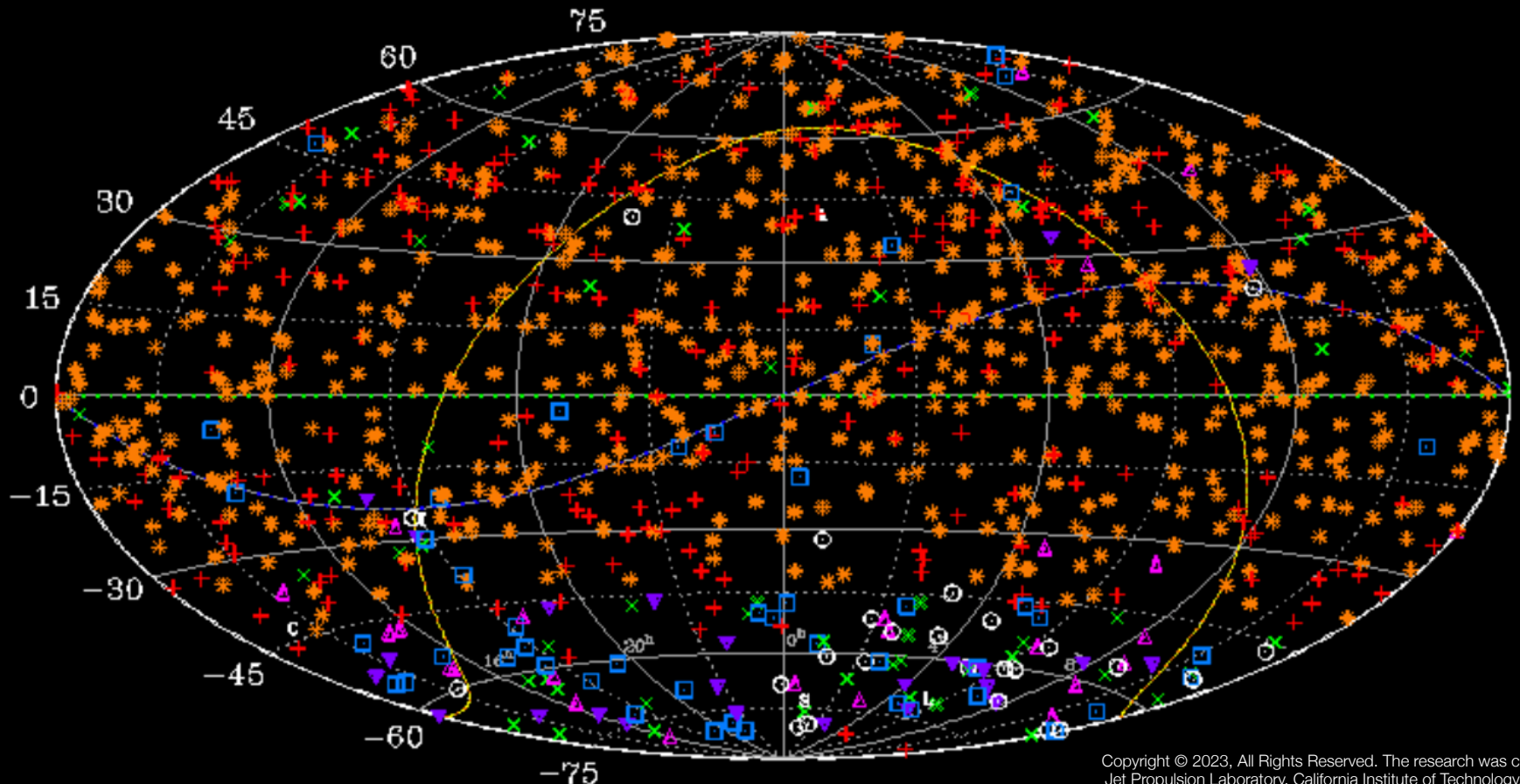
26th EVGA meeting, 11-15 June 2023, Bad Kötzting

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



Aletha de Witt, South African Radio Astronomy Observatory (SARAO), South Africa

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(1) United States Naval Observatory (USNO), US, (2) Jet Propulsion Laboratory, California Institute of Technology/NASA, US, (3) Technische Universität Wien (TU Wien), Austria, (4) Yebes Observatory, National Astronomical Observatory (OAN), Spain, (5) Korea Astronomy and Space Science Institute (KASI), Korea, (6) Sejong University, Korea, (7) University of Tasmania (UTAS)

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

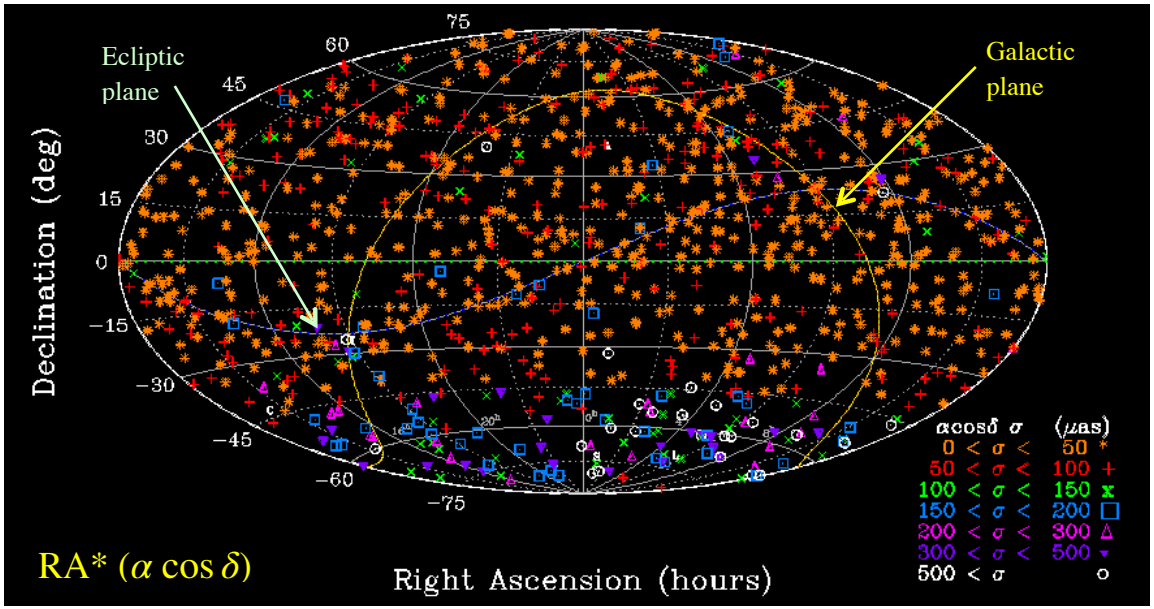
★ **We are investigating the potential for a Q-band CRF (43 GHz, 0.7 cm)**

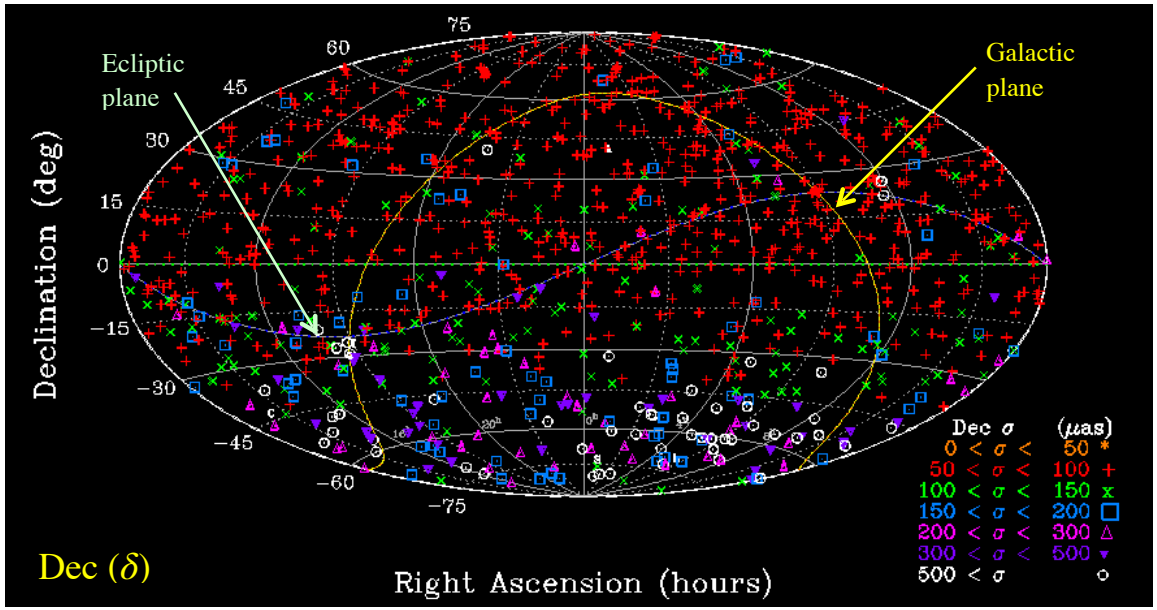
Motivation for higher frequency bands:

- **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





1038 sources (2002-2023)
2 million observations
astrometric solution D. Gordon
K-usno-230110

median precision RA/Dec ~47/80 μas

for 975 source in common with the SX-band frame, and after removing 41 outliers > 5-σ

- Strengths:
  - Uniform spatial density
  - Best band for near Galactic plane
  - Less structure than S/X (3.6 cm)
  - Precision comparable to S/X
  - 2 million observations vs. SX's 17.6 million!

- Weaknesses:
  - Ionosphere imperfectly calibrated by GPS
  - South ($\delta < -30$ 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.

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

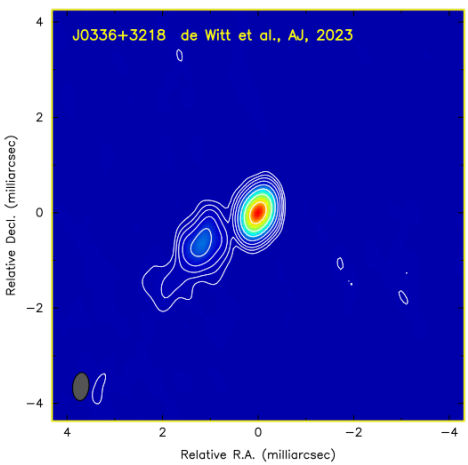
Current Status: K-band Network

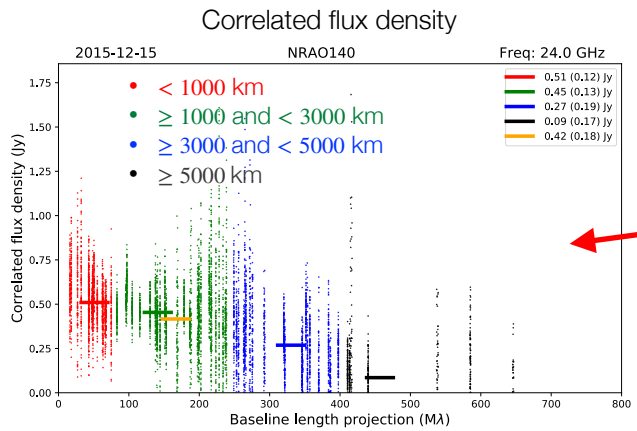
- 10 VLBA Stations (4 Gbps, dual-pol)
- HartRAO-Hobart (2 Gbps, RCP)

- 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)

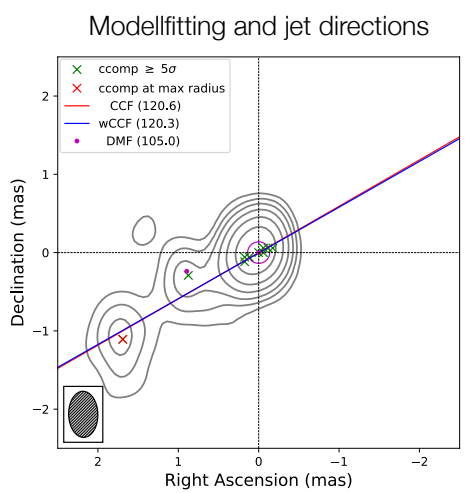
Current Status: Imaging & structure metrics

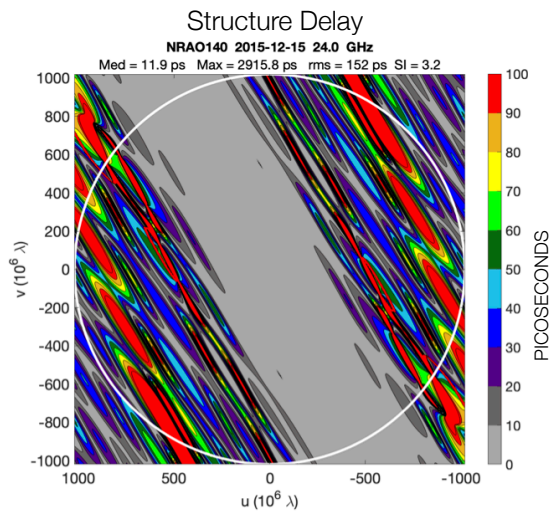
Imaging of VLBA K-band CRF sessions: total of 87 epochs between Jul 2015 and Jan 2023 *(de Witt et al., 2023, AJ & this meeting poster)*

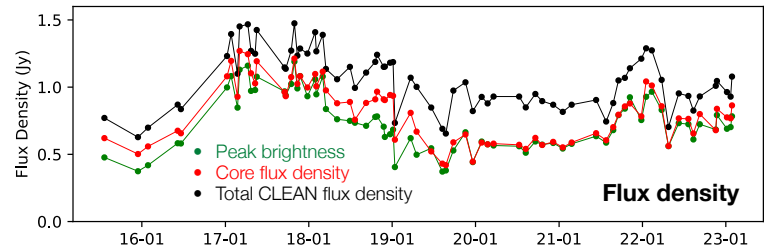


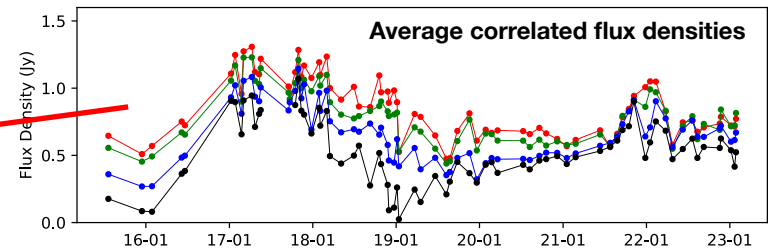


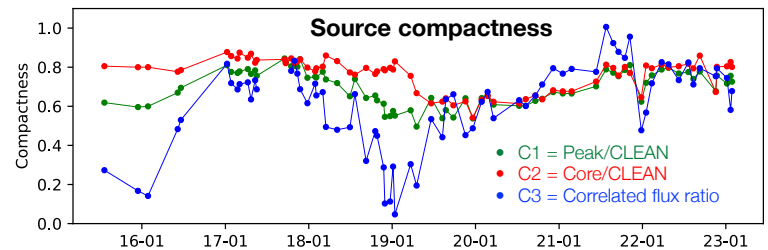
NRAO140: 73 epochs

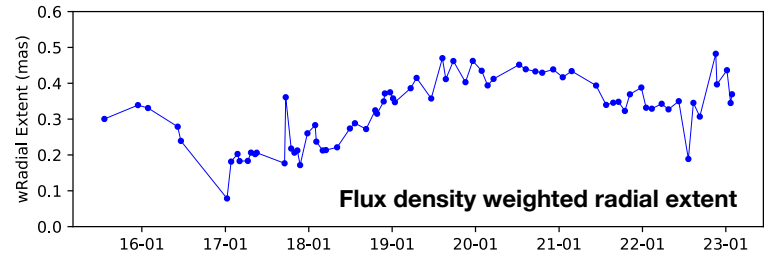


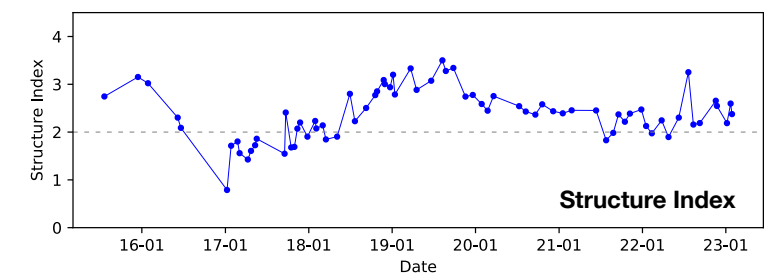










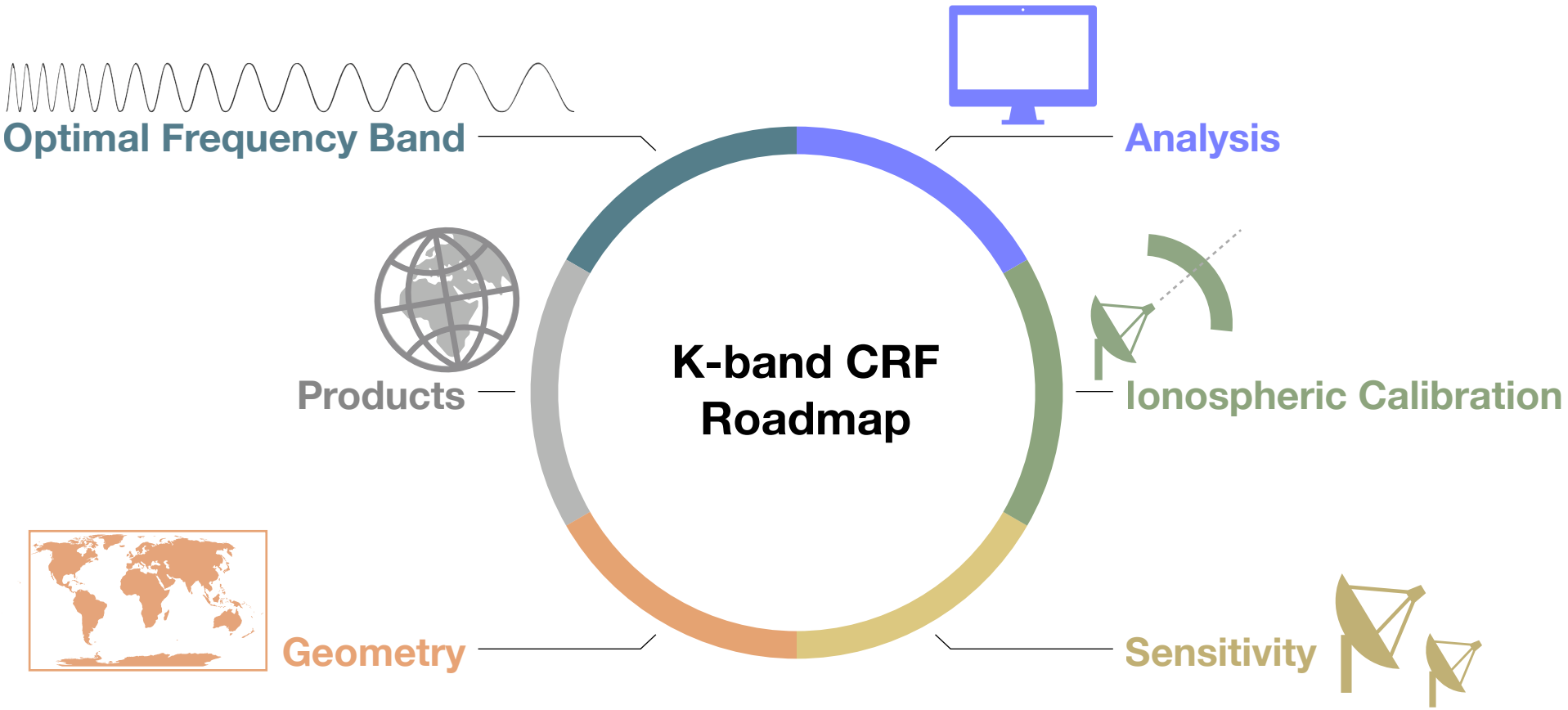


92% of the K-band CRF observations are from VLBA sessions supported through the USNO's 50% timeshare allocation

K-band Roadmap: Overview

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

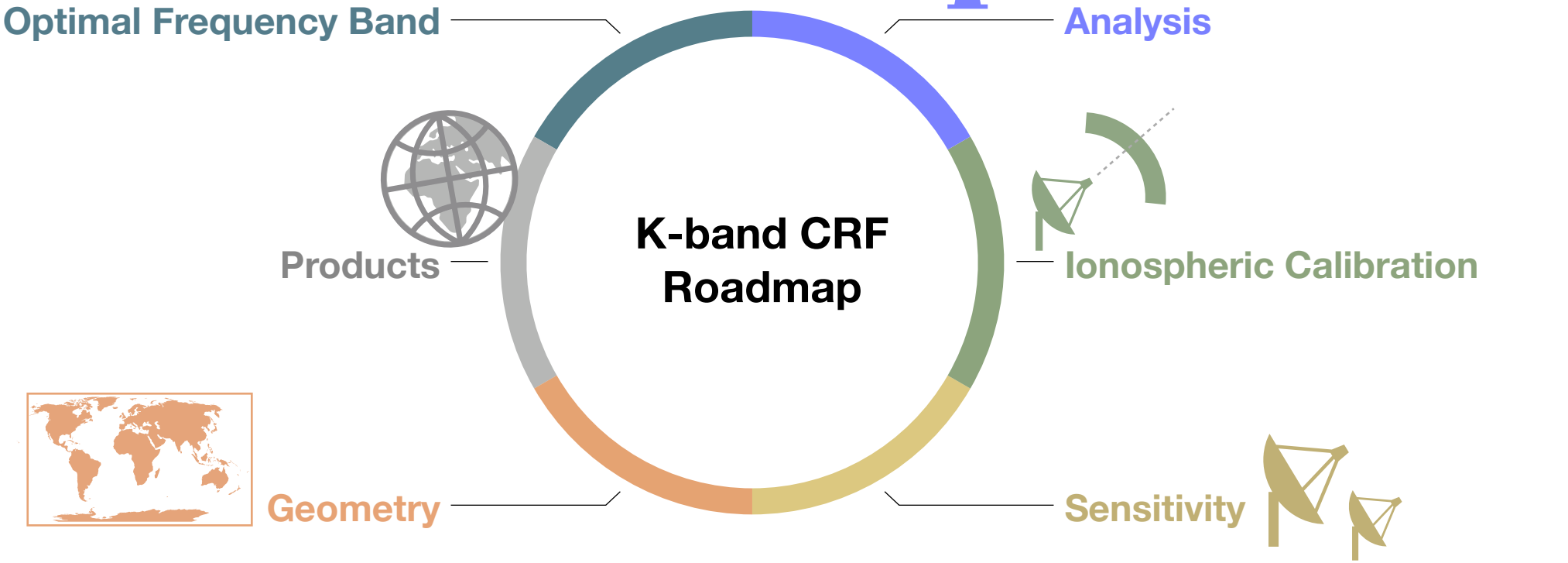
Future ICRF likely to be multi-wavelength, incorporating also optical realization by *Gaia* *(IAU WG: Multi-waveband ICRF)*



K-band Roadmap: Analysis

Improve K-CRF analysis:

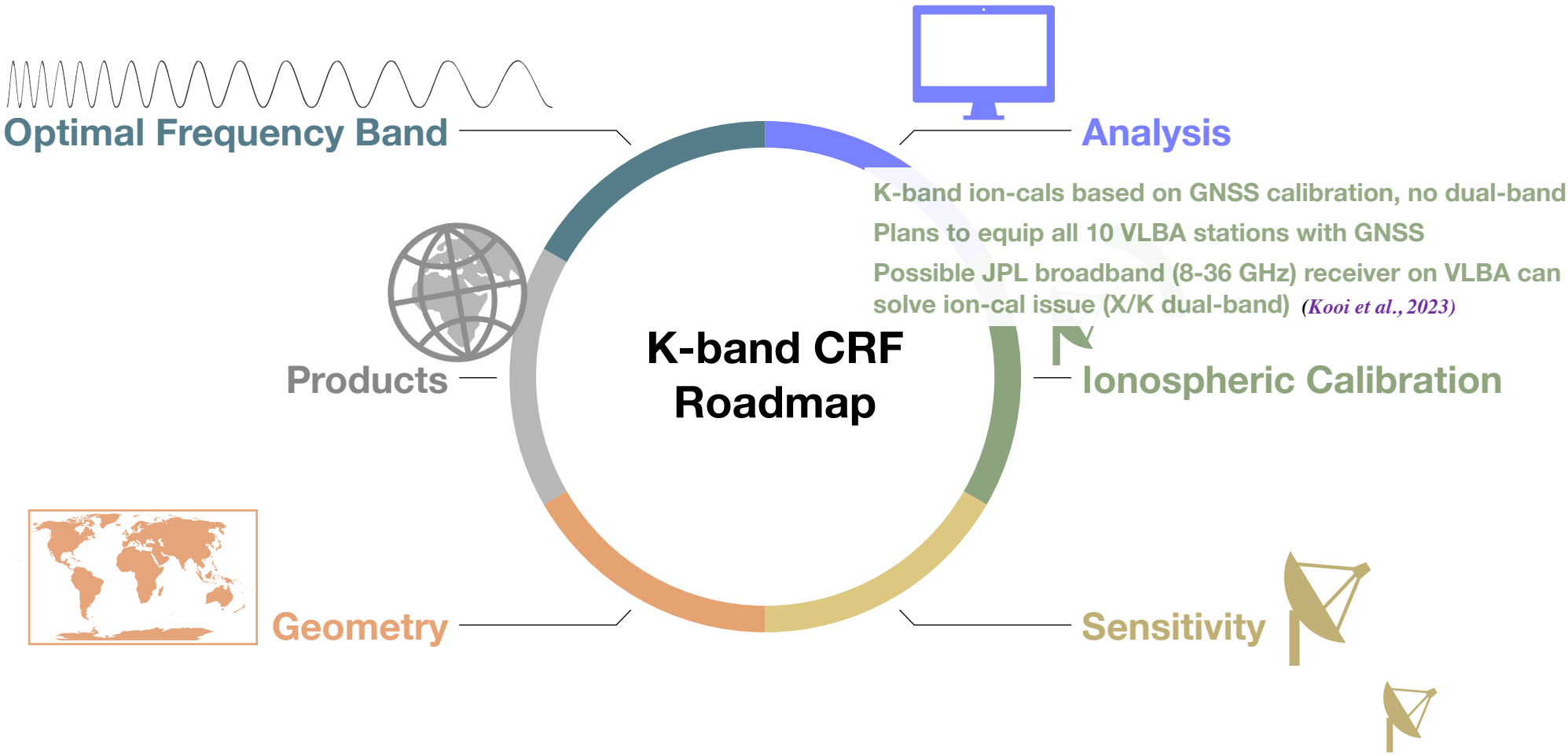
- **Compare independant analysis packages (VieVS & Calc/Solve)** *(Krásná et al., REFAG, 2023)*
- **Troposhere: incorporate elevation dependent weighting** *(Hana Krásná)*
- **Ionosphere cals: modified mapping functions, JPL R&D cals** *(Soja et al., 2019, Krásná et al., 2023)*
- **Correcting for the effects of source structure** *(de Witt et al., this meeting poster)*



** K-band CRF global solution and timeseries 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



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!

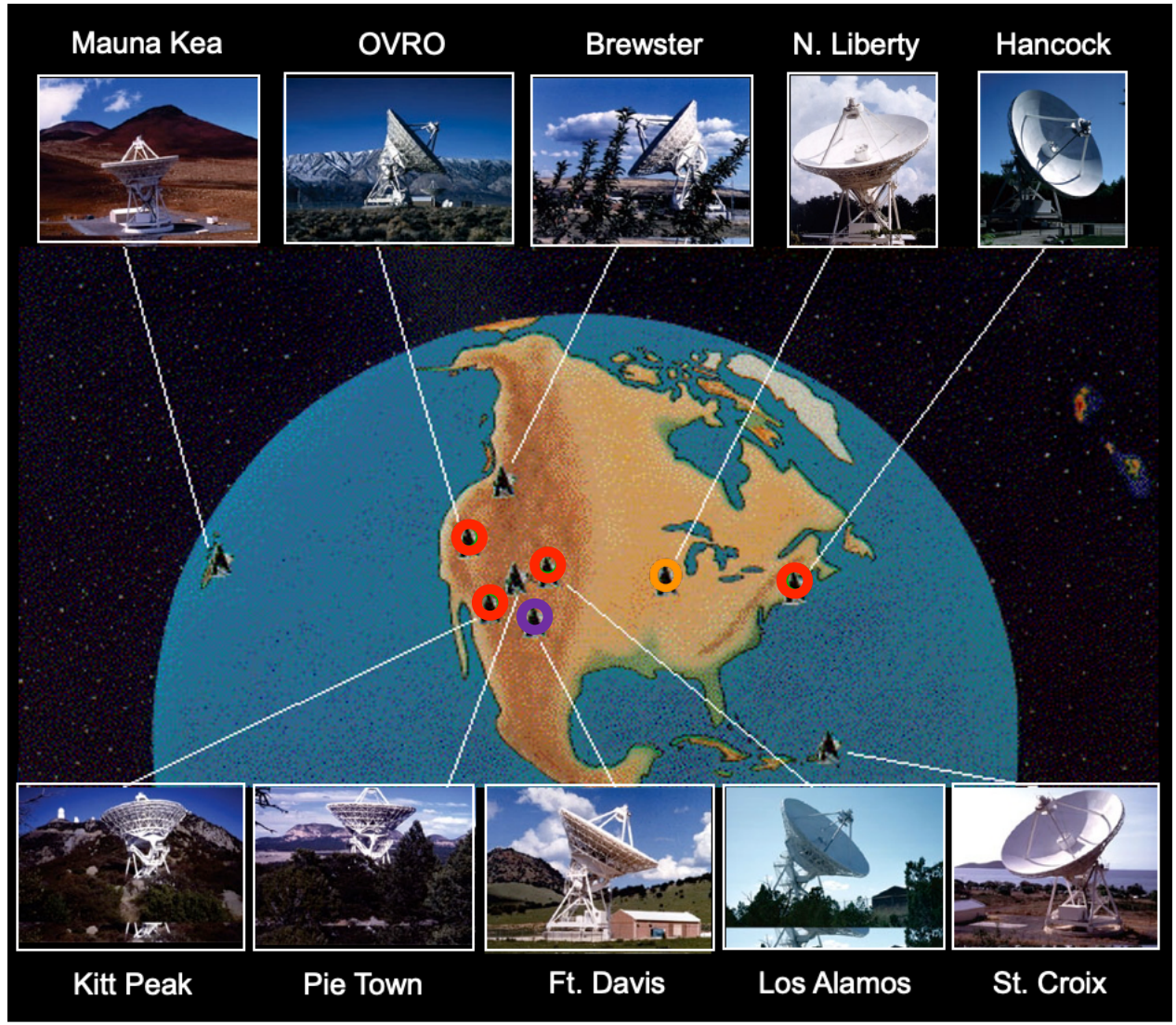


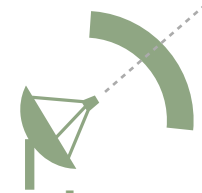
Image Credit: Very Large Baseline Array http://www.vlba.nrao.edu/

K-band Roadmap: Sensitivity

Optimal Frequency Band

Analysis

Products



Ionospheric Calibration

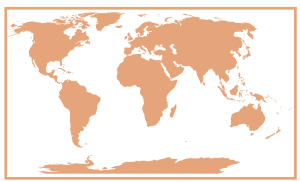
K-band CRF Roadmap

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 ~factor of three increase in sensitivity *(Kooi et al., 2023)*



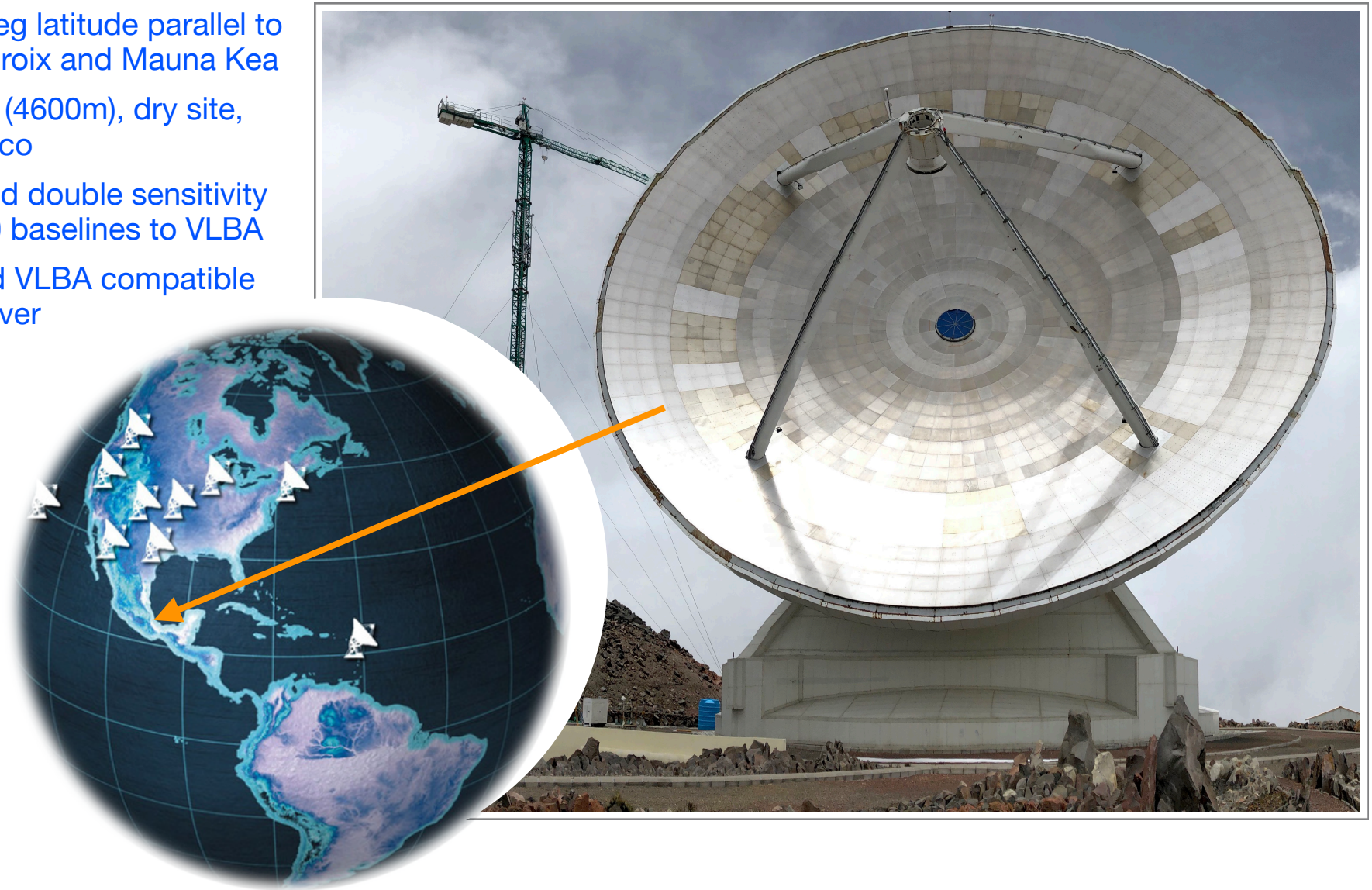
Geometry

Sensitivity

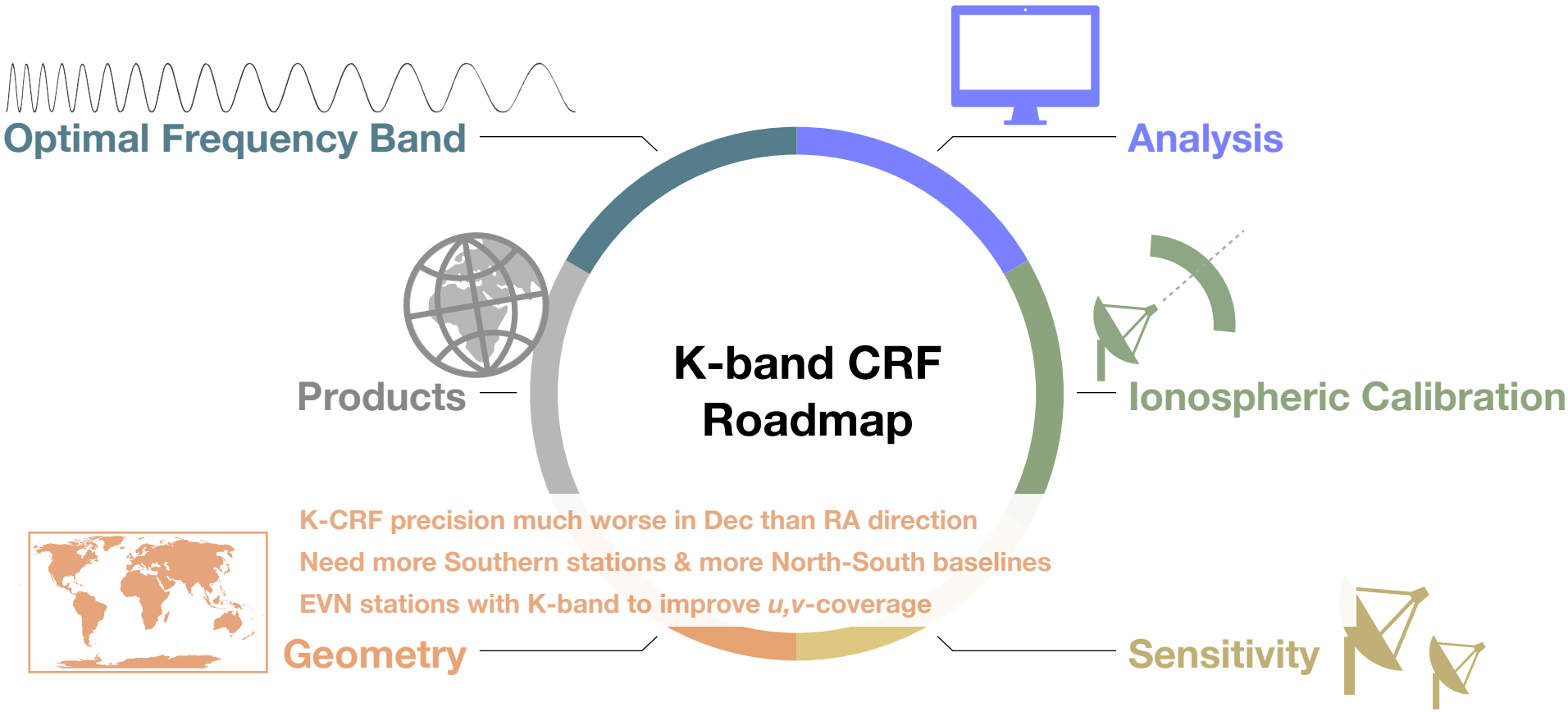
K-band Roadmap: Sensitivity

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

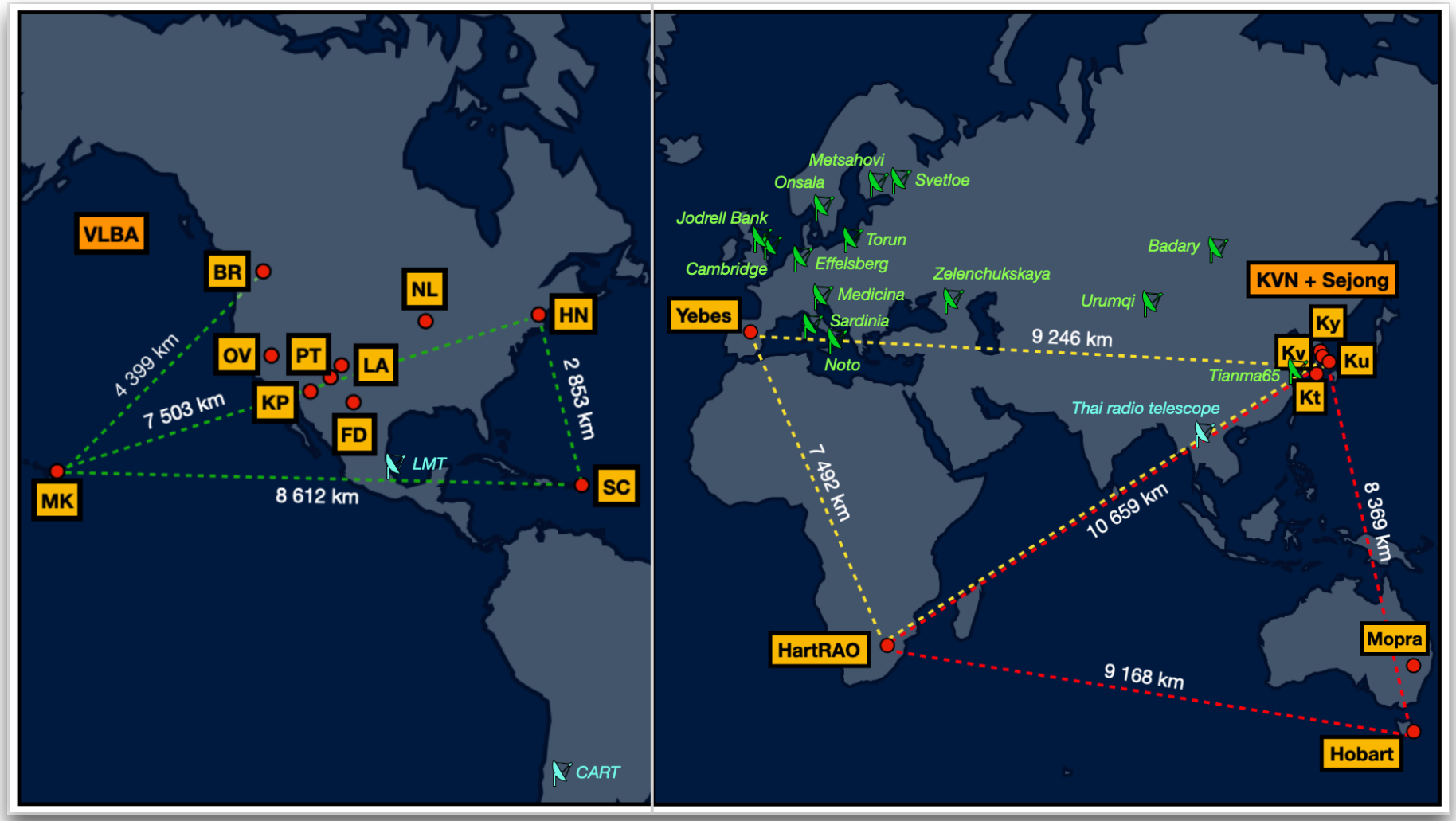
- 19 deg latitude parallel to St. Croix and Mauna Kea
- High (4600m), dry site, Mexico
- Would double sensitivity of 10 baselines to VLBA
- Need VLBA compatible receiver



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



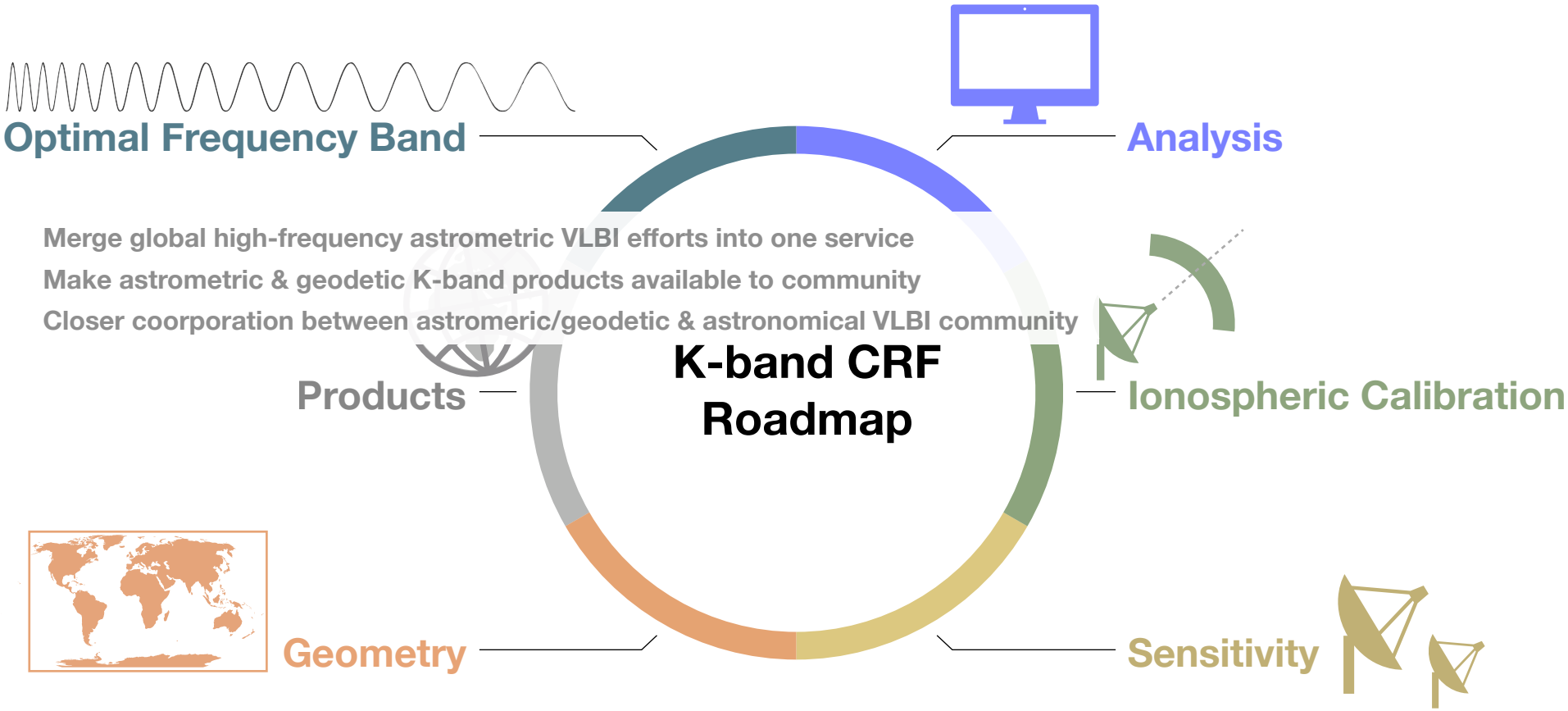
K-band Roadmap: Geometry



K-band CRF stations **EVN stations with K-band** **Future possibile K-band stations**

Need more North-South baselines: benefit of Korean and Yebes geometries for K-band
Need more Southern stations: Tidbinbilla, LBA, Thailand, South America
EVN stations with K-band: to improve *u,v*-coverage

K-band 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
  - —> *combined proposal submitted to 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 small enough, sources weaker

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

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

Analysis

Products

K-band CRF Roadmap

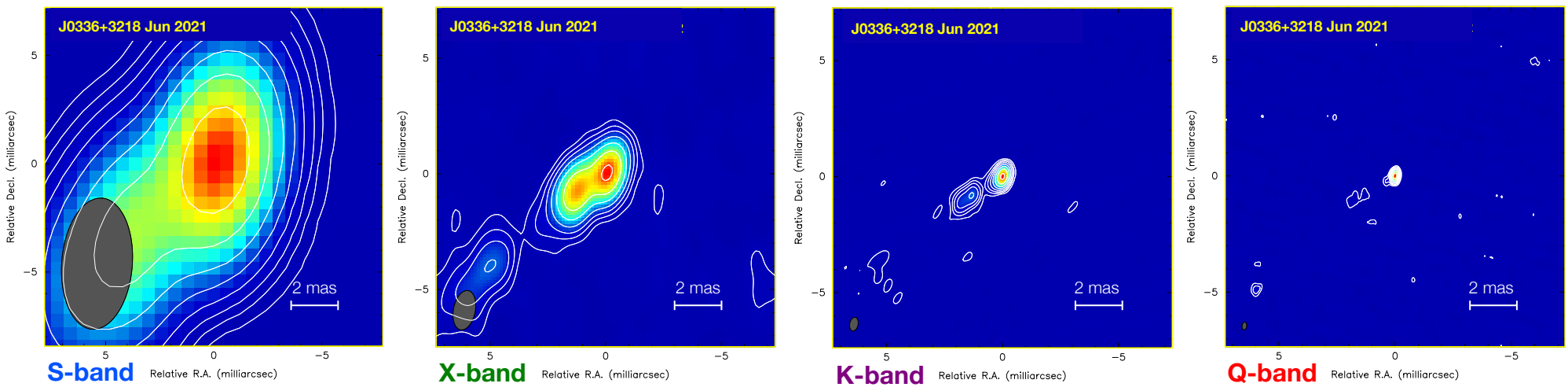
Ionospheric Calibration

Geometry

Sensitivity

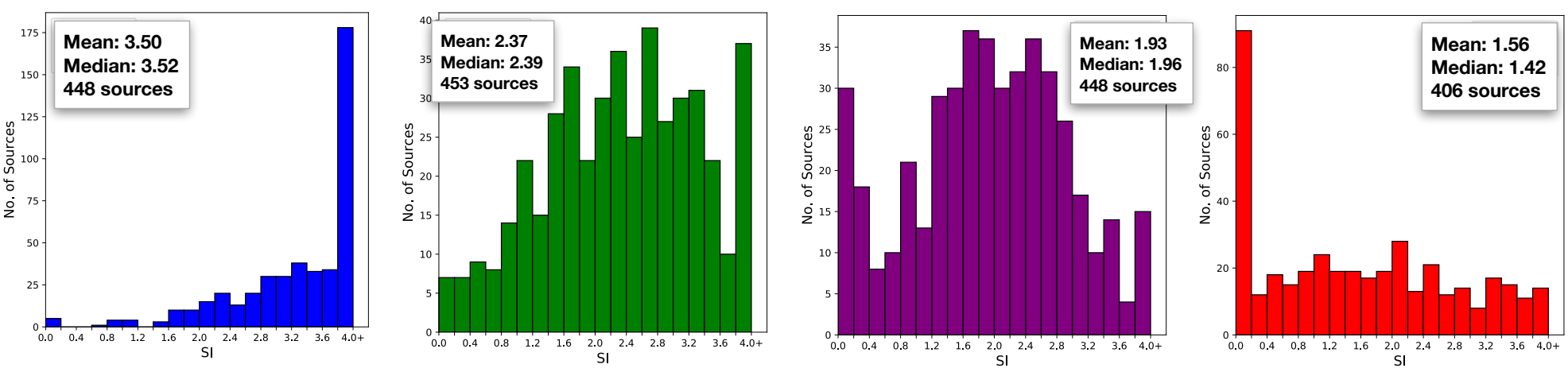
Roadmap: K-band (and Q, W-band?)

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

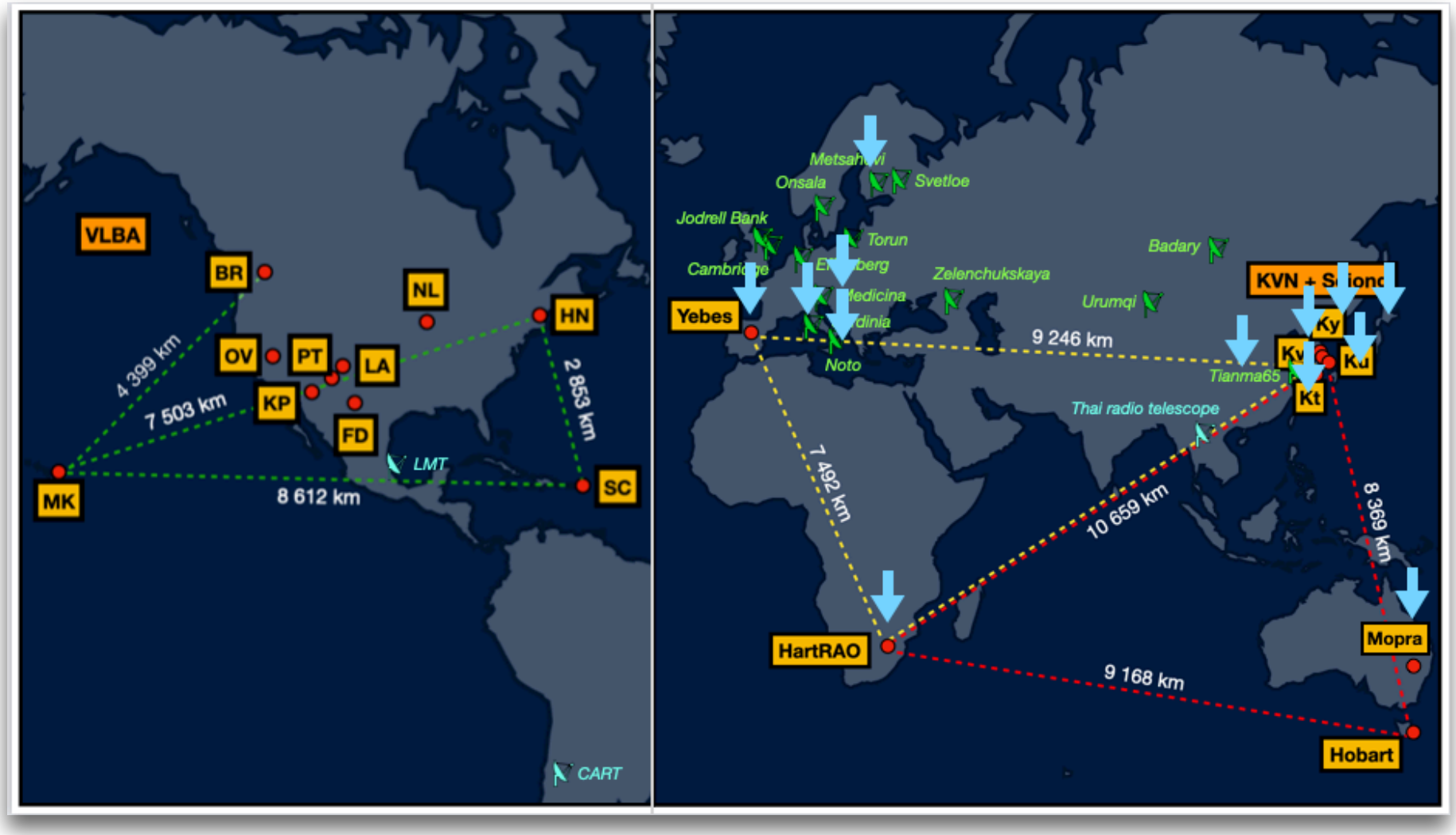
(Fey & Charlot 1997, 2000, McCallum et al., 2020) $\mathrm{SI} = 1 + 2 \times log_{10}(\tau_{\mathrm{median}})$



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.

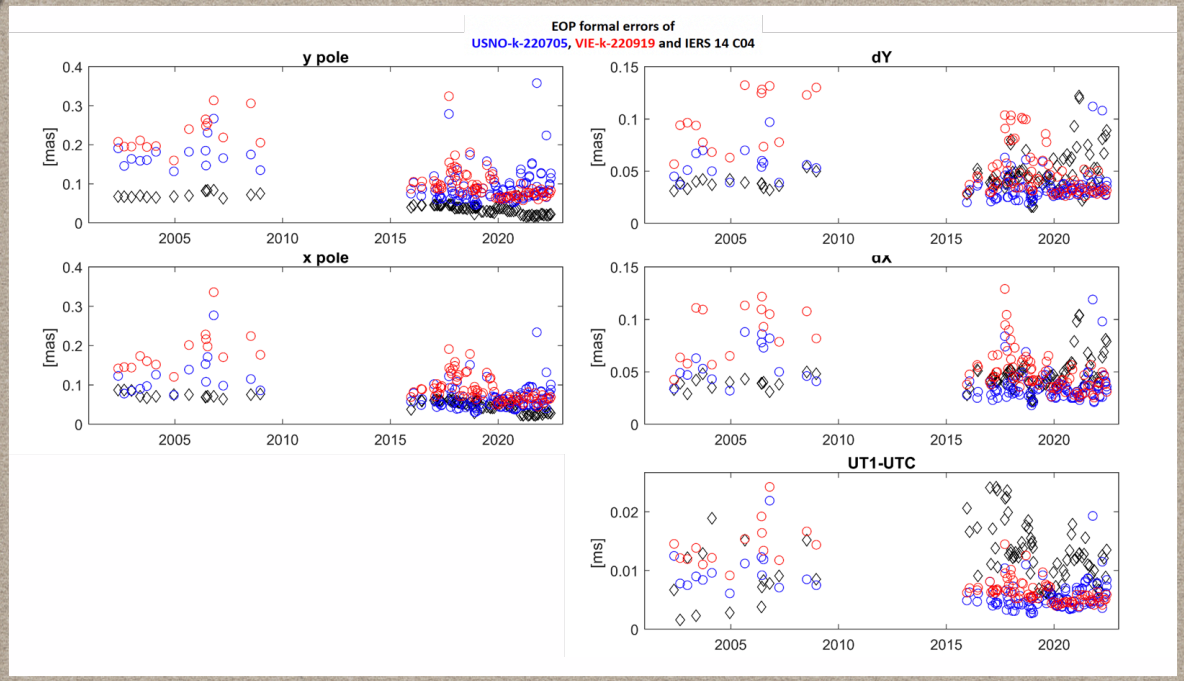
Through data rates, higher and bold,
And larger apertures, a story to be told,
Analysis refined, a meticulous art,
Ionospheric calibrations, a crucial part,

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.

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