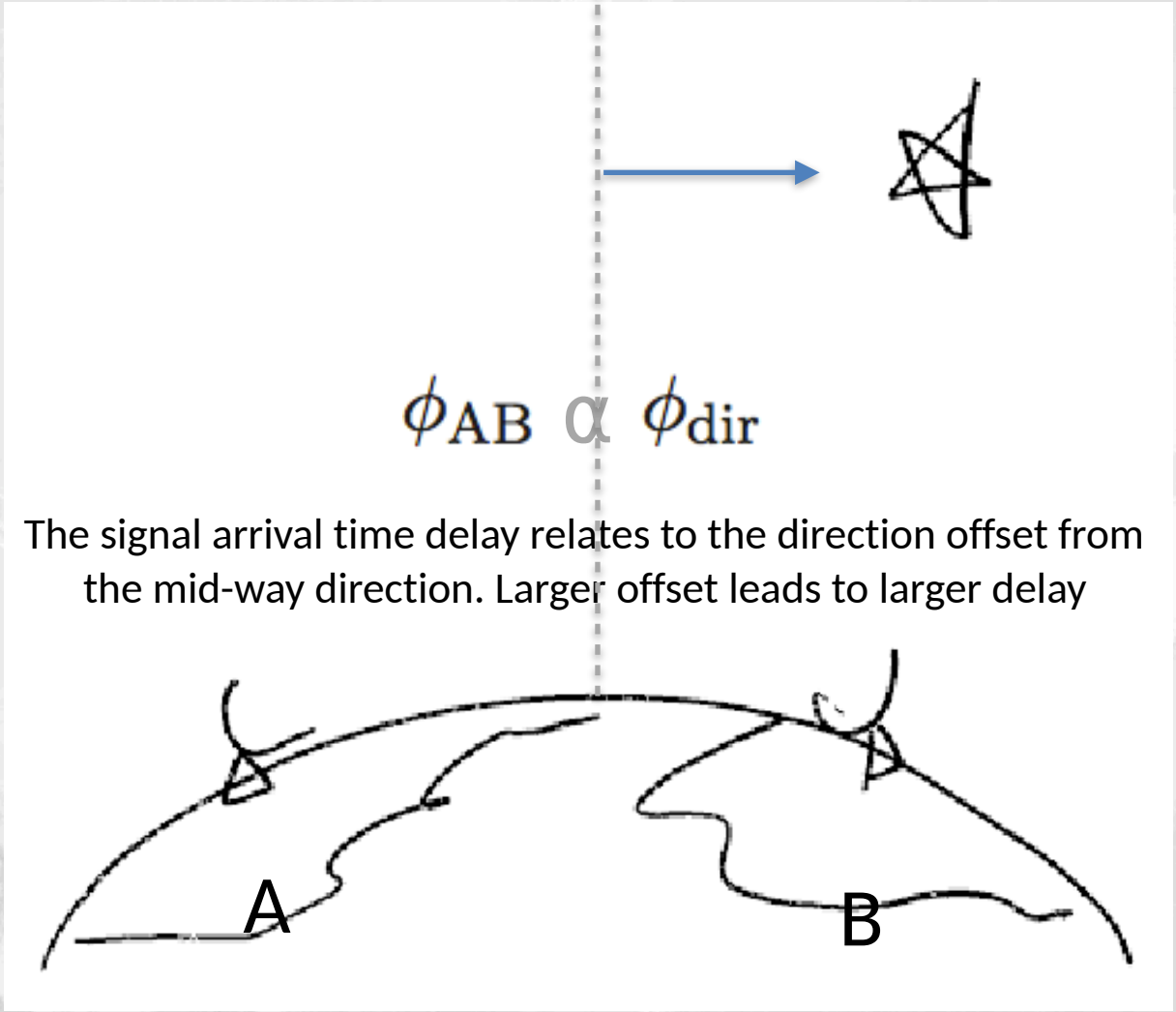

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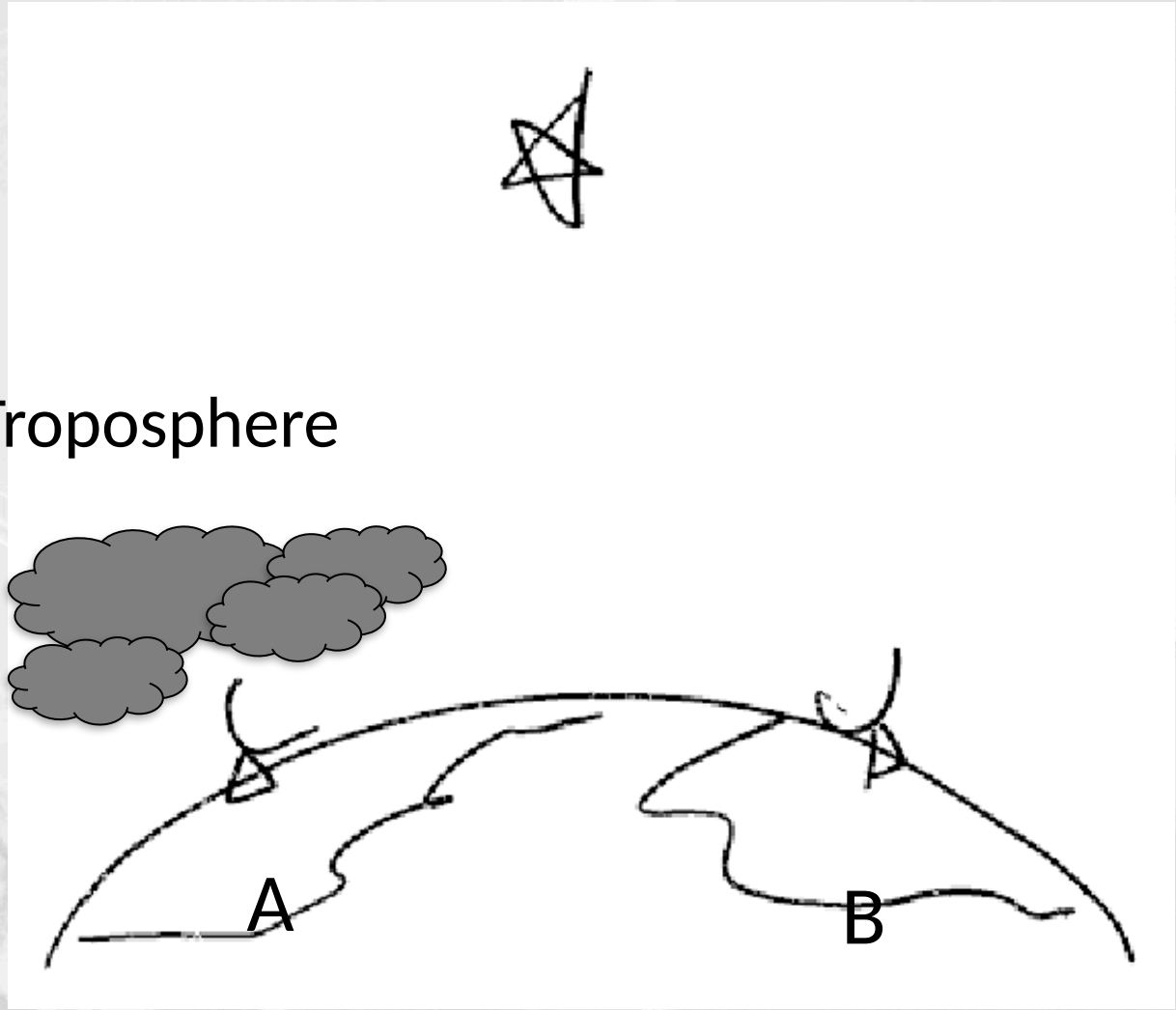

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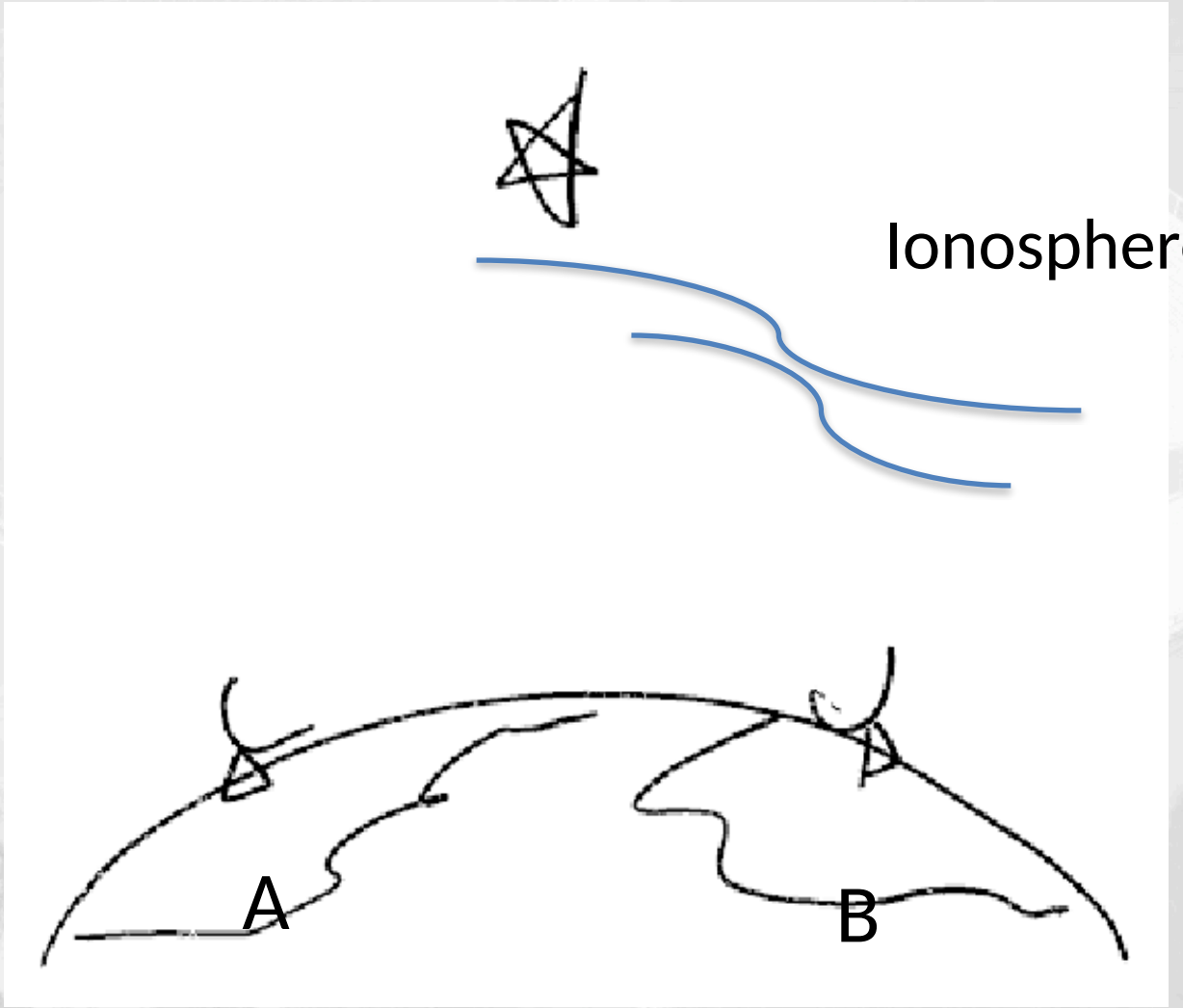

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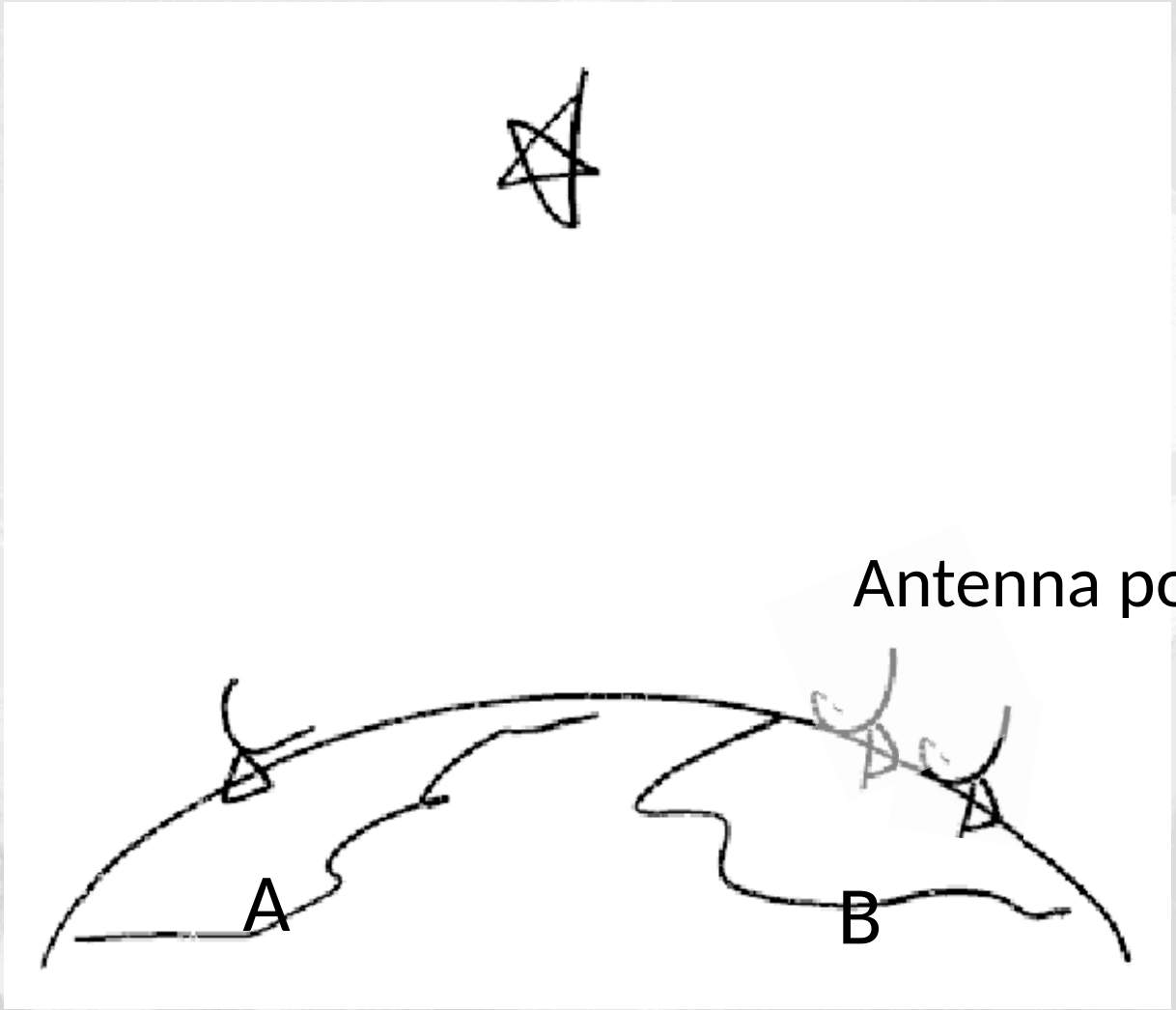

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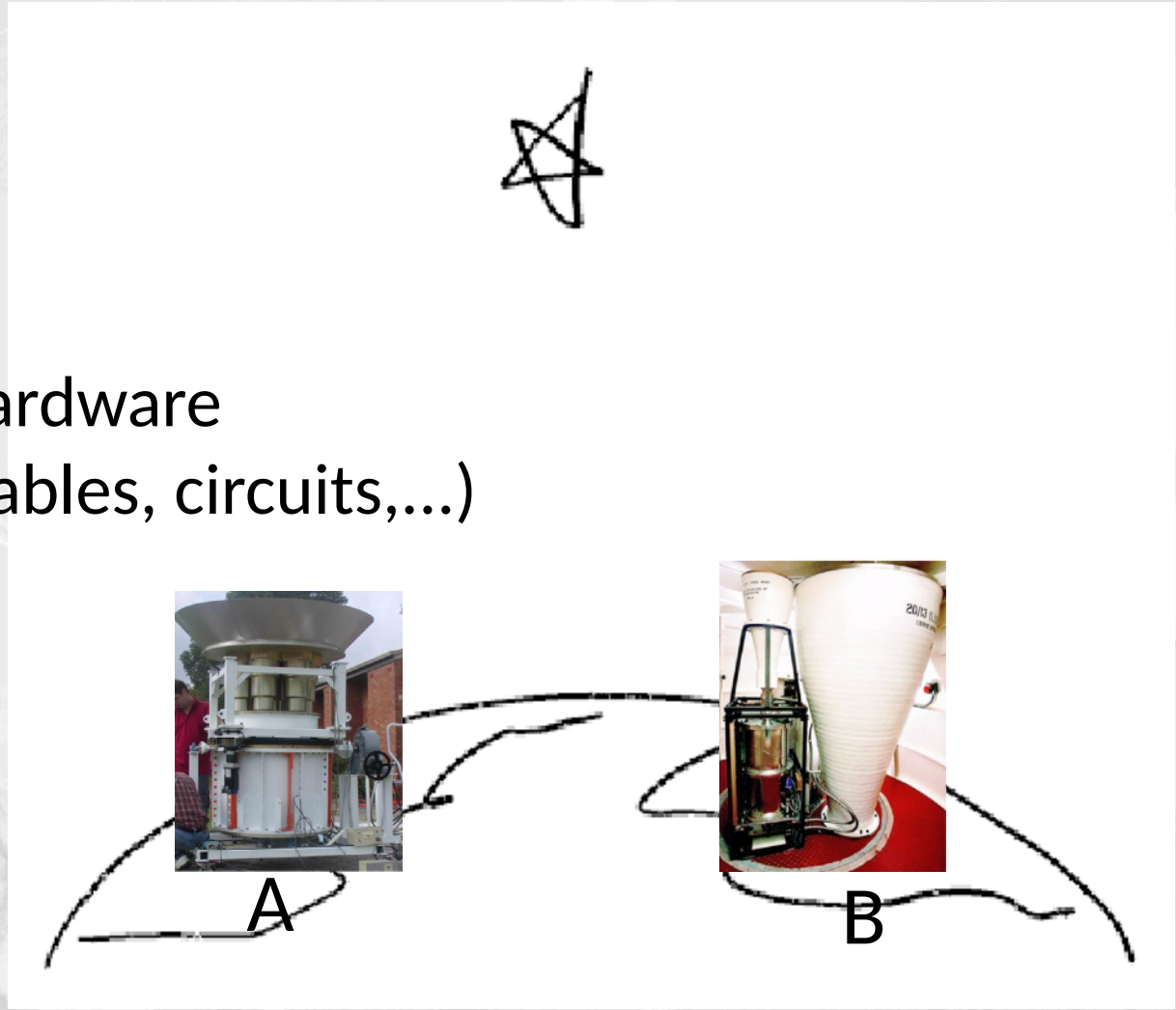

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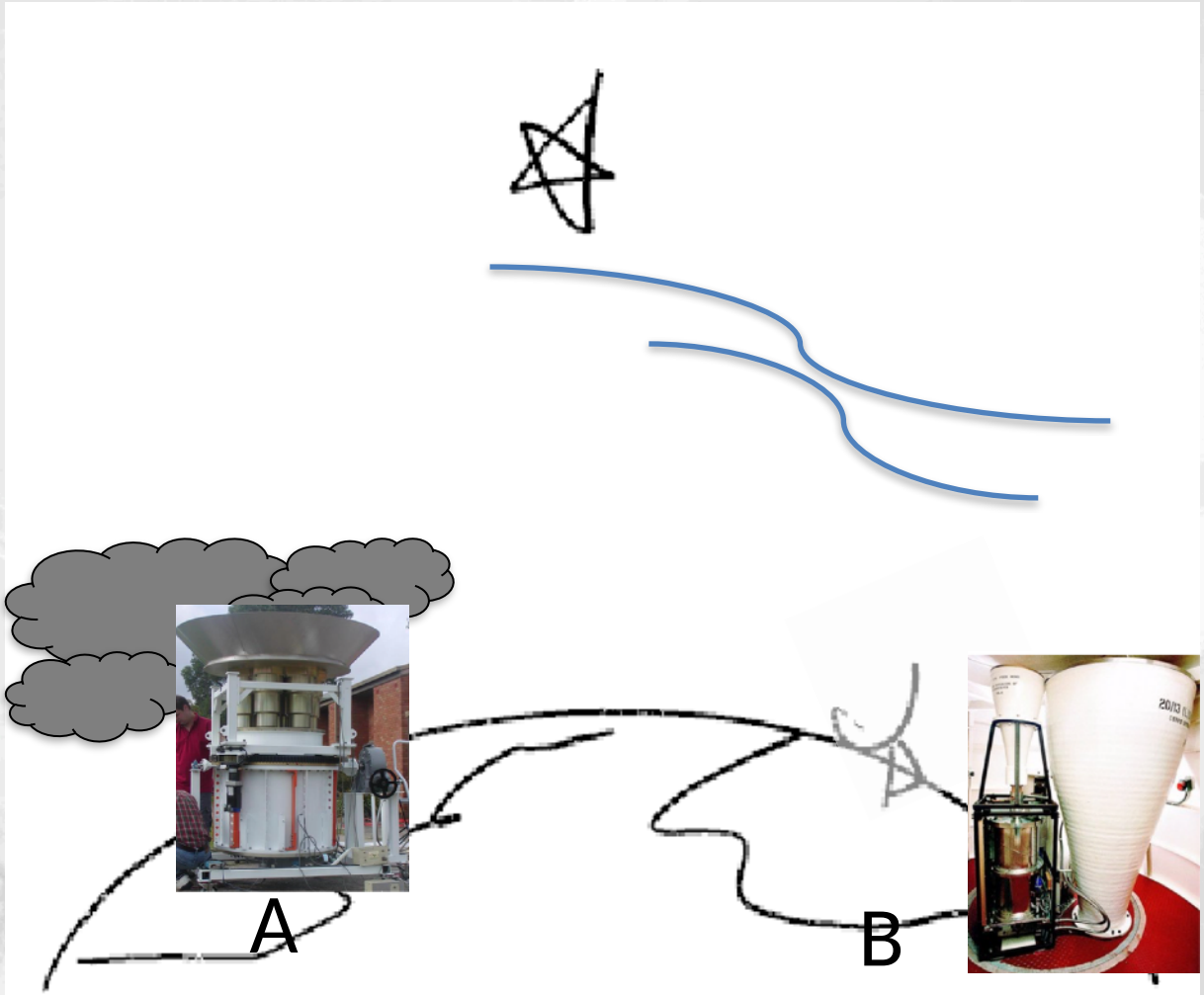


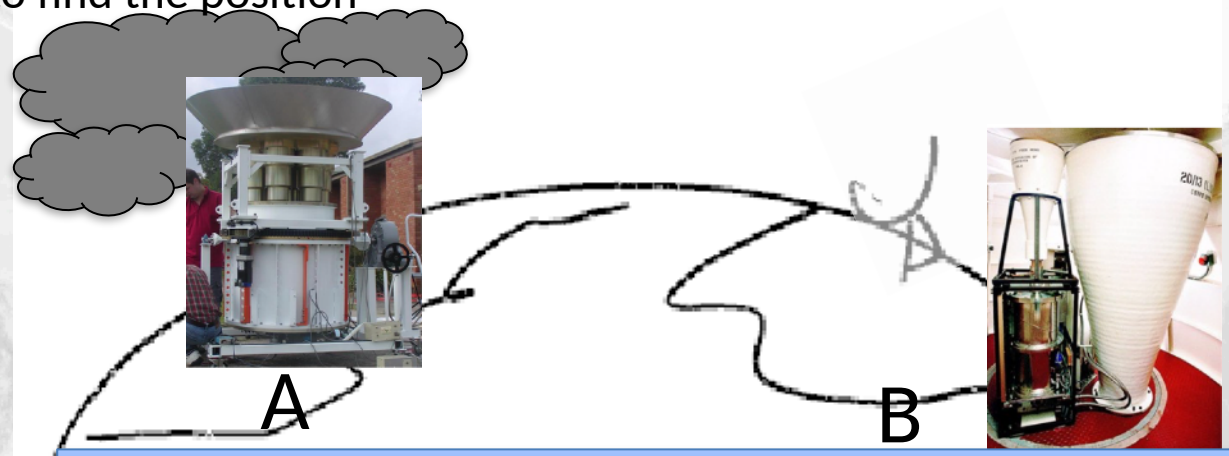
$$\phi_{AB} = \phi_{dir} + \phi_{bl} + \phi_{ion} + \phi_{trop} + \phi_{inst} + \phi_{str} + \epsilon_{therm}$$

In interferometry, the target's location is determined by the signal's arrival time at each antenna

If these delay residuals were zero we could know the position from ϕ_{dir}

Indeed, we can measure ϕ_{AB} but we cannot isolate ϕ_{dir} from the residual delays

We must remove the effects of these delay contributions to find the position

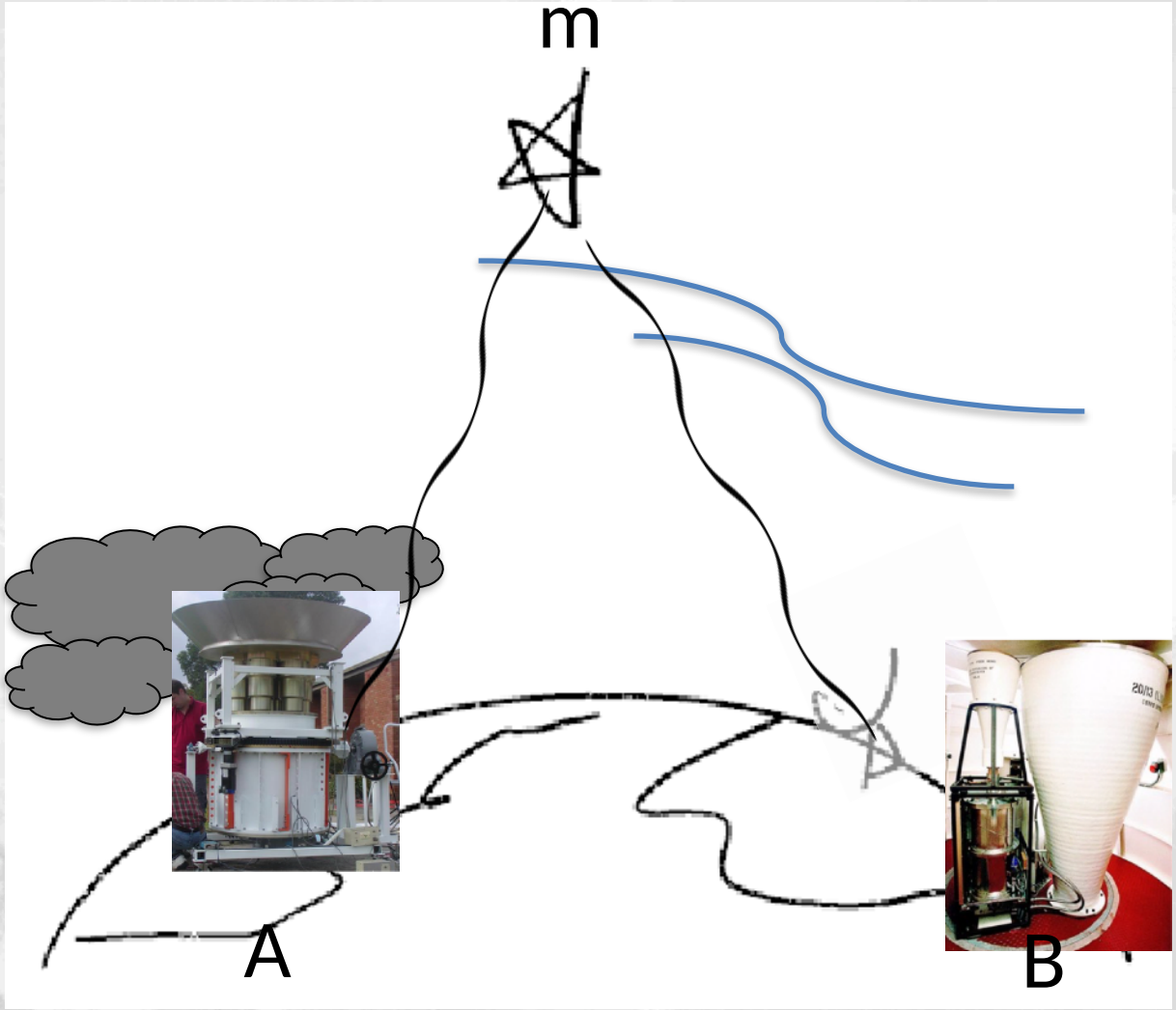


$$\phi_{\mathrm{AB}} = \phi_{\mathrm{dir}} + \phi_{\mathrm{bl}} + \phi_{\mathrm{ion}} + \phi_{\mathrm{trop}} + \phi_{\mathrm{inst}} + \phi_{\mathrm{str}} + \epsilon_{\mathrm{therm}}$$


We use “Phase referencing”

Phase referencing

$$\phi_{AB}^{m} = \phi_{dir}^{m} + \phi_{bl}^{m} + \phi_{ion}^{m} + \phi_{trop}^{m} + \phi_{inst}^{m} + \phi_{str}^{m} + \epsilon_{therm}^{m}$$



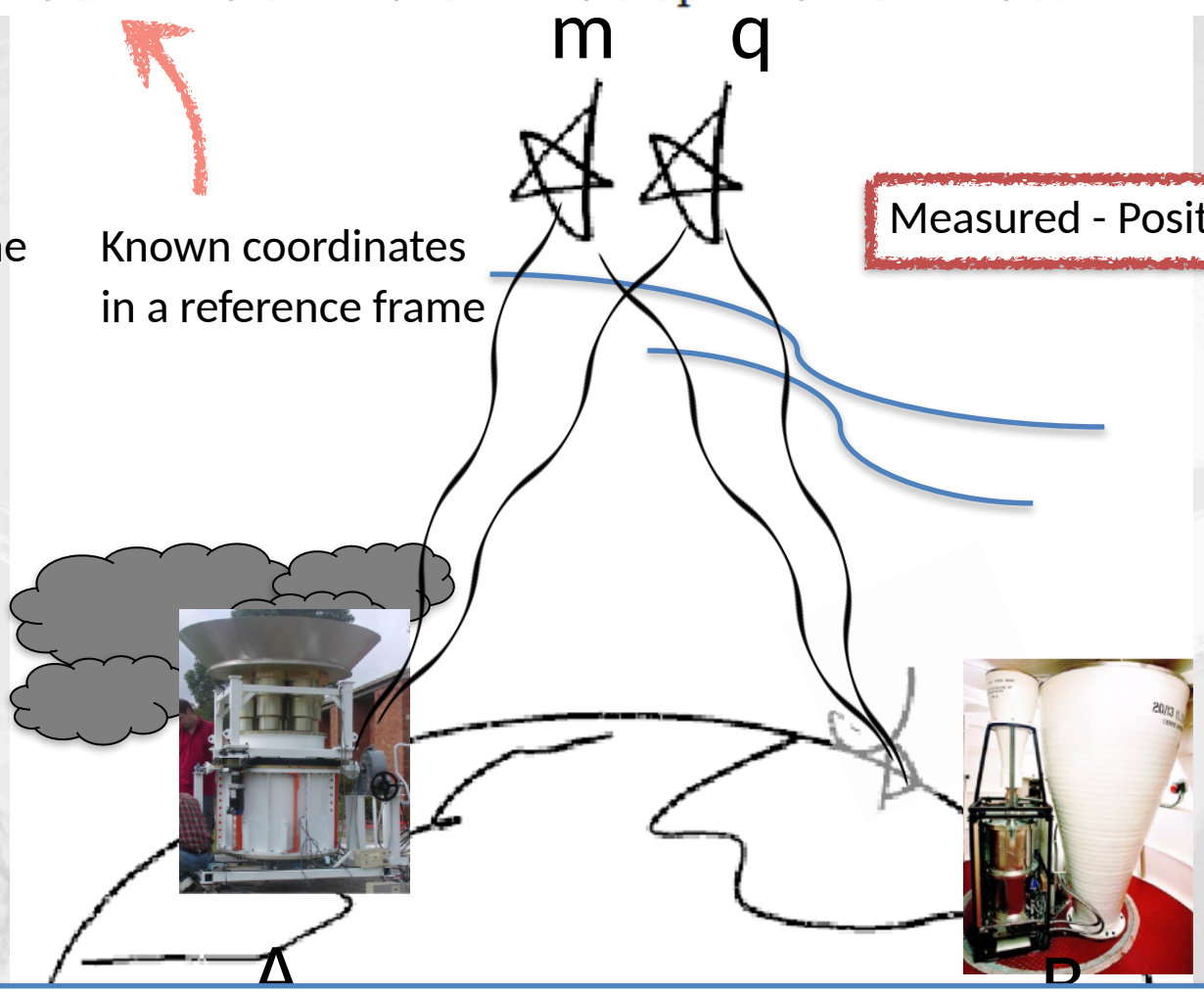
Phase referencing

$$\phi_{AB}^{m} = \phi_{dir}^{m} + \phi_{bl}^{m} + \phi_{ion}^{m} + \phi_{trop}^{m} + \phi_{inst}^{m} + \phi_{str}^{m} + \epsilon_{therm}^{m}$$

$$\phi_{AB}^{q} = \phi_{dir}^{q} + \phi_{bl}^{q} + \phi_{ion}^{q} + \phi_{trop}^{q} + \phi_{inst}^{q} + \phi_{str}^{q} + \epsilon_{therm}^{q}$$

Measured by the interferometer

Known coordinates in a reference frame



Measured - Position = residuals

If we correct for these residuals using the quasar (known position) we can determine the position of the maser using the same corrections, this is “phase referencing”

Phase referencing

$$\phi_{AB}^{m} = \phi_{dir}^{m} + \phi_{bl}^{m} + \phi_{ion}^{m} + \phi_{trop}^{m} + \phi_{inst}^{m} + \phi_{str}^{m} + \epsilon_{therm}^{m}$$

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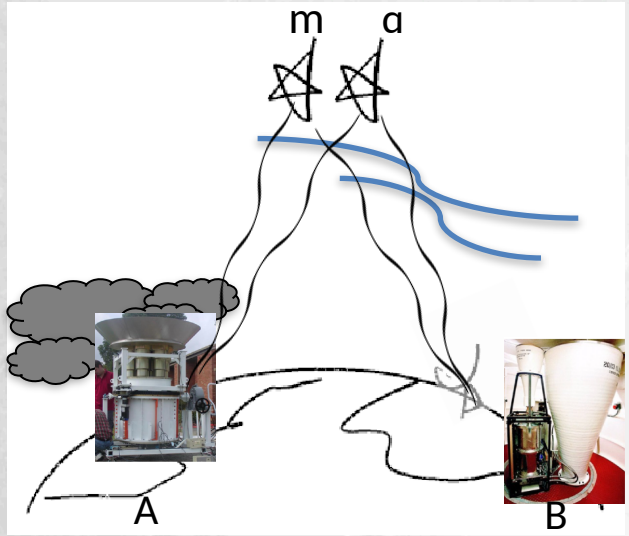
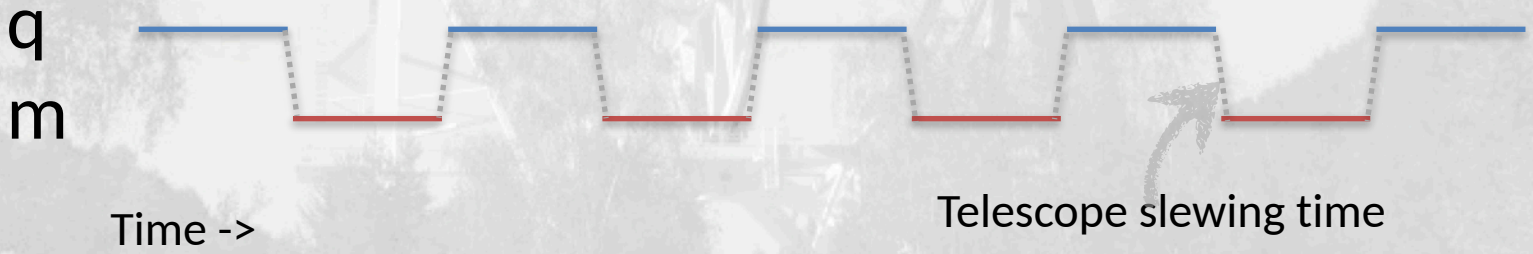


1 - Observe, and measure the arrival time delay when looking at the quasar. Knowing its true direction, calculate the residuals

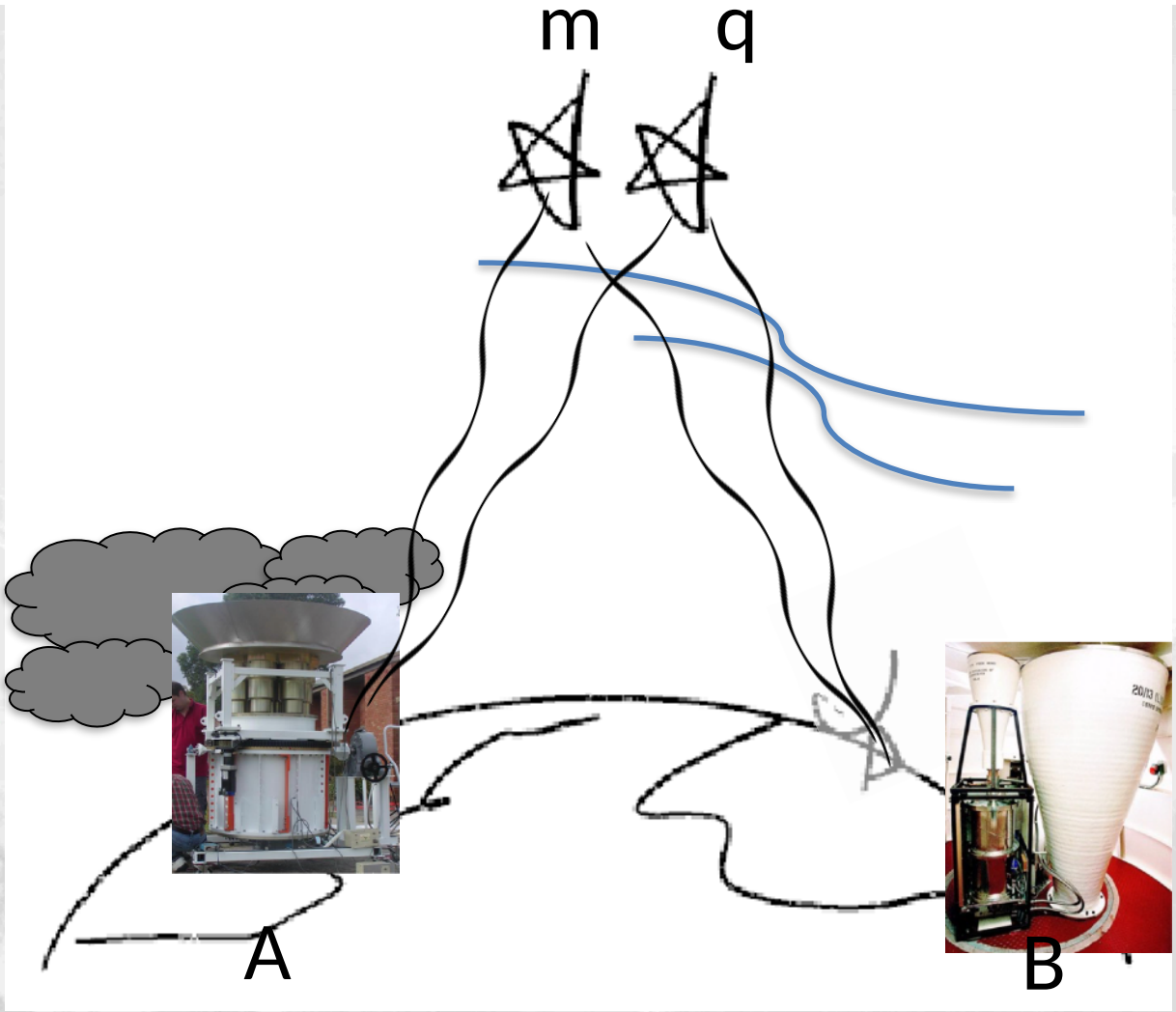
2 - Observe the target source

3 - Return to the quasar and repeat step 1, (the residuals will be slightly different now).

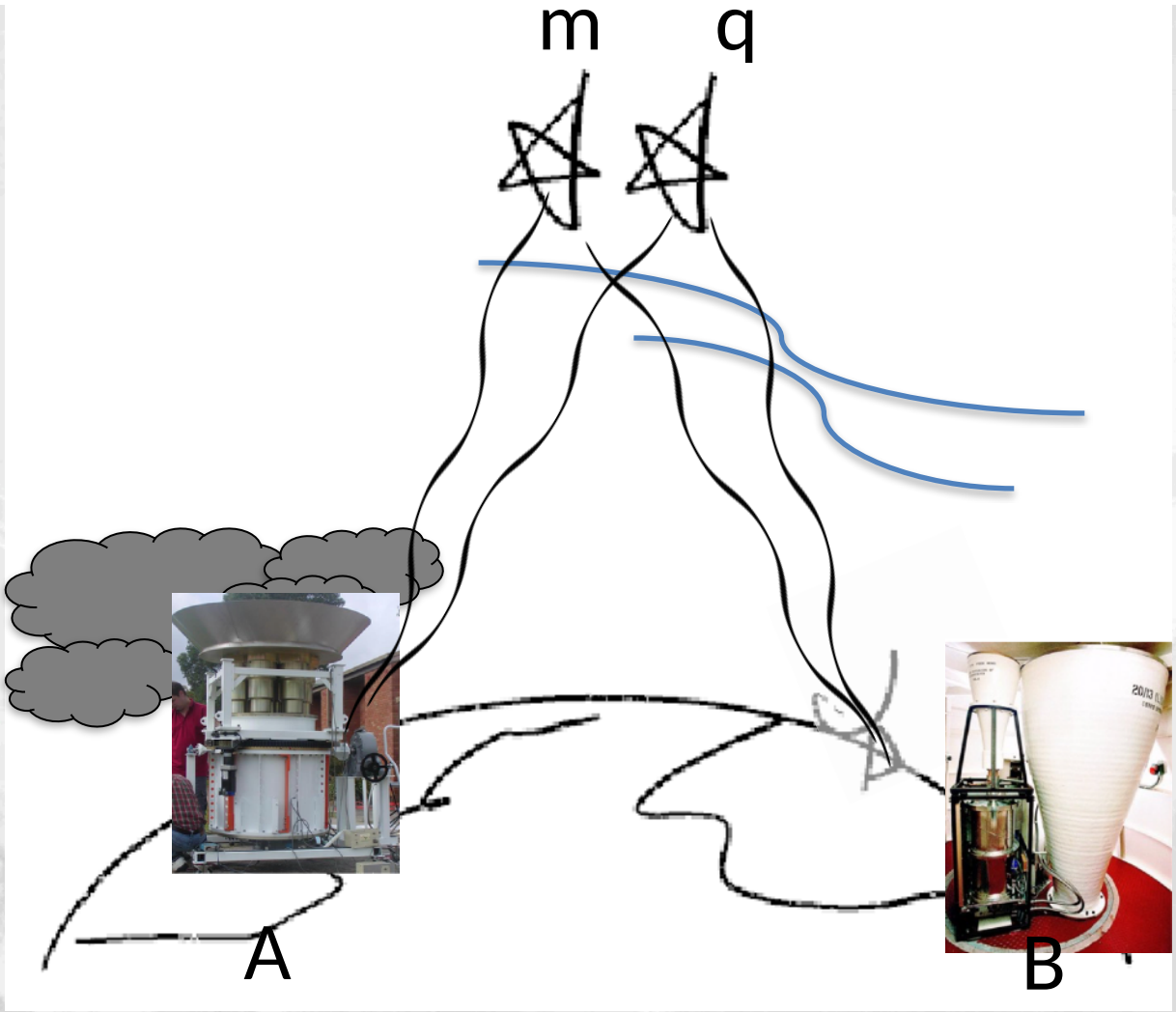
4 - Apply the corrections to the maser by interpolation



$$
\begin{aligned}
\phi^m_{\rm AB} - \phi^q_{\rm AB} &= (\phi^m_{\rm dir} - \phi^q_{\rm dir}) \\
&+ (\phi^m_{\rm bl} - \phi^q_{\rm bl}) + (\phi^m_{\rm ion} - \phi^q_{\rm ion}) + (\phi^m_{\rm trop} - \phi^q_{\rm trop}) + (\phi^m_{\rm inst} - \phi^q_{\rm inst}) \\
&+ (\phi^m_{\rm str} - \phi^q_{\rm str}) - \epsilon^m_{\rm therm} - \epsilon^q_{\rm therm}
\end{aligned}
$$



$$\phi^m_{\rm AB} - \phi^q_{\rm AB} = (\phi^m_{\rm dir} - \phi^q_{\rm dir}) + (\phi^m_{\rm bl} - \phi^q_{\rm bl}) + (\phi^m_{\rm ion} - \phi^q_{\rm ion}) + (\phi^m_{\rm trop} - \phi^q_{\rm trop}) + (\phi^m_{\rm inst} - \phi^q_{\rm inst}) + (\phi^m_{\rm str} - \phi^q_{\rm str}) - \epsilon^m_{\rm therm} - \epsilon^q_{\rm therm}$$



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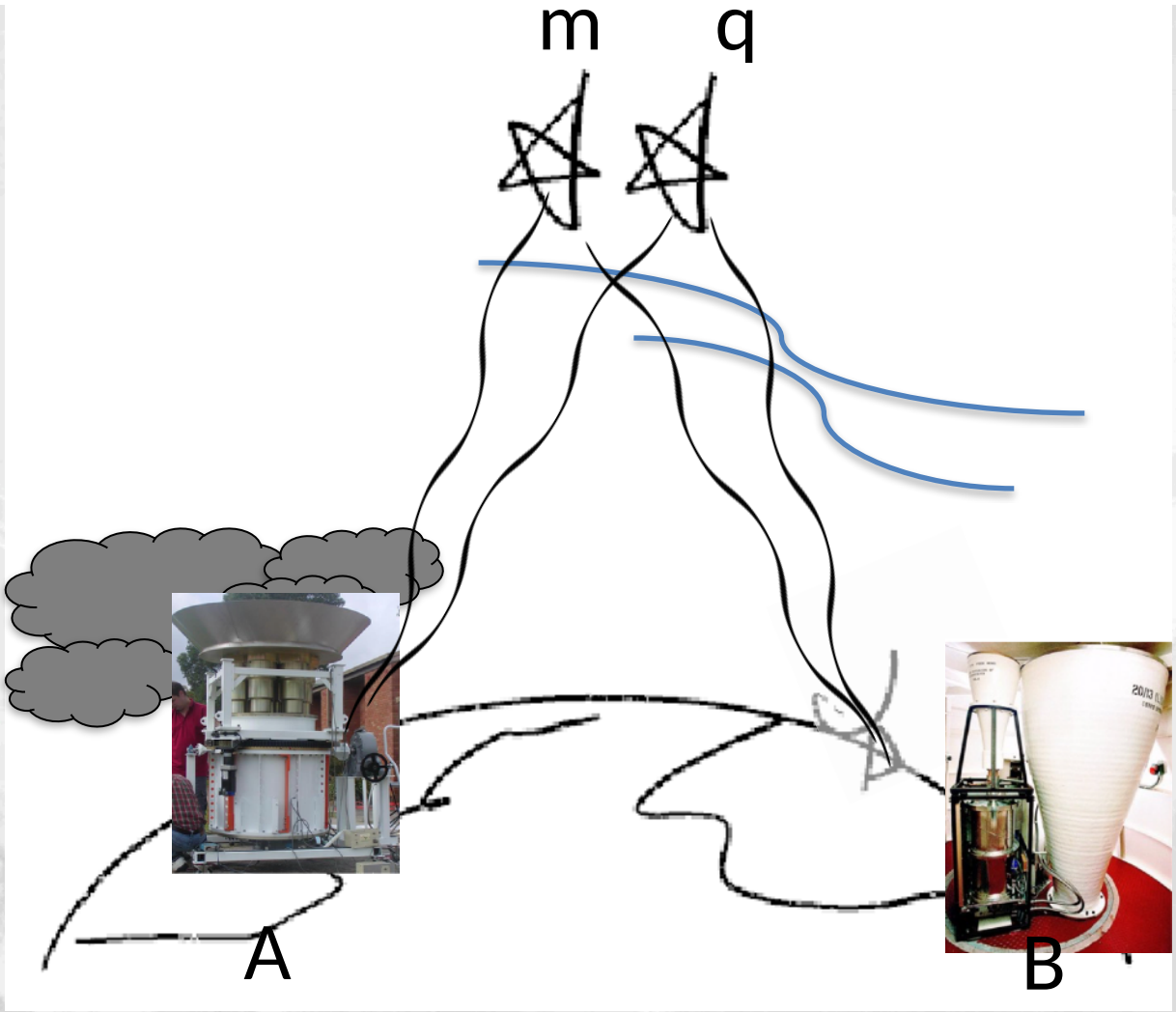

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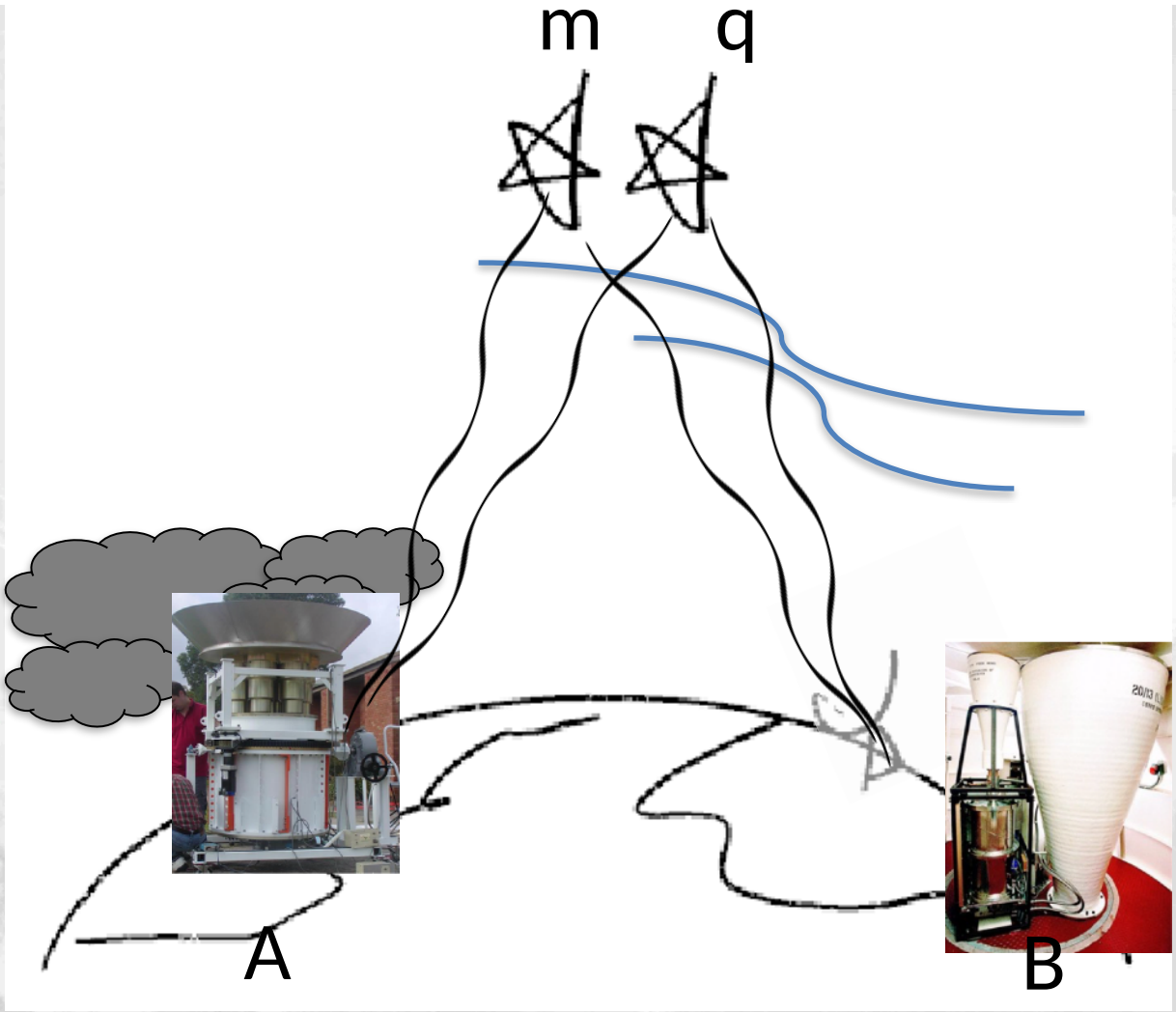

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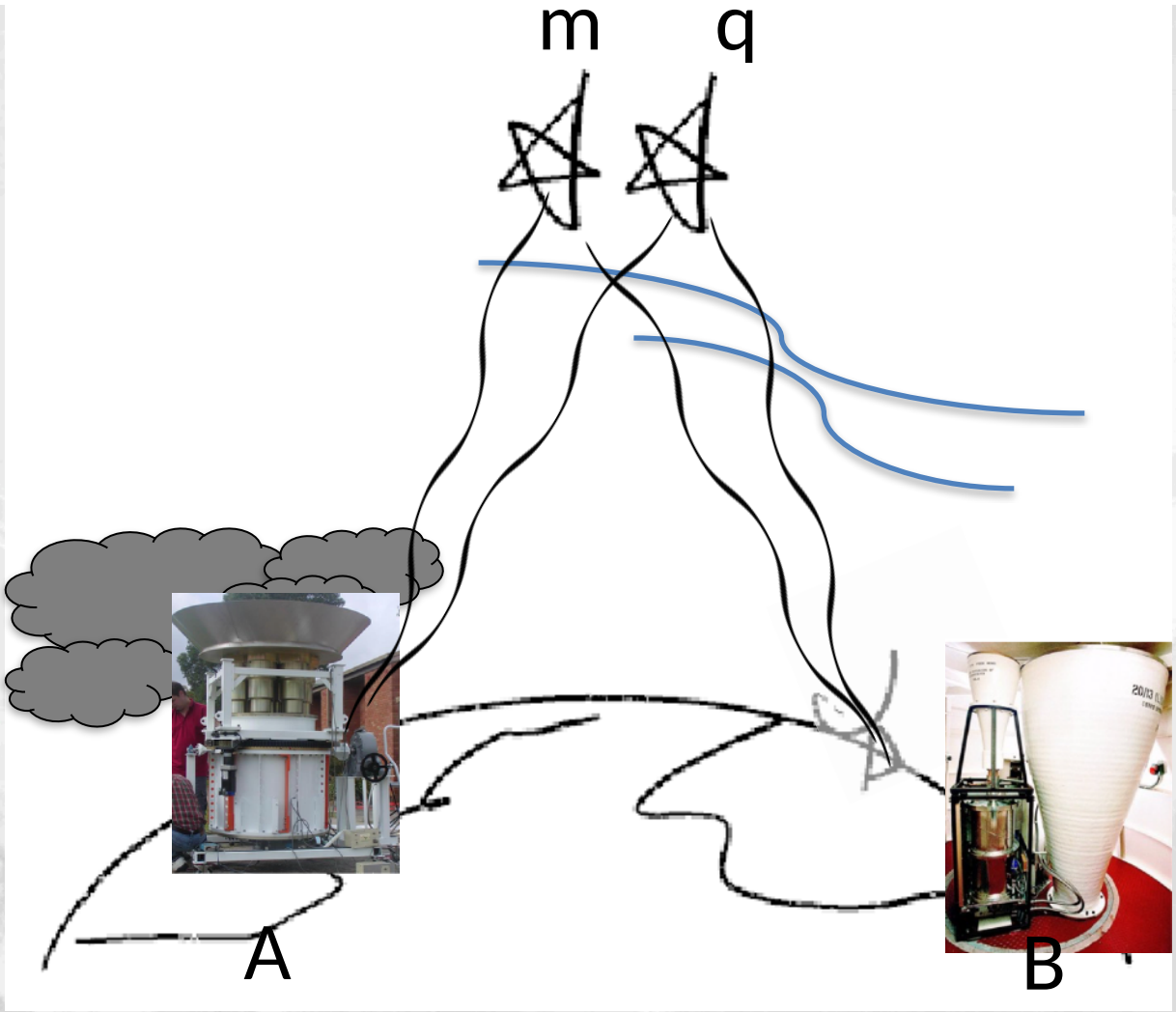
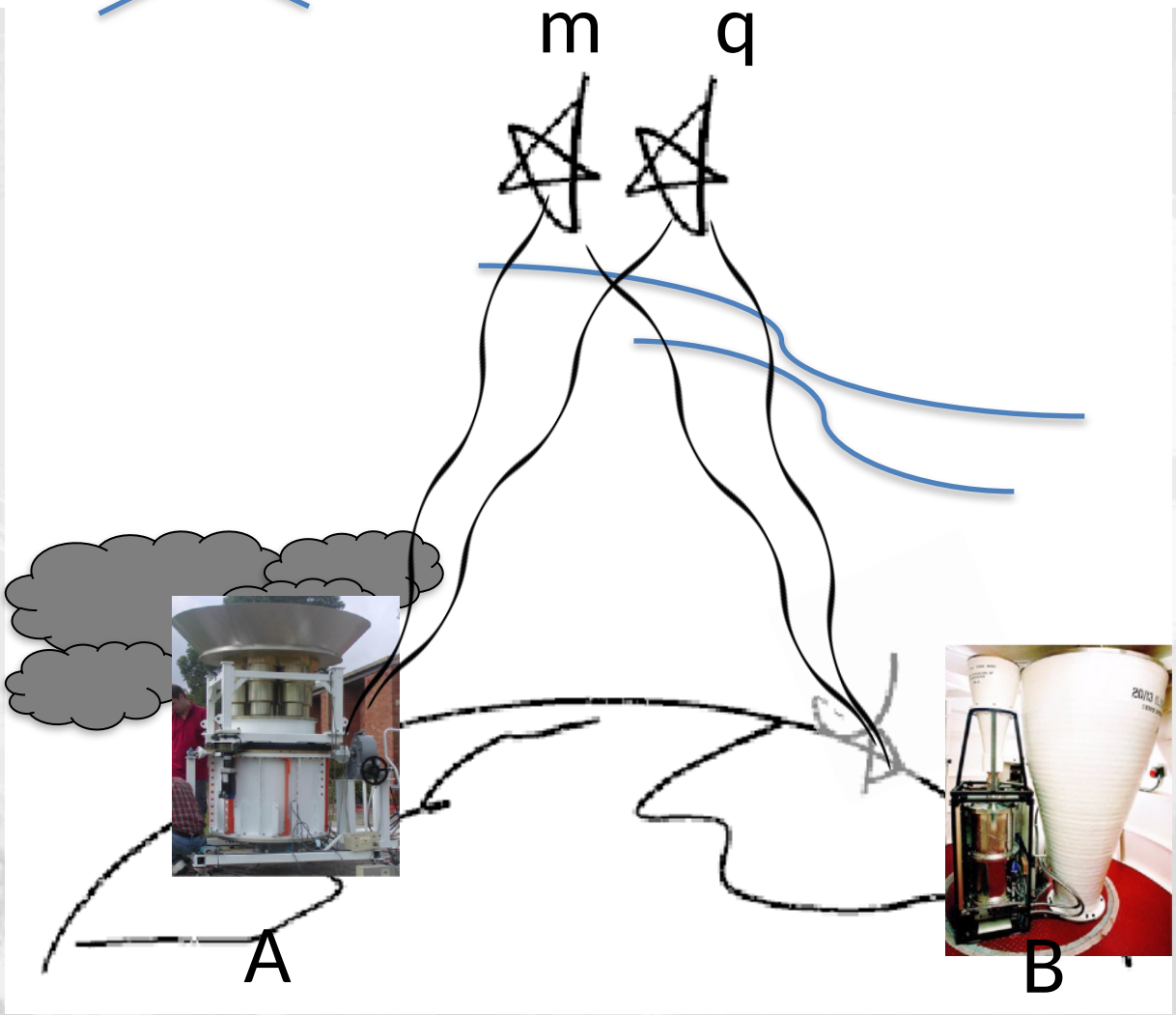


$$\phi^m_{AB} - \phi^q_{AB} = (\phi^m_{dir} - \phi^q_{dir}) + (\phi^m_{bl} - \phi^q_{bl}) + (\phi^m_{ion} - \phi^q_{ion}) + (\phi^m_{trop} - \phi^q_{trop}) + (\phi^m_{inst} - \phi^q_{inst}) + (\phi^m_{str} - \phi^q_{str}) - \epsilon^m_{therm} - \epsilon^q_{therm}$$



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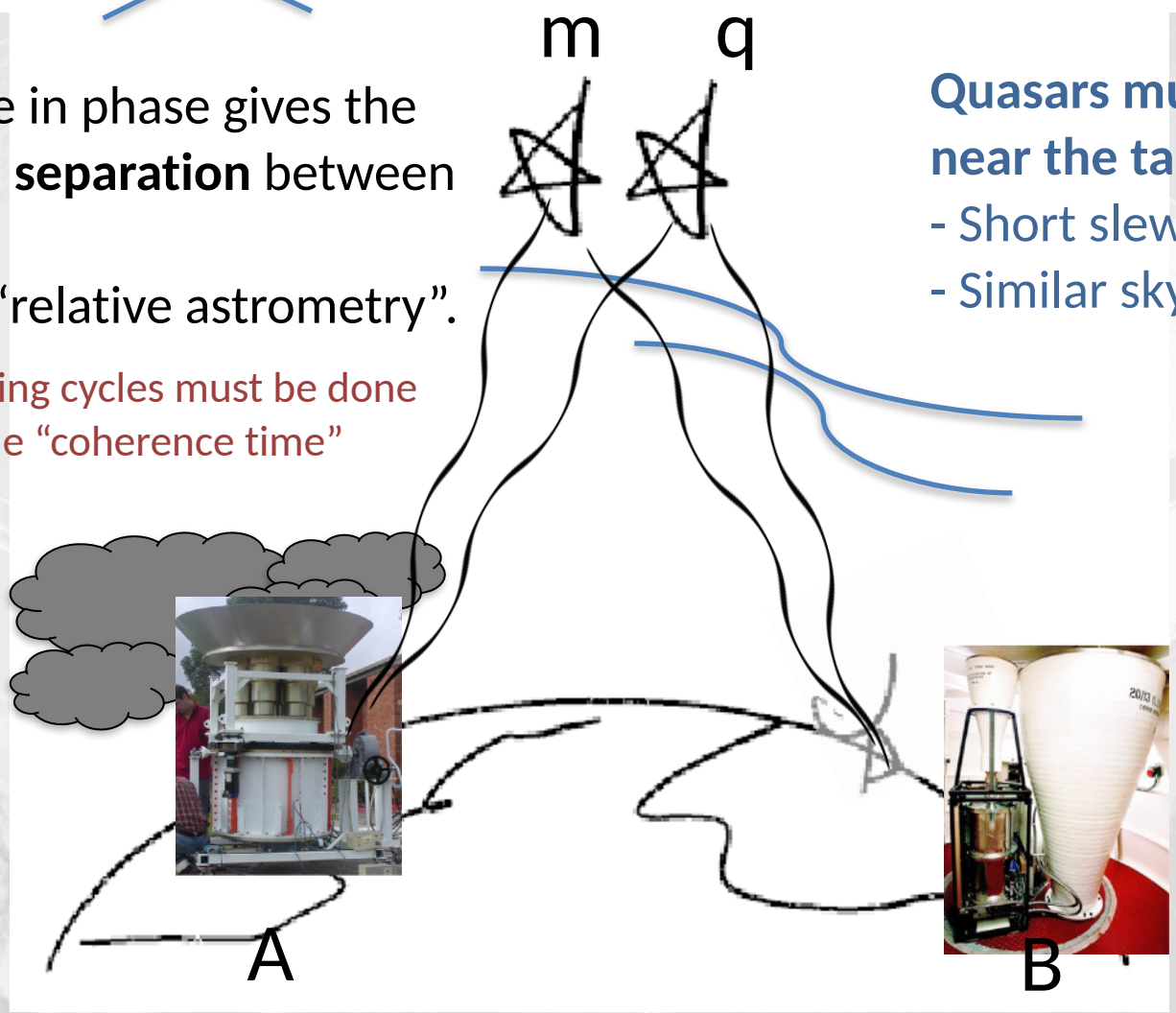
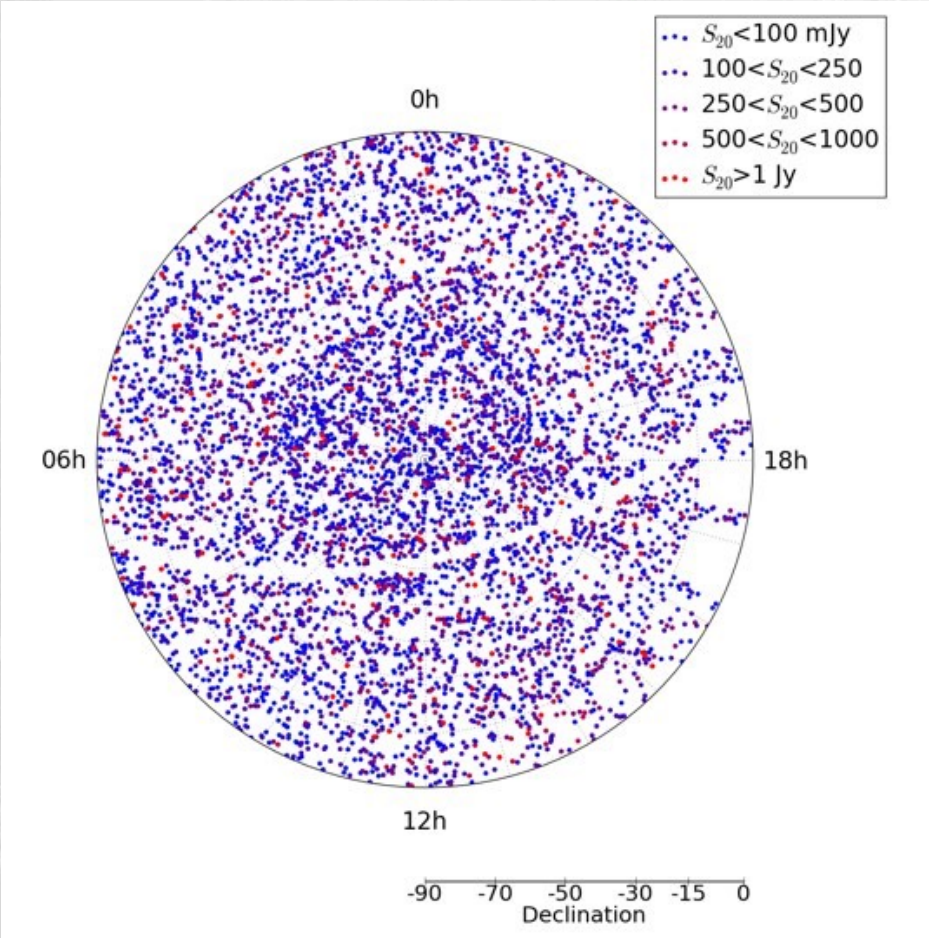
The difference in phase gives the the positional **separation** between m and q.
This is called “relative astrometry”.

Phase referencing cycles must be done quicker than the “coherence time”



Quasars must be near the target for:
- Short slewing times
- Similar sky conditions

Necessities for Phase referencing



Quasars must be near the target for:

- Short slewing times
- Similar sky conditions

We need to know the coordinates of the quasar. Then using “relative astrometry” we can get the coordinates of the target

We need a large number of quasars with known coordinates to do relative astrometry in interferometry and VLBI

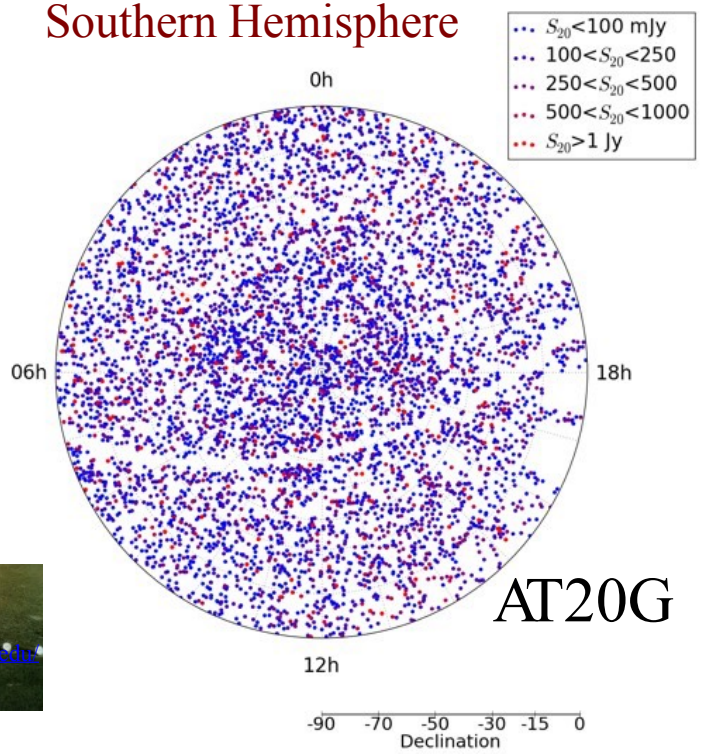
II.A. Surveys: How are sources found? Positions?

1. Single dish surveys: A single radio telescope sweeps the sky to search for point-like sources. Example: Parkes-MIT-NRAO 4.8 GHz (Griffith & Wright, 1993) ~10 arcsec positions.
http://www.parkes.atnf.csiro.au/observing/databases/pmn/pmnpubs.html 1993AJ....105.1666G

2. Connected element array surveys:
- next step is interferometric connected arrays such as the Very Large Array or ATCA
- Positions improved to 10s of milli-arcsec

• North: Jodrell Bank VLA Survey (JVAS) (Patnaik et al, MNRAS, 1992)
http://adsabs.harvard.edu/abs/1992MNRAS.254..655P

• South: ATCA 20-GHz (AT20G), 5890 sources, Southern hemisphere (Murphy et al, MRAS, 2010)
http://www.atnf.csiro.au/research/AT20G http://adsabs.harvard.edu/abs/2010MNRAS.402.2403M

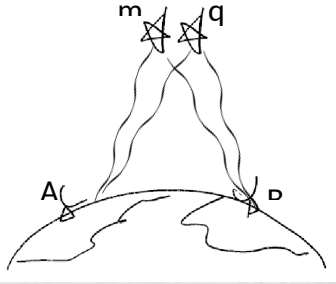


3. Final Survey stage: VLBI gets ~milli-arcsec positions e.g
• North: VLBA Calibrator Survey (Beasley et al, ApJS, 2002)
http://adsabs.harvard.edu/abs/2002ApJS..141...13B

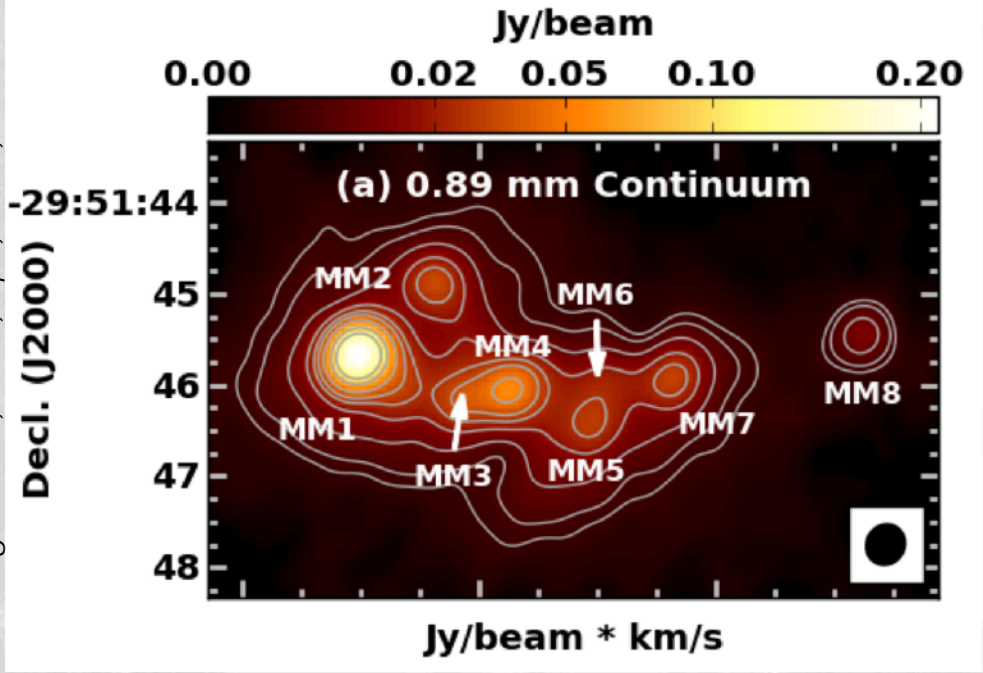
• South: LBA Calibrator Survey, (Petrov et al, MNRAS, 2011)
http://arxiv.org/abs/1012.2607 http://adsabs.harvard.edu/abs/2011MNRAS.414.2528P

http://www.narrabri.atnf.csiro.au/public/

Using relative astrometry we can get the precise location of our target, this is necessary for context

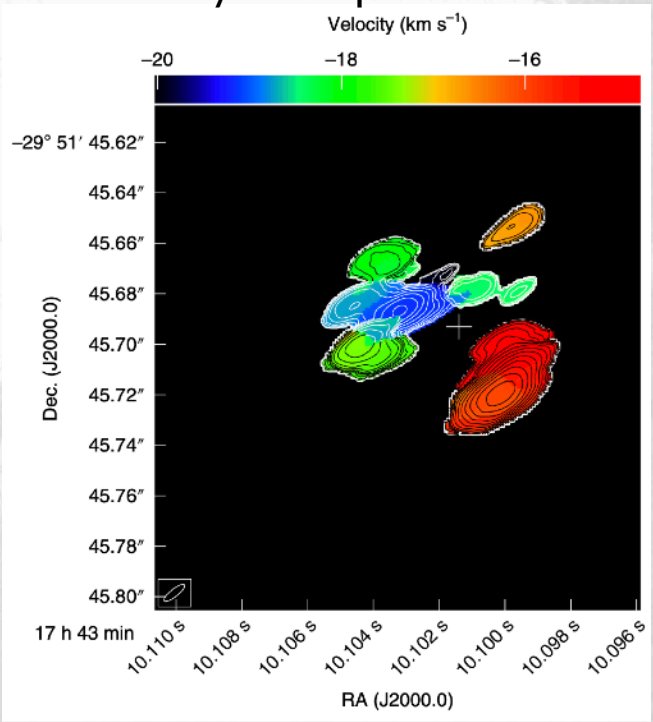


ALMA observations using phase referencing and relative astrometry to a nearby ICRF quasar



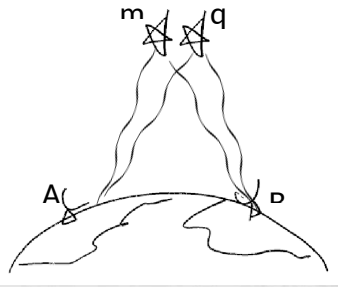
Brogan et al., 2019, ApJ, 881L, 39B

LBA observations using phase referencing and relative astrometry to a nearby ICRF quasar



Burns et al., 2020, Nature Astronomy, vol 4, 506

Using relative astrometry we can get the precise location of our target, this is necessary for context



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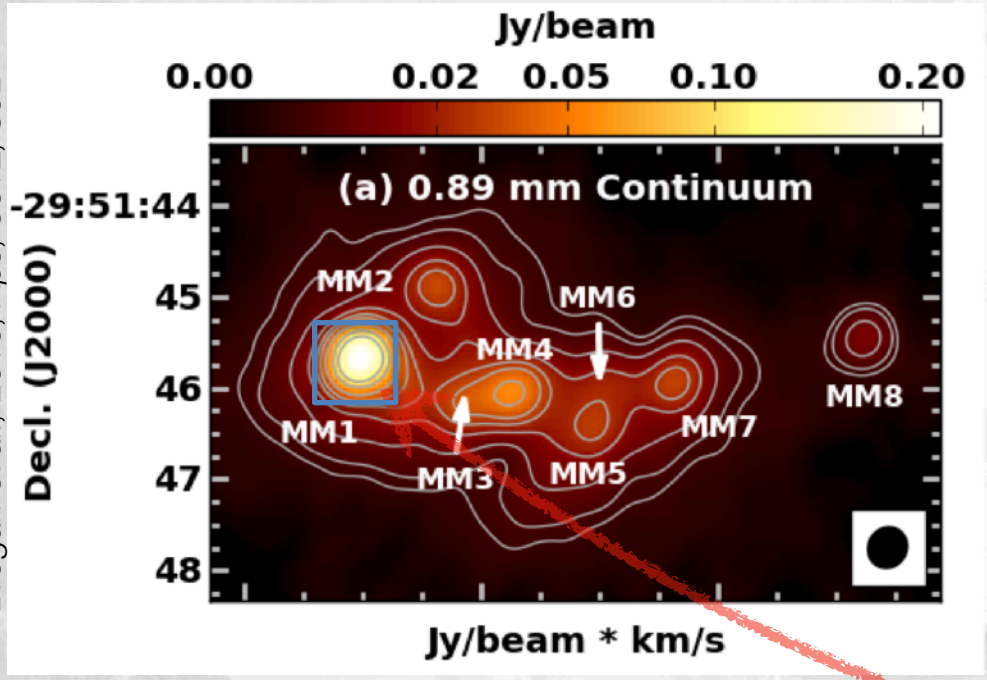

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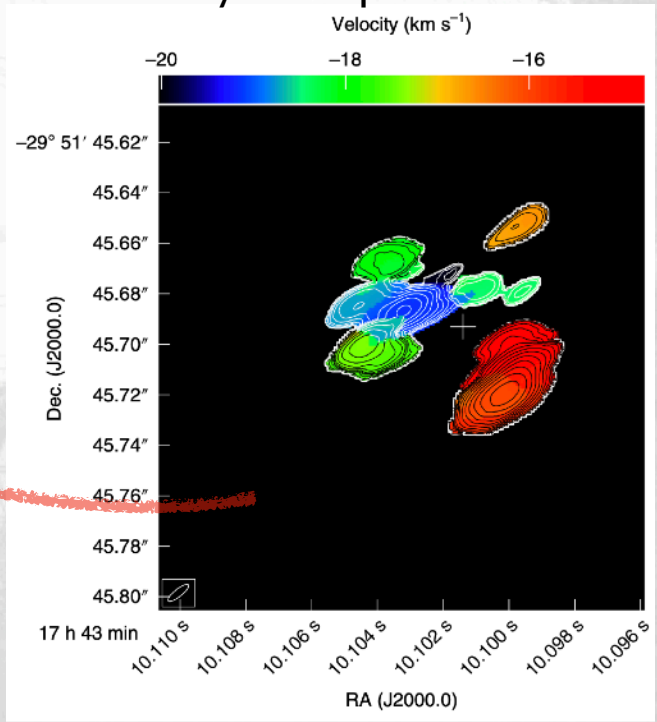

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If everyone uses the same coordinate system we can compare data from different observations.

This is only possible with astrometry