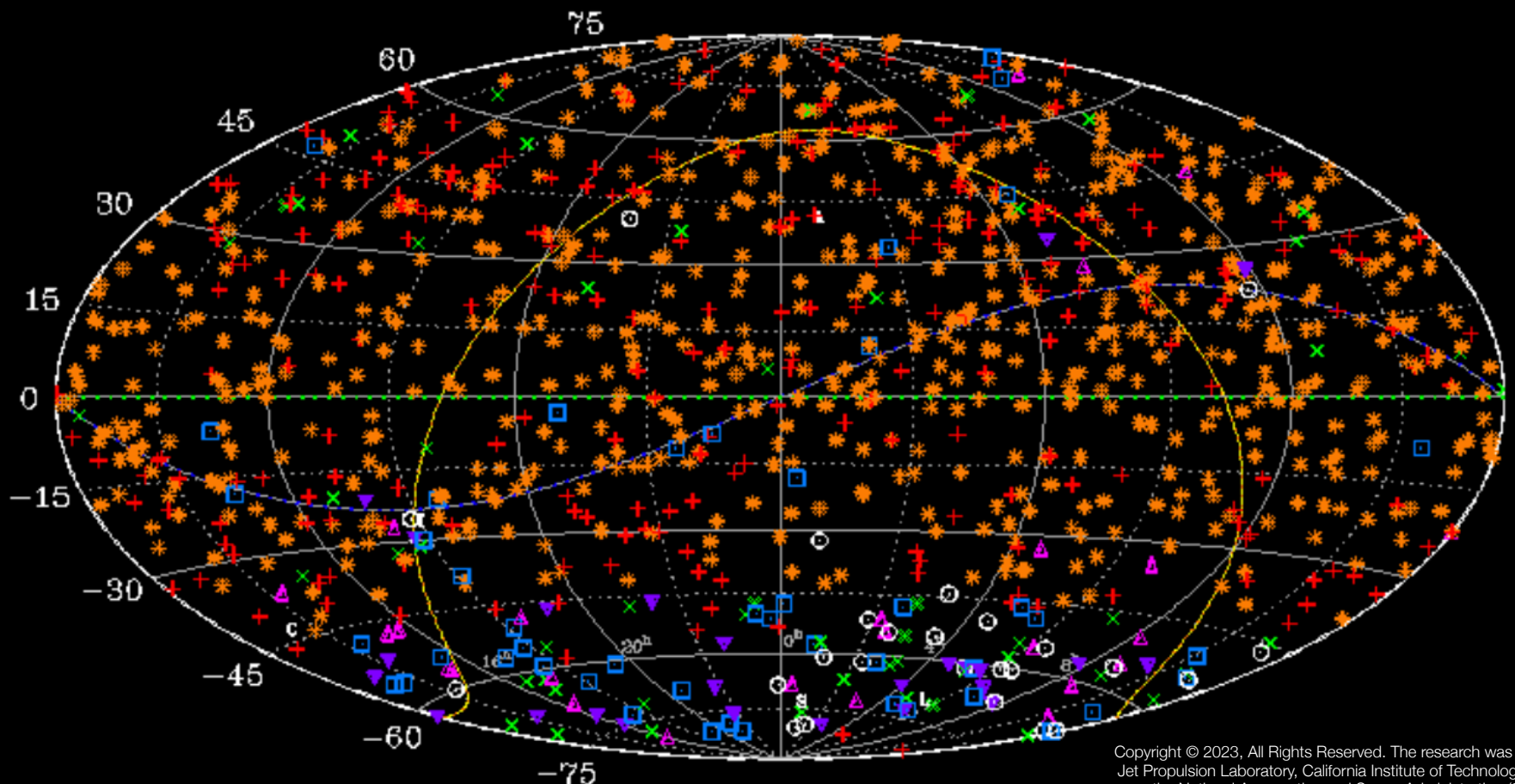
Journées des systems de référence spatio-temporels, Nice, France, 11-13 September 2023

The K-band (24 GHz) Celestial Reference Frame: Current Status and Roadmap



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A. de Witt (2), D. Gordon (3), H. Krásná (4), C. García Miró (5), M. Johnson (3), T. Jung (6), J. Hodgson (7), J. McCallum (8), J. Kooi (1), J. Blanchard (9)

(2) SARAO, South Africa, (3) United States Naval Observatory (USNO), USA, (4) Technische Universität Wien (TU Wien), Austria, (5) Yebes Observatory, National Astronomical Obs. (OAN), Spain, (6) Korea Astronomy and Space Science Institute (KASI), Korea, (7) Sejong University, Korea, (8) University of Tasmania (UTAS), (9) NRAO, USA.

Context: Celestial Reference Frames

Current standard International Celestial Reference Frame (ICRF):

- ICRF-3 adopted by IAU in Aug 2018 *(Charlot et al, 2020)*
- High precision VLBI astrometric measurements of positions of ~ 5000 AGN
- First multi-frequency frame with catalogs at S/X, K, and X/Ka-band

- S/X-band (8 GHz, 3.6 cm)
- K-band (24 GHz, 1.2 cm)
- X/Ka-band (32 GHz, 0.9 cm)

~100 μas or better precision

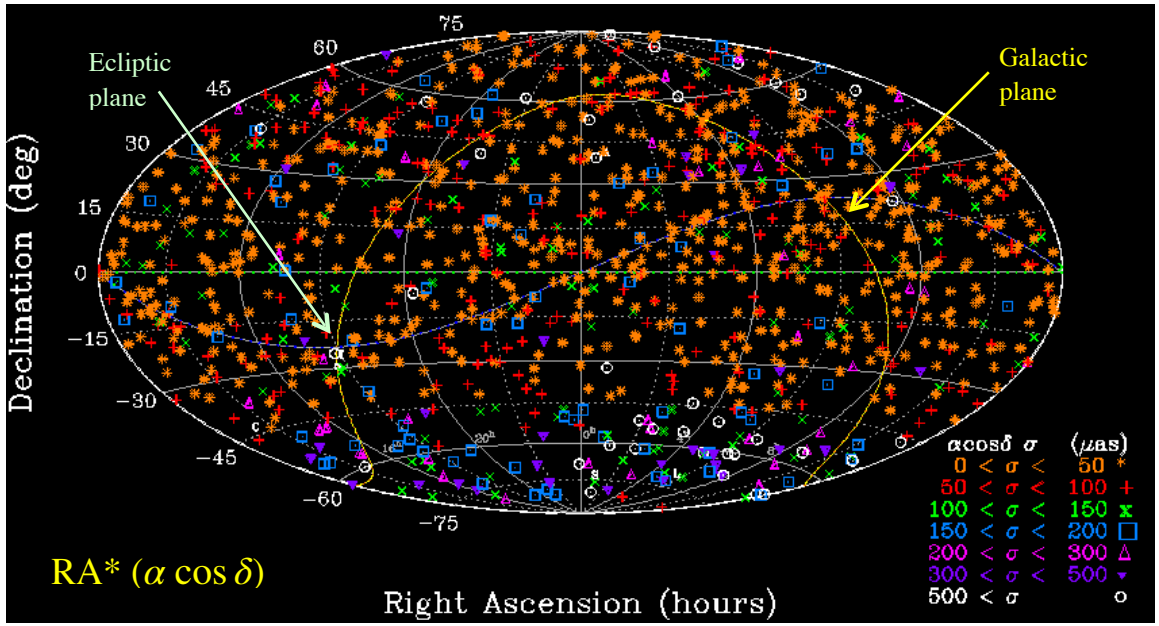
★ **We are investigating the potential for a Q-band CRF (43 GHz, 0.7 cm)**

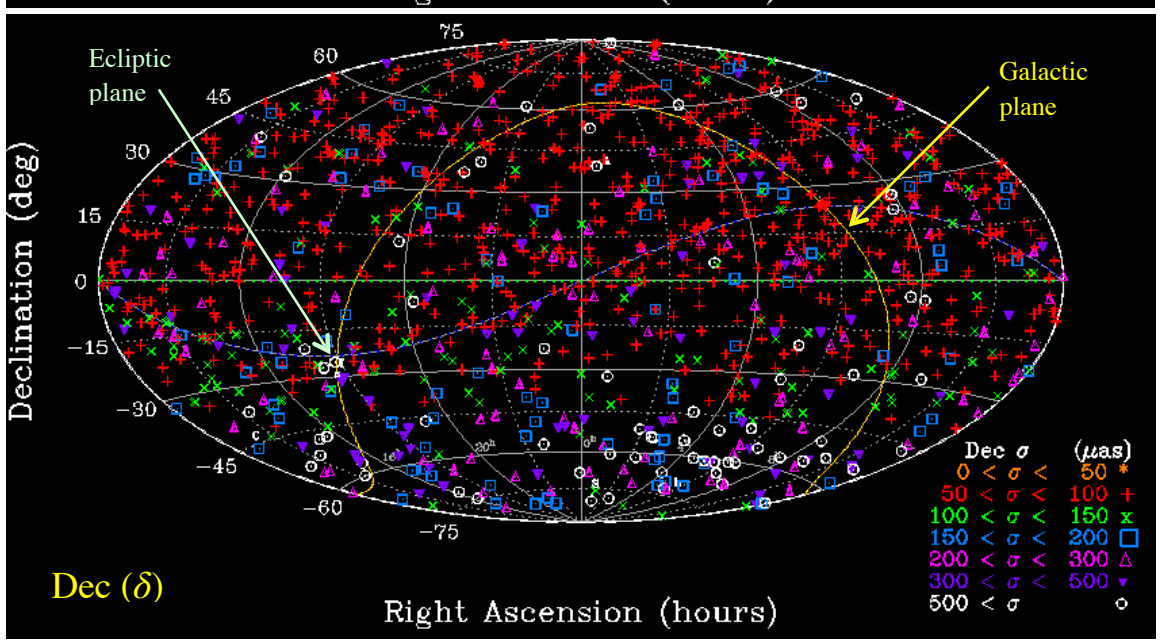
Motivation for higher frequency bands:

- **S/X-band being hurt by S-band RFI issues** —> degrading ability to collect clean S/X data
- **Allows observations closer to Sun** —> solar plasma effect reduced as 1/ freq squared
- **Allows observations closer to Galactic plane** —> less broadening by Galactic scattering
- **Provides calibrators for VLBI** —> phase-referencing + differential astrometry at higher frequencies
- **Many stations typically have K-band receivers** —> precise station locations for EVN *(Gomez et al, 2020)*
- **Factor of ~3 improvement in interferometer resolution relative to standard S/X-band**

★ More compact source morphology and reduced core-shift effect

Current Status: K-band CRF





1187 sources (2002-2023)
2.3 million observations
astrometric solution D. Gordon
solution date 2023 Aug 24.

K median precision RA*/Dec 50 / 84 μas

1089 sources in common with the SX-band frame, after removing 61 outliers > 5-σ

wRMS K vs. ICRF3-SX 117/ 165 μas in RA/Dec*

Vector spherical harmonic difference: largest ~60 μas

- Strengths:
  - Uniform spatial density
  - Best band for near Galactic plane
  - Less structure than S/X (3.6 cm)
  - Precision comparable to S/X
  - 2.3 million observations vs. SX's 17.6 million!
- Weaknesses:
  - Ionosphere imperfectly calibrated by GPS
  - South (δ < -30 deg) weak due to limited South Africa-Tasmania data
  - Precision much worse in Dec than RA direction, lack of data on north-south baselines longer than ~3000 km.

Over 90% of the K-band CRF observations are from VLBA sessions supported through the USNO's 50% timeshare allocation

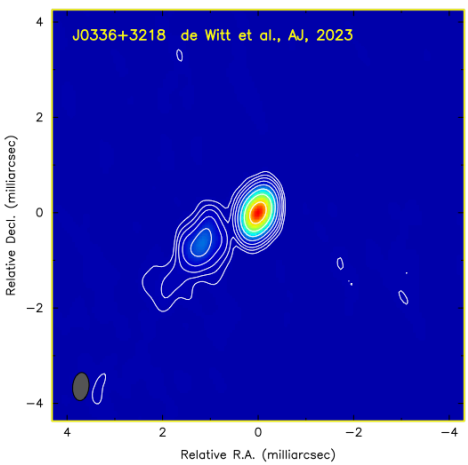
Current Status: K-band Network

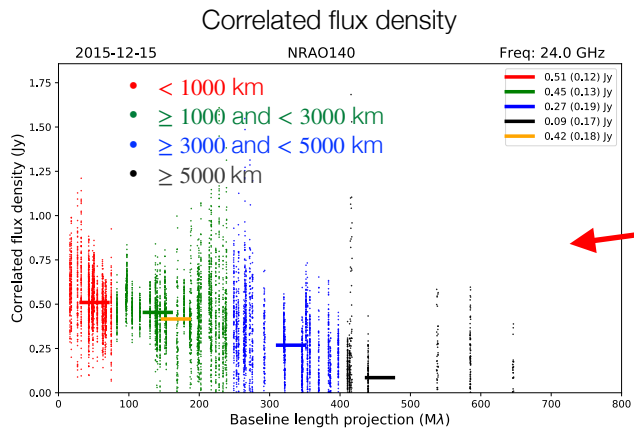
- 10 VLBA Stations (4 Gbps, dual-pol)
- HartRAO-Hobart (2 Gbps, RCP)

- HartRAO-Yebes (4 Gbps, dual-pol, Oct 2022, 2 sessions in K-CRF)
- HartRAO-KVN-Yebes (2 Gbps, RCP, March 2023)
- HartRAO-KVN-~~Hobart~~-Mopra (2 Gbps, RCP, March 2023)

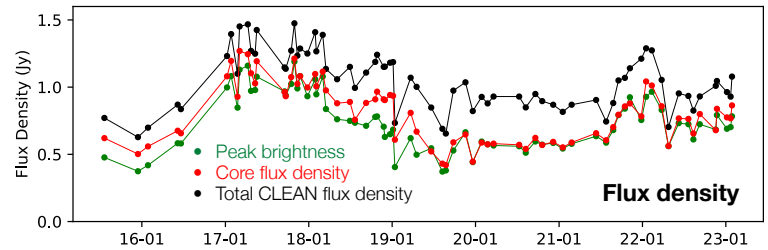
Current Status: Imaging & structure metrics

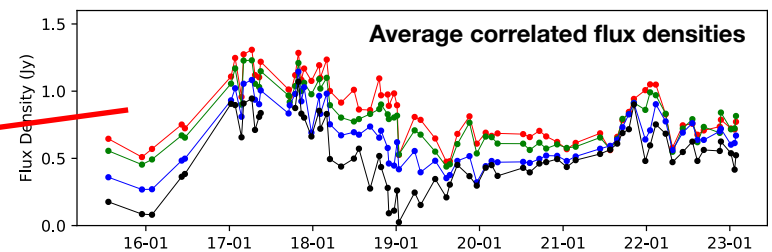
Imaging of VLBA K-band CRF sessions: total of 87 epochs between Jul 2015 and Jan 2023 *(de Witt et al., 2023, AJ & this meeting poster)*

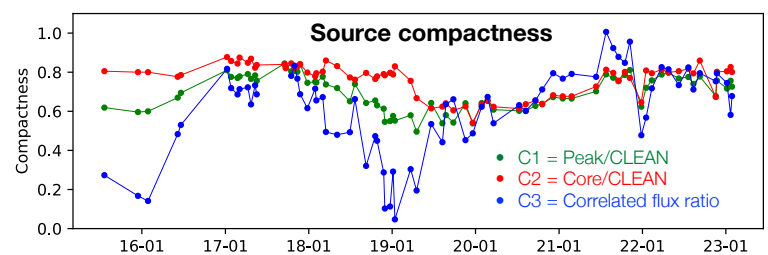


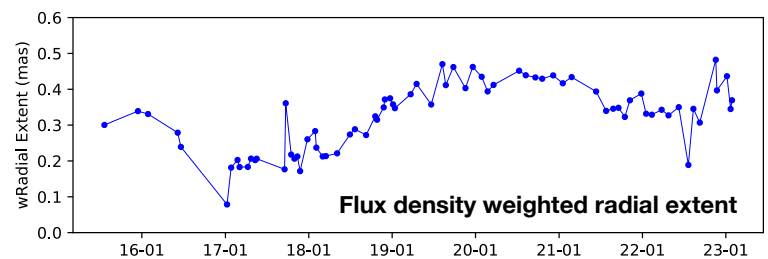


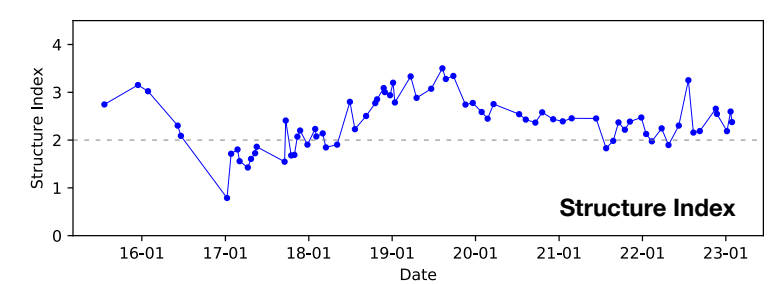
NRAO140: 73 epochs



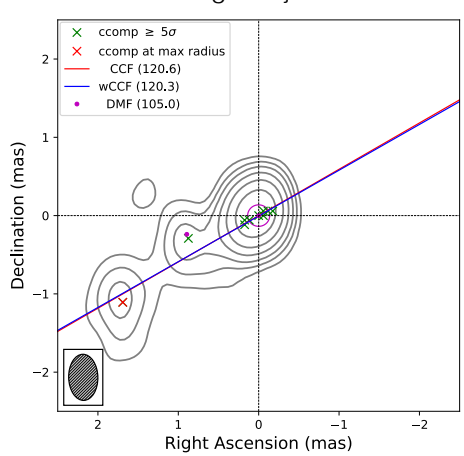




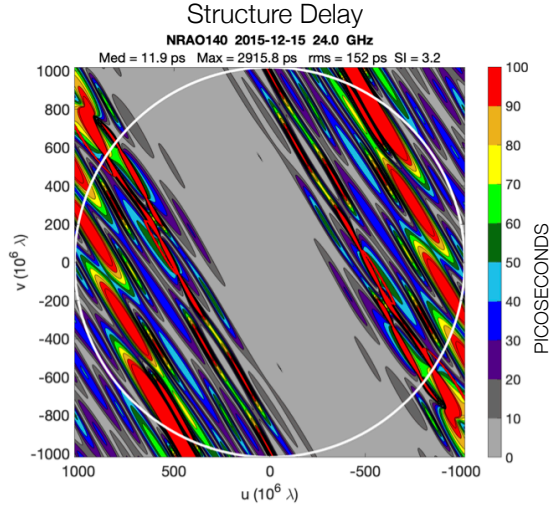




Modellfitting and jet directions



Structure Delay

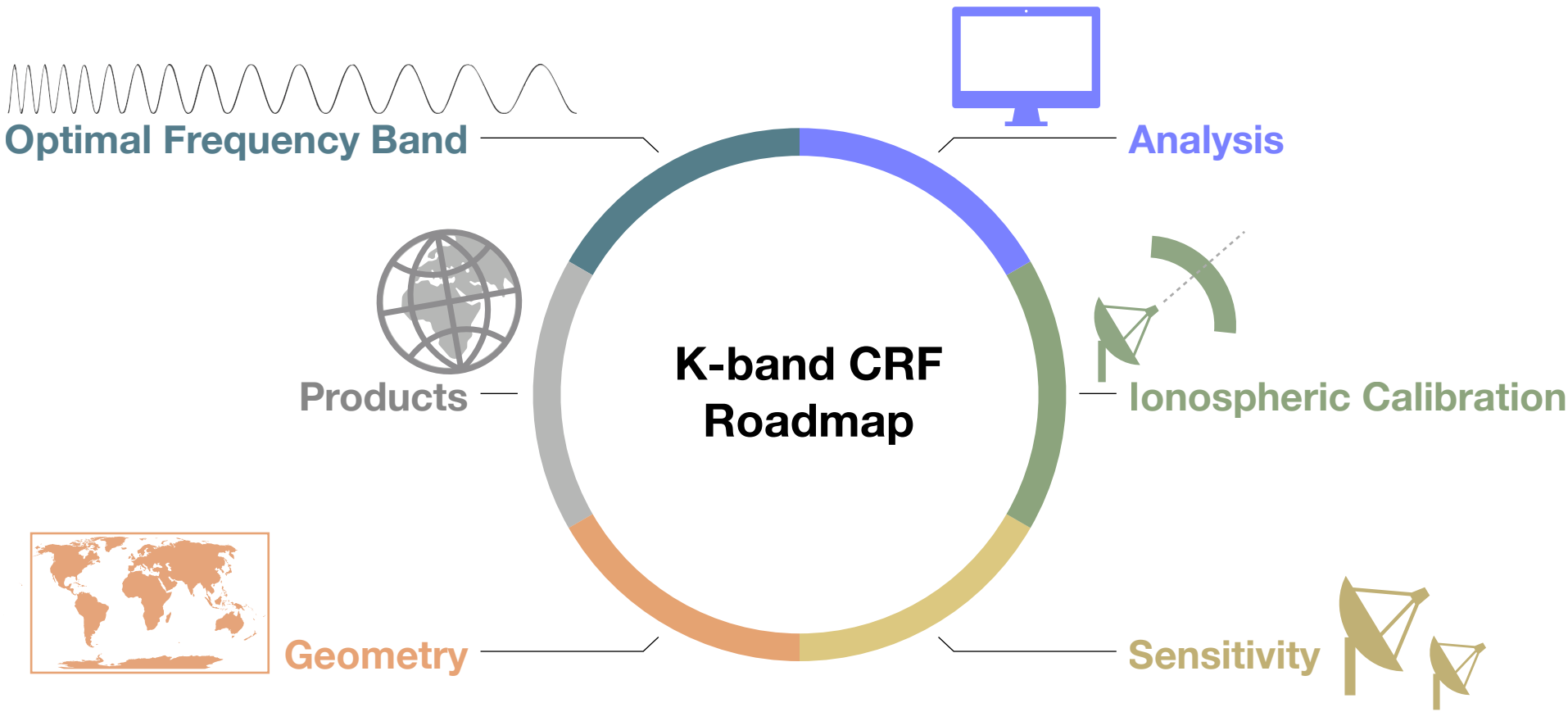


92% of the K-band CRF observations are from VLBA sessions supported through the USNO's 50% timeshare allocation

K-band Roadmap: Overview

Many efforts to continue the maintenance and improvement of the ICRF *(IAU 2018 Resolution B2, de Witt et al., 2022)*

Future ICRF likely to be multi-wavelength, incorporating also optical realization by *Gaia* *(IAU WG: Multi-waveband ICRF)*



K-band Roadmap: Analysis

Improve K-CRF analysis:

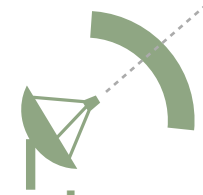
- **Analyst noise: Compare software packages (VieVS & Calc/Solve)** *(Krásná et al., REFAG, 2023)*
- **Troposphere: incorporate elevation dependent weighting** *(Hana Krásná)*
- **Ionosphere cals: modified mapping functions, JPL 3-D cals** *(Soja et al., 2019, Krásná et al., 2023)*
- **Source structure effects corrected from images** *(de Witt et al., this meeting poster)*

Optimal Frequency Band

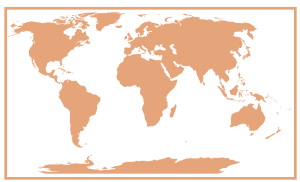
Analysis

Products

K-band CRF Roadmap

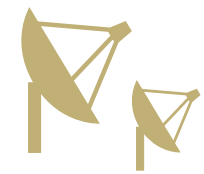


Ionospheric Calibration



Geometry

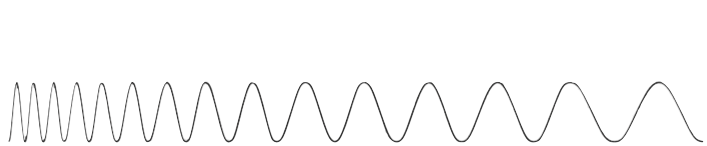
Sensitivity



** K-band CRF global solution and time series results are available from USNO: https://crf.usno.navy.mil/quarterly-vlbi-solution

** K-band data is available in the NRAO archive (both Mark4 and idifits databases): https://data.nrao.edu

K-band Roadmap: Ionospheric Calibration



Optimal Frequency Band

Analysis

K-band ion-cals based on GNSS calibration, no dual-band

Plans to equip all 10 VLBA stations with GNSS

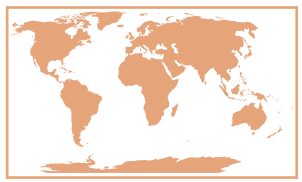
JPL 3-D ion cals, 15 minute resolution *(Soja al., 2019)*

JPL broadband (8-36 GHz) receiver on VLBA has potential to solve ion-cal issue (X/K dual-band) *(Kooi et al., 2023)*

Products

K-band CF.. Roadmap

Ionospheric Calibration



Geometry

Sensitivity

K-band Roadmap: Ionospheric Calibration

- VLBA has geodetic quality GNSS receivers at only 5 of 10 sites

Coverage Gaps:

NL broken
HN missing
OV missing
KP missing
LA missing
FD offset (McD)

- W. Brisken made recommendation to install new GNSS receivers at all 10 sites to National Academics geodetic infrastructure committee.
- Expected to be installed soon!

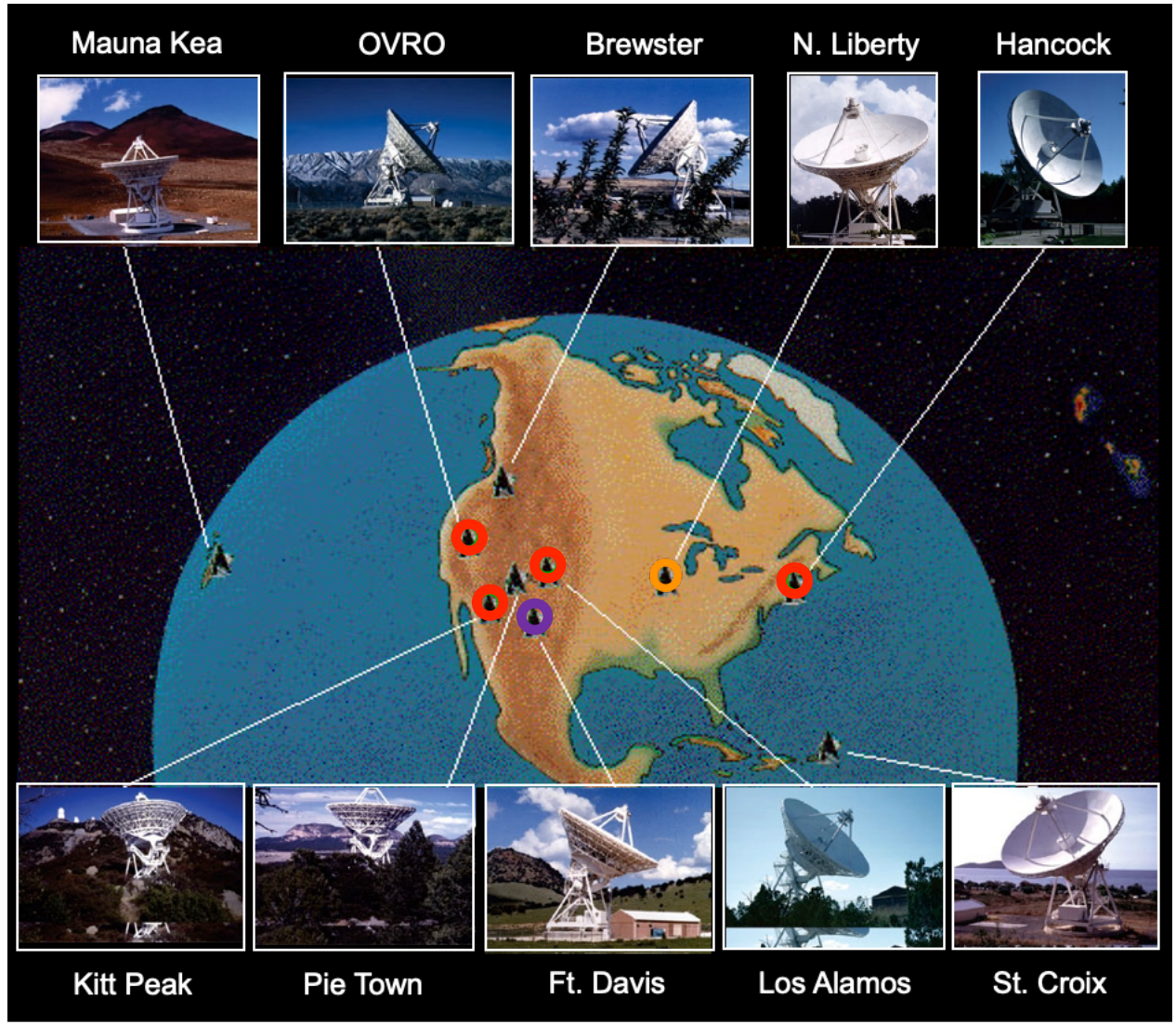


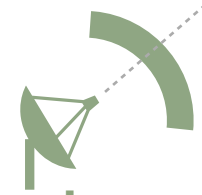
Image Credit: Very Large Baseline Array http://www.vlba.nrao.edu/

K-band Roadmap: Sensitivity

Optimal Frequency Band

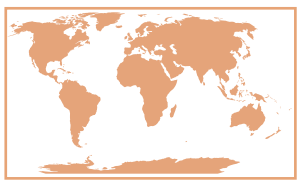
Analysis

Products



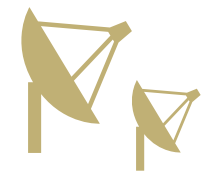
Ionospheric Calibration

K-band CRF Roadmap



Geometry

Sensitivity



VLBA planning to upgrade to data rate of 8 Gbps

Plan to upgrade HartRAO/Hobart to 4 Gbps

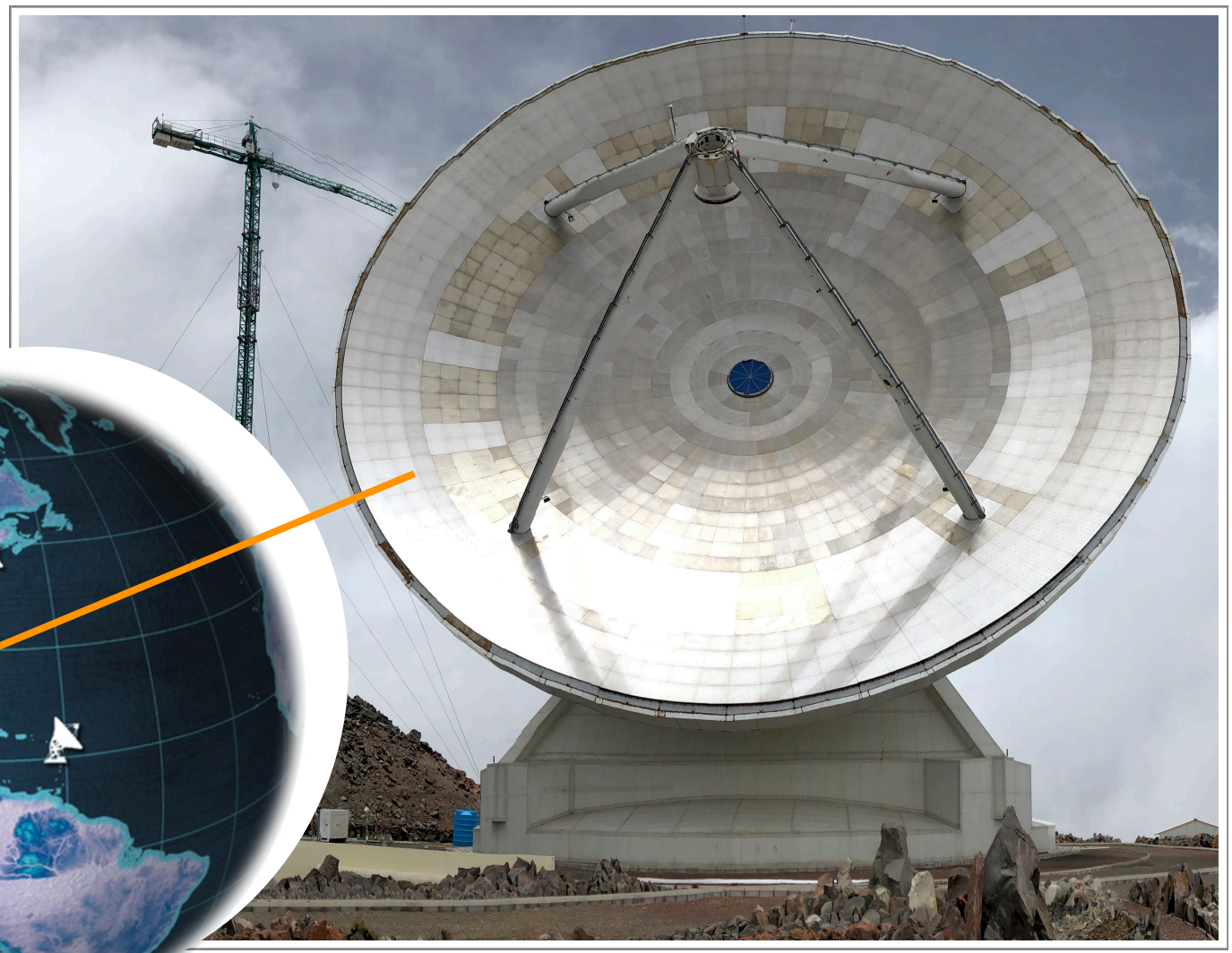
K-band on LMT 50m ~double sensitivity of VLBA baselines *(Kurtz et al., SPIE, 2020)*

JPL broadband receiver potential for 4 GHz analog ~factor of three increase in sensitivity *(Kooi et al., 2023)*

K-band Roadmap: Sensitivity

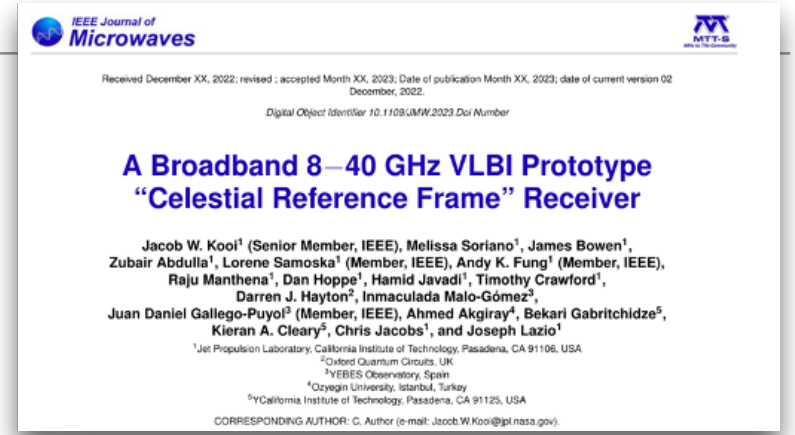
Large Millimeter Telescope (50-m) interested in joining K-CRF on VLBA *(Kurtz et al., SPIE, 2020)*

- 19 deg latitude parallel to St. Croix and Mauna Kea
- High (4600m), dry site, Mexico
- Would double sensitivity of 10 baselines to VLBA
- Need VLBA compatible receiver

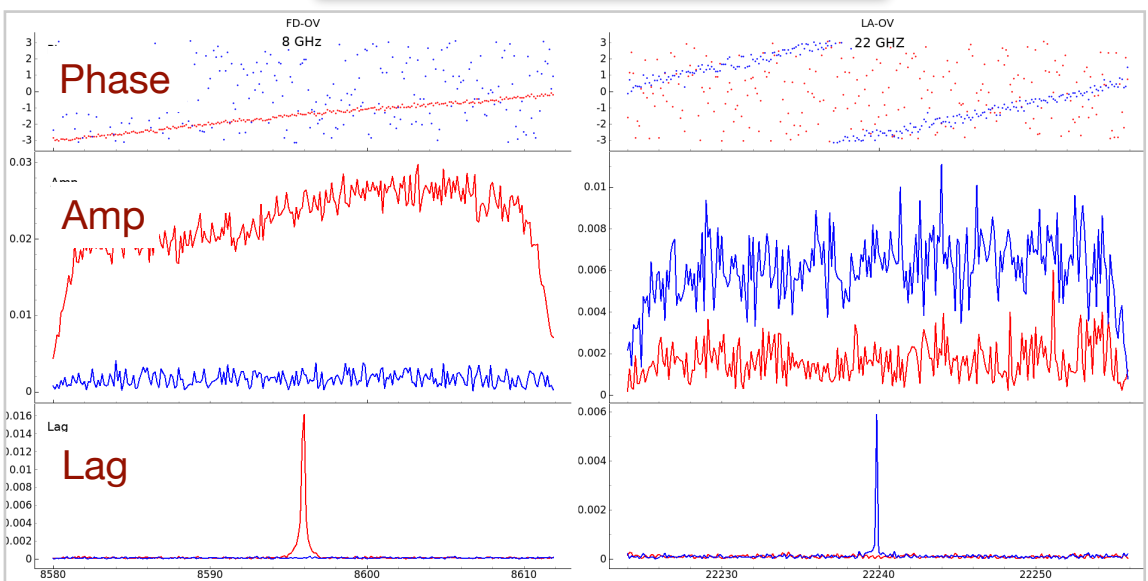


K-band Roadmap: Sensitivity - JPL Broadband

- Broadband continuous coverage 8-40 GHz
  - Quad ridge feed
  - 4-bands: X, Ku, K, Ka
  - Dual pol: RCP, LCP
- Potential for 4 GHz analog per band,
  - limited by backend record rate
  - current e-transfer rate
- Prototype mounted on OVRO-VLBA feed ring



First Fringes / First Light !!!



Ft. Davis legacy X-band Los Alamos legacy K-band

OVRO-VLBA prototype broadband: simultaneous

X-band and K-band

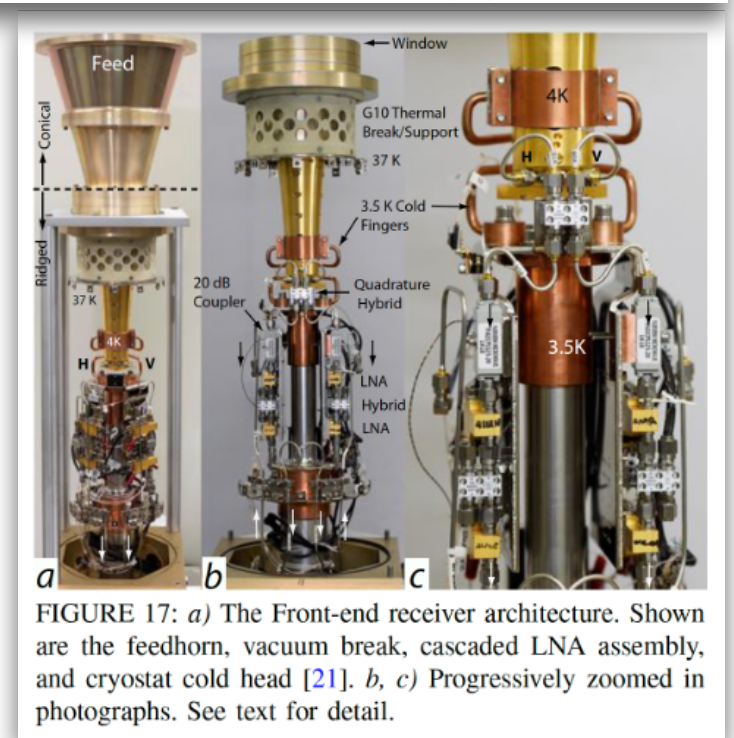


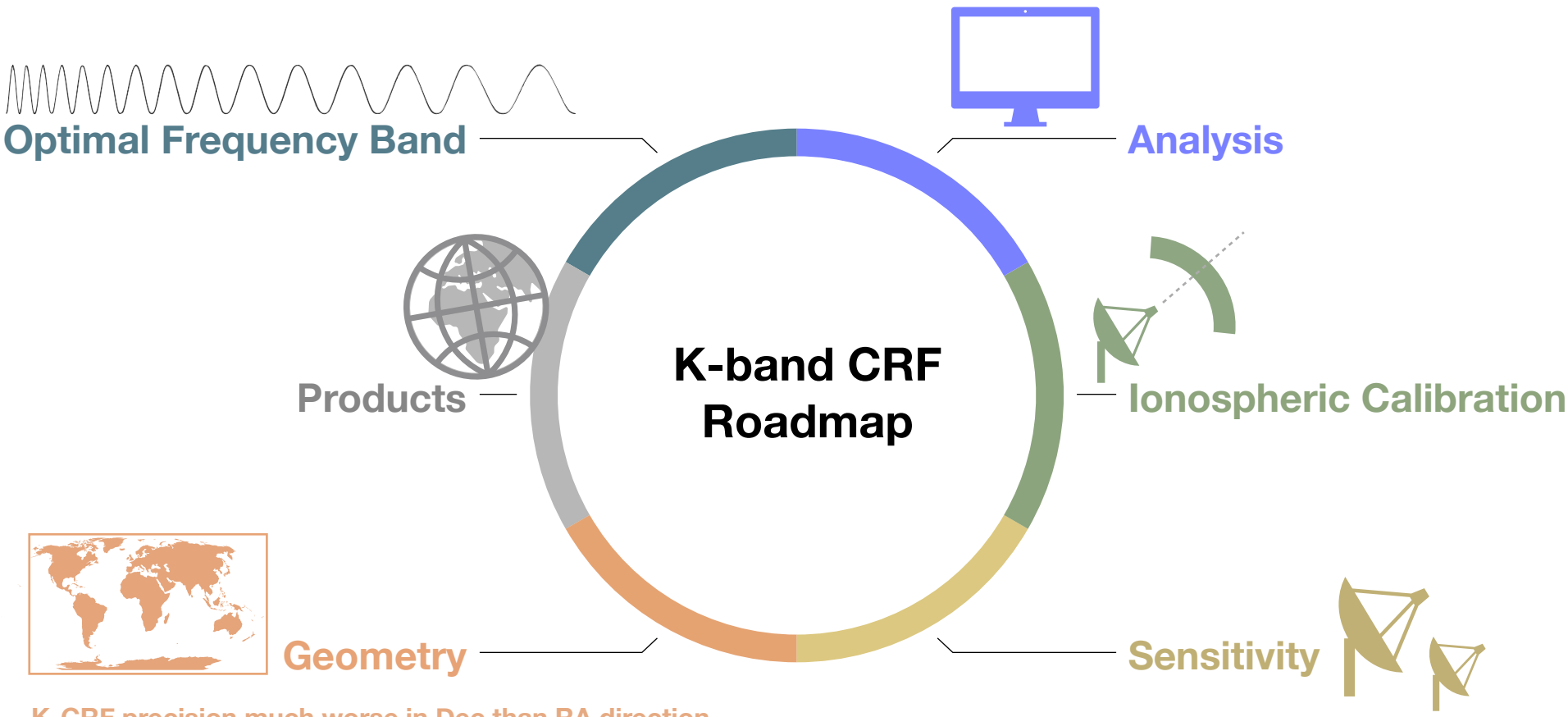
FIGURE 17: *a)* The Front-end receiver architecture. Shown are the feedhorn, vacuum break, cascaded LNA assembly, and cryostat cold head [21]. *b, c)* Progressively zoomed in photographs. See text for detail.

Source 4C 39.25, 32 MHz channel, 128 Mbps, 20 sec average, date 2023 Jul 23

JPL Broadband at OVRO as part of full 24-hour RCP-LCP astro-geo pass

Recorded on 2023 Aug 31. Processing underway. . .

CRF Roadmap: K-band (and Q, W-band?)

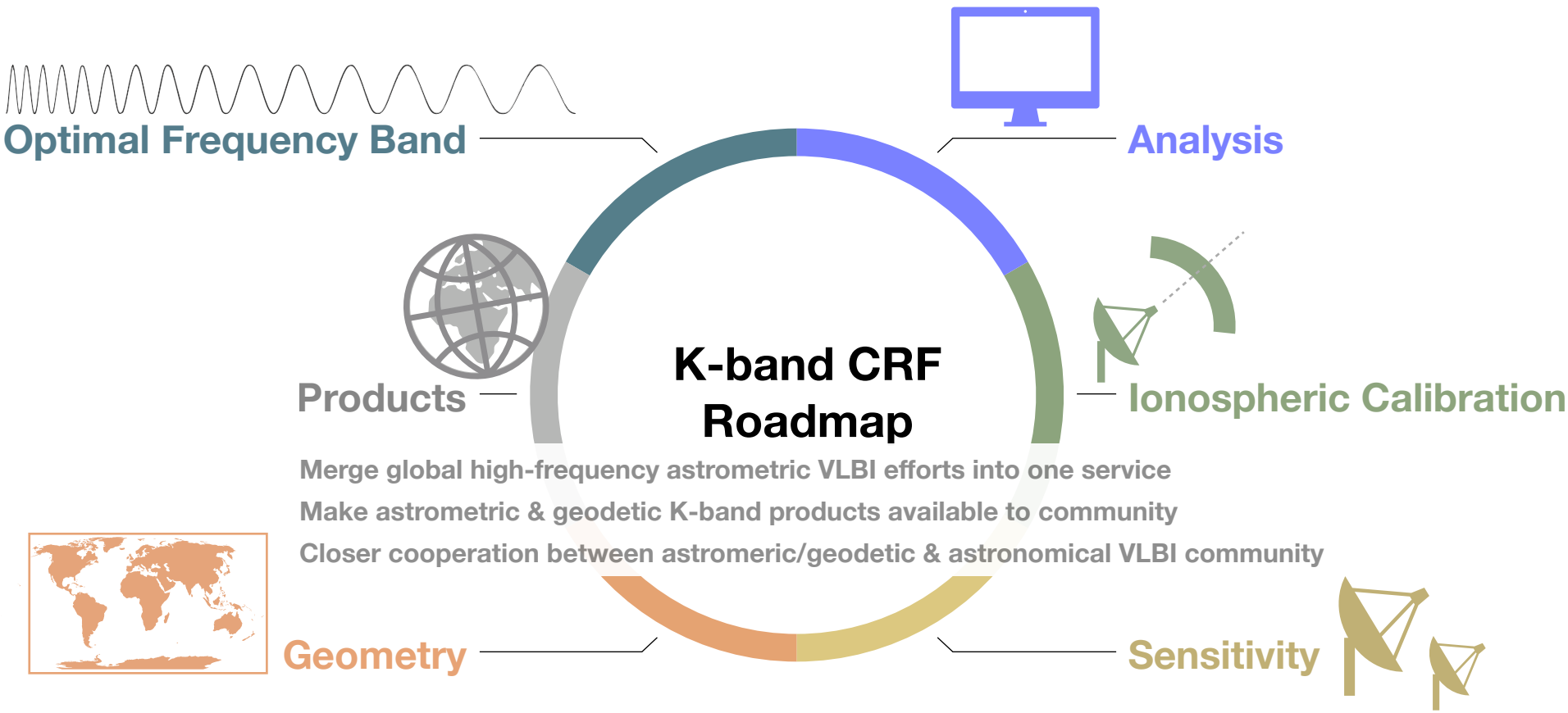


K-CRF precision much worse in Dec than RA direction

Need more Southern stations & more North-South baselines

EVN stations with K-band to improve *u,v*-coverage

CRF Roadmap: Products



K-band Roadmap: Products

Merge global K-CRF efforts into one service

- K-band CRF collaboration since 2014 and ongoing, ICRF3 K-band
- EVN K-band geodetic sessions for station location maintenance *(Gomez et al., 2020)*
- KVN K-band calibrator catalog *(Jung et al, 2018)*, and ongoing K-band geodesy campaign on EAVN *(Xu et al, 2020)*

Make astrometric and geodetic K-band products available to community

- K-band CRF astrometric solutions —> ICRF4 WG, comparisons with SX, XKa, and *Gaia*
- K-band geodetic products —> EOP's and station positions *(Krásná et al., REFAG, 2023; Gomez et al., 2020)*
  - —> *pilot project: transitioning from S/X to K-band for VLBA Intensive Sessions* *(de Witt et al., 2023)*
  - —> *Make astrometric/geodetic K-band products available through the IVS?*

Closer cooperation between the astromeric/geodetic and astronomical VLBI communities

- Provide database of high-resolution, multi-epoch K-band images for the astronomical community
  - —> *K-band calibrator sources, e.g. water masers BeSSeL project* *(http://bessel.vlbi-astrometry.org/)*
  - —> *Full polarization imaging of VLBA dual-pol astrometric sessions* *(in collab. with D. Gabuzda, Ireland)*
  - —> *Multi-wavelength correlations to understand blazar physics* *(in collab. with J. Valverde, GSFC & P. Van Zyl, SARAO)*
  - —> *SMBH binary candidates* *(in collab. with A. Squillace, JPL)*
- Combine astrometric & astronomical sessions, for efficiency and better use of available resources
  - —> Approved observing *proposal: KVN + HartRAO + Mopra* *(in collab. with J. Hodgson, Sejong Uni, Korea)*

Roadmap: K-band (and Q, W-band?)

Optimal Frequency Band

K-band needs dual-band X/K for ionosphere calibration

Q-band ionosphere smaller, but sources weaker

W-band ionosphere not a problem but efficiency and pointing issues

Korean 22/ 43/ 86/ 129-GHz receiver for simultaneous K/ Q/ W CRF observations

Analysis

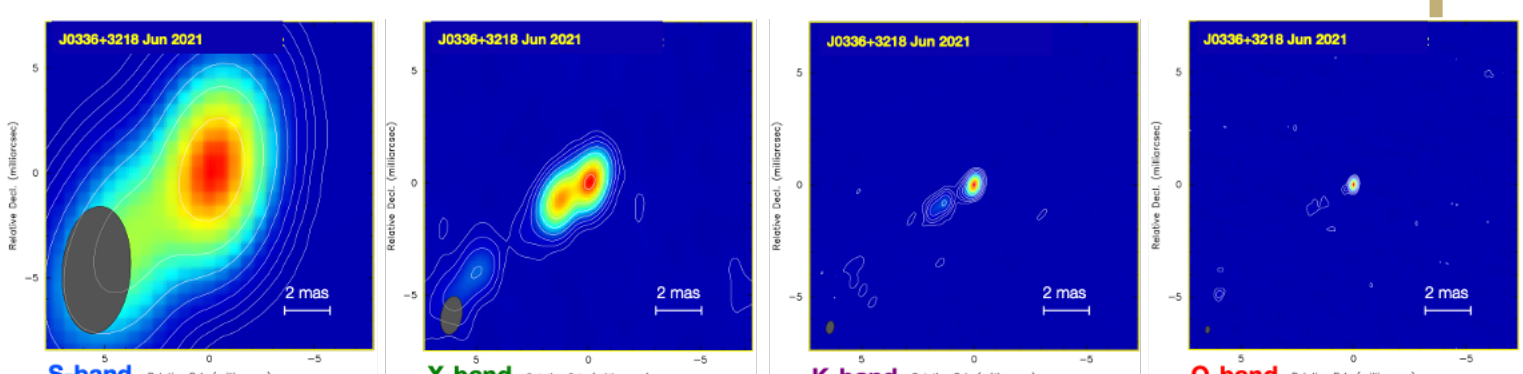
K-band CRF Roadmap

Products

Ionospheric Calibration

Geometry

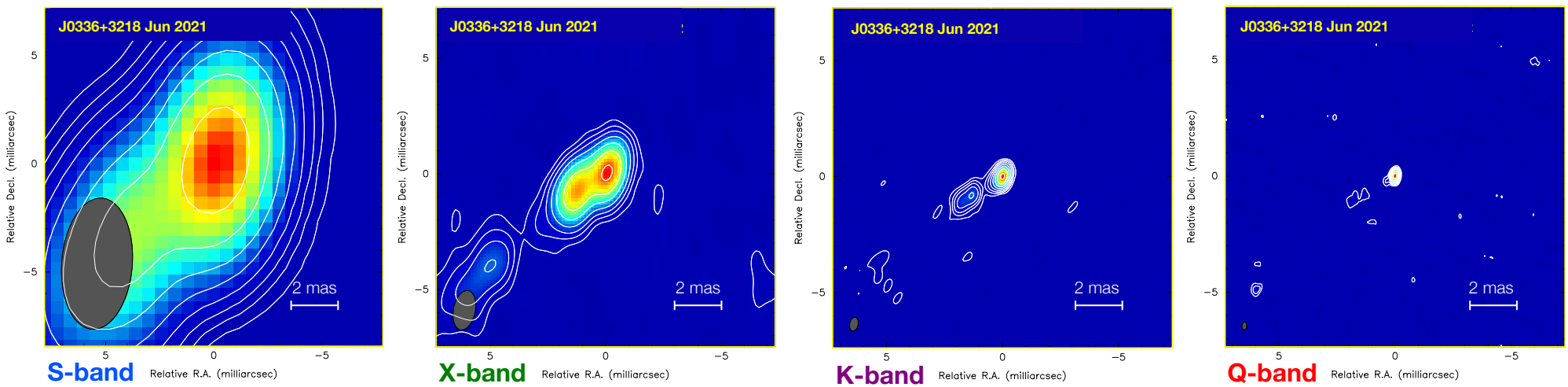
Sensitivity



NRAO 140 near simultaneous images from 2021 at 4-bands data (Hunt et al, 2022, de Witt et al., 2022)

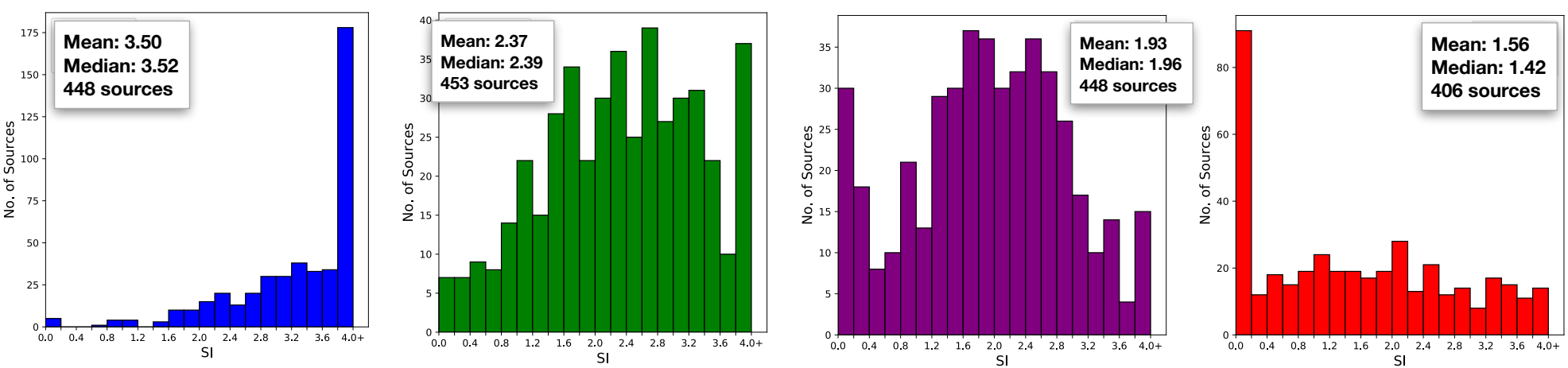
Roadmap: K-band (and Q, W-band?)

Three near-simultaneous S (2.3 GHz), X (8.4 GHz), K (22 GHz) and Q-band (43 GHz) astrometric-imaging VLBA observations of 453 ICRF sources between April - June 2021 *(Hunt et al, 2022, de Witt et al., 2022)*



Structure Index (SI) —> derived from median value of structural delay values for a range of VLBI baselines

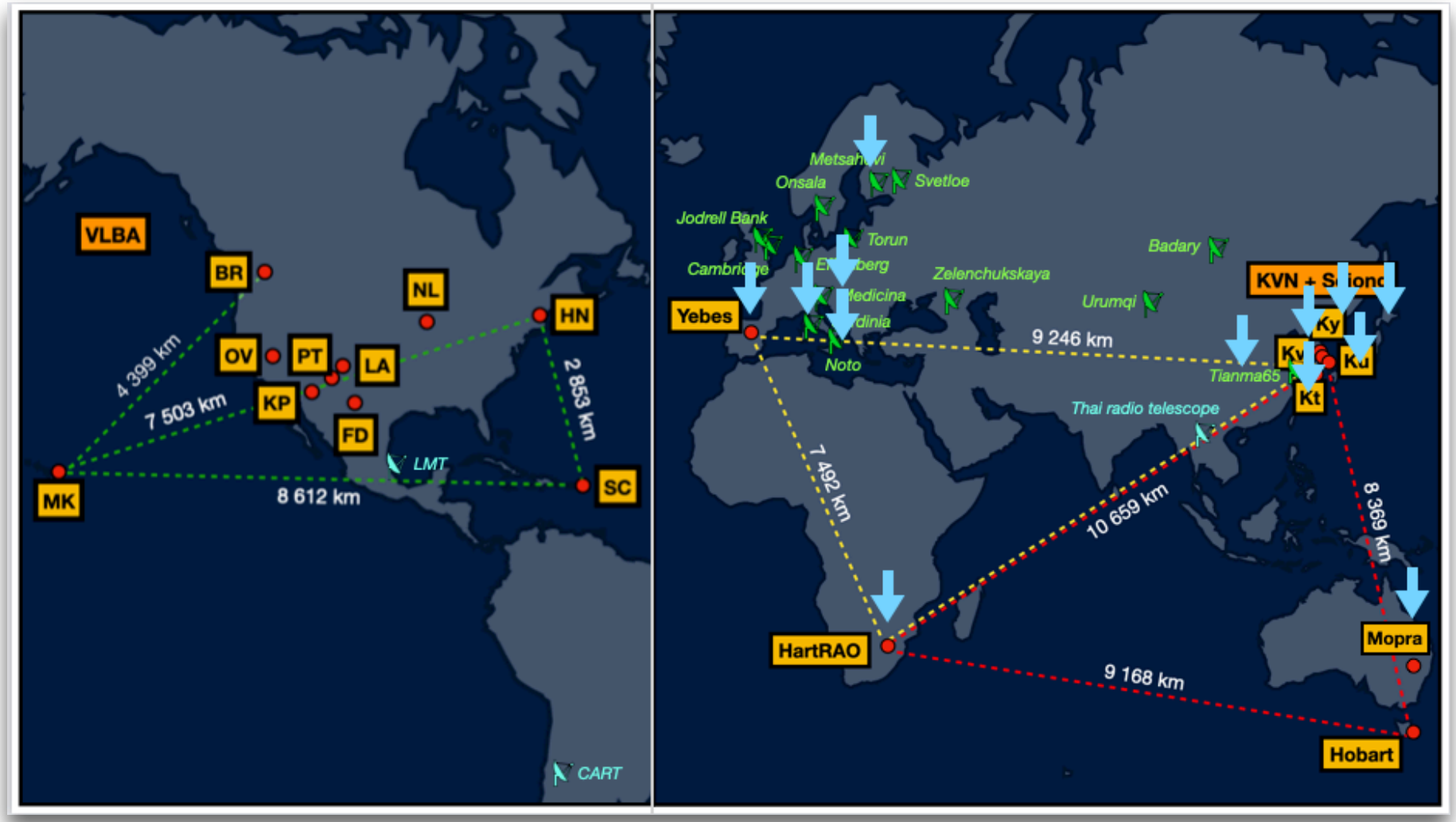
(Fey & Charlot 1997, 2000, McCallum et al., 2020) $\mathrm{SI} = 1 + 2 \times log_{10}(\tau_{\mathrm{median}})$



Improvement in interferometer resolution and more compact source morphology at higher frequencies!

All of the S, X, K, Q near-simultaneous observations are from VLBA sessions supported through the USNO's 50% timeshare allocation

Roadmap: K-band (and Q, W-band?)



K/Q/W receiver system implemented or on-going

Korean-type tri-band (22/43/86-GHz) receiver system for simultaneous K/Q/W (or K/Q) CRF observations (KVN, Sejong, Yebes, VERA, Nobeyama, ATCA, Metsahovi, Tianma, Medicina, Noto, Sardinia, Mopra, HartRAO)

(Jung et al., Bologna VLBI Meeting, 2023)

K-band CRF Status & Roadmap: Summary

The K-band CRF's Journey

A poem by ChatGPT-4

In the realm of celestial dreams,
The K-band CRF brightly gleams,
Growing strong with each passing day,
A world-class program leading the way.

1038 AGN, uniformly spread,
Observed with care, a stellar thread,
From 2002 to 2023,
2 million observations, a sight to see.

Precision rivaling S/X-band's fame,
In K-band's glory, they are the same,
Compact sources, enhanced resolution,
A leap forward, a grand evolution.

A vast database, treasure trove divine,
16000 VLBA images, source metrics entwined,
Through 87 epochs, knowledge refined,
AGN's secrets, unveiled, clearly defined.

Gazing into tomorrow's skies,
The K-band CRF collaboration implies,
A roadmap unfolding, questing for more,
Enhancing observations like never before.

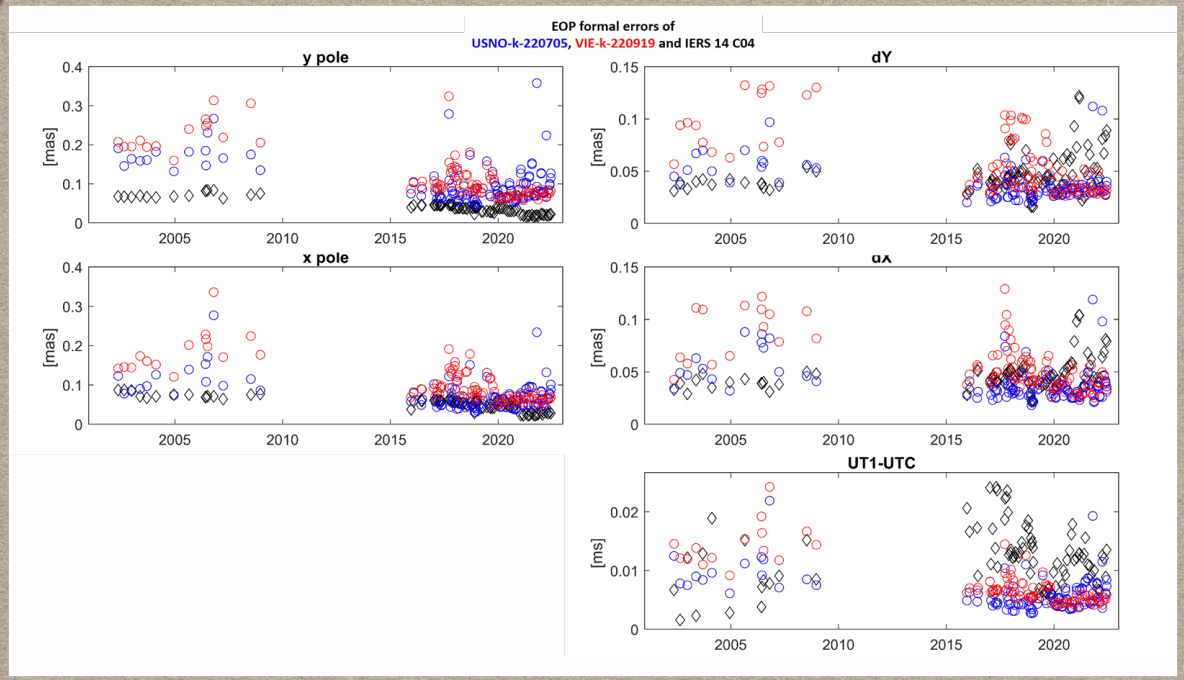
Through data rates, higher and bold,
And larger apertures, a story to be told,
Analysis refined, a meticulous art,
Ionospheric calibrations, a crucial part,

Expanding our reach, networks anew,
Yebes, Spain, and the Korean VLBI crew,
With their collaboration, accuracy shall rise,
In declination, our aim, reaching the skies.

Towards a global alliance we aspire,
Unifying efforts, our burning desire,
Geodesy and astronomy in harmonious embrace,
Bridging gaps, creating cosmic grace

Acknowledgements:
The VLBA is managed by NRAO, funded by the National Science Foundation, and 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. This work was supported by the South African Radio Astronomy Observatory (SARAO,) a facility of the National Research Foundation (NRF) of South Africa.

Backup: K-band EOP and Geodesy



K-band EOP vs. official IERS 14 CO4 time series (Krásná et al., REFAG, 2023)

- **Precision of EOP from K-band VLBA observations**
  –> Polar motion formal errors dominated by GNSS
  –> K-band formal errors for UT1-UTC and nutation below IERS 14 C04 values in recent years
- **EVN K-band geodetic sessions for station locations**
  (Gomez et al., 2020)
- **Pilot project: transitioning from S/X to K-band for VLBA Intensive sessions** –> to start July 2023