Influence of Site on VLBI Capabilities

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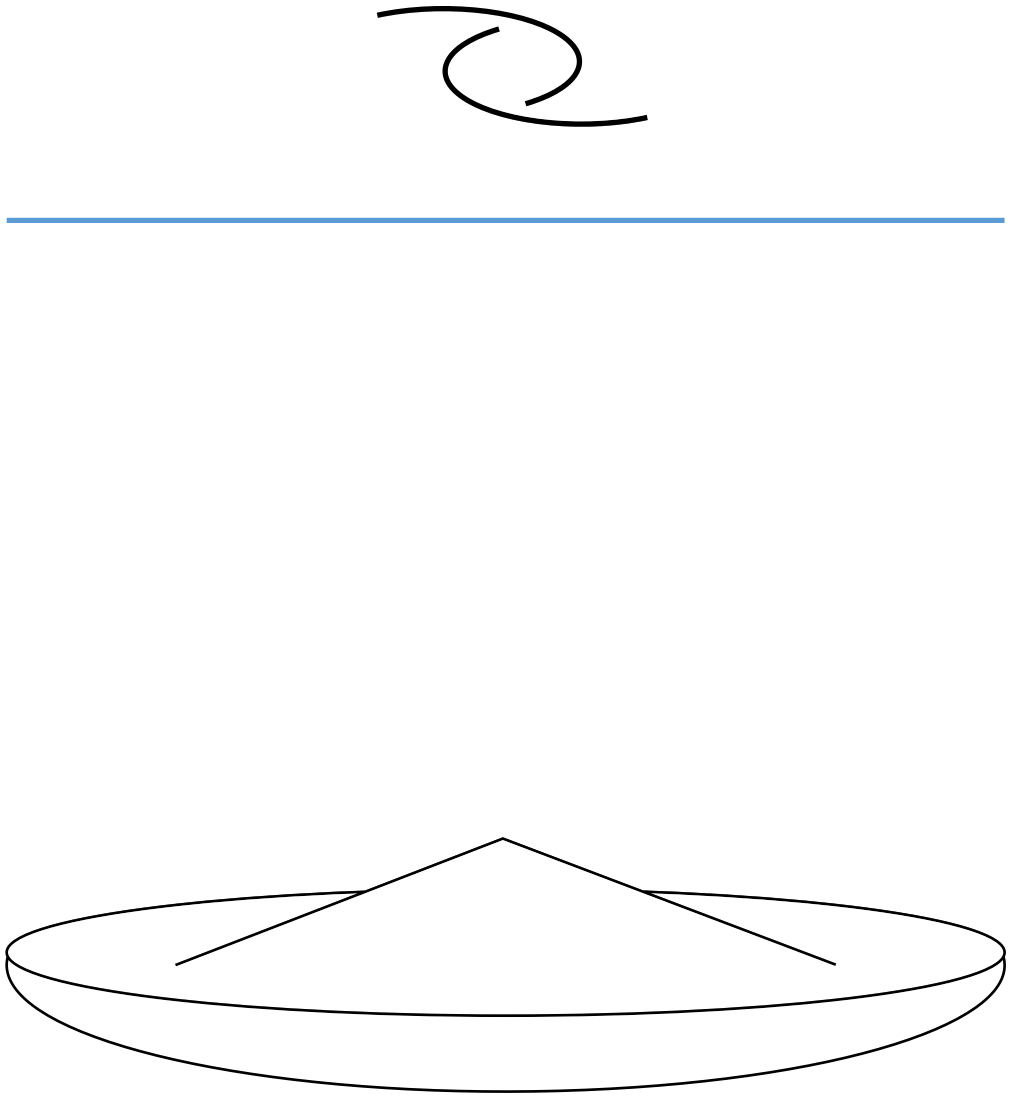
Phase Stability

Effect on Pointing & Phase Fluctuation

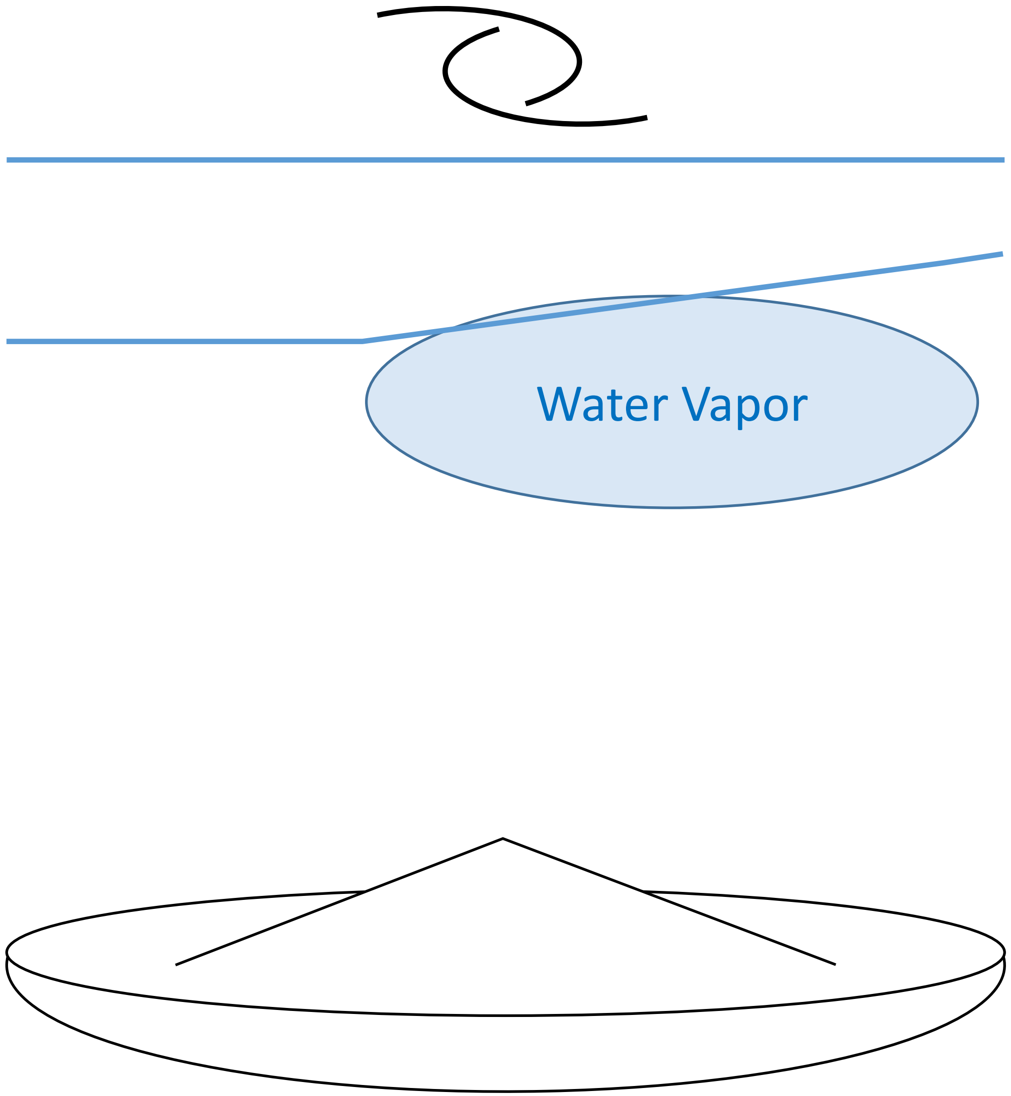
Phase Stability: Effect on Pointing

- Why the phase stability is related to pointing?

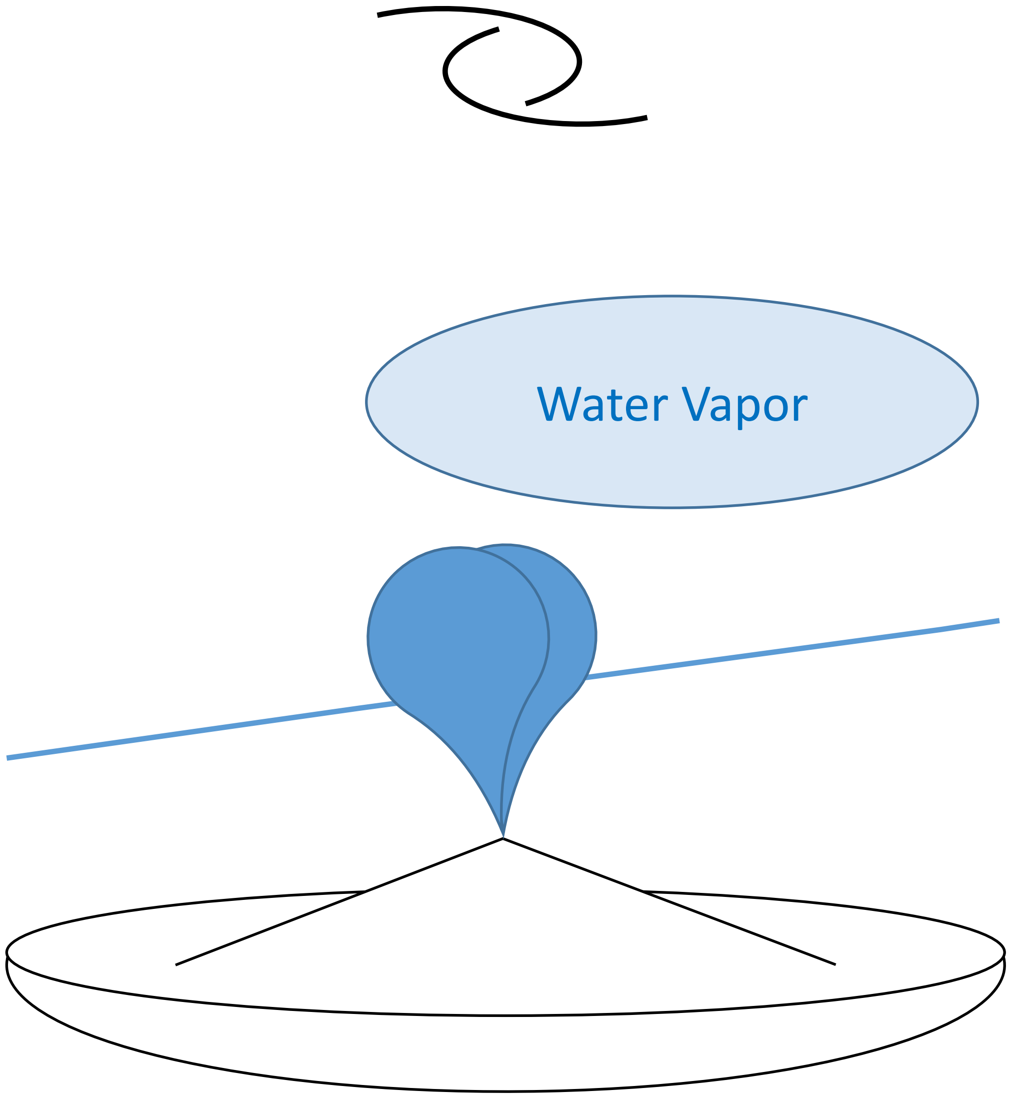
Without Atmosphere



With Atmosphere



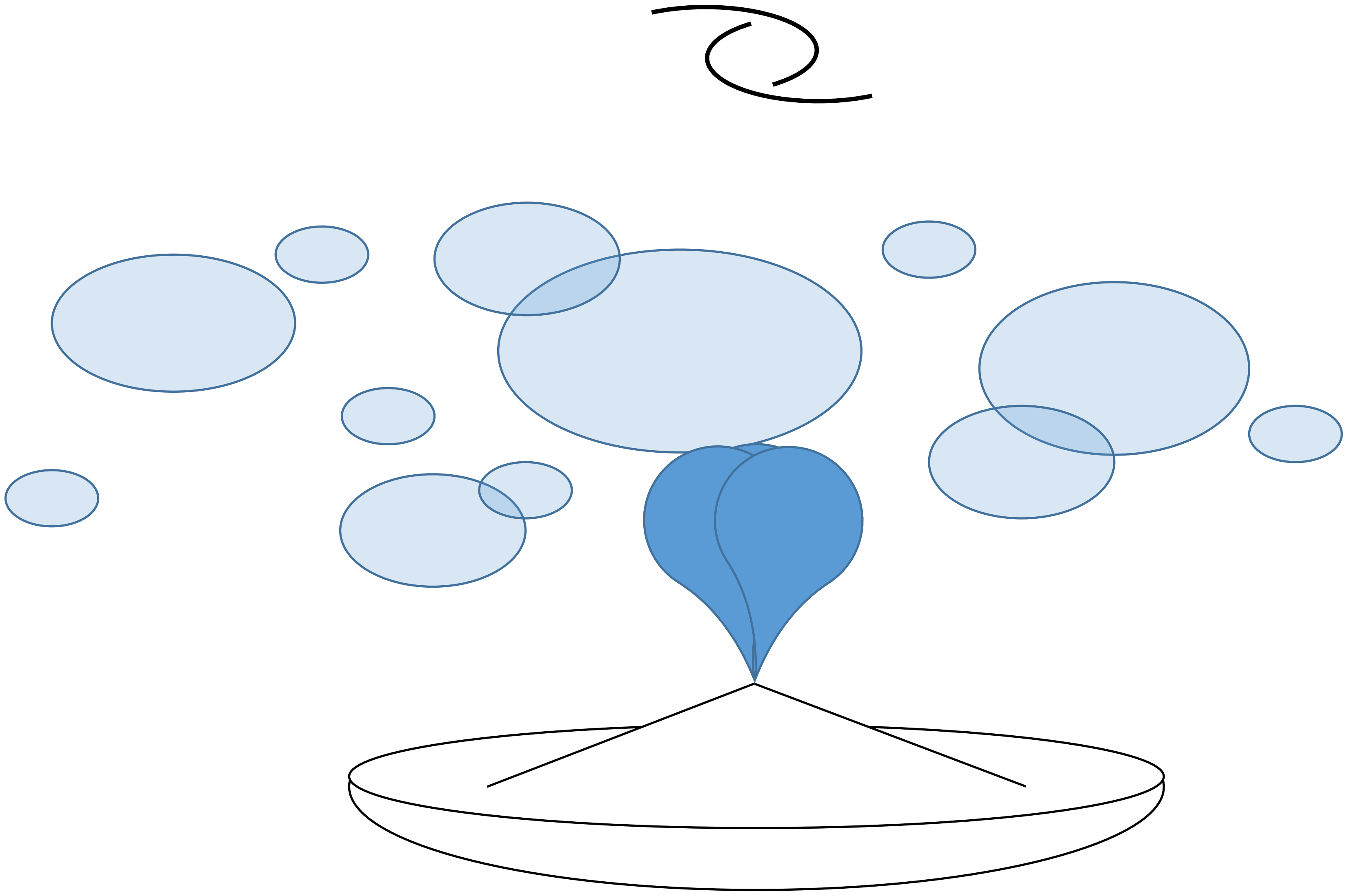
This corresponds to pointing change



From the antenna point of view, wave front has been tilted.
= Change in pointing direction.

Anomalous Refraction / Pointing Jitter

Altenhoff et al. 1987, A&A, 184, 381

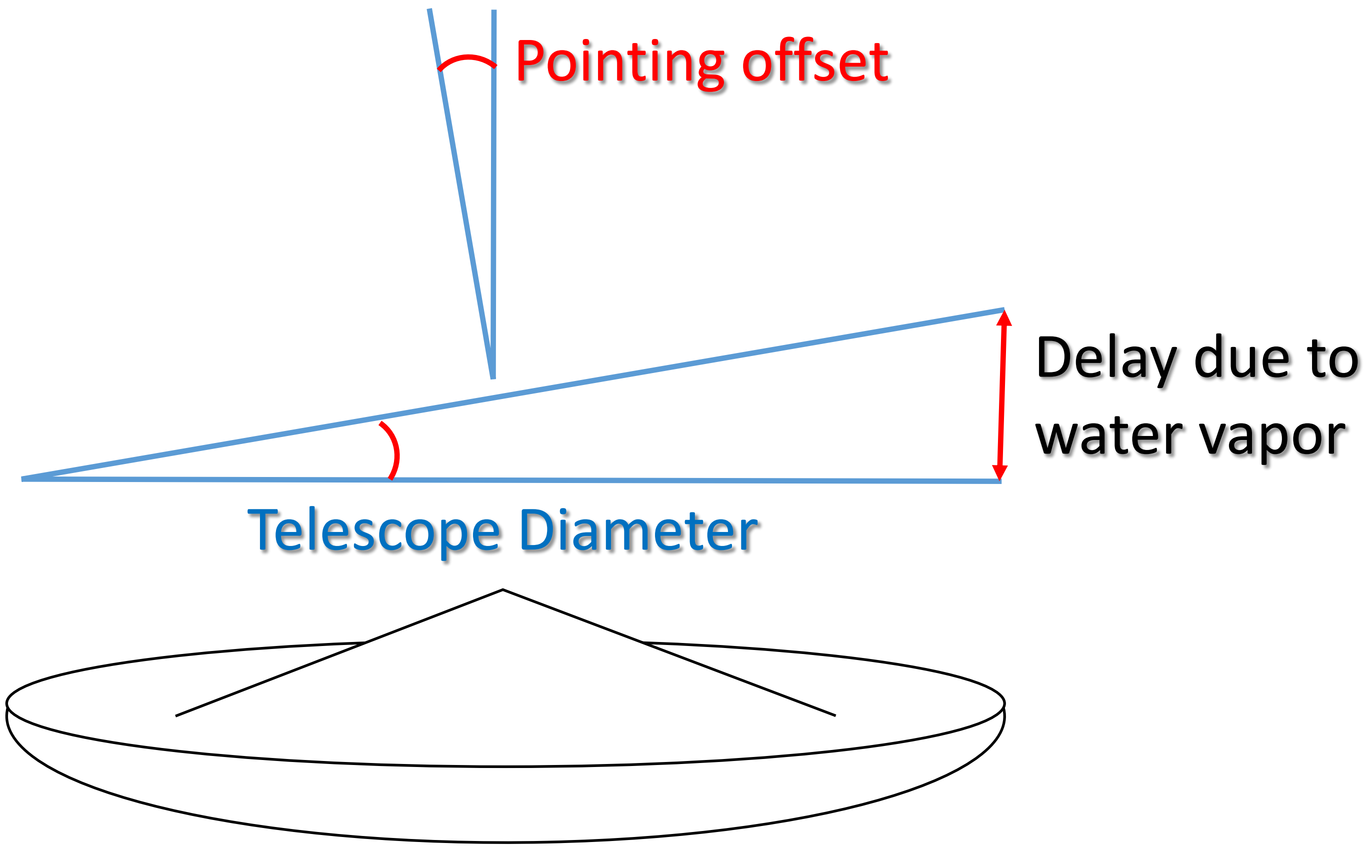


Anomalous Refraction / Pointing Jitter

Altenhoff et al. 1987, A&A, 184, 381

Pointing offset

= [Delay due to water vapor] / [Telescope Diameter]



Spatial Structure Function (SSF)

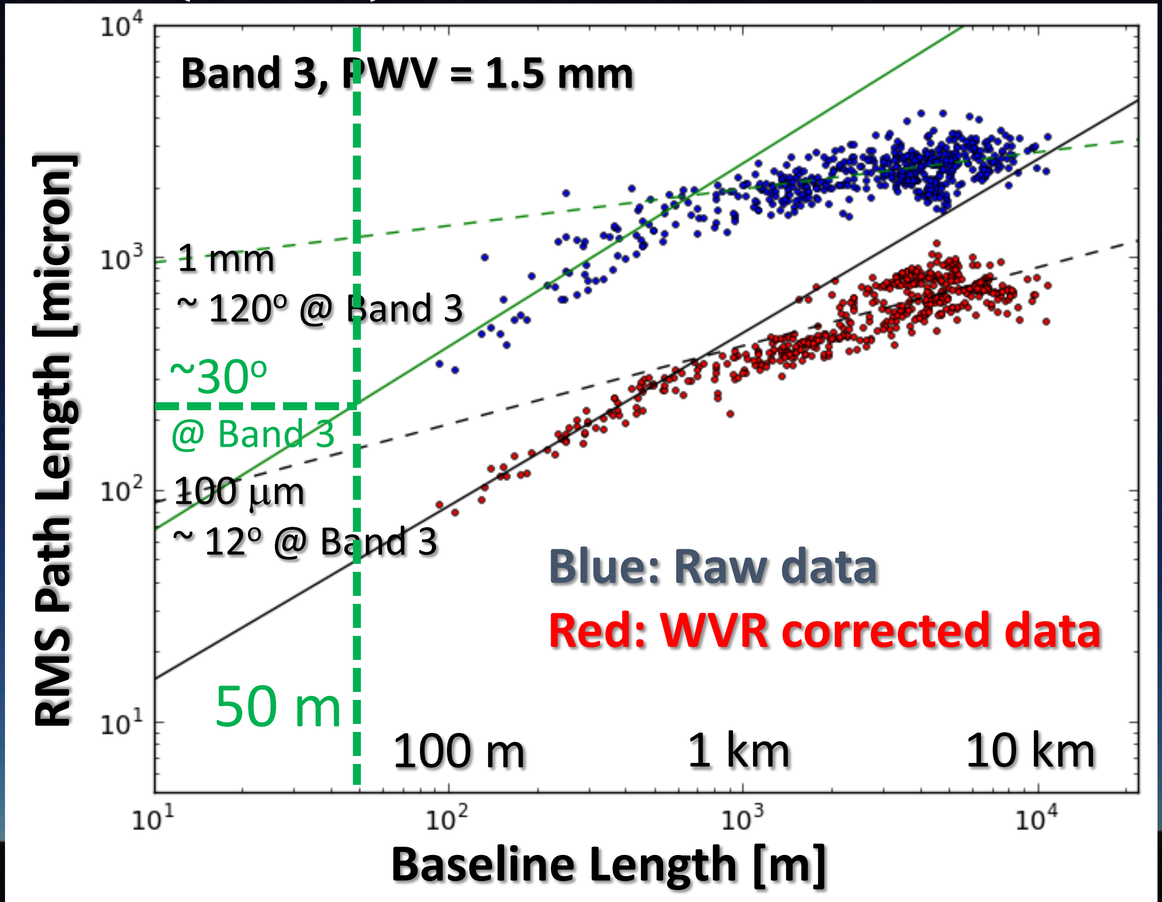
- Spatial Structure Function (SSF):
  RMS phase fluctuation as a function of baseline length.

$$[\text{RMS phase}] = \sqrt{\langle\{Phase(x) - Phase(x-d)\}^2\rangle}$$

(namely, the phase difference at the baseline length of d).

⇨ Possible to reveal statistically the size distribution of water vapor clumps in the atmosphere.

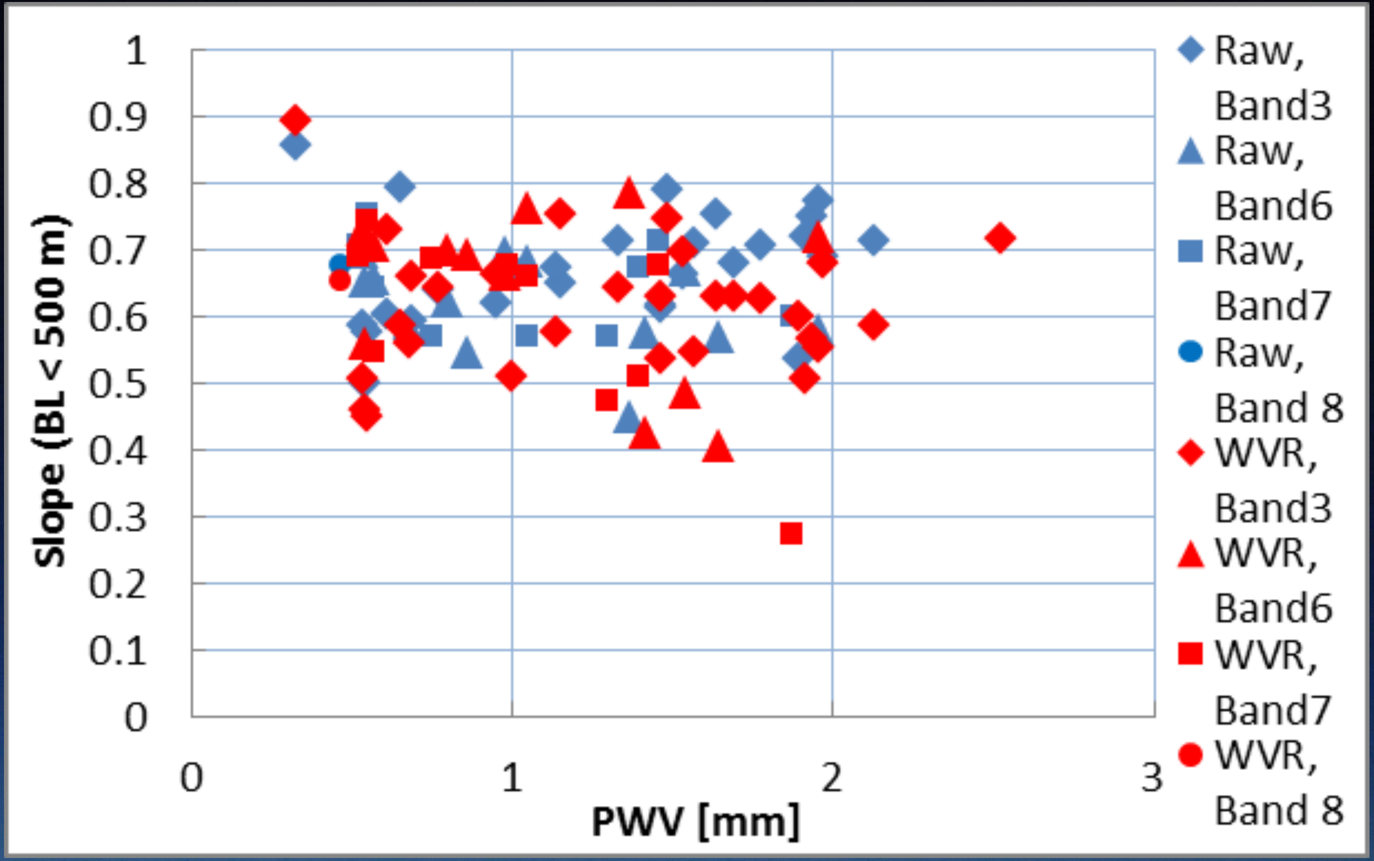
- 3-D Kolmogorov turbulence: slope = 0.83
- 2-D Kolmogorov turbulence: slope = 0.33



Matsushita et al. 2017, PASP, 129, 035004

SSF Slopes at Short Baseline Lengths

- At short baselines (< 500 m), SSF slopes are almost constant under whatever conditions:
  - Before WVR: 0.65 +- 0.06
  - After WVR: 0.62 +- 0.09
- 50% quartile slope for the 3-year 11.2 GHz Radio Seeing Monitor data: 0.63 (Butler et al. 2001)
  - Raw data we took seem typical phase fluctuation condition at the ALMA site.



Matsushita et al. 2017, PASP, 129, 035004

Anomalous Refraction at the ALMA Site

- Based on the ALMA Long Baseline Campaign data, the empirical relationship between the rms excess path length (= phase fluctuation) and the baseline length is:

$$log_{10}(\Delta L[micron]) = 0.65 \times log_{10}(D[m]) + 0.3 \times PWV[mm] + 0.1$$

(Matsushita et al. 2017, PASP, 129, 035004)

- So, the anomalous refraction ($\Delta\theta = \Delta L/D$) is expressed as:

$$\Delta\theta = \sqrt{2} \times 10^{0.3 \times PWV[mm] - 5.9} D[m]^{-0.35} [rad]$$

(the factor of $\sqrt{2}$ is for 1-D to 2-D correction, since the SSF above is 1-D, but the dish is 2-D)

Phase Stability: Effect on Pointing

- For VLBI, telescope pointing is not very critical, as far as the source is near the center of the primary beam.
  - If the source is located off from the center of the primary beam, then the source amplitude will be affected.

Anomalous Refraction at the ALMA Site

- 50 m diameter telescope at PWV = 1 mm (assume [beam size] = 1.2λ/D):

Frequency	Anomalous Refraction	Beam Size	1σ pointing fluctuation compared to beam size
100 GHz	0.19”	14.9”	1%
230 GHz		6.5”	3%
350 GHz		4.2”	5%
490 GHz		3.0”	6%
650 GHz		2.3”	8%
850 GHz		1.7”	11%
1000 GHz		1.5”	13%
1500 GHz		1.0”	19%

Anomalous Refraction at the ALMA Site

- Slope and constant are 1σ larger, or PWV = 2 mm:

Frequency	Anomalous Refraction	Beam Size	1σ pointing fluctuation compared to beam size
100 GHz	0.37”	14.9”	2%
230 GHz		6.5”	6%
350 GHz		4.2”	9%
490 GHz		3.0”	12%
650 GHz		2.3”	16%
850 GHz		1.7”	22%
1000 GHz		1.5”	25%
1500 GHz		1.0”	37%

Phase Stability: Effect on Pointing

- For VLBI, telescope pointing is not very critical, as far as the source is near the center of the primary beam.
  - If the source is located off from the center of the primary beam, then the source amplitude will be affected.
- Anomalous refraction will be severe on high frequency observations.

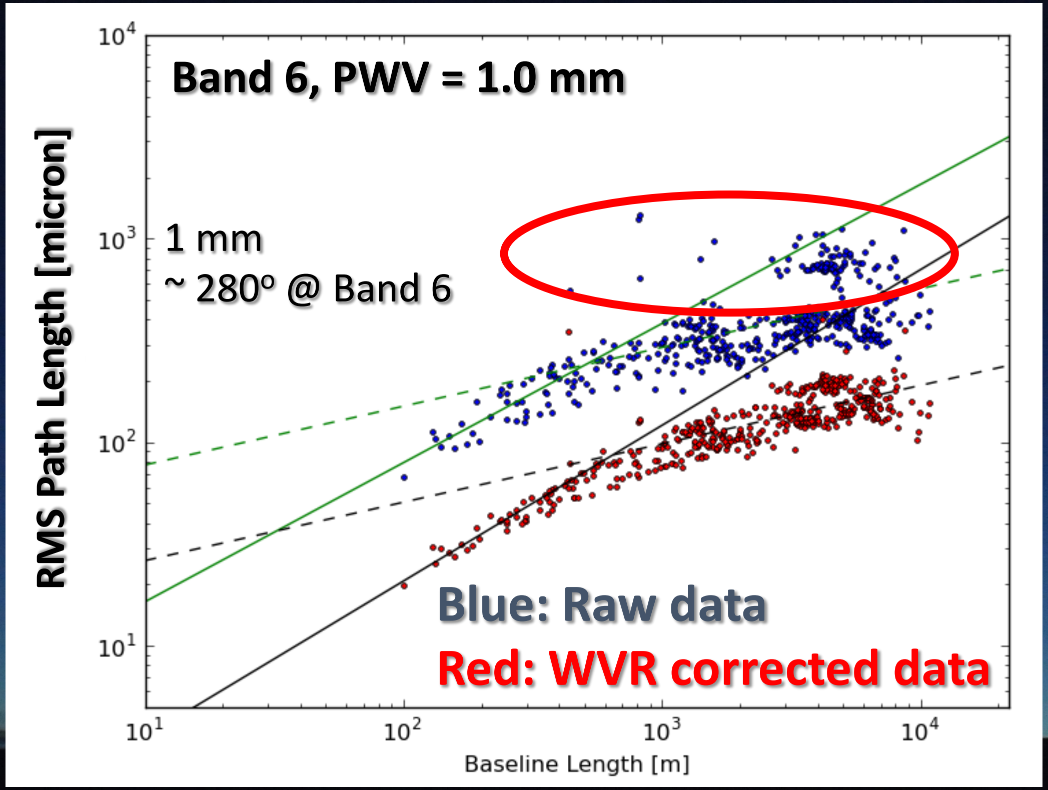
Phase Stability: Effect on VLBI Phase

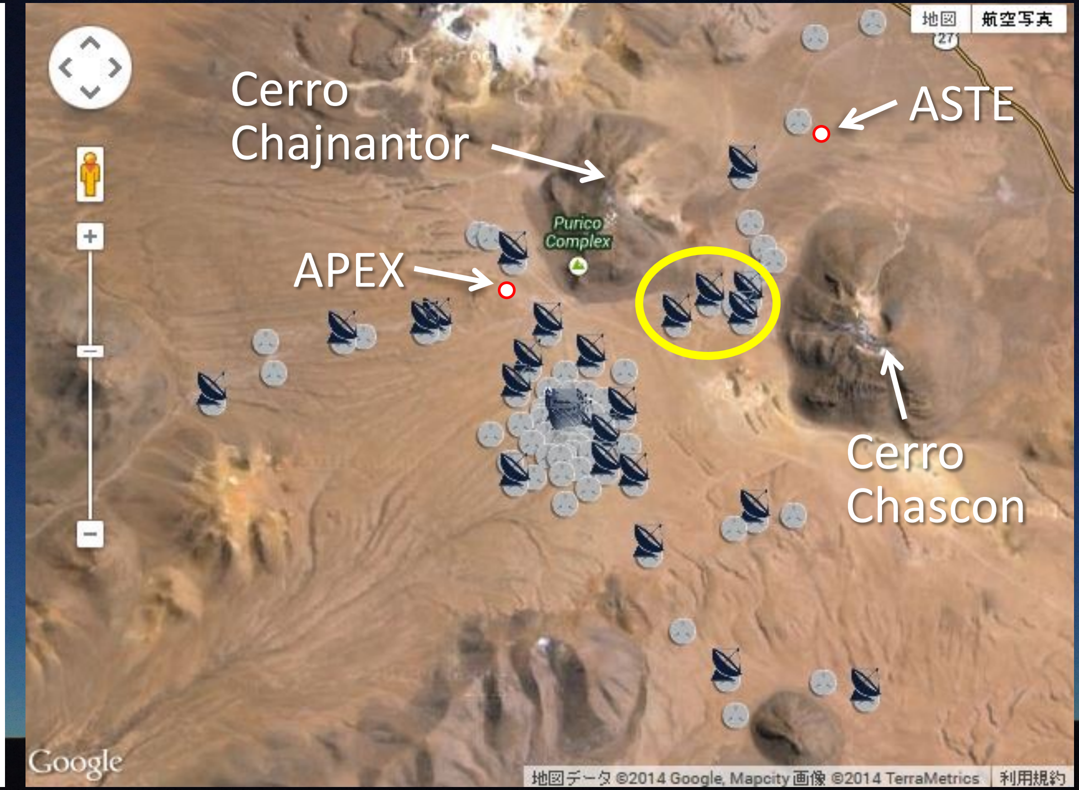
- Having stable phase is an important factor for VLBI.
- Selecting a phase-stable site is important.

Large Phase Fluctuation Between Mountains

- Large phase fluctuation has often (13/22) been observed with the antennas between Cerro Chajnantor and Cerro Chascon.
- WVR phase correction works well.
- Water vapor turbulence due to the mountains.

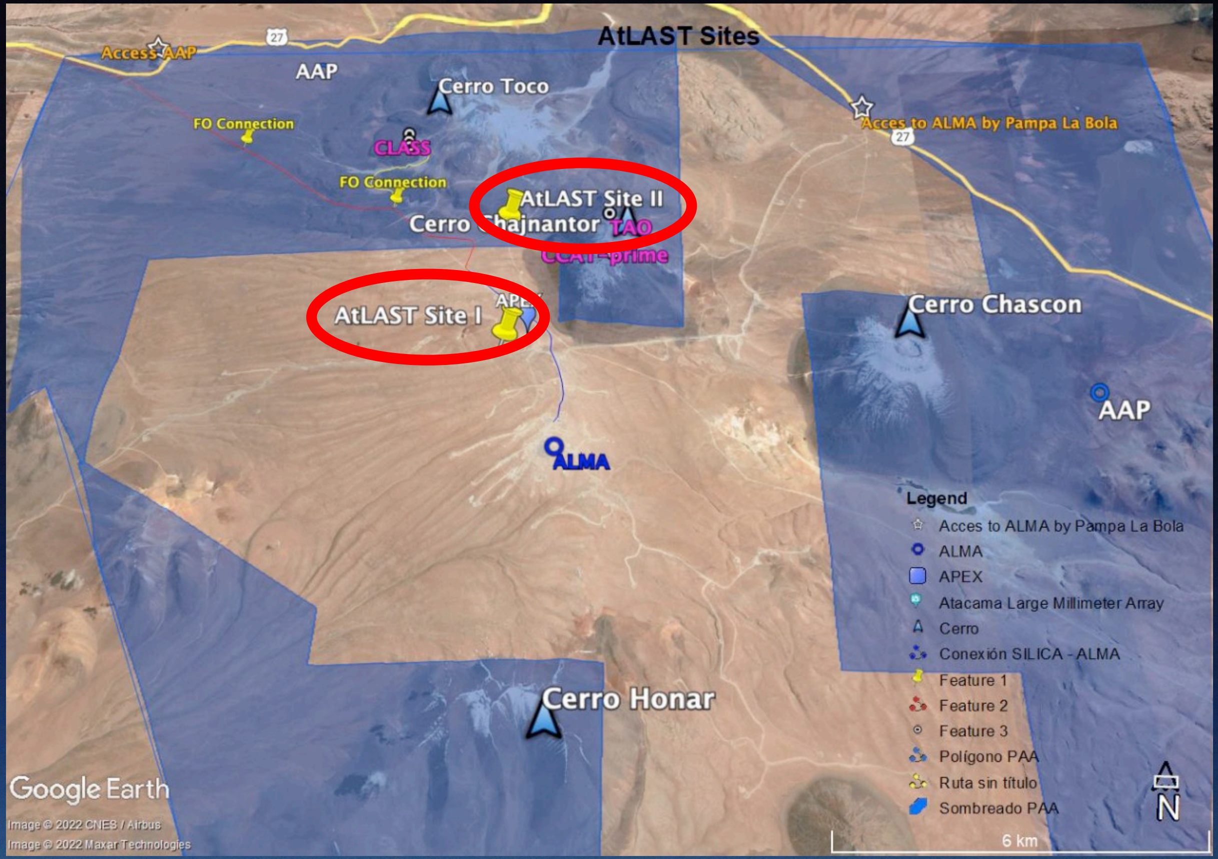
Asaki, Matsushita, et al. 2016, Proc. SPIE, 9906, 99065U





Which is Better AtLAST Site?

- Two possible AtLAST sites: Site testing is ongoing.
  - AtLAST Site 1: Near APEX
    - Near ALMA antenna pads.
    - Phase fluctuation data exist.
  - AtLAST Site 2: Near Cerro Chajnantor
    - No ALMA antenna pads nearby.
    - No phase fluctuation data.
- Phase fluctuation at the Site 1 should follow similar way as the typical ALMA baselines.
- Site 2 is unclear, but near Cerro Toco and Cerro Chajnantor is a worrisome factor.



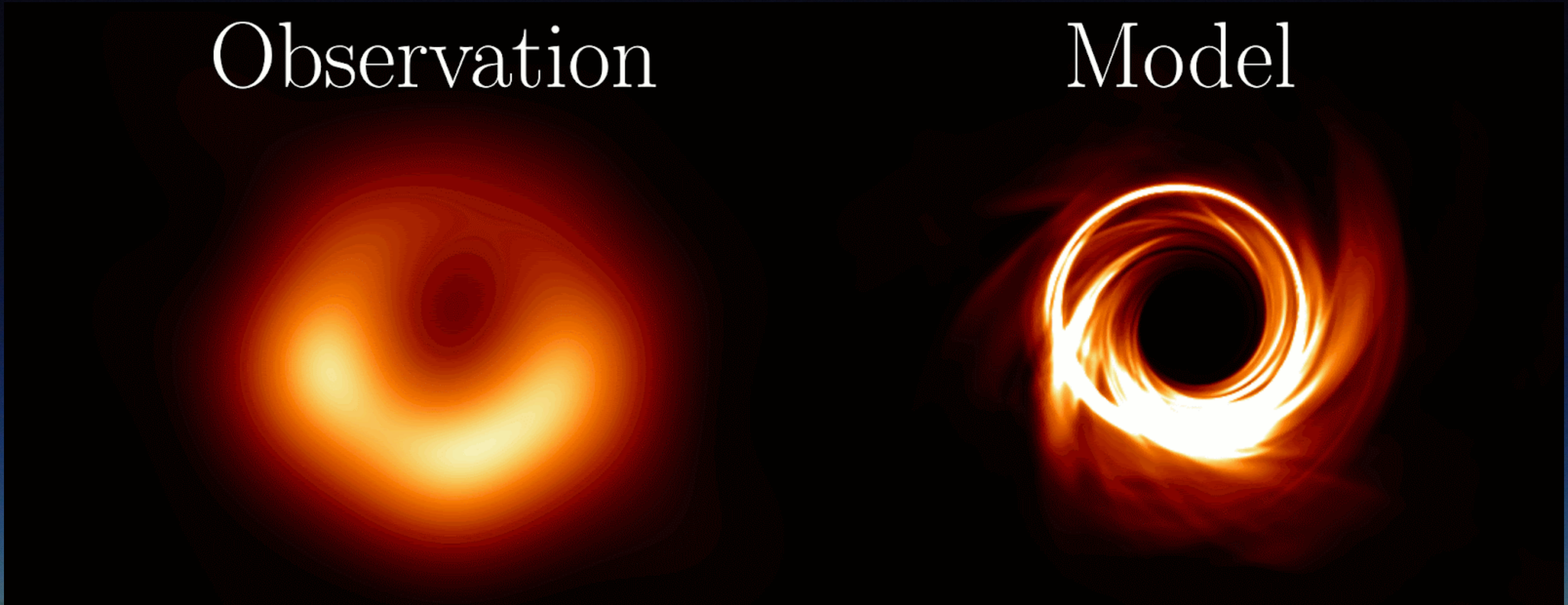
AtLAST Work Package 3
D3.1, “Site selection criteria”

690 GHz VLBI

Future High-Frequency VLBI

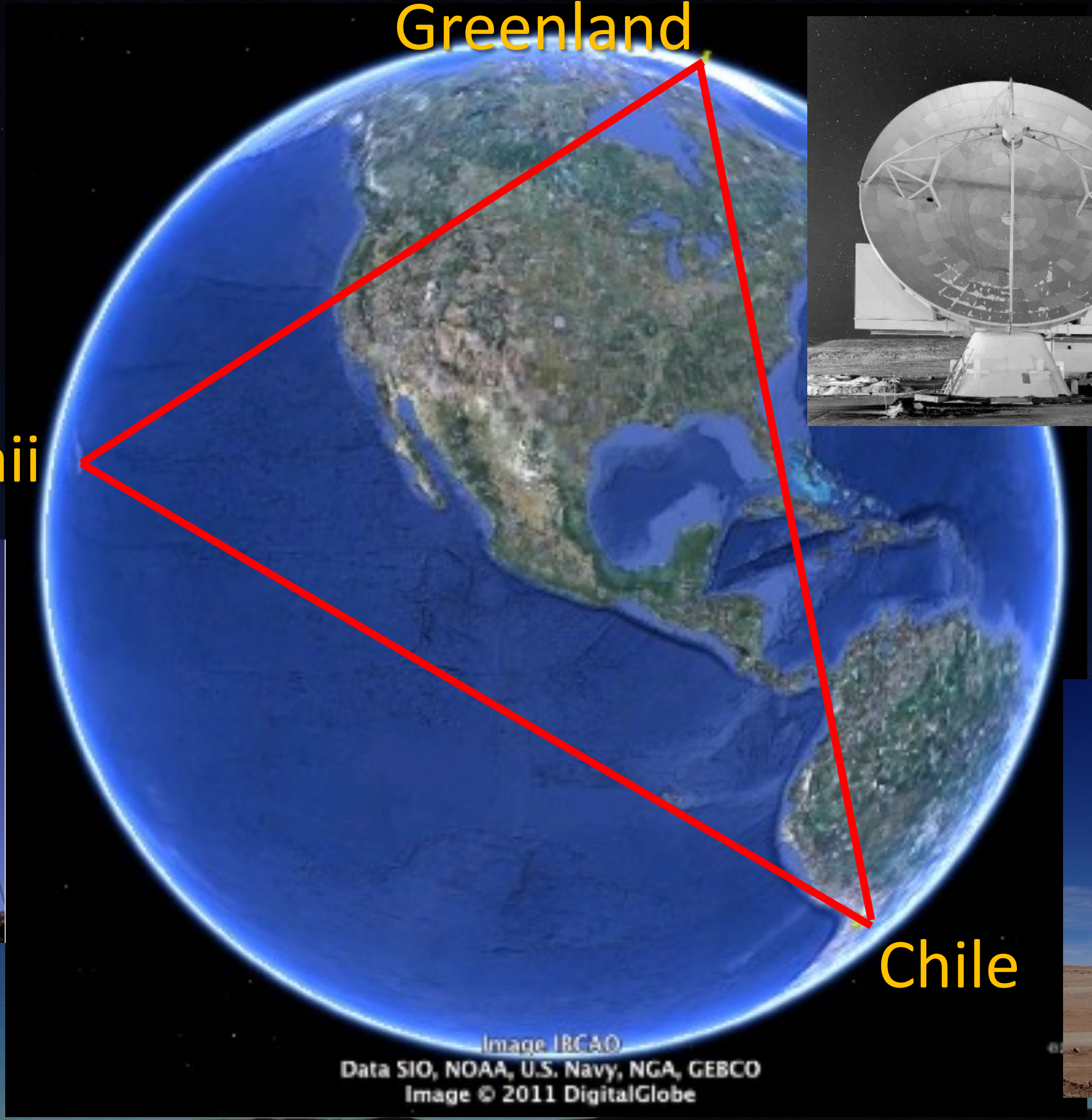
690 GHz VLBI: Toward Higher Resolution

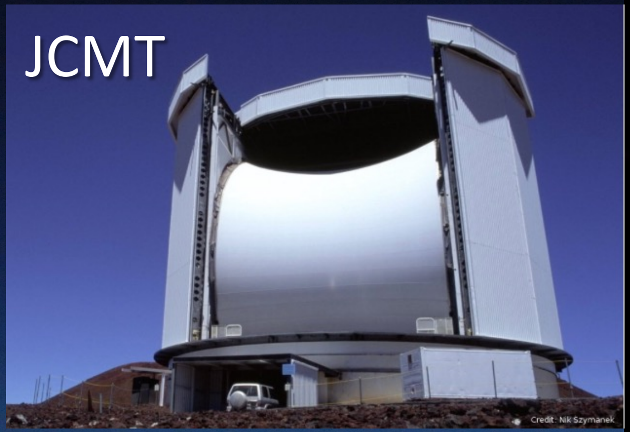
- Next Step for the Black Hole Shadow Imaging:
  - Higher spatial resolution to see the “real” event horizon.



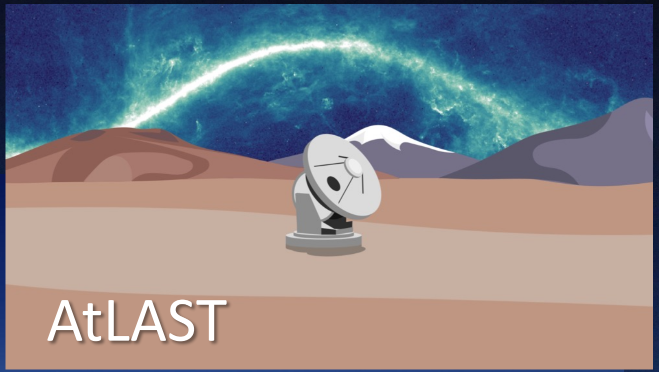
Credit: EHT Collaboration, Moscibrodzka et al.

VLBI at 690 GHz



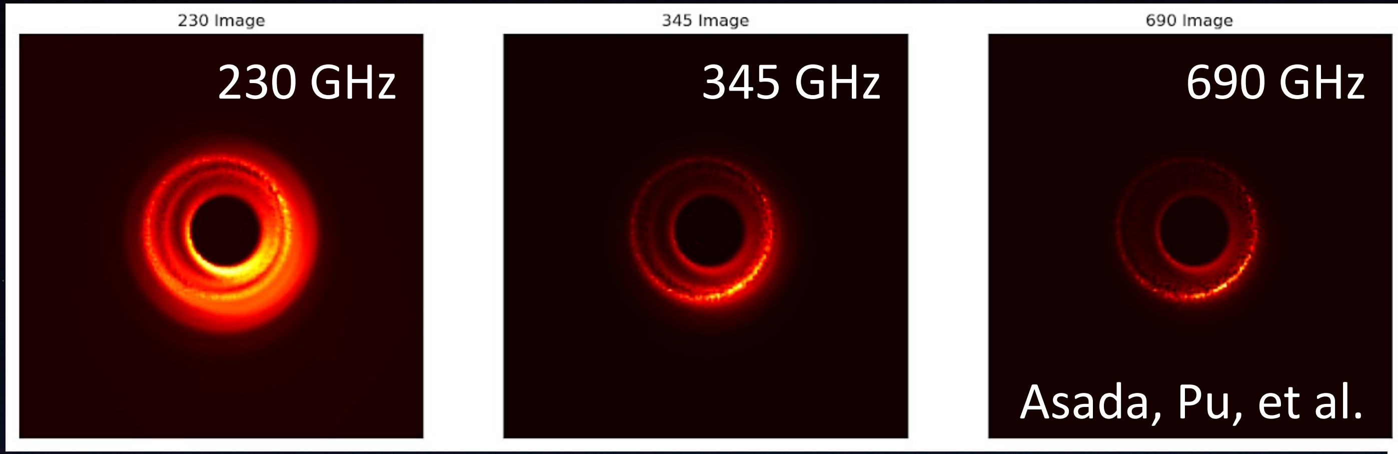


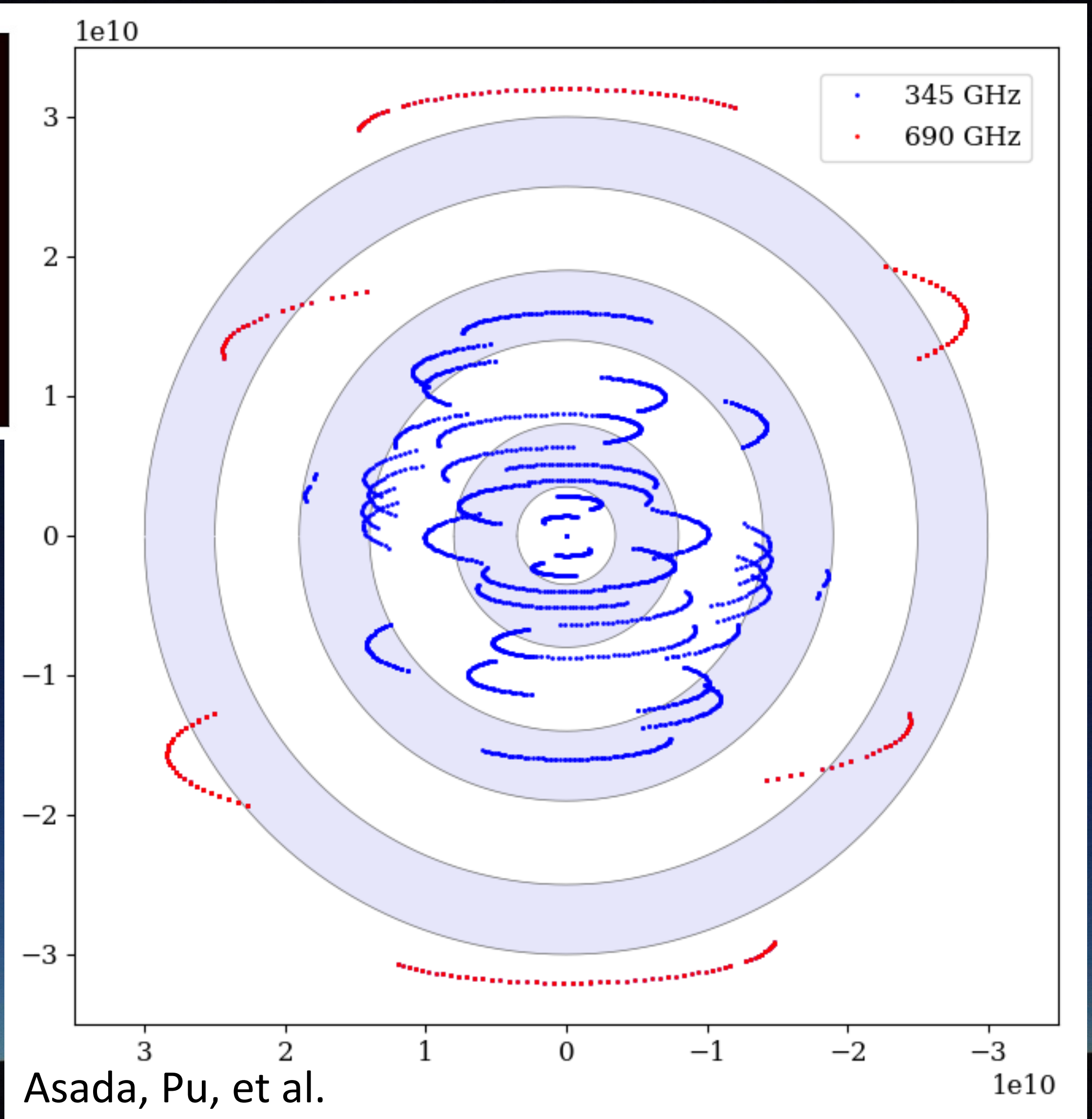
EAO



Baselines are 9,000 km long, and the resolution reaches 4 μas at 690 GHz.

690 GHz VLBI to See Event Horizon





- 690 GHz VLBI telescopes:
  - GLT Summit, JCMT/SMA, & ALMA (AtLAST & LLAMA in the future).
- Multi-Frequency Synthesis.

690 GHz VLBI: AtLAST vs ALMA

- AtLAST will be affected less phase fluctuation.
  - Size (~ baseline length) is limited to the telescope diameter of 50 m.
- ALMA at good weather season tends to be at its long baseline configurations.
  - Difficult to phase-up all antennas (i.e., limited to short baseline antennas).
  - Affected largely by the phase fluctuation.
- Limited VLBI time for ALMA.
  - ALMA Phase-Up mode is a special mode.
  - Need special personnels to be at the site.

Summary

- Phase fluctuation at the site will affect both the telescope pointing and the VLBI phase.
  - Better to select the AtLAST site where phase is stable.
- Mountains disturb the phase nearby.
  - Better to select the AtLAST site far from mountains.
  - Probably the AtLAST Site 1 is better than Site 2.
- Having the AtLAST at the Atacama benefits a lot for the VLBI over ALMA from phase fluctuation point-of-view.