Data transfer from ALMA to North America

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National Radio Astronomy Observatory

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NRAO and ALMA

ALMA is a multinational project with many partners, and three ALMA Regional Centers (ARCs):

- NA: NRAO, Charlottesville, VA, USA
- EU: ESO, Garching (Munich), Germany
- EA: NAOJ, Mitaka (Tokyo), Japan

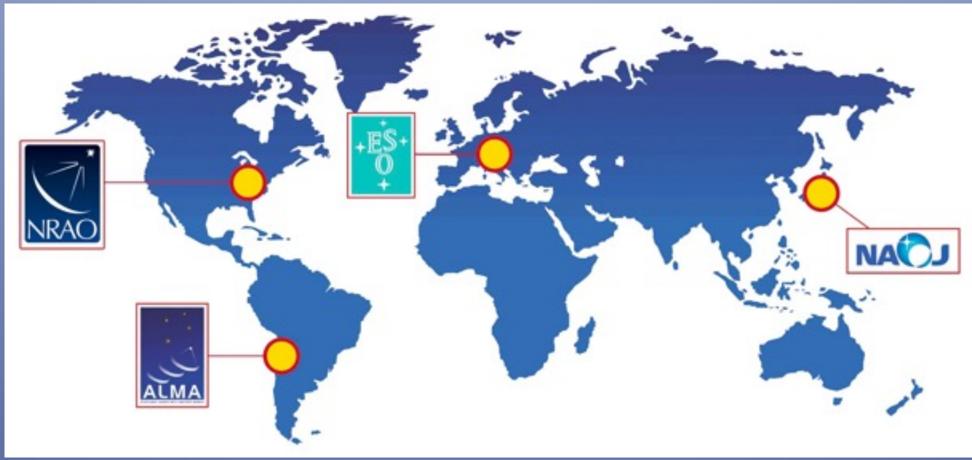


Image: https://science.nrao.edu/facilities/alma/images/arcs.jpg

ALMA telescope

- Largest mm/submm telescope ever built. As an interferometer, it combines signals from multiple antennas to form an image.
- All 66 antennas operational at high site (except for maintenance)
- Sub-arrays possible, and generally 3 projects observed at once:
  - 50 x 12m-antennas (main array)
  - 12 x 7m-antennas
  - 4 x 12m-antennas, observing in “Single Dish” mode (“Total Power”)
- Operated “space mission” style, with pipeline data processing and a science archive at each ARC (and Chile).
- First PI projects released to public from the ARCs January 2013.
- Annual calls for proposals in March-April (currently for Cycle 9)
- “Control Room Extension” at Santiago Central Office.
- Cycle 7 observations began in October 2019, but halted due to pandemic shutdown in March 2020: *Cycle 7 restarted in March 2021*
- *Cycle 8 observing runs through September 2022.*

Radio Interferometry relies on pairs of antennae to emulate a much larger dish

Artificially create a large “dish” using many smaller ones...

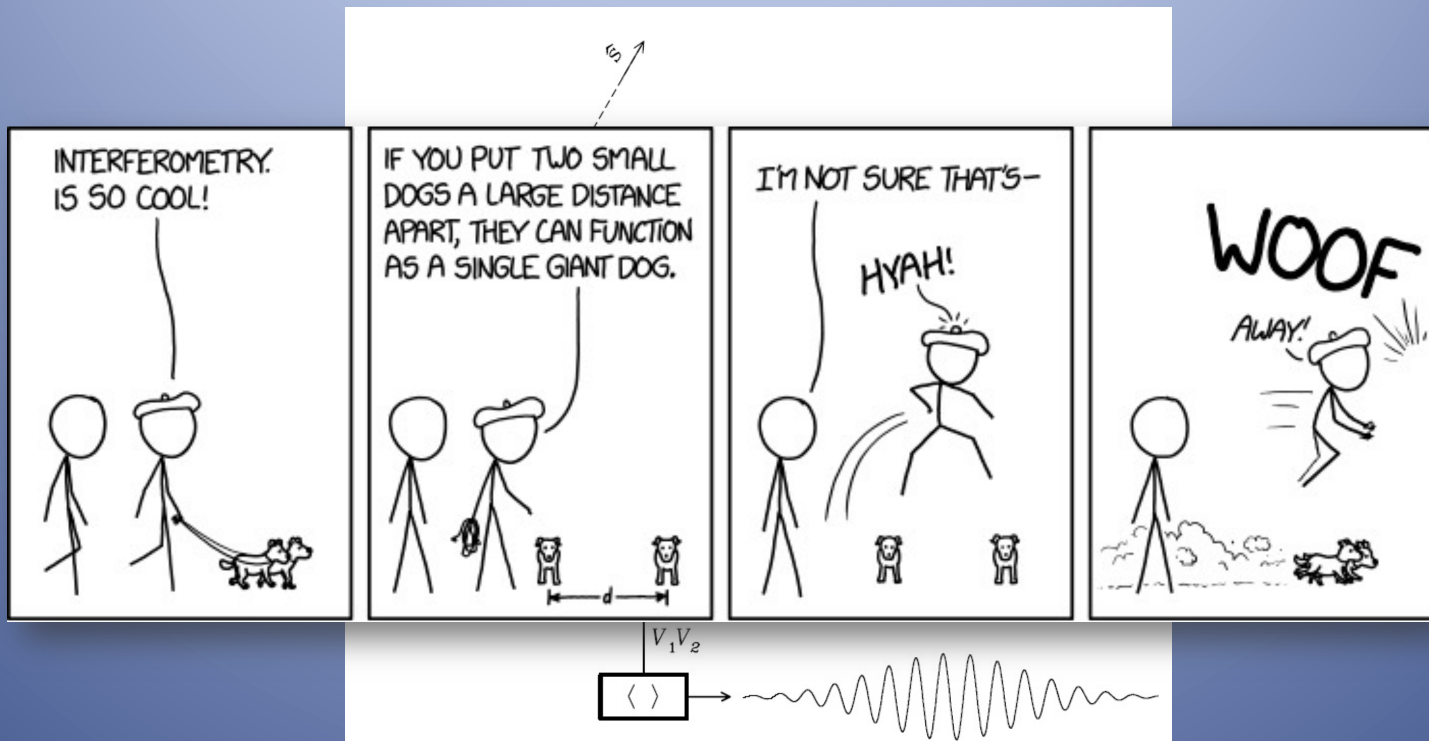
... this is called “Aperture Synthesis”

But ... this large “dish” is not a real reflecting surface.....

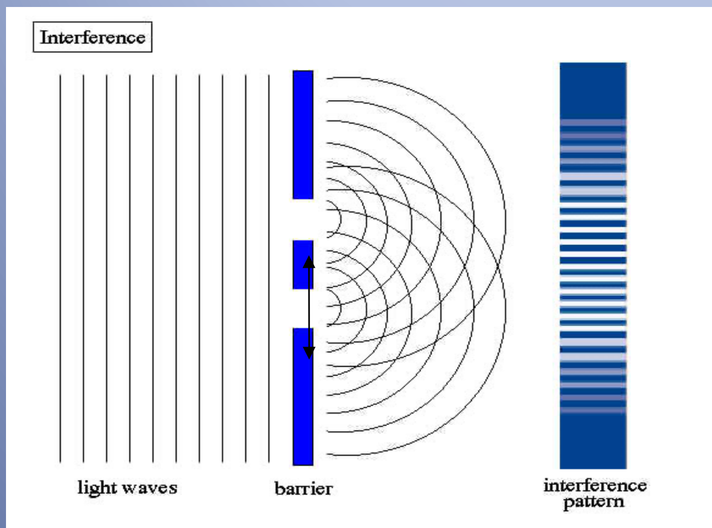
So how do you make it behave like one ?

... imitate the Physics of a lens.

Radio Interferometry: Relies on pairs of antennae to emulate a much larger dish

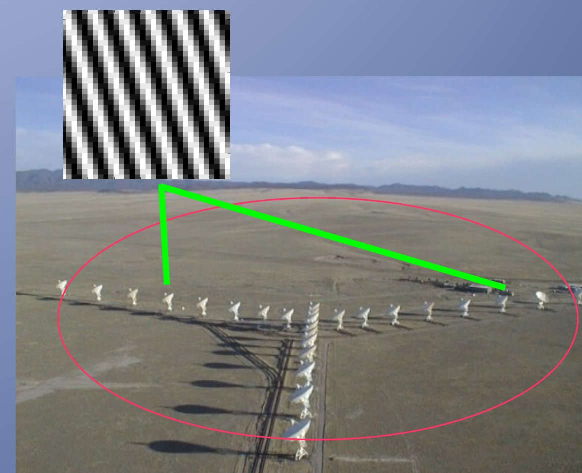


Measure interference fringes



Young's Double-Slit Experiment

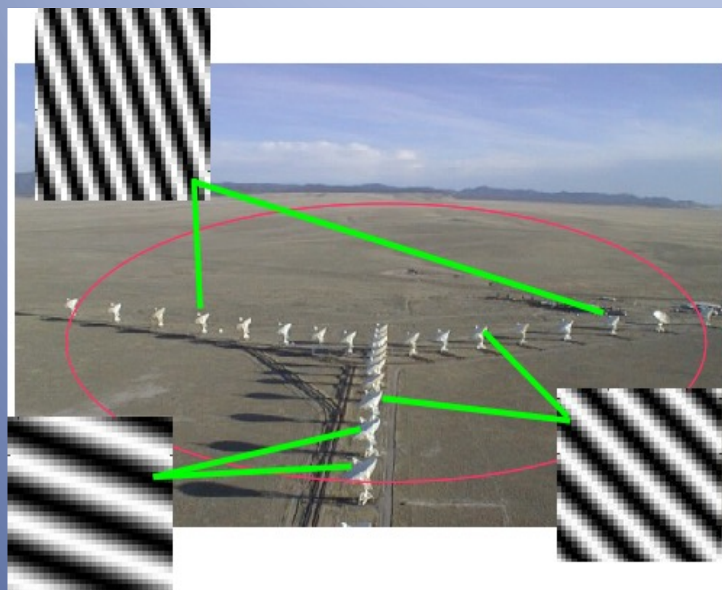
Distance between slits controls the wavelength of interference fringes



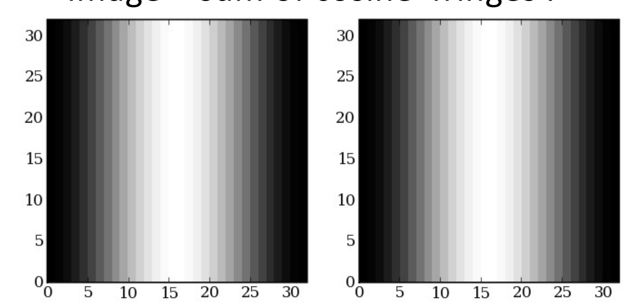
One dish = One slit

Each pair of antennas captures a different 2D fringe

Image Formation



Build an image by combining all measured fringes in a custom built High-Throughput SuperComputer called a Correlator.

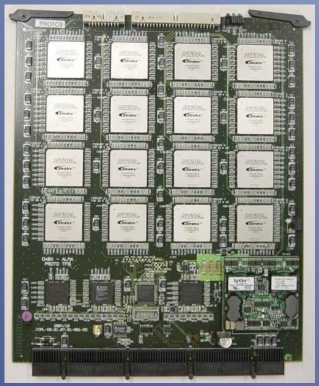


The number of fringe scales with the (number of dishes)^2

ALMA Correlator: HPC@ 16,200 feet

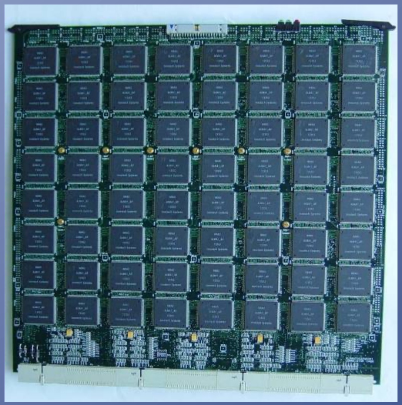
Correlator Quadrant

Tunable Filter Bank Card

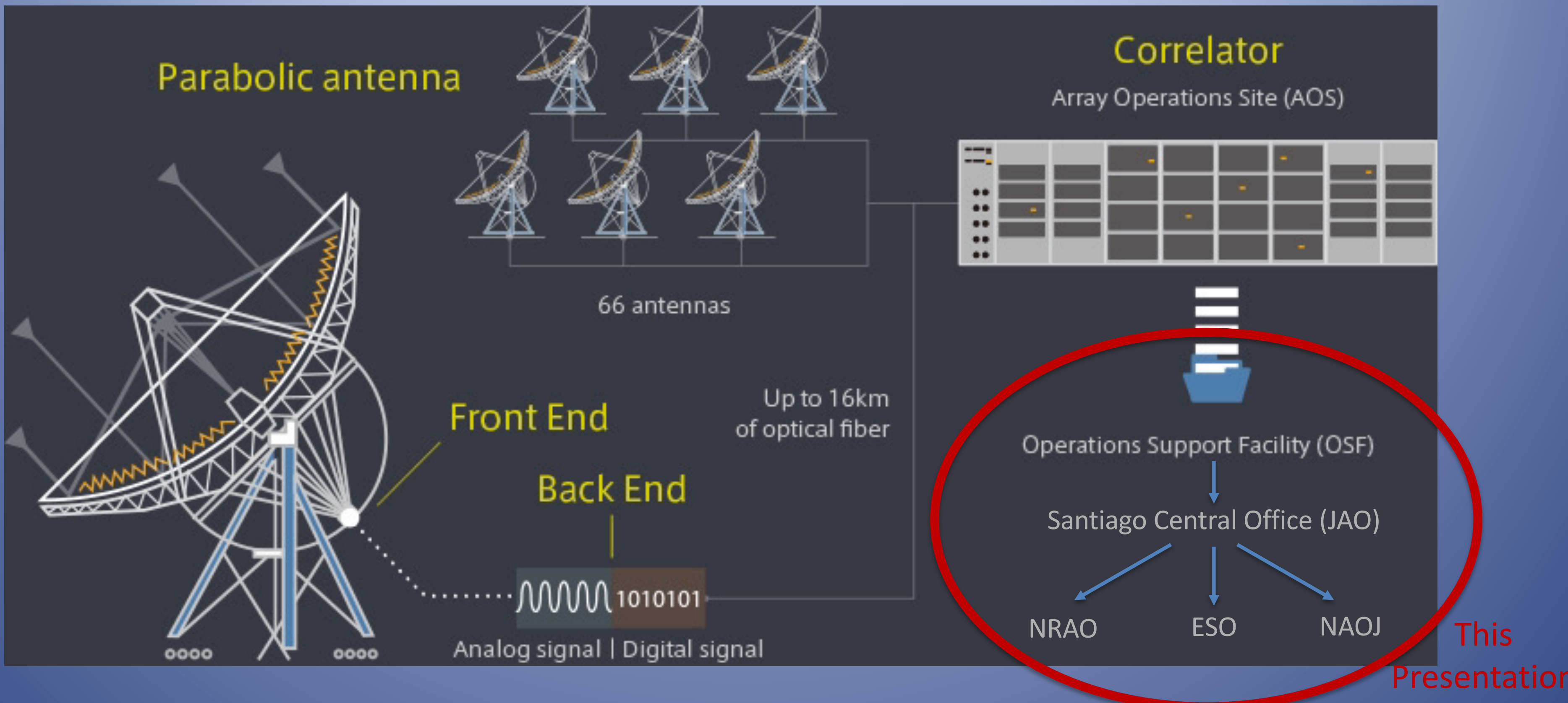


- Receives signals from 50x12m antennae
- 2551 printed circuit boards total in system
- 8192 Altera Stratix II FPGAs on TFB cards
- 32768 custom correlator chips with 4096 processors for multiply-and-add calculations
- Cross-correlation rate 17 Peta ops/sec
- Output specified at 6-60MBytes/sec

Correlator Card



ALMA Telescope Data Flows

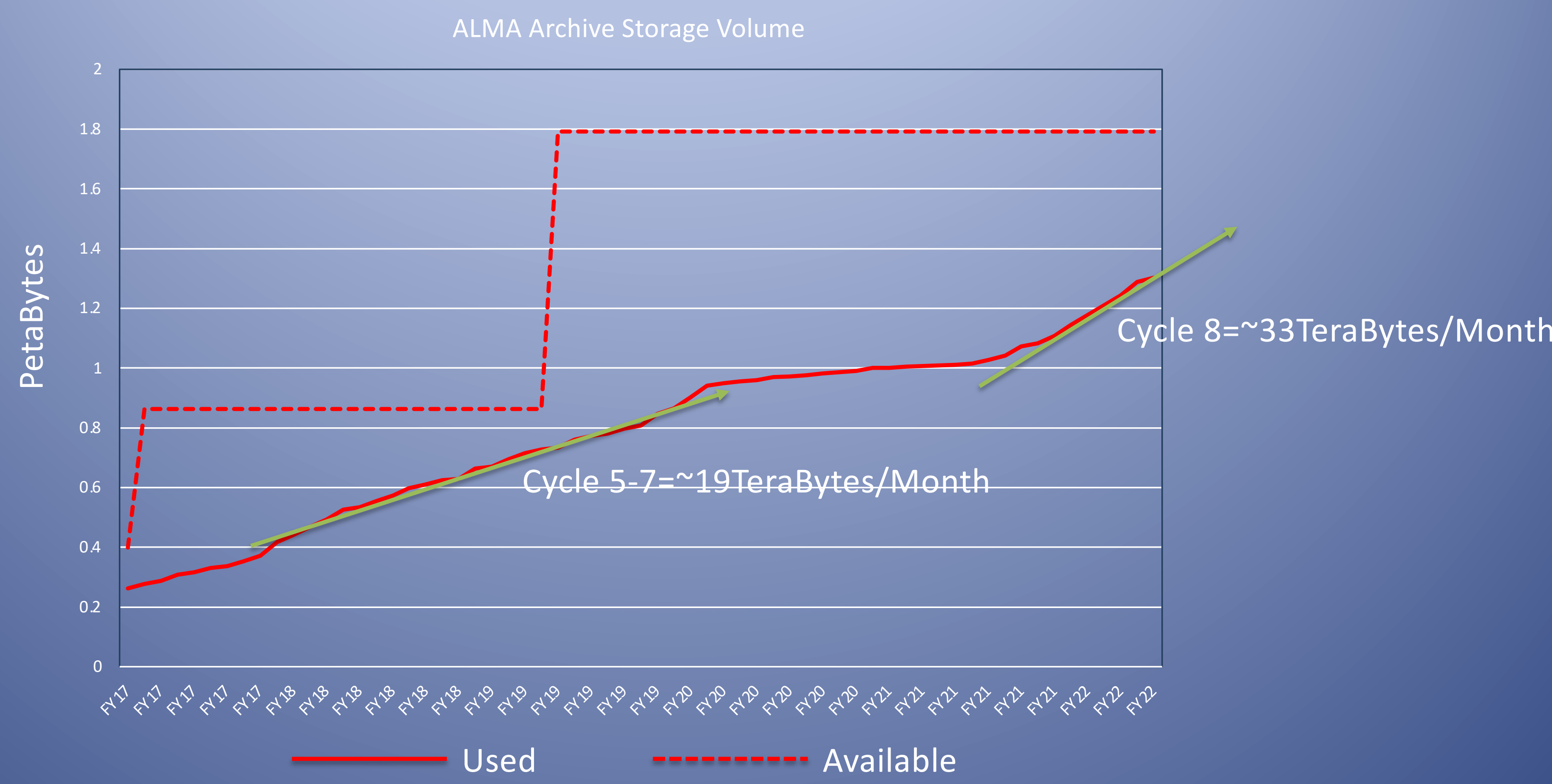


System diagram of ALMA. Various instruments including antennas, receivers, correlators, and data archive work in unison.
Credit: ALMA (ESO/NAOJ/NRAO)

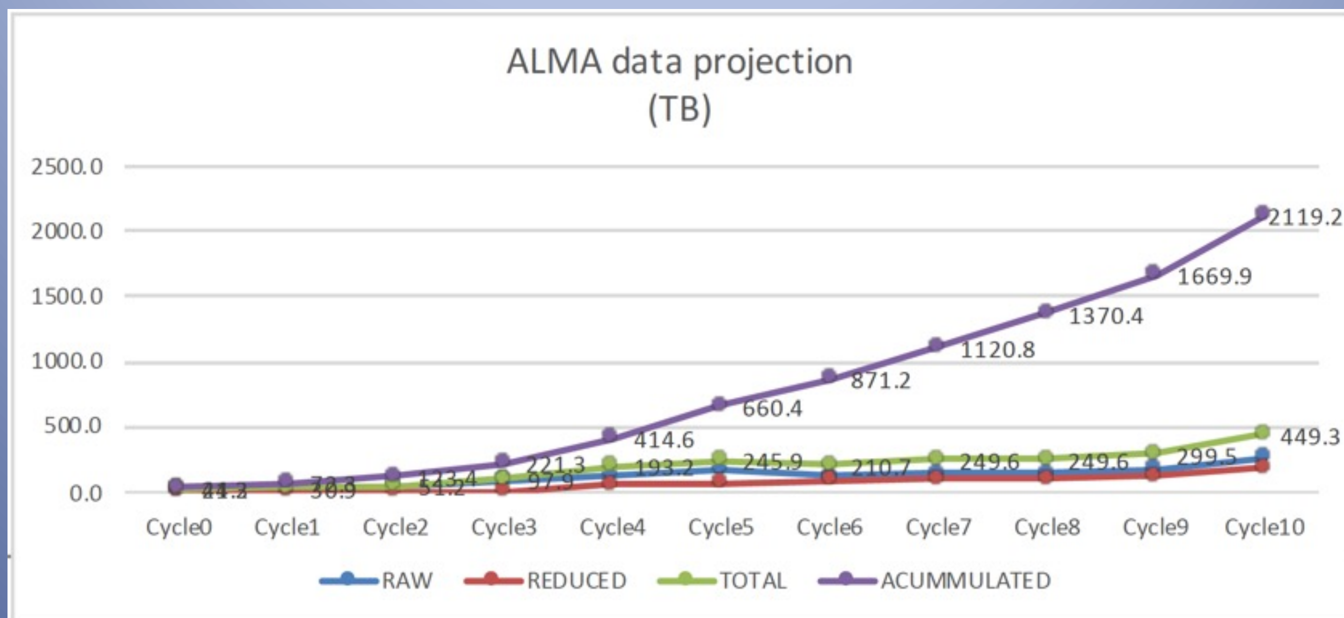
Data transport
Chile to Charlottesville (NAASC)

- MOU between AUI/REUNA for local link to SCO
- Santiago to ARCs: individual ARC contracts with REUNA and NRENs.
  - NA: Joint AURA-AUI agreement for 1Gbps committed (burstable to 10 Gb/s capacity) from Santiago to US NREN via Latin America's Nautilus Point of Presence
  - Link from NRAO to Internet2 through UVa is 10Gb/s
- Typical rate obtained during peak data transfer periods is 2-300Mb/s, with bursts up to 600Mb/s
- Recent transition to most data processing being done in Santiago. Some manual processing at ARCs.
- The North American ALMA Science Center (NAASC) hosts the ALMA Archive, and computing for NA users.

North American ALMA Archive

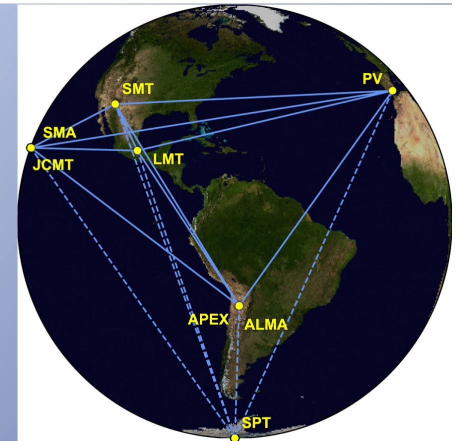


ALMA Science data projection



Based on: ALMA data rates and archiving at the NAASC NAASC Memo 110 (v5.1)
ALMA Archive Review, 2019

Opportunities



ALMA was a key contributor to the Event Horizon Telescope (EHT) imaging the Black Hole at the center of Messier 87 (M87), 55 million light-years from Earth.

- All ALMA dishes were "phased" to provide a single stream of data for the multi-day, multi-telescope observation BUT…
- Due to bandwidth constraints from geographically distributed telescopes, data was shipped on disk for correlation.

Katie Bouman, S/W developer for EHT, currently CalTech Professor of Computing and Mathematical Sciences (CMS)

Testing New Capabilities: High Data Rate Observations

Higher data rates are due to shorter dump-times, larger number of channels per dump, and/or a combination of both

Needed for bright, variable objects:

- Solar: ~ 82msec/dump (TDM) (<30MB/s)
- FRBs: ~a few msec/dump (TDM) **(<500MB/s)**
- Occultations: ~100msec/dump (TDM) (<25MB/s)
- Planet Atmospheres: ~100msec/dump (FDM) **(<750MB/s)**

Heavier Observations:

- Reduction of systematic spectral binning? (Data Mining, etc.)

Current "LIMIT": 70MB/s

Status: Tested data rates of 55.86 MB/s, 66.96MB/s, 77.13MB/s, 95.8MB/s, 168MB/s successfully.

“Next ALMA Correlator”

- A correlator upgrade is being developed
  - In line with ALMA Development Roadmap [1], and ALMA2030 vision
  - Likely completion ~2028, as part of ALMA2030 upgrade
  - Specifications available in draft by working group [2]
- Deployable location physically separate from BLC (potentially OSF)
- Expected data rate increase is about a factor of four, corresponding to a data rate of ~1PB/yr (not all projects will need the extra channels)
- Details to be defined in cooperation with correlator partner

[1] https://www.almaobservatory.org/en/publications/the-alma-development-roadmap
[2] https://science.nrao.edu/facilities/alma/science_sustainability/Specifications2ndGenCorrelatorV2.pdf

Disaster Recovery Concern

- The current NA ALMA archive is ~1.3 PetaBytes
- In the event of data loss, the Regional Centers would recover data from the primary ALMA Archive in Santiago
- Over the current 1Gbps link, this would take ~5-6months!
- NA ALMA archive access would be re-directed to ESO during any outage

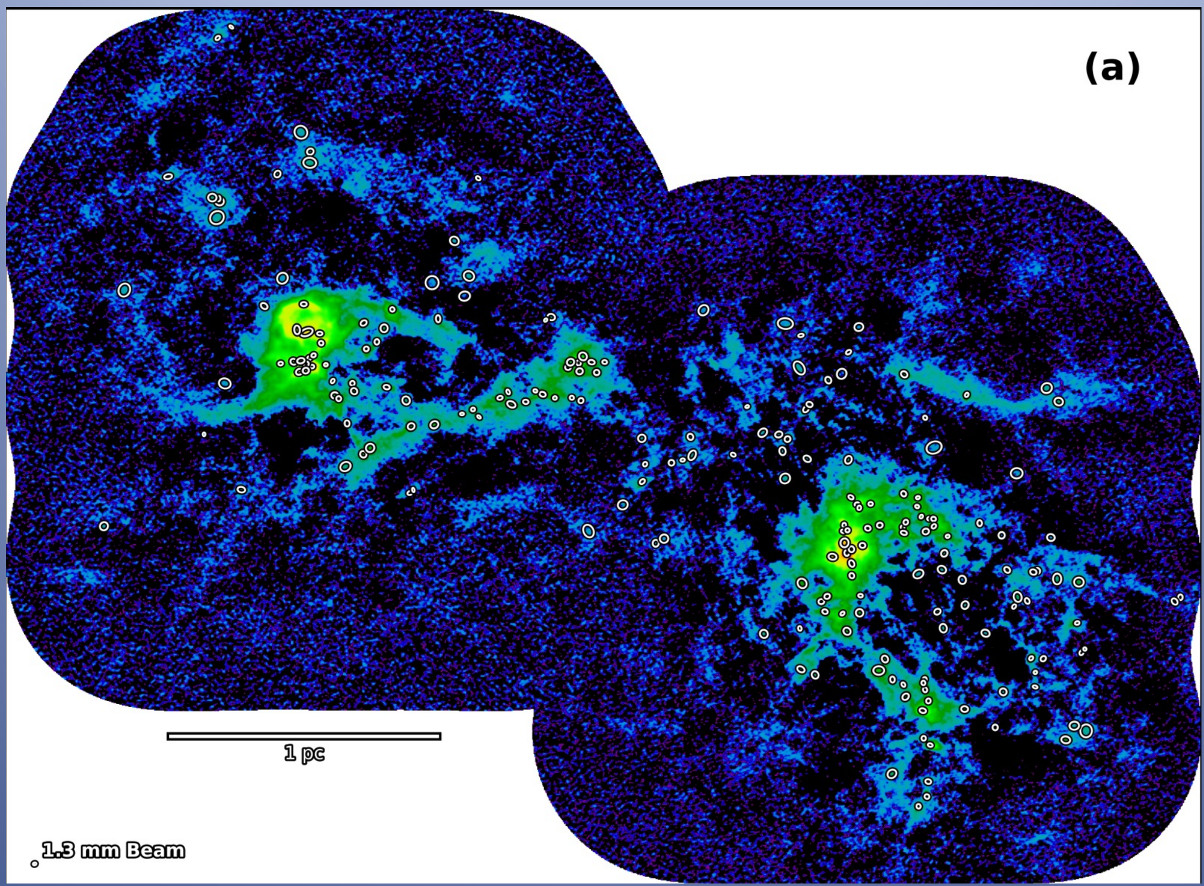
Future Cycles

- Now running in “Full Science” state, with mean data rates ~100Mb/s during observations
  - “Duty cycle” of observations will slowly increase as testing and maintenance procedures improve.
- Best guess estimate for Archive growth in the next 3 years is around 400-500TB/yr (raw data and products roughly equal)
- Important to note that data rates vary through the configuration cycle. When long baseline configurations are scheduled the data rate goes up for these reasons:
  - Data sampling needs to be faster to prevent beam smearing at the field edges
  - The data products, which are also mirrored from Santiago, also increase in size, to become larger than the raw data in the largest configurations
  - So far, long baseline campaigns have tended to have low observing efficiencies, however this may change
- Science Ready Data Products
  - Archive access will be enhanced by providing interactive tools for research using public data

Summary

- Ramp-up of the ALMA data rate has been slower than anticipated, allowing us to stay ahead of the curve.
- Data flow mostly from JAO to ALMA Regional Centers, with data processing mostly at JAO.
- Still monitoring how the network performs when transferring ~10TB/day in multiple parallel streams.
- We must establish a link with 10Gb/s of dedicated bandwidth within the next 1-2 years to improve transfer speed to and from Chile for bulk reprocessing, and to help with occasional large data and metadata transports (e.g. a DB export).
- Most new developments (e.g. next generation correlator) on ~5yr timescale can probably be accommodated without increasing the data rate by more than a factor ~4.

Questions?



Mini "star-burst" studied by Pouteau et al. (2022), based on ALMA Large Program data