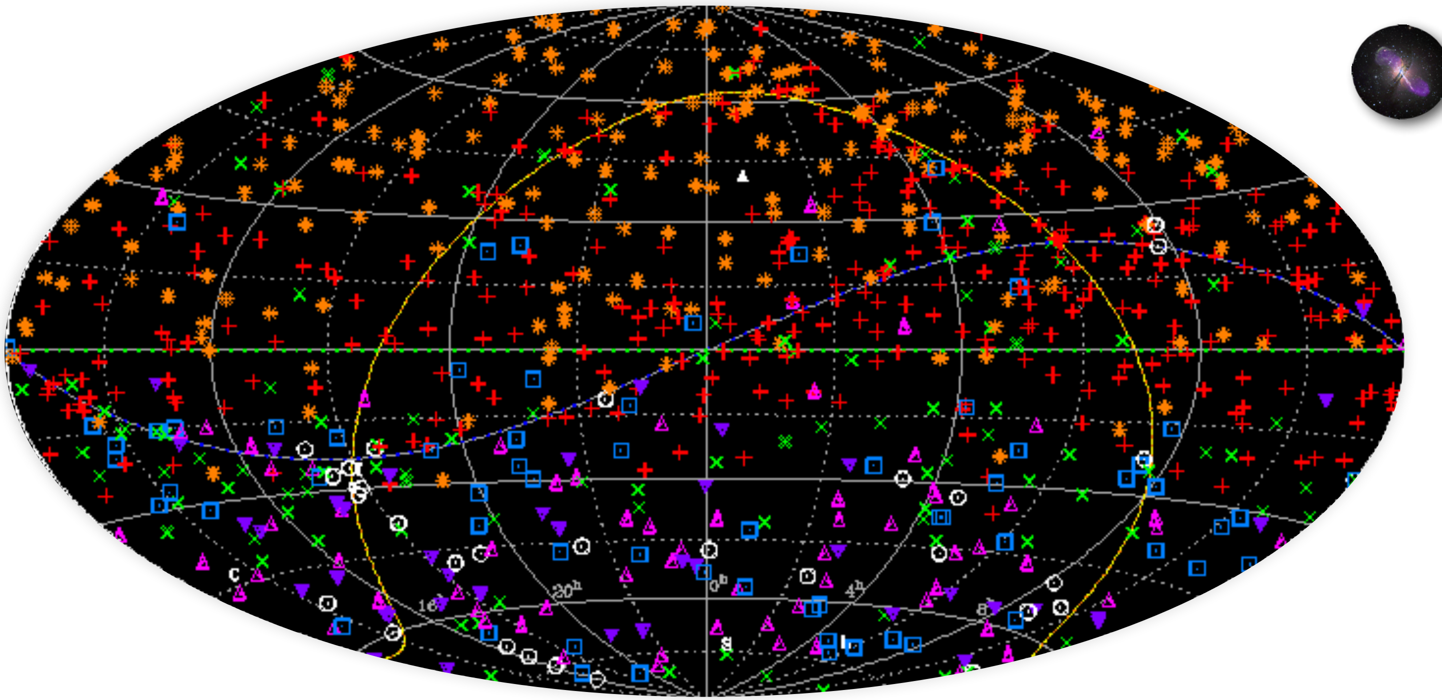
Journées, Paris, October 2019

K-band Celestial Reference Frame: Roadmap



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NASA NRF National Research Foundation SARAO South African Radio Astronomy Observatory UTAS Astronomical Institute of the Czech Academy of Sciences TU WIEN NVI, INC.

Context: Celestial Reference Frames

History: VLBI at SX (8 GHz, 3.6cm) has been only sub-mas frame until last 10 years
(e.g. *Ma+, ICRF1, 1998, Ma+, ICRF2, 2009*)

VLBI: ~100 μas or better precision

- SX-band (8 GHz, 3.6cm) *(Charlot et al, ICRF-3, 2019, in prep)*
- K-band (24 GHz, 1.2cm) (*Lanyi+, 2010; de Witt+, 2018*)
- X/Ka-band (32 GHz, 9mm) (*Jacobs+, 2018*)

- Accuracy limited by VLBI systematics due to weak southern geometry, troposphere etc.

Optical

- Gaia Data Release #2 precision ~250 μas for radio loud quasars (*Mignard+, 2018*)

Goal: Address K-band limitations from Sensitivity, Ion cals, and Geometry
to drive K-band accuracy below S/X structure noise floor

Why build a Celestial Reference Frame at K-band?

- S-band usefulness is decreasing

  Very few new missions at S-band

  RFI at S-band is degrading the band (Wi-Fi etc.)

  Source structure worse at low frequencies

- X-band the "workhorse" frequency for now

  but SX being hurt by S-band RFI issues

  X-band has structure issues

- **K-band advantages:**

  More compact source morphology

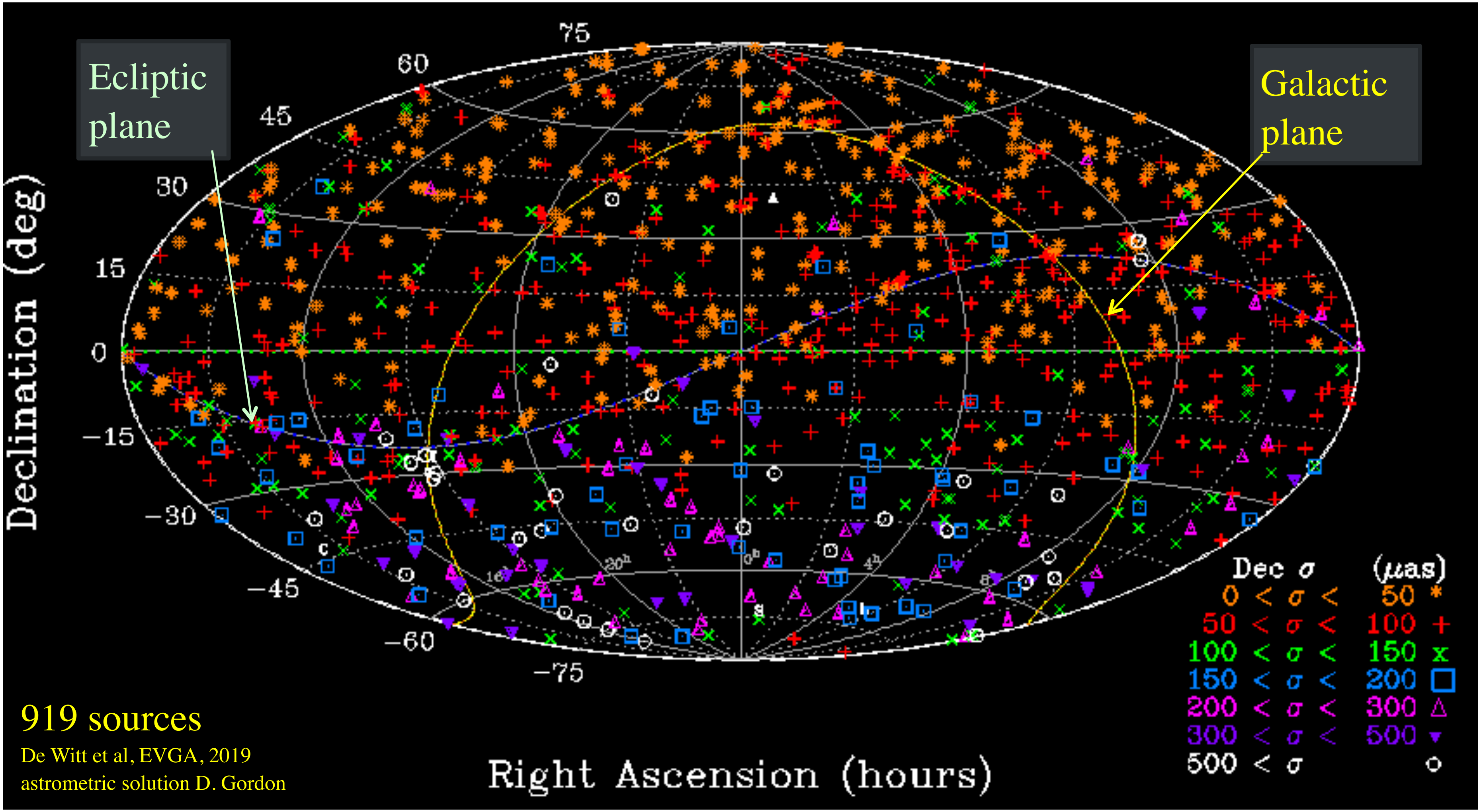
  Solar plasmas effect reduced as 1/ frequency squared

  Allows observations closer to Sun

  Allows observations closer to galactic plane

  Allows differential VLBI on water masers e.g. BESSEL project

K (24 GHz, 1.2cm) *VLBA+(HartRAO-Hobart)*



- Strengths:
  - Uniform spatial density, 919 sources
  - Galactic plane sources (Petrov+ 2011)
  - less structure than S/X (3.6cm)
  - median RA/Dec precision ~40 / 80 μas
  - needed ~ 0.5 million observations vs. SX's 13 million!

- Weaknesses:
  - Ionosphere imperfectly calibrated by GPS. Few %?
  - South ($\delta < -30$ deg) weak due to limited South Africa-Tasmania data

The VLBA is operated by the LBO since Oct. 2016 (previously by NRAO), both facilities of the National Science Foundation operated under cooperative agreement by Associated Universities.
The authors gratefully acknowledge use of the VLBA under the USNO's time allocation. This work supports USNO's ongoing research into the celestial reference frame and geodesy.
HartRAO is a facility of the National Research Foundation (NRF) of South Africa.
The Hobart telescope is operated by the University of Tasmania and this research has been supported by AuScope Ltd., funded under the National Collaborative Research Infrastructure Strategy (NCRIS)

K-band Limitations

- Many errors in common with S/X: troposphere, clocks, geophysics

K-band differences from S/X

- **Ionosphere:** no dual band, must use GNSS calibrations
  Solar plasma negligible at K (24 GHz) [Soja, EVGA, 2019]

- **Geometry:** far fewer K-band stations doing reference frames

- **Sensitivity:**
  Water line (22 GHz) increases system temperatures,
  pointing, surface accuracy etc. more difficult
  sources lower flux or flux resolved out

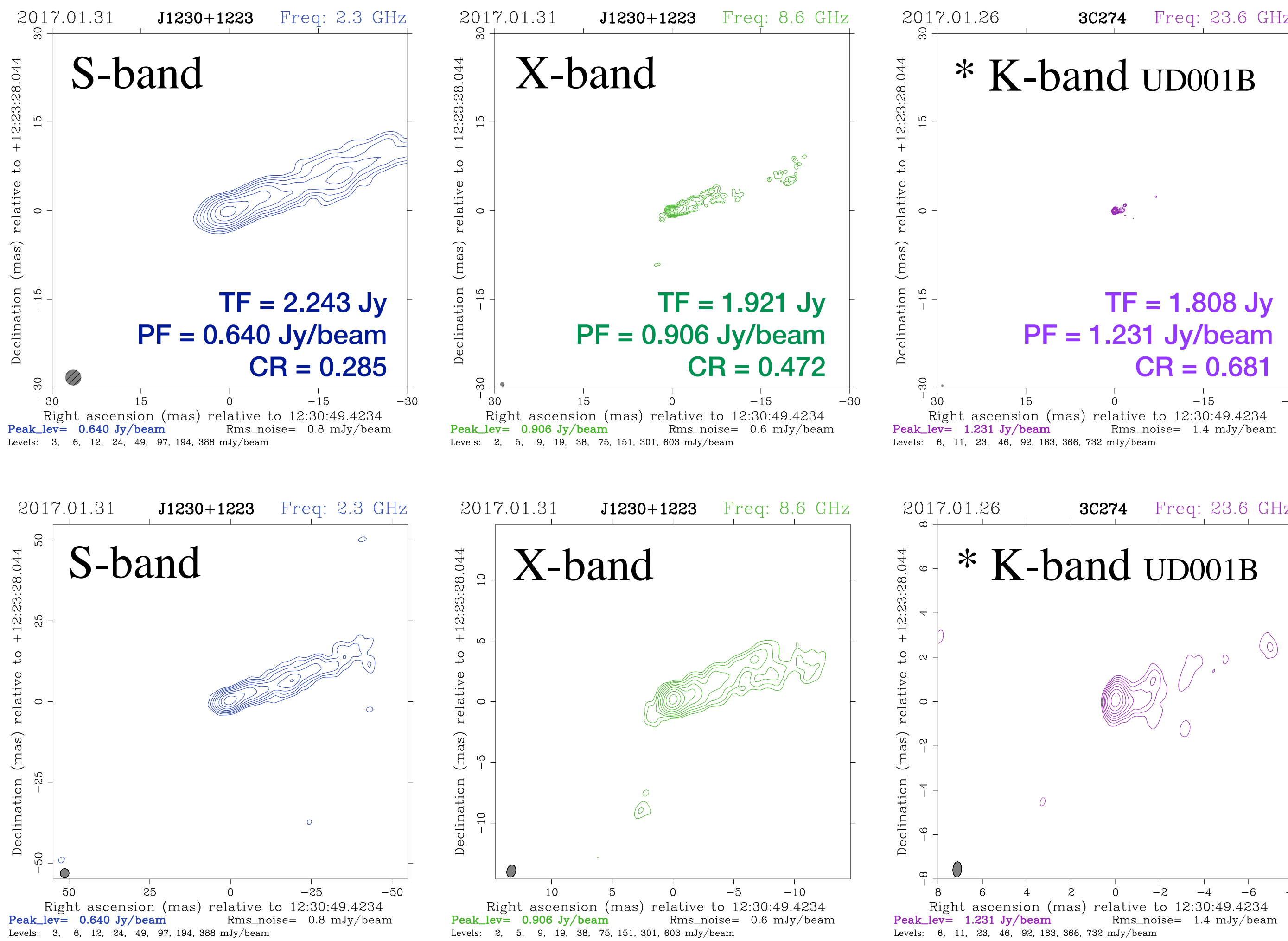
- **K-band structure is better**

Source Structure: Imaging Results

3C 274

January 2017
30x30 mas maps

January 2017
(same beam_min axis)



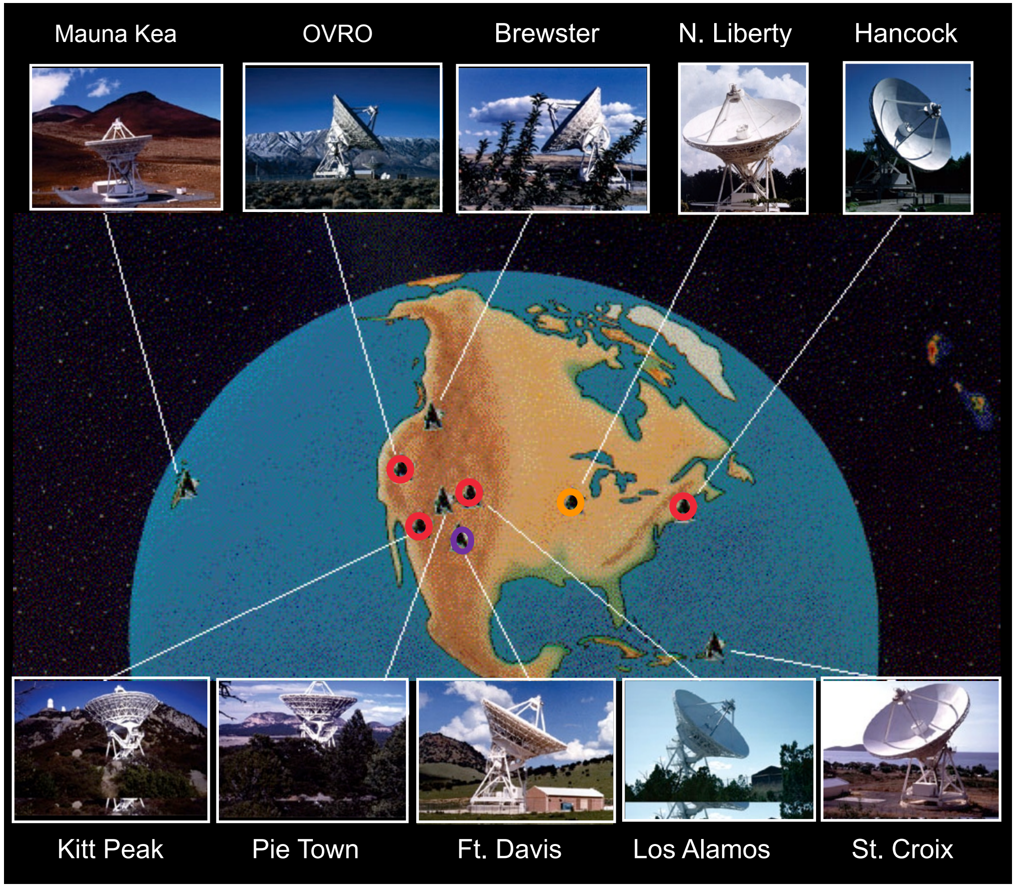
see poster by de Witt et al., Journées 2019

Image credit: S- and X-band, Leonid Petrov, www.astrogeo.org

Ionosphere Calibrations

- Total effect on CRF is Δδ ~ 350 μas cos(δ) [before calibration]
  Current cals appear to get at least 90% of long term effect
- **Improving coverage:** VLBA has geodetic quality receivers at only 5 of the 10 sites
  - Coverage gaps:

    NL broken
    HN, OV, KP, LA missing
    FD offset (McD)
  - W. Brisken made recommendation to fill in other 5 sites to National Academies geodetic infrastructure committee at Oct. 2018 meeting. Good response.
  - NOAA interested



Very Large Baseline Array http://www.vlba.nrao.edu/

Ionosphere Calibrations

- **Current GNSS cals:** JPL operational ion maps
  2 hour average, 2.5 x 5 deg spatial resolution.
  2-D shell model

- **Improved analysis:** JPL R&D cals
  15-minute temporal resolution: 8X improvement
  3-D ionosphere model (using *radectec* software)
  15 min cals work well for all stations except Hobart
  (not enough data from GNSS stations in the vicinity)

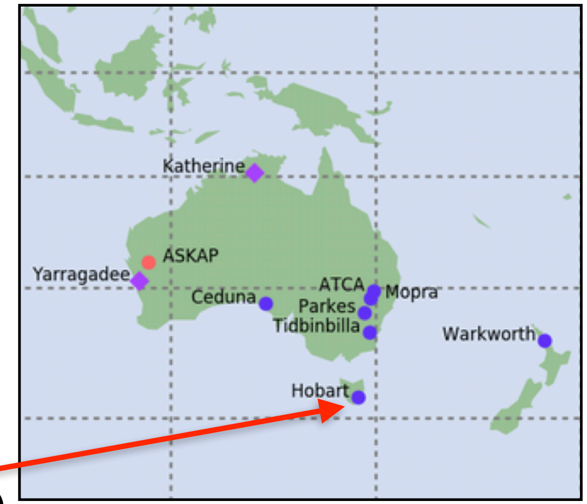
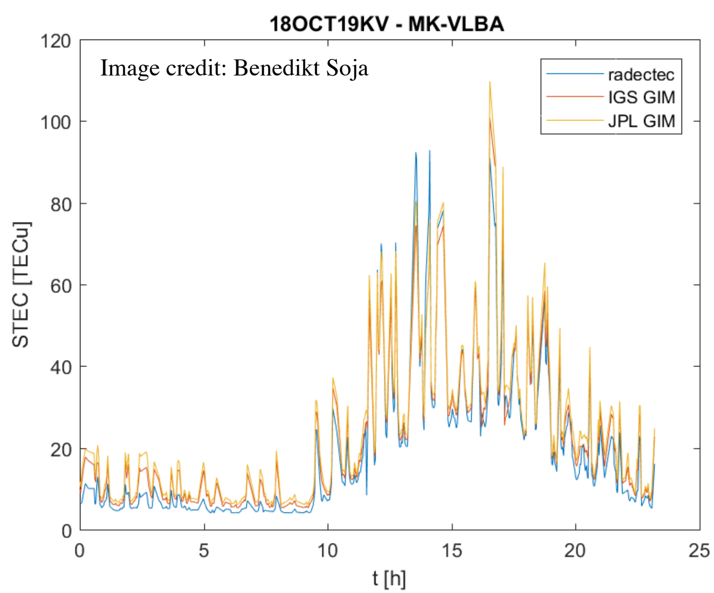


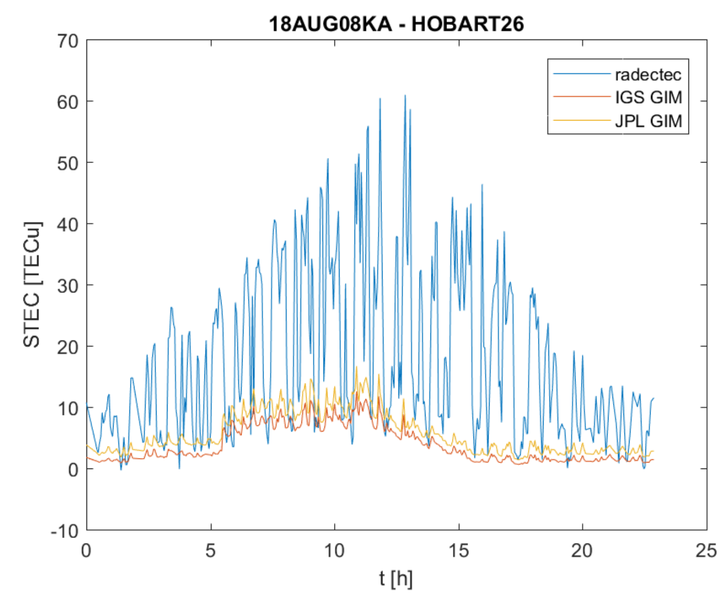
Image credit: Cormac Reynolds, VLBI Developments in Australia

STEC for VLBA & Hobart

IGS & JPL 2 hr GIMS

radectec 15 min cals



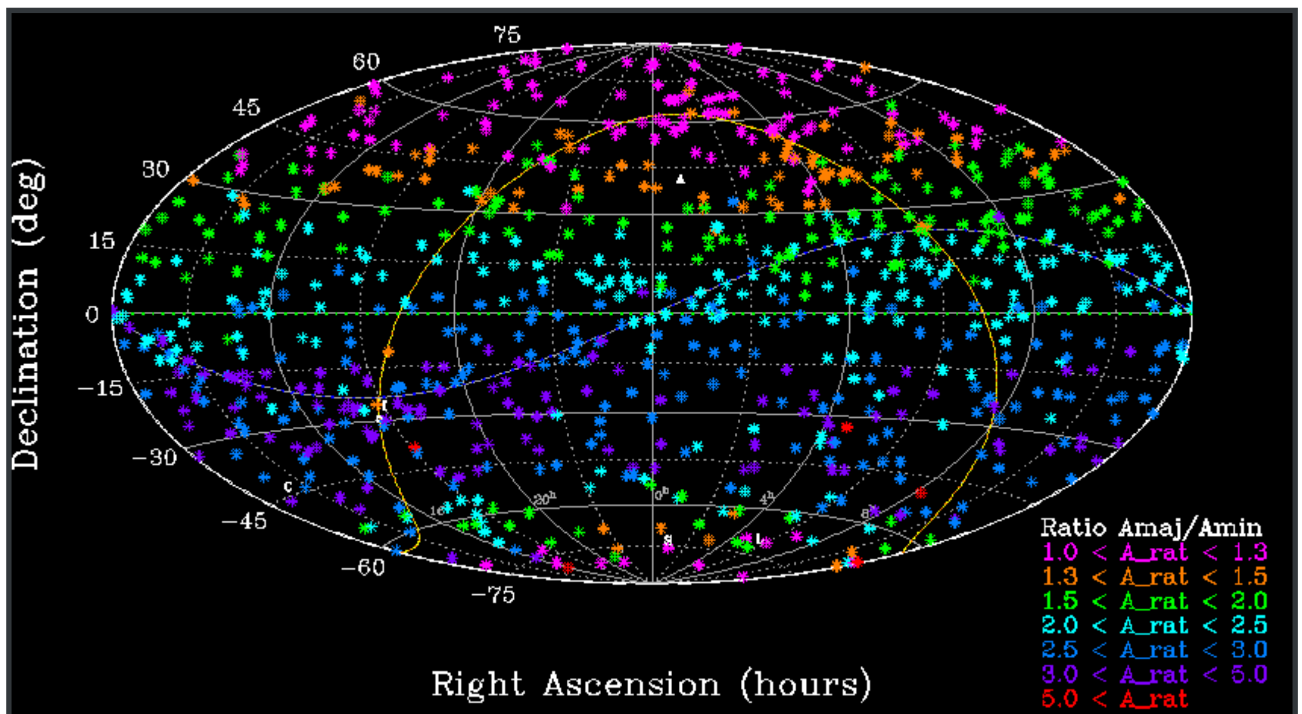


Geometry: Network limitation

- K-band network is essentially two independent networks with partially overlapping coverage
  North: VLBA covers +90 to -40 deg Declination
  South: HartRAO-Hobart covers -90 to +0 deg Declination

- Need North-South baselines to improve declination precision > 2X

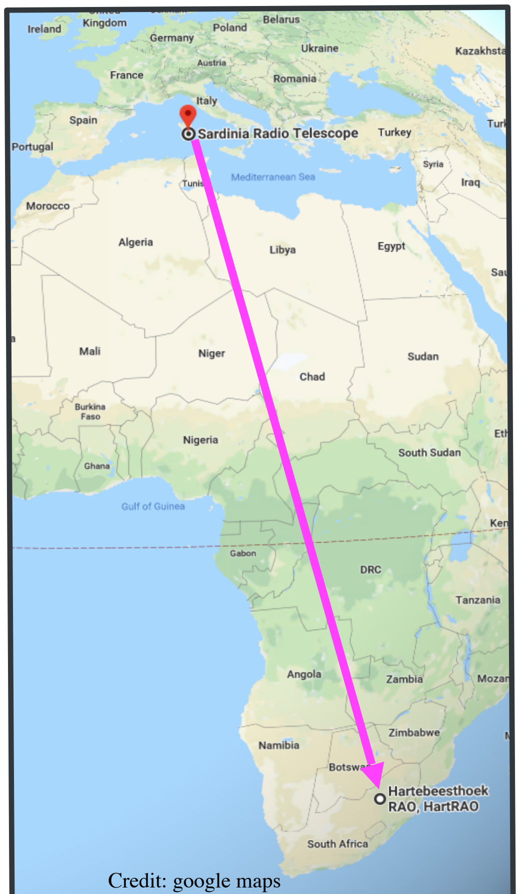
Error ellipses
Elongated
by 2-5X
in δ direction



Geometry: Need North-South Baselines

- Need North-South baselines to improve δ precision 2 to 5X

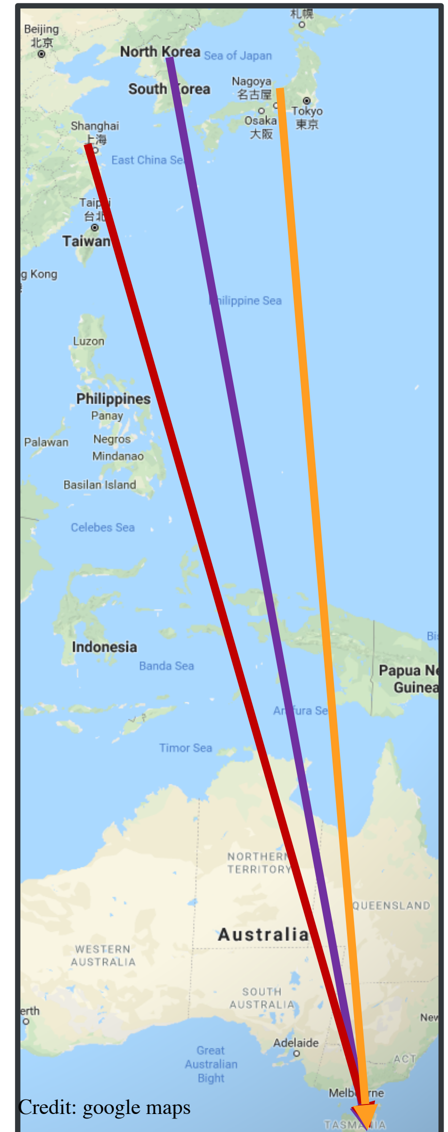
Investigating:



Credit: google maps

- Sardinia 64m (Noto/Medicina 32m) to HartRAO, South Africa fringe test in preparation (Matteo Stagni is point of contact)

- Korea VLBI Network/ Shanghai 64m/ Japan to Hobart, Tasmania

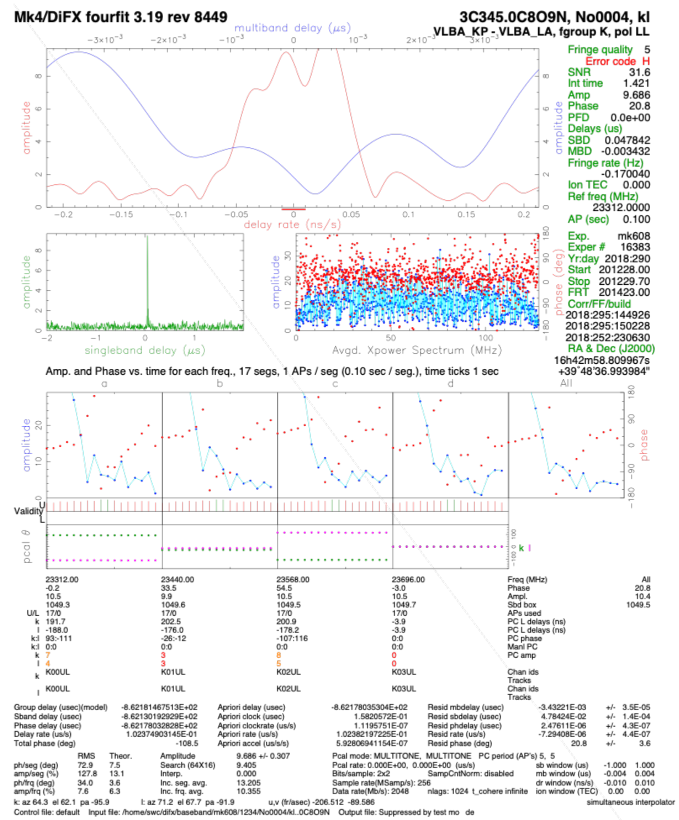


Credit: google maps

Sensitivity: 2 Gbps -> 4 Gbps

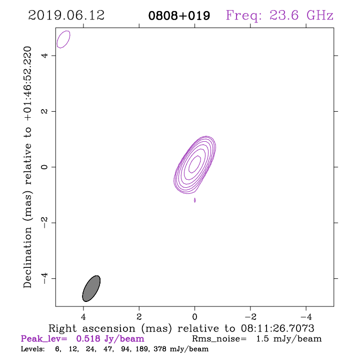
VLBA Mark6 first 4 Gbps fringes at K-band!

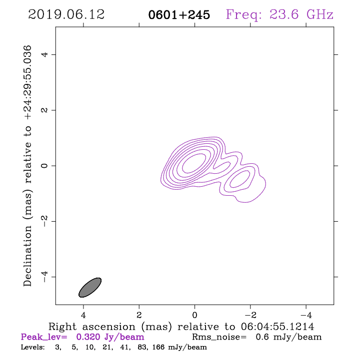
RCP-RCP
512 MHz, 2-bit
SNR 26.9, Tint=1.4 sec



Credit W. Brisken et al, 2018

LCP-LCP
512 MHz. 2-bit
SNR 31.6, Tint=1.4 sec





Full stokes intensity images

9 stations tested so far and first imaging results! see poster by de Witt et al., Journées 2019

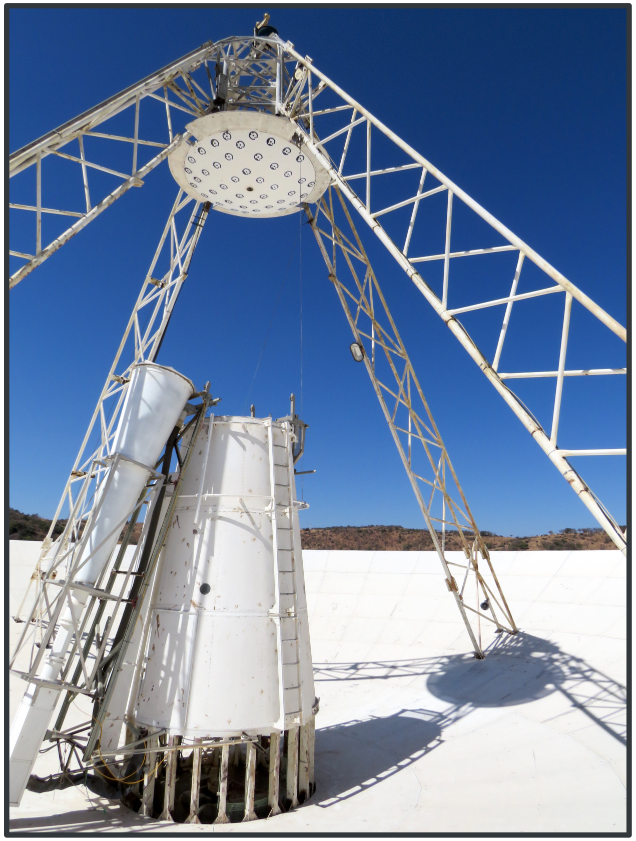
Sensitivity: Improve HartRAO

- HartRAO 26m, South Africa is workhorse in south
- Panels upgraded in 2005 to K-band quality

Possible improvements on few year timescale

- Subreflector has been set, new tilt and focus encoders installed.
  control system upgrade should allow focusing
- Encoders ageing, new ones purchased, awaiting bearing repair
  should allow pointing refinements
- Digital Back End enhancements
  may allow 4-8 Gbps in few years

see poster by Nickola et al., Journées 2019



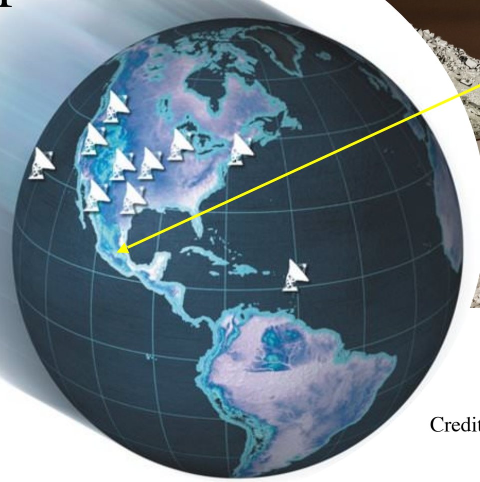
HartRAO 26m Photo credit: Marisa Nickola

Sensitivity: Add large aperture

- Large Millimeter Telescope (50-m)
  interested in joining K-CRF session on VLBA
  19 deg latitude parallel to St. Croix and Mauna Kea
  High (4600m), dry site, Mexico

- Would double sensitivity of 10 baselines to VLBA
- Laurent Loinard is point of contact
- Need VLBA compatible receiver

Credit: Meridith Kohut for The New York Times

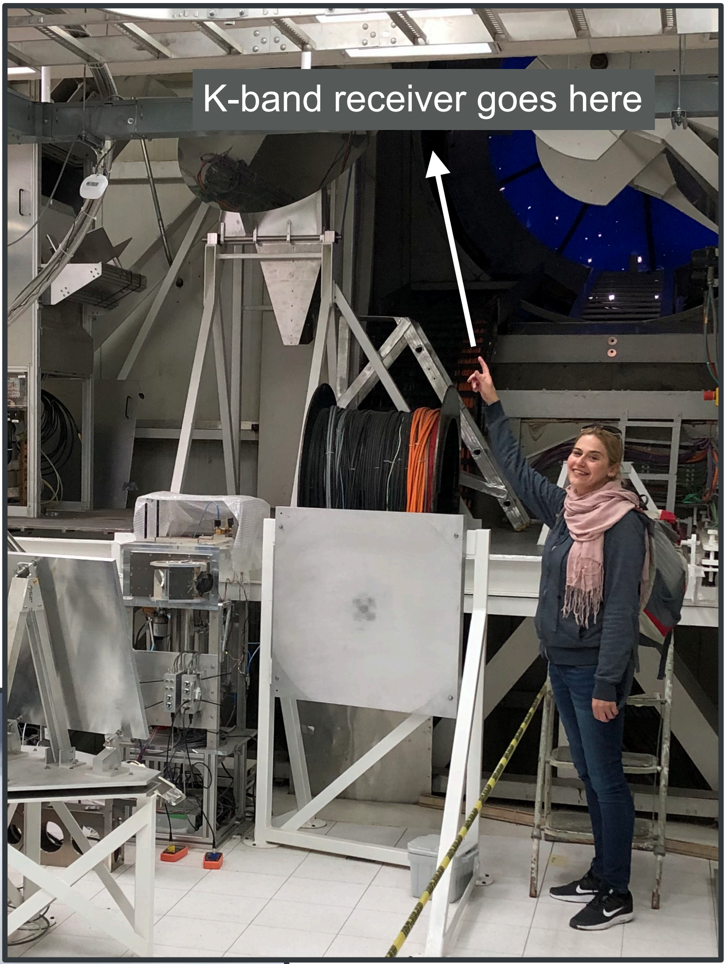


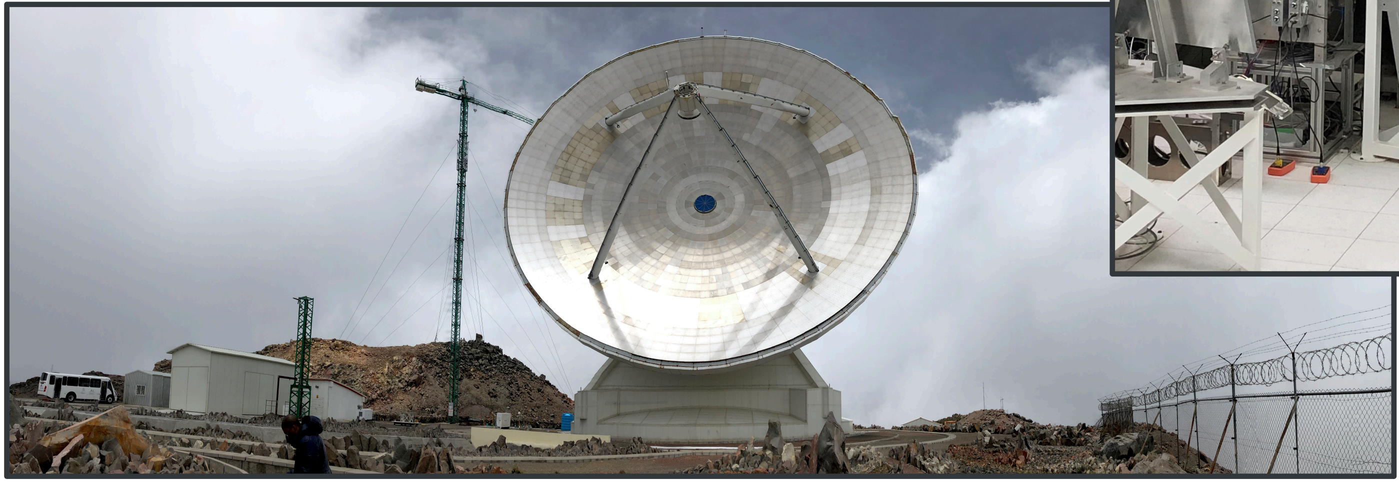
Credit: NRAO/AUI

Sensitivity: Add large aperture

[Roadmap for LMT K-band receiver]

- January 2019 INAOE, Mexico:
  1st meeting on K-band receiver for LMT
- June 2019 INAOE, Mexico:
  2nd meeting and visit to LMT site
- Next step: white paper to be completed by October 2019





LMT, Photo credit: Aletha de Witt

Summary: K-band (24 GHz) Roadmap

- **Motivation:** 3rd International Celestial Reference Frame (ICRF-3) adopted K-band as a component in August 2018.
  For the first time ICRF is multi-wavelength.
  Images re-confirm structure is better

Roadmap to overcoming three main current limitations:

- **Ion cals:** Equip remaining 5 VLBA sites with GNSS receivers
  Move to JPL R&D 15 minute maps, 3-D modelling

- **Geometry:** Add North-South baselines
  Sardinia 64m - HartRAO
  East Asia - Hobart, Tasmania

- **Sensitivity:** VLBA increase to 4 Gbps
  HartRAO: subreflector, encoders, 4 Gbps
  Add LMT: doubles sensitivity on 10 baselines to VLBA!