Recent and Planned VLBI Developments at ALMA

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in Collaboration with

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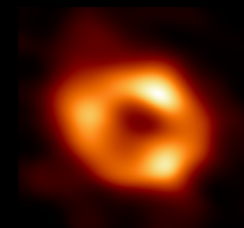
Talk Outline

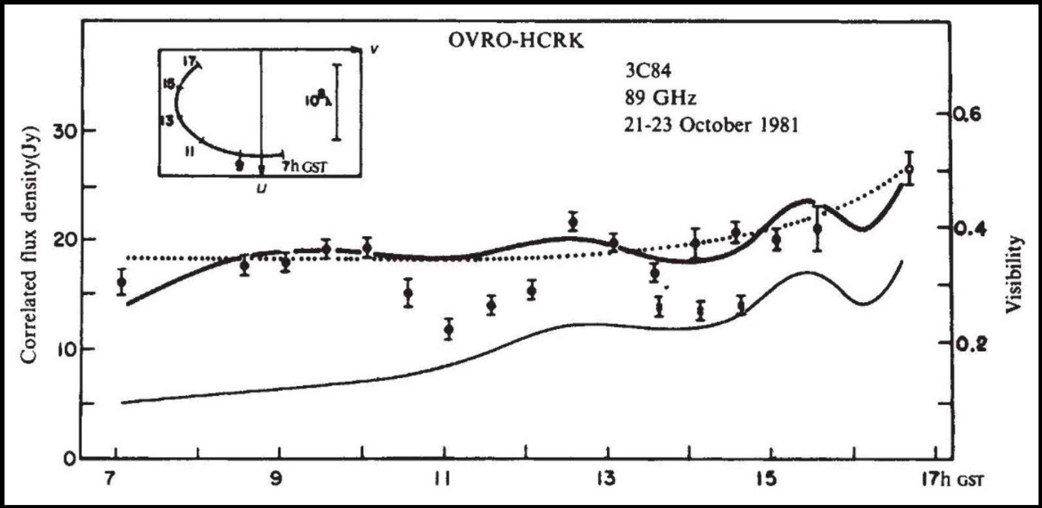
I. Brief history of the development of mm VLBI
II. Overview of ALMA's VLBI capabilities
III. Recent VLBI upgrades and enhancements (APP2 & APP3)
IV. The Wideband Sensitivity Upgrade (WSU) and the future of ALMA VLBI



Black Hole Image Credits: Event Horizon Telescope Collaboration

Credit: Y. Beletsky/ESO; Goddi et al. 2019

First successes in extending VLBI techniques to $\lambda \lesssim 3$ mm were made in the early 1980s:



3C84 visibility amplitude @89 GHz
Haystack-Hat Creek
(Readhead et al. 1983)

Science drivers:

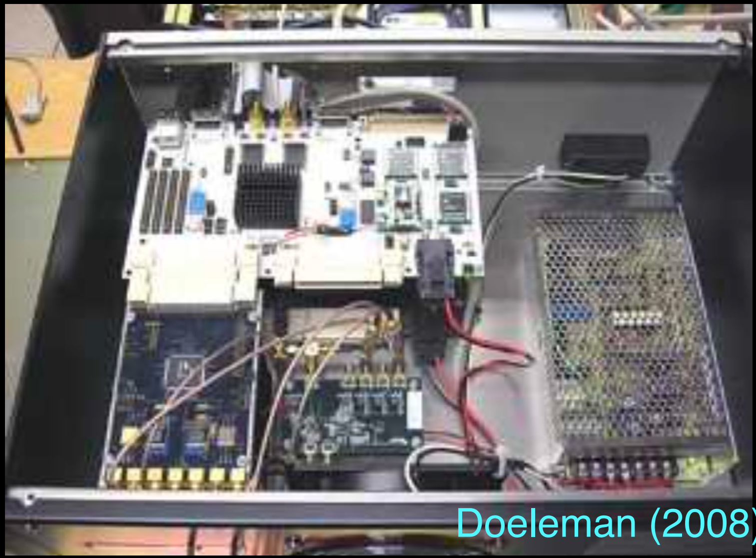
- Achievable (Earth-based) angular resolution: <50 μas
- Ability to probe sources that are absorbed or scatter-broadened at longer λ

Challenges:

- Higher atmospheric opacity
- Shorter coherence times ⇒ need for new fringe-finding algorithms (Rogers et al. 1984, 1995)
- Small receiver bandwidths; high T_{sys}
- Limited network of VLBI-equipped telescopes capable of mm operations → poor *u-v* coverage
- Limited apertures of existing mm antennas → poor per-baseline sensitivity

During the 2000s, advances in instrumentation continued to advance mm VLBI, e.g.:

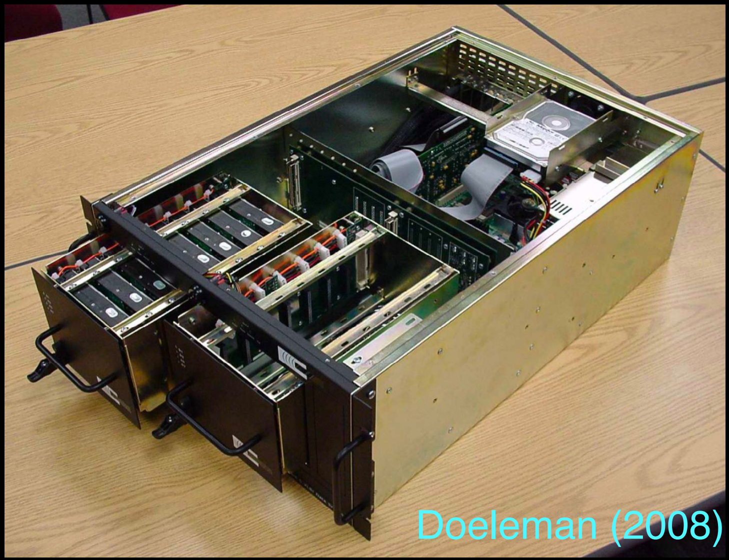
FPGA-based VLBI Digital Backend (DBE)



Doeleman (2008)

- Developed by MIT Haystack/UC Berkeley
- Fully digital
- 2 x 2Gbps output streams

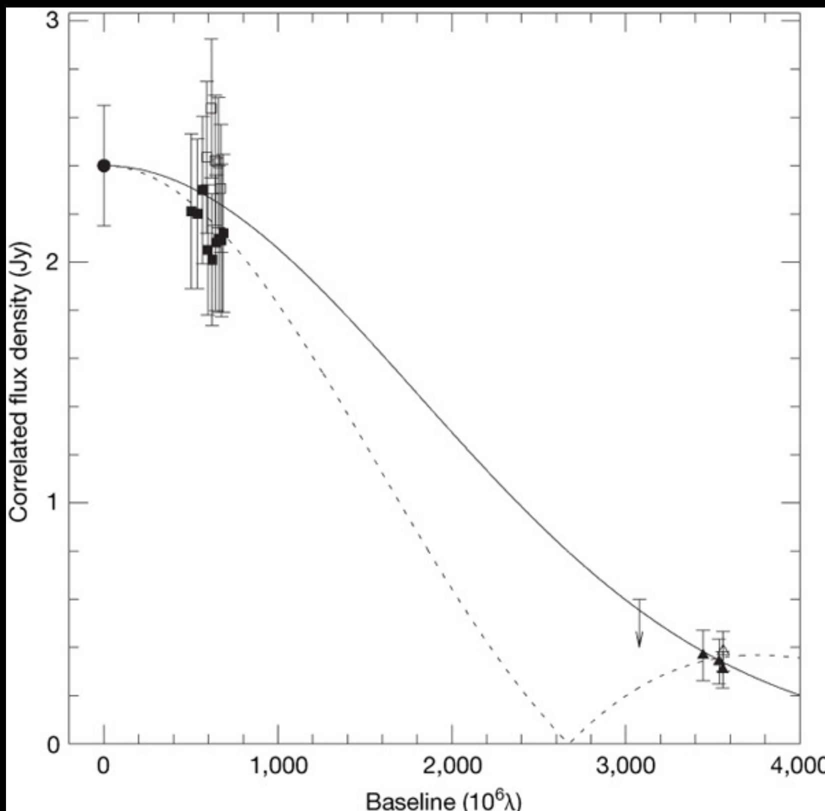
Mark 5 VLBI recorder



Doeleman (2008)

- Developed by MIT Haystack
- First high-speed recorder based on hard disks
- Up to 2 Gbps recording speed

In 2007: first detection of Event Horizon Scale Structure in SgrA* using Event Horizon Telescope (EHT) Prototype Array



- $\lambda \approx 1.3$ mm
- SMT + CARMA + JCMT
- Result: intrinsic diameter of SgrA* ~37 μas
  ⇒ Smaller than expected for BH event horizon
  ⇒ emission likely arises from surrounding accretion flow.
- Firmly established mm VLBI as a tool for studying fundamental black hole physics.

Doeleman *et al. Nature* **455**, 78-80 (2008) doi:10.1038/nature07245

The early 2000s marked the beginning of the construction of the world's most powerful mm/sub-mm telescope: the Atacama Large Millimeter/submillimeter Array (ALMA).

- International project that merged the U.S. 'Millimeter Array' with European 'Large Southern Array' and the Japanese 'Large Millimeter and Submillimeter Array'.
- Built at elevation of ~5000m in the Atacama Desert of northern Chile
- 66 antennas (54 x 12m; 12 x 7m); total collecting area of ~6570 m^2
- Frequency coverage 35 – 950 GHz
- Bandwidths ≥ 8 GHz/pol
- Science operations began in 2011.

- VLBI was long viewed as a "requirement" for ALMA.

→ "Hooks" for phased array/VLBI operations were part of the design of the 64 antenna ALMA Baseline Correlator (Escoffier et al. 2007; Baudry et al. 2012):

  - Spare card slots and rack space
  - Extra power capability
  - High-resolution digital adjustment capability for LO phases in the tunable filter banks
  - FPGAs dedicated to computing a sum of a selectable set of antennas


Baudry et al. (2012)

- The game-changing potential of ALMA for mm VLBI was also eagerly anticipated by the scientific community (e.g., Krichbaum, Witzel, & Zensus 2002; Shaver 2003).

However: the initial ALMA construction phase did <u>not</u> include the additional electronics, hardware, software, and firmware needed to support VLBI.

Use of phased ALMA to advance mm VLBI was strongly endorsed by the Astro2010 Decadal Survey RMS Panel:

from Astro2010 Decadal Survey Panel Reports

Small Projects

Keeping a balance between large projects and national/international facilities and smaller projects is vitally important. Examples of excellent projects of this kind are the enhancement of millimeter-wave VLBI to create the Event Horizon Telescope, adding the huge collecting area of ALMA, and the addition of multifeed receivers to the CARMA telescopes. The panel recommends a total of $25 million for this effort over the decade, most likely funded by ATI or MRI.

⇒ The ALMA Phasing Project (APP) was born.

The ALMA Phasing Project (APP)

- **Principal Investigator:** Shep Doeleman
- **Funding:** NSF Major Research Instrumentation (MRI) + ALMA North America Development award (approved 2012).
- **Participating Organizations:**
  - MIT Haystack Observatory (USA, lead)
  - ASIAA (Taiwan)
  - Harvard-Smithsonian Center for Astrophysics (USA)
  - Max Planck Institut für Radioastronomie (Germany)
  - NAOJ (Japan)
  - NRAO (USA)
  - Onsala Observatory (Sweden)
  - University of Concepción (Chile)

The ALMA Phasing Project (APP)

Objectives:

- Turn ALMA into the world's most sensitive station for VLBI at (sub)mm wavelengths.
- Provide a dramatic boost in **sensitivity** (×10), ***u-v* coverage**, and north-south **angular resolution** (×2) of global VLBI networks operating at mm wavelengths.
- Enable detections on any EHT baseline in ~10 s.

Requirements:

- Provide hardware and software to coherently sum signals from up to 61 ALMA antennas
- Record VLBI format data.
- Leave ALMA's regular signal paths intact.

What Did Equipping ALMA for VLBI Entail?

Hardware:

- ✓ Install new frequency standard (***H maser***) to replace ALMA's Rb clock
- ✓ Design and install Phasing Interface Cards (***PICS***) in ALMA correlator (2 per quadrant, 8 total) to serve as VLBI backend
- ✓ Install bank of Mark 6 high-speed ***VLBI recorders*** at ALMA Operations Support Facility (OSF)
- ✓ Build and install ***optical fiber link*** system to carry data from ALMA high site to the recorders

Software:

- ✓ Implement new VLBI Observing mode (***VOM***) into existing ALMA software to coherently phase the array and operate the VLBI backend
- ✓ ***VEX2VOM*** (translates VEX to an ALMA Scheduling Block)
- ✓ ***PolConvert*** (to convert ALMA's linearly polarized data to a circular basis)

Commissioning and Science Verification (CSV):

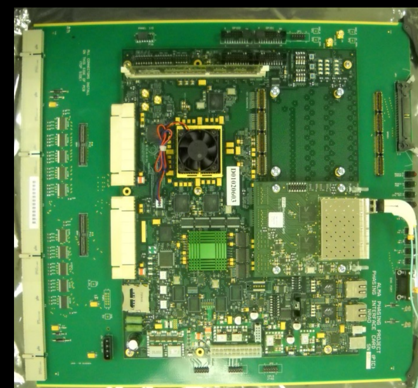
- ✓ End-to-end, on-sky testing of the entire APS

See Matthews, Crew, Doeleman, et al. 2018 (PASP, 132, 5002) for details.

APP Hardware Components

(Half of)
Optical Fiber
Link System

Mark 6
VLBI
Recorders



Phasing
Interface
Cards (PICs)

Hydrogen
Maser

Summary of Phased ALMA Capabilities (circa 2017)

Equivalent collecting area: 73-m parabolic dish
(assuming 37 phased 12-m antennas)

Bandwidth: 7.5 GHz per polarization

SEFD: ~65 Jy @ λ3 mm (86 GHz)
~97 Jy @ λ1.3 mm (230 GHz)

VLBI Recording: 64 Gbps (4 Mark-6 units, each 16 Gbps)

Polarization: dual pol. recording; full Stokes data sets

First ALMA VLBI science observations carried out in April 2017 (ALMA Cycle 4):

- Conducted in fixed date "campaign" mode
  - 3mm (Band 3) in conjunction w/ GMVA (~0.2 GHz BW, dual pol.)
  - 1.3mm (Band 6) in conjunction w/ EHT (~4 GHz BW, dual pol.)

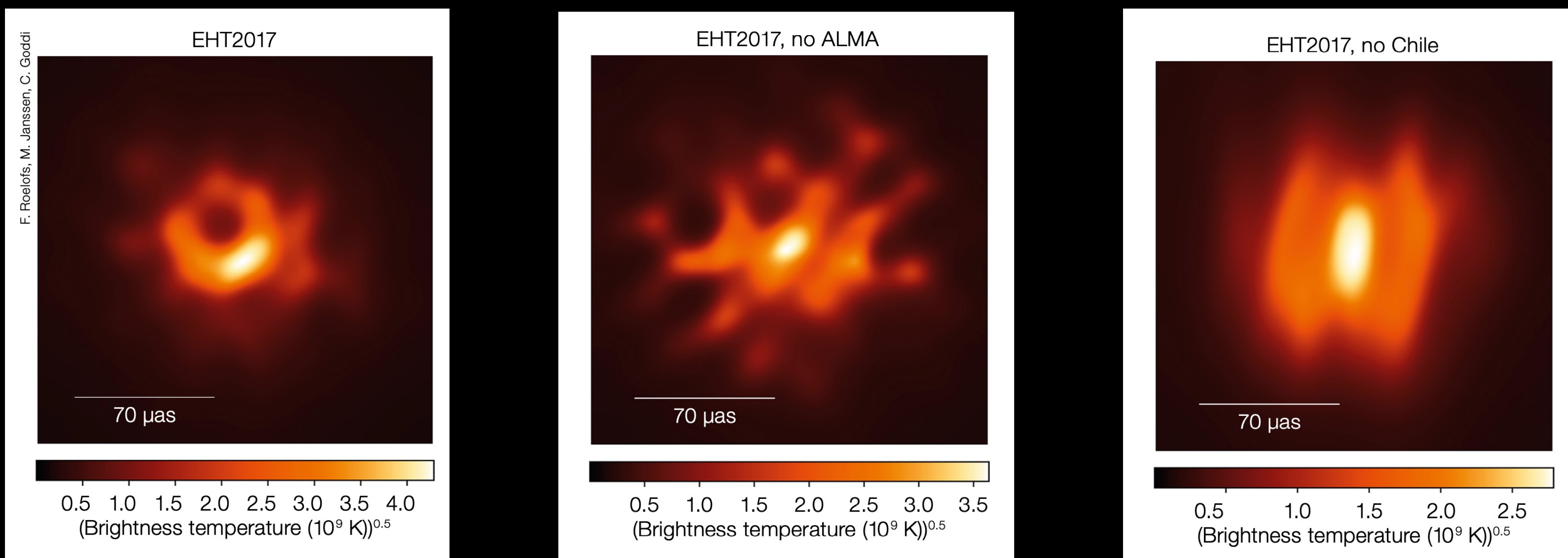
Credit: eventhorizontelescope.org

Target Distance: ~17 Mpc
Observing frequency: $\nu \approx 230$ GHz
Measured angular size: $\theta \sim 52\mu$as
Derived black hole mass: $M \approx 6.5{\times}10^9\ M_\odot$

Event Horizon Telescope Collaboration et al. (2019)

M87* image reconstructions from synthetic data with different combinations of telescopes show:

(1) The importance of a telescope in Chile for providing sufficient *u-v* coverage for imaging.
(2) The black hole shadow can only be seen with phased ALMA as part of the 2017 EHT Array.



Goddi et al. (2019)

The first VLBI science observations with ALMA in 2017 were an extraordinary success!

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BUT:

- The scientific potential of a phased ALMA extends well beyond imaging black holes (Doeleman 2010; Falcke et al. 2012; Fish et al. 2013, Tilanus et al. 2014) .

and

- The initial implementation of the APS offered only a *subset* of its fully envisioned capabilities.

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Limitations:

- VLBI allowed in Band 3 (λ3 mm) or Band 6 (λ 1.3 mm) only
- Fixed tunings
- Continuum mode only (no spectral line science)
- Targets must be bright enough for direct phase-up (≥500 mJy on baselines <1 km).

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⇒ Motivation for APP “Phase 2” and "Phase 3"

Two extensions of APP were launched, funded by the ALMA North America Development Program:

APP "Phase 2" (APP2)
PI: L. Matthews (MIT Haystack)
Software Lead: G. Crew (MIT Haystack)
Period of performance: January 2018 – August 2024

APP "Phase 3" (APP3)
PI: L. Matthews
Software Lead: G. Crew
Period of performance: January 2022 – July 2024

Key goals of both projects:

- *Enhance ALMA's existing VLBI capabilities*
- *Diversify the breadth of science that can be undertaken with the ALMA Phasing System (APS).*

Project closeout reports: https://science.nrao.edu/facilities/alma/science_sustainability/alma-develop-history

New ALMA VLBI Capabilities Introduced by APP2 and APP3: Submillimeter (345 GHz) VLBI

- Move to higher frequencies:
  - Allows increase in angular resolution
  - Augments *uv* coverage at 86 & 230 GHz
  - Minimizes image blurring from scattering effects toward Galactic Center

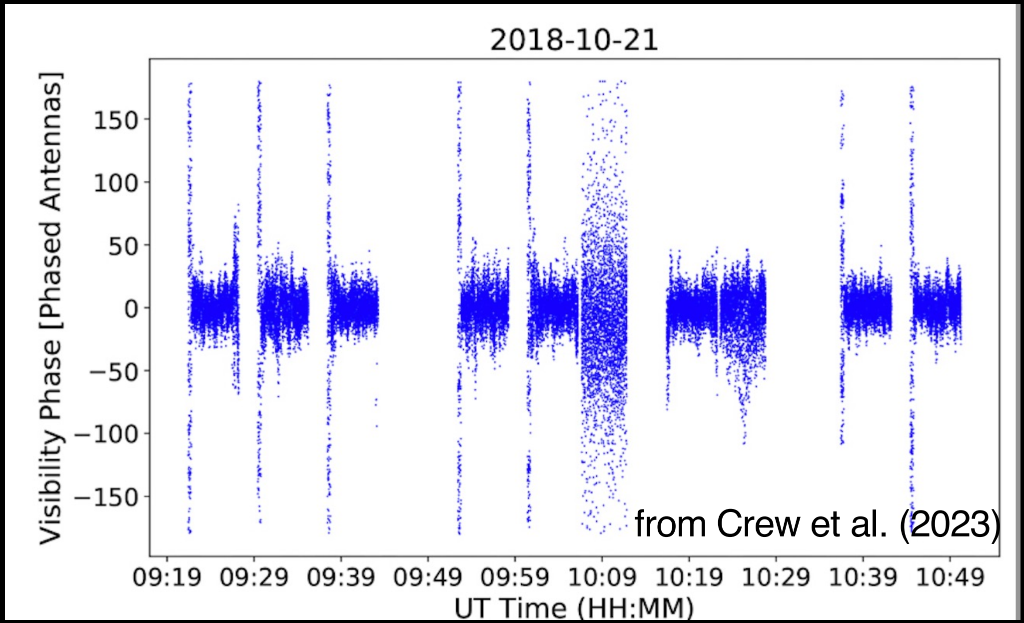
- Proposed as part of APP, but was descoped.

- Core functionality of APS is band agnostic. But:
  - Variety of software updates needed to support additional band.
  - Greater coherence losses from tropospheric water vapor
    → impact on local phasing efficiency *and* ability to achieve VLBI fringes
  - Scheduling windows far more restrictive

- Prior to APP2, a handful of attempts to detect submm VLBI fringes, *but none successful*.

Evaluation of ALMA 345 GHz (Band 7) Phasing Performance

PWV ~ 0.8 mm
v_{wind} ~ 3 m/s
$\eta \approx 0.93$



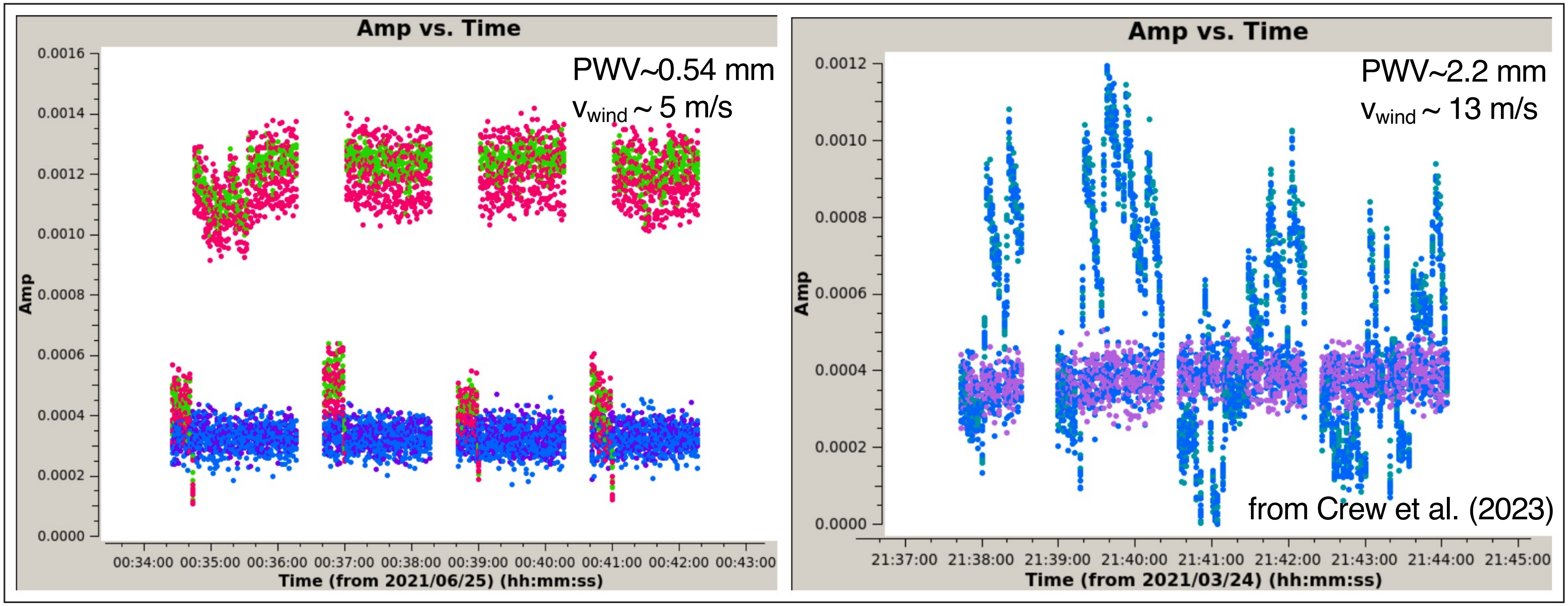
Various standalone ALMA phasing tests were performed in Band 7 over several years (see Crew et al. 2023, PASP, 135, 5002).

Conclusions:

⇒ Under nominal submm observing conditions, ALMA can perform as a highly efficient phased array (phasing efficiency > 90%).

⇒ Potential to provide order of magnitude boost in sensitivity to submm VLBI arrays.

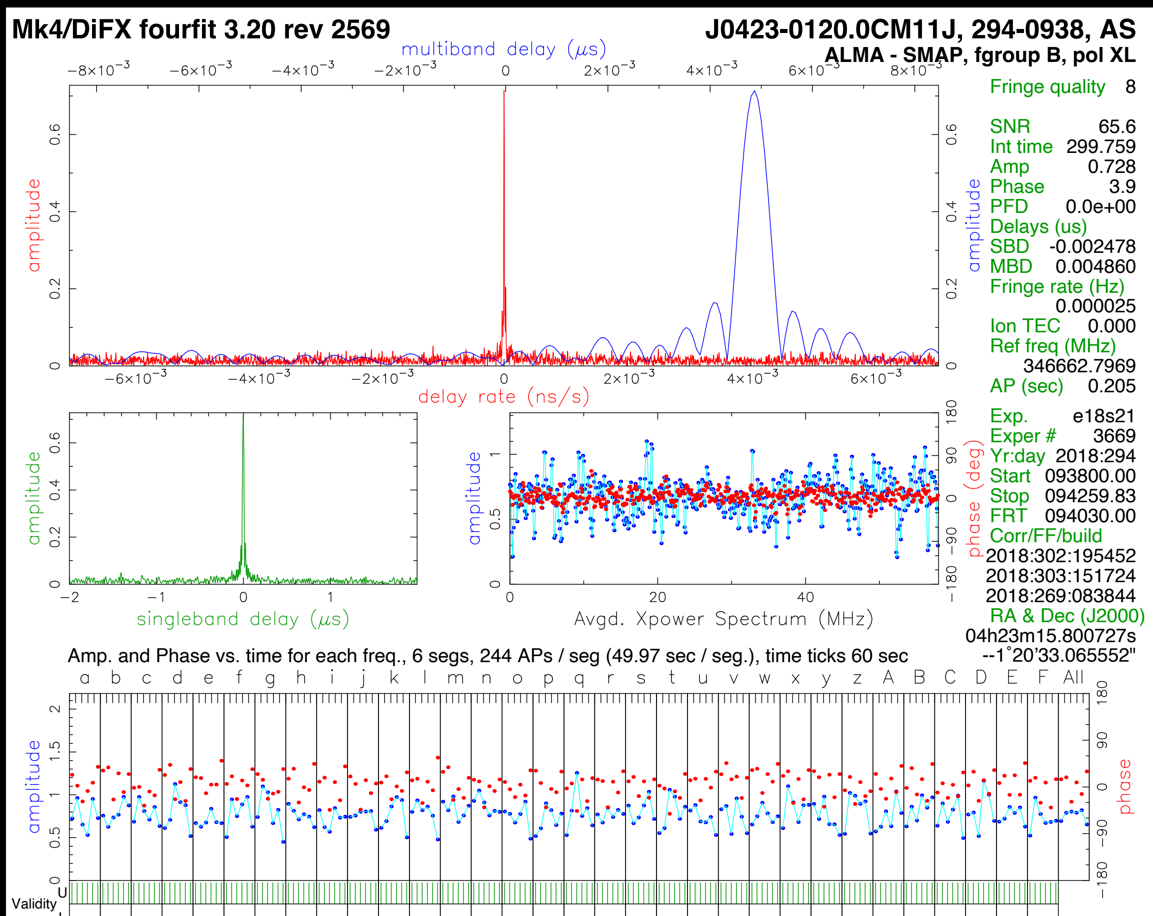
Evaluation of ALMA 345 GHz (Band 7) Phasing Performance: Effect of High Winds



⇒ Phased array operations are best avoided in Band 7 when $v_{wind} \geq 10$ m/s.

Data source: uid://A002/Xed4381/X1ec and uid://A002/Xea6cf9/X1c1

First Submillimeter (346 GHz) VLBI Fringe Detection



- First global VLBI fringe tests at 345 GHz conducted in 2018 in collaboration with EHT.
- Fringe detected on 9448 km baseline between ALMA and SMA (SNR~65).

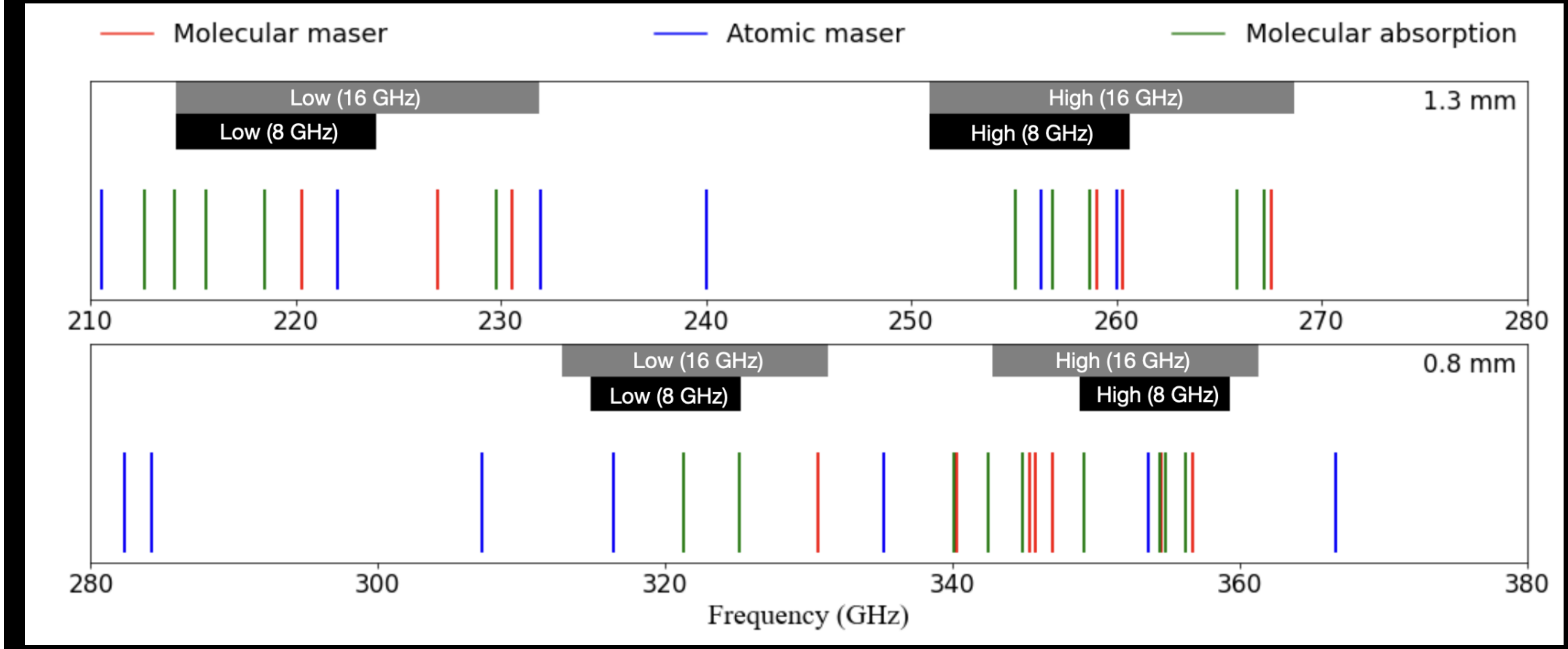
  ⇒ First submm VLBI fringes!

- Fringes also detected on other baselines to ALMA during 2018 & 2021 APP2 commissioning tests.

from Matthews & Crew (2024), APP2 Closeout Report; see also Raymond et al. (2024, AJ 168, 130)

New ALMA VLBI Capabilities Introduced by APP2 and APP3: Spectral Line VLBI

- ALMA bands contain numerous astrophysically important lines
- Many scientific applications benefit from their study with extraordinarily high angular resolution (e.g., Fish et al. 2013; Tilanus et al. 2013; Kim & Fish 2023).
- Collecting area is key for spectral line sensitivity
  ⇒ phased ALMA poised to be a game-changer for (sub)mm spectral line VLBI science.

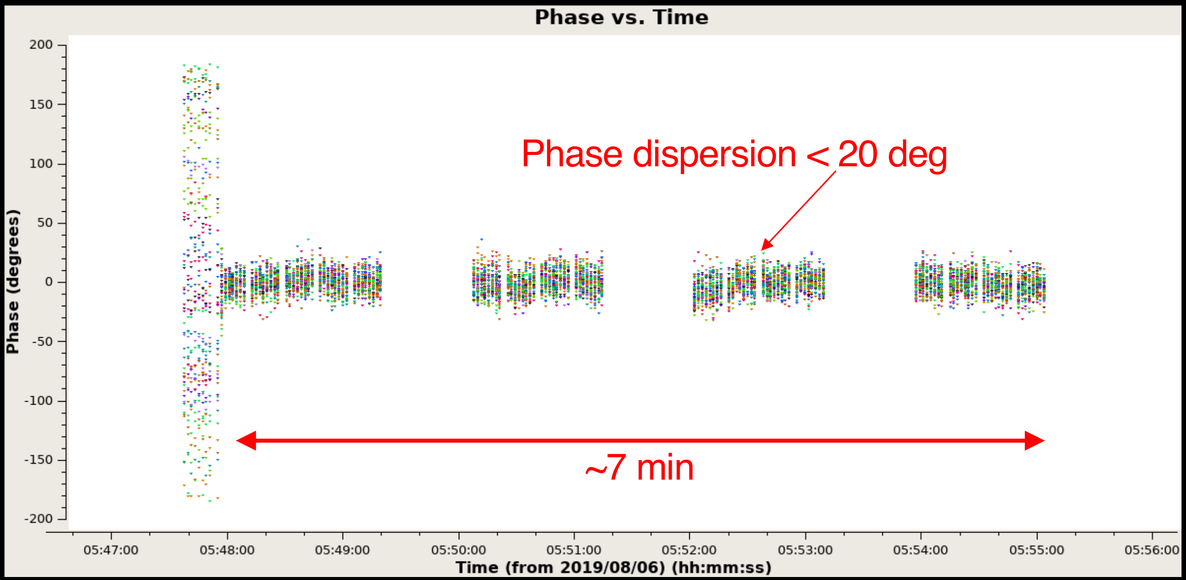


from Kim & Fish (2023)

New ALMA VLBI Capabilities Introduced by APP2 and APP3: Spectral Line VLBI (cont.)

Implementation requirements at ALMA included:

- Ability to phase up the array using emission from a bright line
- Enabling flexible tuning for VLBI
- Allowing non-VLBI basebands to be flexibly configured for commensal ALMA observations at high spectral resolution observations.
- Modifications to correlation and post-processing strategies.

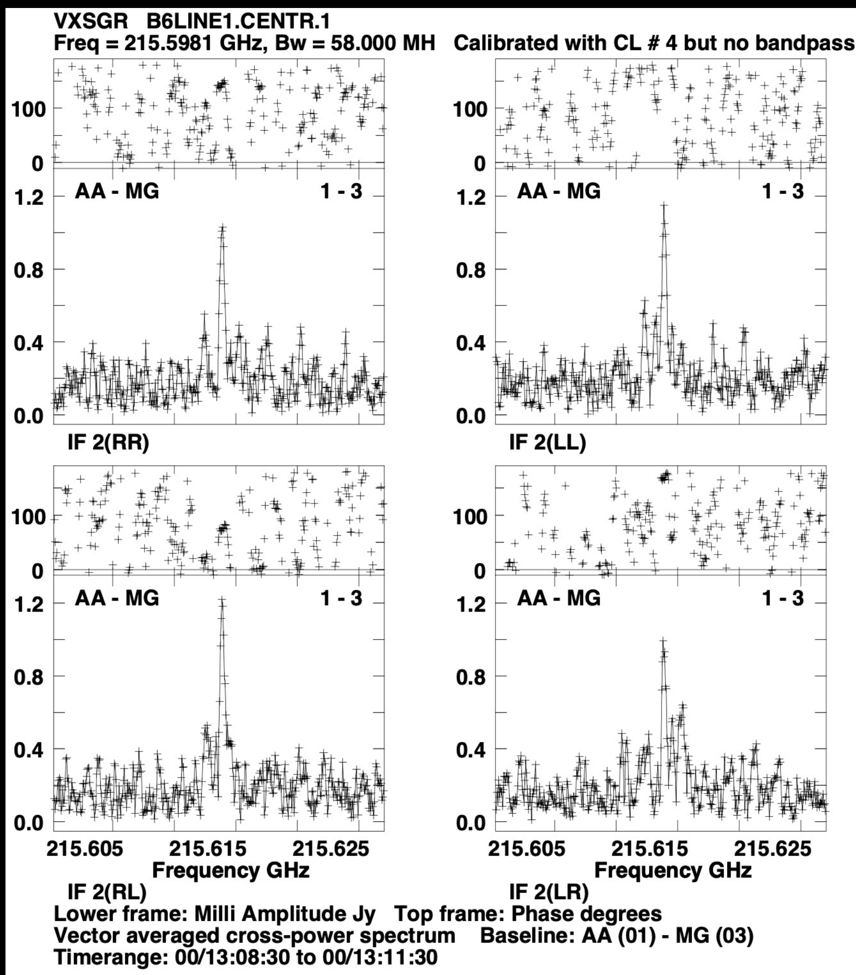


uid://A002/Xdf9c1c/X873b

Example of ALMA phase-up using ^{28}SiO *v*=1, *J*=2-1 line emission from WX Psc (86.2 GHz).

- Array baselines up to 3 km
- Peak line flux ~50 Jy
- Phasing efficiency > 99%.

New ALMA VLBI Capabilities Introduced by APP2 and APP3: <u>Spectral Line VLBI</u> (cont.)



During APP3 commissioning, <u>first ever</u> long baseline detections of high-frequency (ν>200 GHz) masers:

- Target: VX Sgr
- ^{28}SiO, v=1, *J*=5-4 line (ν ~215 GHz)
- 7176 km baseline (ALMA-SMT)

Credits: Matthews & Crew (2024), APP3 Closeout Report. SMT data used courtesy of D. Marrone and the EHT Collaboration.

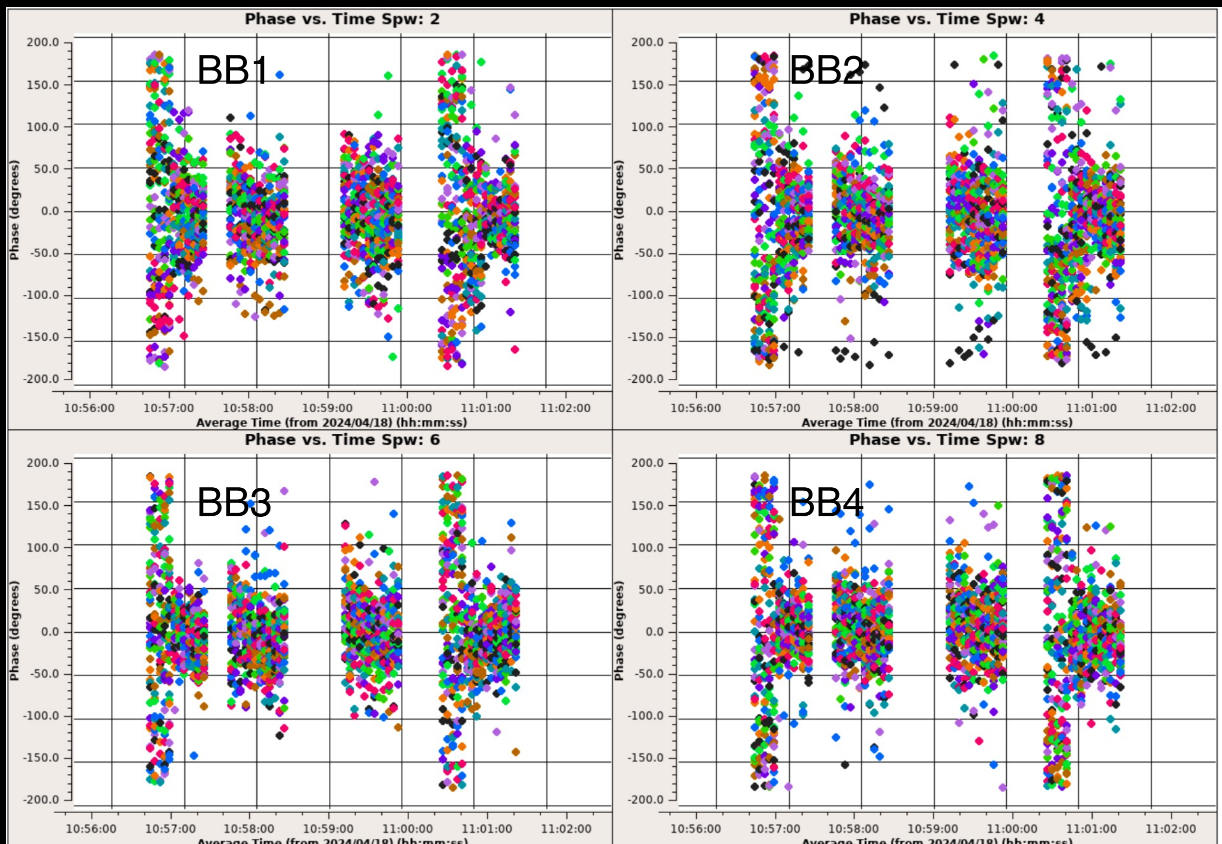
New ALMA VLBI Capabilities Introduced by APP2 and APP3: The Delay Fix

- The manner in which various baseband delays are handled in the ALMA system introduced a fatal flaw in the original ALMA Phasing System (APS) design (see Matthews et al. 2018).
- A workaround involved partitioning each baseband into 8 chunks, with independent phasing solutions computed for each.
- Allowed working APS, but has drawbacks, including a loss of ~ sqrt(8) in sensitivity for the phase-solver.

Starting in Cycle 11 (2025):

- New option available for handling baseband delays during VLBI mode operations
- Improved SNR on phasing targets ⇒ more efficient phase-up on weaker targets

Phasing Test in ALMA Band 9 (ν~640 GHz) in April 2024, using the 'Delay Fix'



phase (±180 deg)

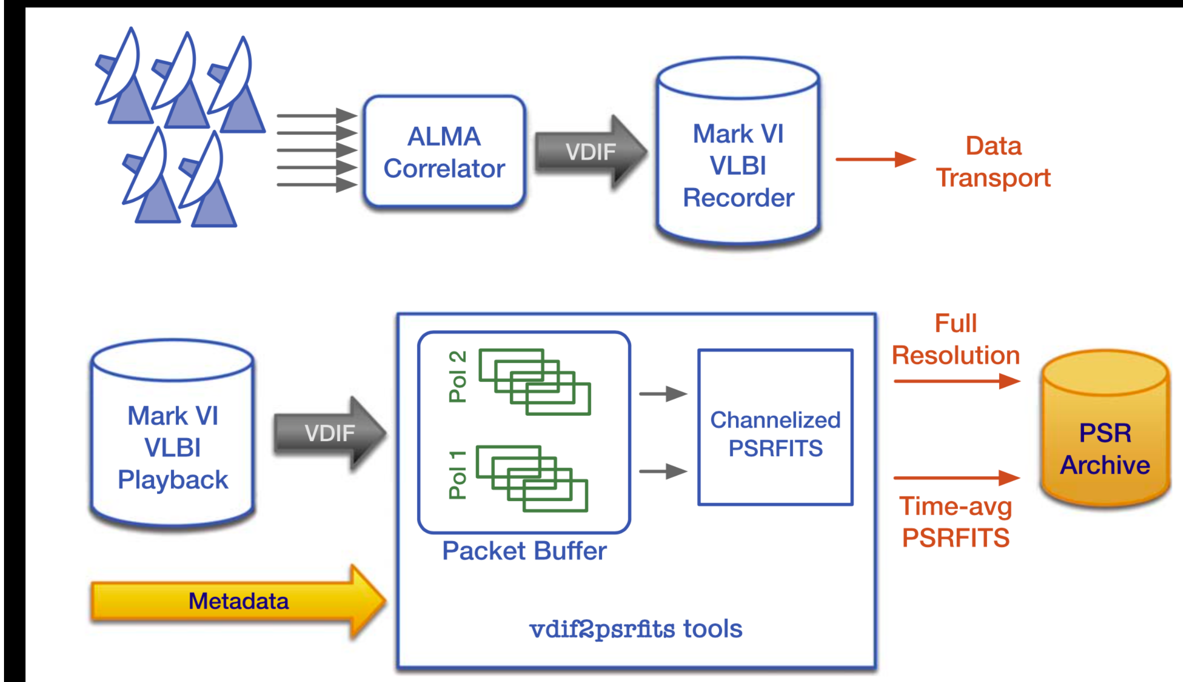
time (~4.5 minutes)

- Band 9 receivers are DSB
- T_{sys}~1000-2500 K (vs. ~60-100 K in Band 6)
- ~1 Jy source
- ~90% phasing efficiency!

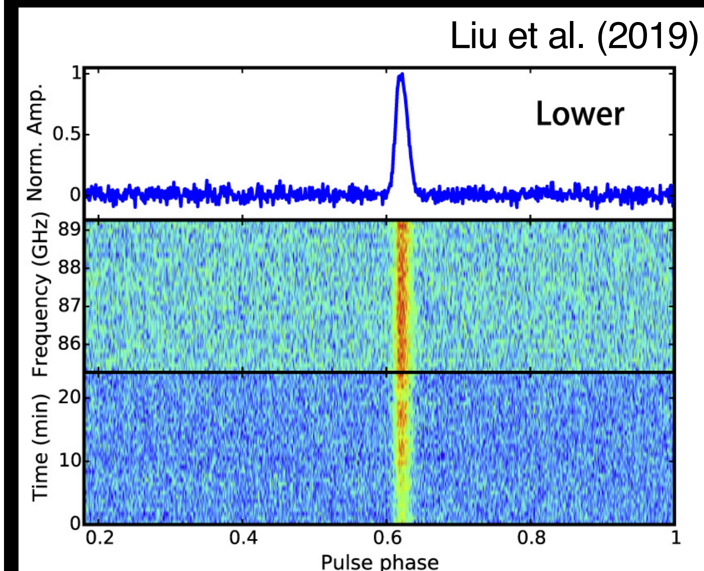
Data source: uid://A002/X116120b/X2a36

New ALMA VLBI Capabilities Introduced by APP2 and APP3: Phased Array (Pulsar) Mode

- Allows use of ALMA as standalone phased array
- VLBI (baseband) data recorded in parallel with ALMA interferometric data
- Pulsar post-processing carried out at MPIfR in Bonn → PSRFITS file



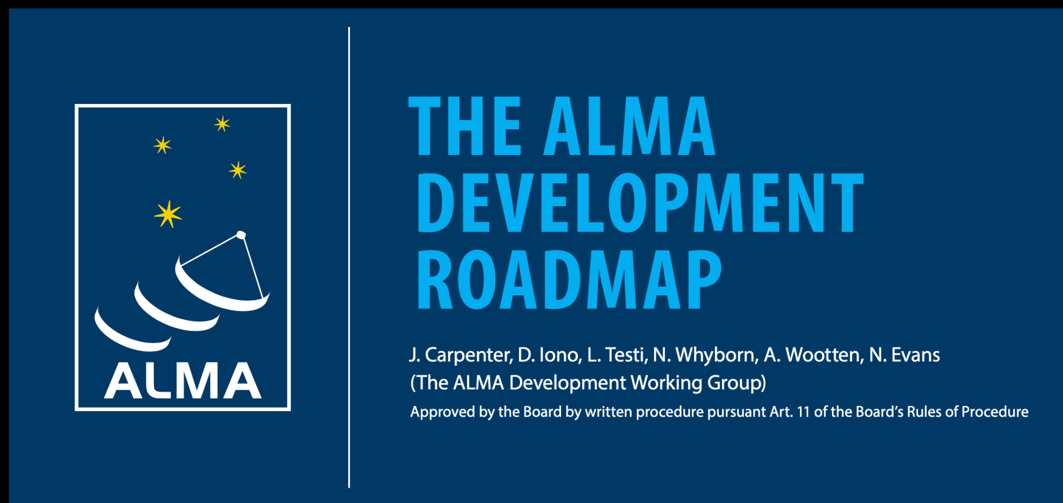
Liu et al. (2019)



ALMA detection of pulsed emission from Vela pulsar @86 GHz

'ALMA 2030' and the Future of VLBI at ALMA

"The ALMA Development Roadmap" was released in 2018, describing a strategic vision for ALMA out to 2030 (Carpenter et al. 2018, ALMA Memo 612).



Two of the top priorities identified were:

(1) Broaden receiver IF bandwidth by at least a factor two

(2) Upgrade associated signal chains, electronics, and correlator

These efforts now comprise ALMA's ongoing 'Wideband Sensitivity Upgrade' (WSU).

https://science.nrao.edu/facilities/alma/science_sustainability/wideband-sensitivity-upgrade

ALMA WSU: 2nd Generation Correlator (ATAC)

- Project to build a next-generation ALMA correlator (Advanced Technology ALMA Correlator=ATAC)
- Effort is ongoing (started 2023), funded by ALMA North America Development program .
- Collaboration between National Research Council (Canada) and NRAO, with subaward to MIT Haystack to support VLBI mode.
- Passed Preliminary Design Review in 2024; now in Critical Design Review phase.
- FFX architecture; based on COTS FPGA cards + data center-grade 400 G ethernet switches
- To be installed in new correlator room at the Operations Support Facility (2900 m), *not* at Array Operations Site (5000 m).
  ⇒ improve accessibility, simplify maintenance, reduce power and operational constraints.
- Onsite integration, verification, and testing expected mid-2026—late 2028.

ALMA WSU: 2nd Generation Correlator (ATAC) (cont.)

Overview of capabilities:

- Increase of maximum correlated bandwidth to 16 GHz per pol
- 13.4% improvement in digital sensitivity
- Subarraying (up to 6 arrays)
- Two operational modes: "imaging correlation" and "VLBI beam-forming"

  → **Commitment to maintaining ALMA's VLBI capabilities**

- Common 'F' stage for both modes produces "frequency slices" with (usable) 200 MHz BW per pol.

Possible advantages for VLBI as a result of the WSU/ATAC:

- Potential for higher cadence phasing
- Current baseband "delay problem" goes away.
- Ability to do single-antenna VLBI without interruption to main array
- Flexible subarraying (multi-frequency) capabilities
- Sensitivity improvements:
  - continuum: 2–4× higher BW
  - continuum & spectral line: ×1.5 gain from digital + receiver improvements

Caveats:

- Commissioning of ATAC VLBI will be done *after* the imaging correlator mode (late 2028?).
- Possibility of period of 1-2 years where VLBI is unavailable at ALMA (2028+?).
- Solution for *recording* expanded bandwidth is currently under study.
- ALMA will not having simultaneous, multi-frequency capabilities for the foreseeable future.
- Without funding for sufficient study and implementation efforts, future VLBI runs risk of providing *fewer* capabilities than present.

Summary

- The advantages of Phased ALMA for (sub)mm VLBI are now well known and well demonstrated:
  - Extraordinary sensitivity
  - Exceptional observing site
  - Broad frequency coverage
  - Strategically located for enhanced *u-v* coverage, north-south angular resolution
  - Provides commensal interferometric observations of target

- Newly developed VLBI capabilities resulting from APP2 and APP3, including submillimeter VLBI, spectral line VLBI, a pulsar observing mode, and enhancements for phase-up on faint targets are beginning to be exploited for new VLBI science.

- ALMA is committed to maintaining VLBI capabilities in the WSU era.

- The WSU/next-generation ALMA correlator (ATAC) has the potential to bring additional enhancements to ALMA's VLBI capabilities, including wider bandwidths, subarraying, and single-dish VLBI.