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The K-band (24 GHz) Celestial Reference Frame

Executive Summary: Celestial angular coordinates (α,δ) of 1327 sources are derived from VLBI measurements at 24 GHz (1.2 cm) of Active Galactic Nuclei. Agreement with S/X is at the part per billion level. K-band has reduced astrophysical systematics vs. S/X.

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Abstract:

The K-band (24 GHz) Celestial Reference Frame became one of three components of the ICRF-3 in 2018 (Charlot et al, 2020). As of January 2024, the K-band data set has increased to 1315 sources, 161 sessions (55 sessions since 2019 are dual polarization), and 2.57 million observations (4.8X increase)---as well as adding north-south geometry from Spain to South Africa and Korea to Australia. This solution from 2024 January 19th has median formal precisions of 52 μas in α cosδ and 91 μas in δ. The largest spherical harmonic distortions seen in the K-band CRF vs. ICRF3-SX are a Y-rotation term of -46+- 6 μas and quadrupole 2,0 magnetic term of -26 +- 4 μas and quadrupole 2,0 electric term of -35 +- 7 μas. The K-band frame is dominated by the northern geometry of the VLBA. Recently begun observing programs from Yebes, Spain to Hartebeesthoek, South Africa and from the Korean VLBI Network to Mopra, Australia are expected to improve declination precision as well as reduce the above systematic distortions. The prospects for future improvements are bright with the aforementioned north-south baselines as well as plans for increasing VLBA data rates to 8 Gbps, and potentially adding dual band X/K (8/ 24 GHz) to the VLBA with the JPL designed broadband receiver (Kooi et al, 2023) in order to improve ionosphere calibrations.

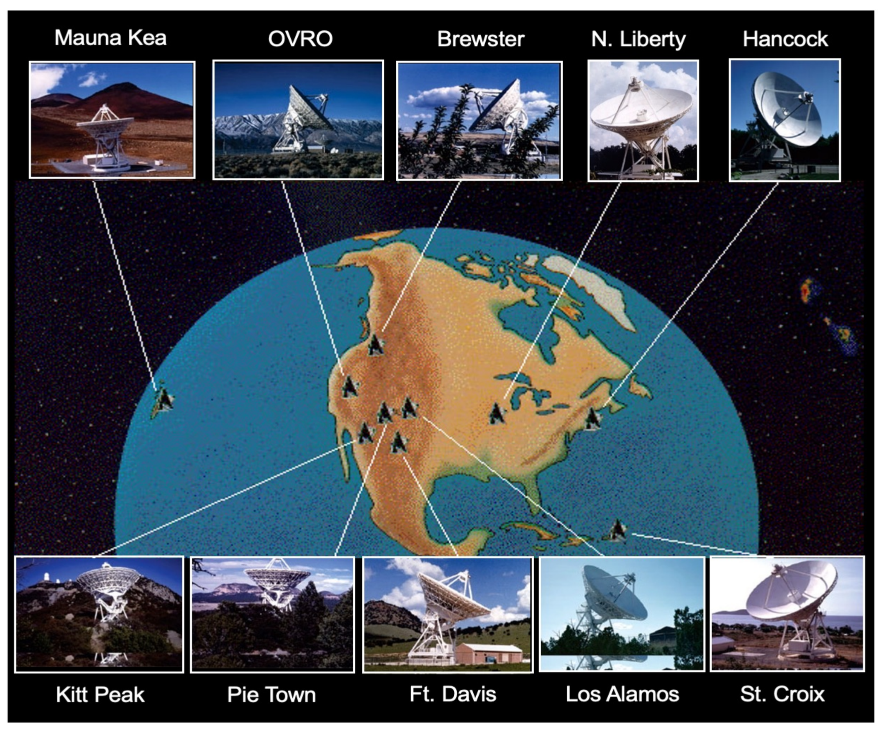

Fig. 1. The vast majority of the data collected so far has been observed with the Very Long Baseline Array (VLBA) of ten 25-meter telescopes which form 45 baselines with the longest East-West baseline being over 8000 km. The longest North-South baseline is about 3000 km leading to significantly lower declination precision. Long North-South baselines from Yebes, Spain to HartRAO, South Africa and Korean VLBI Network to Mopra, Australia were recently added to overcome this limitation. (*VLBA time is being sponsored under the USNO time allocation*)

I. High Frequency Radio Frames: As radio frequencies increase, sources tend to be more core dominated as the extended structure in the jets tends to fade away with increasing frequency (Fig. 3,4). The spatial offset of the emissions from the AGN engine due to opacity effects ("core shift") is reduced as frequency increases.

Advantages of K-band compared to S/X-band:
- More compact, stable sources (Fig. 3,4)
- Reduced opacity effects: "core shift"
- Ionosphere & solar plasma effects reduced by 9X.

Disadvantages of K-band:
- More weather sensitive (Fig. 5)
- Shorter coherence times.
- Weaker sources, many resolved.
- Antenna pointing is more difficult.
- Combined effect is lower sensitivity.

Increasing data rates are rapidly compensating.
VLBA operates at 4 Gbps and has plans for 8 Gbps.

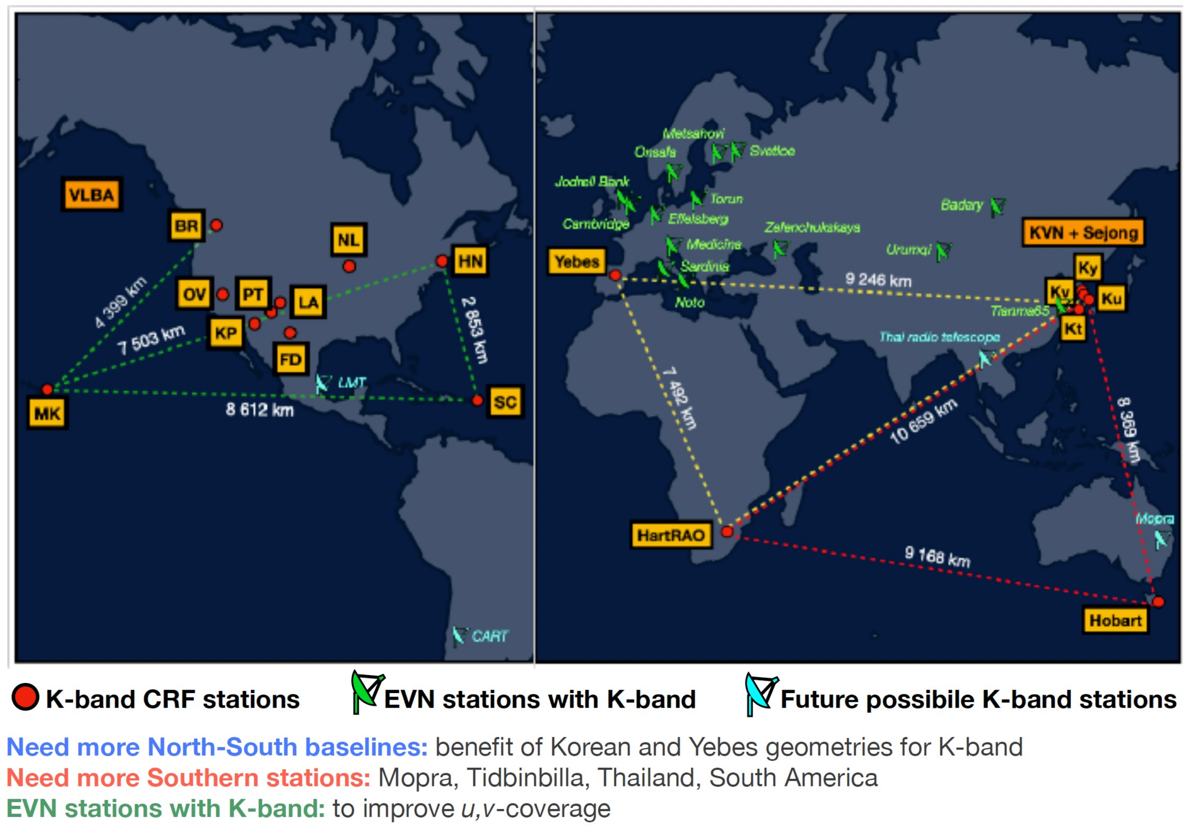

Fig. 2. K-band Antenna Network

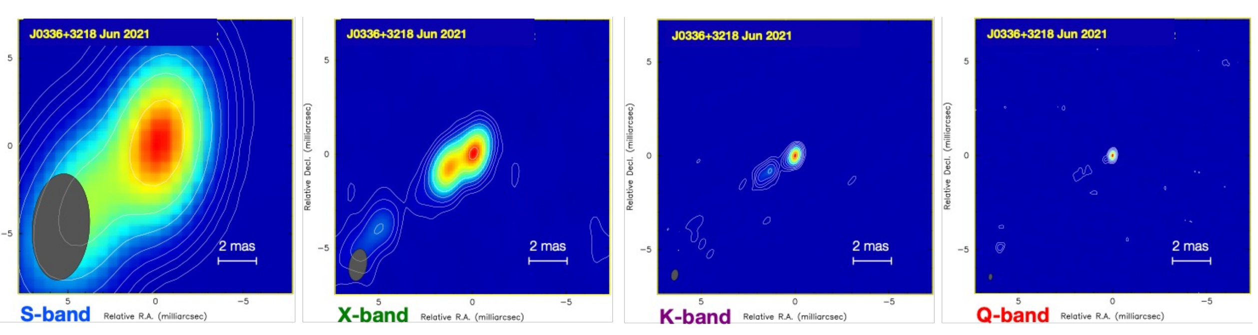

Fig. 3: Near-simultaneous S (2.3 GHz), X (8.4 GHz), K (22 GHz) and Q-band (43 GHz) images based on VLBA observations of 453 ICRF sources between April - June 2021 (*Hunt et al, 2022, de Witt et al, 2022*) demonstrate that VLBI calibrator sources get more compact with increasing frequency. In particular, note how the jet fades with increasing frequency. The example shown is of source NRAO 140 (J0336+3218). The VLBA synthesized beam is shown as the grey ellipse in each sub-figure.

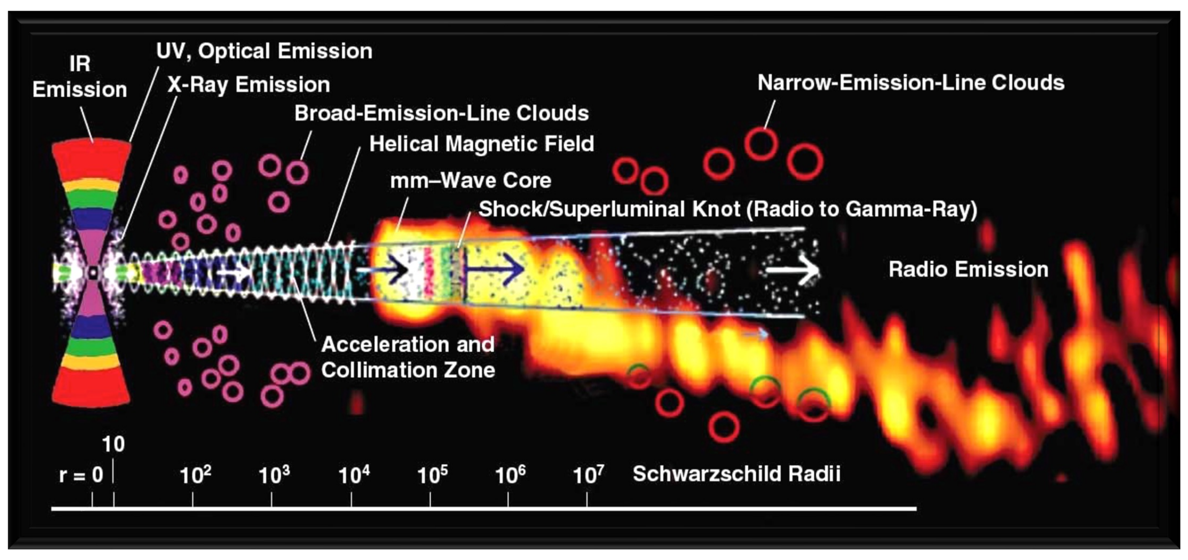

Fig. 4: Schematic of Active Galactic Nuclei (Marscher, 2006, Krichbaum, 1999, Wehrle, 2010)

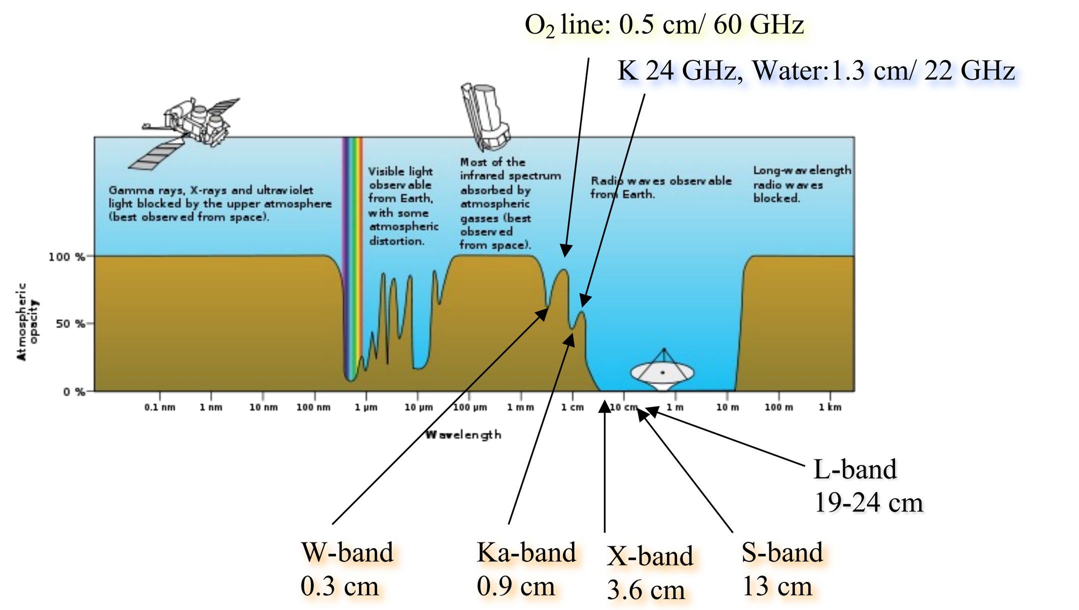

Fig. 5: The radio "window" is transparent compared to most of the spectrum (credit: NASA) K-band (24 GHz) is just above the H_20 line at 22 GHz.

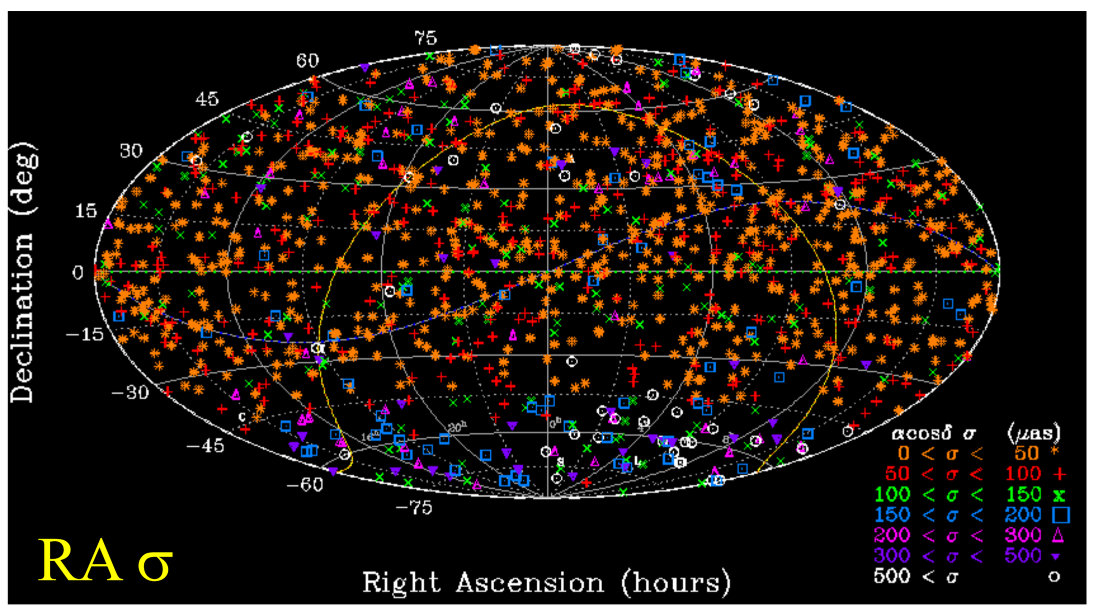

Fig. 6 RA* (arc) precision: Median σ 52 μas for 1315 sources. Median 190 μas for Dec < -45 deg.

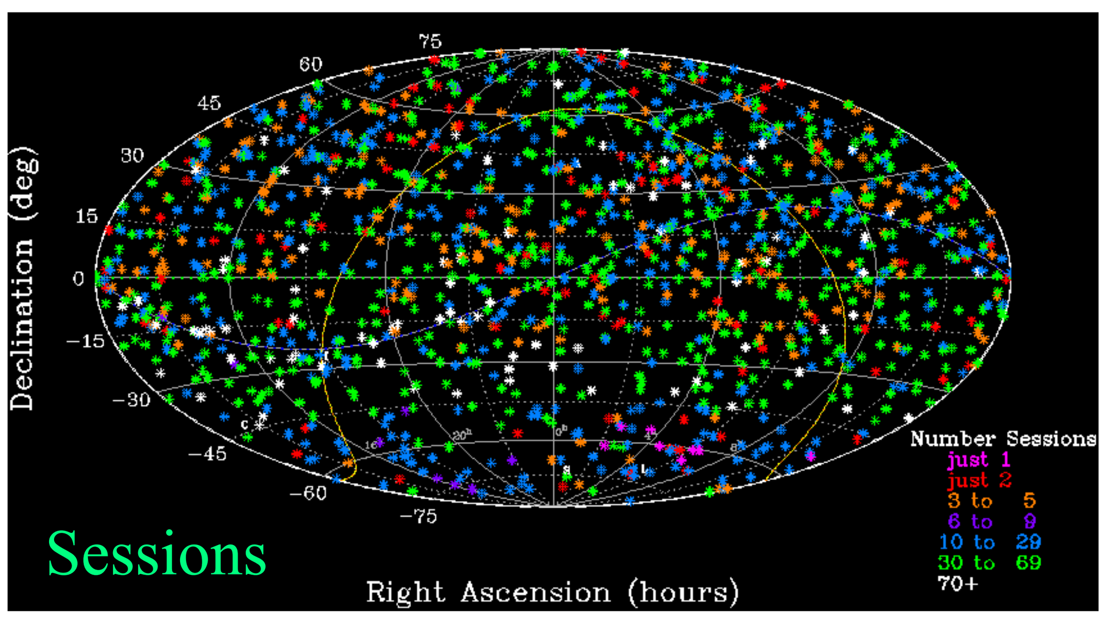

Fig. 8: Number of sessions: Median number of sessions is 27, but only 13 in far south

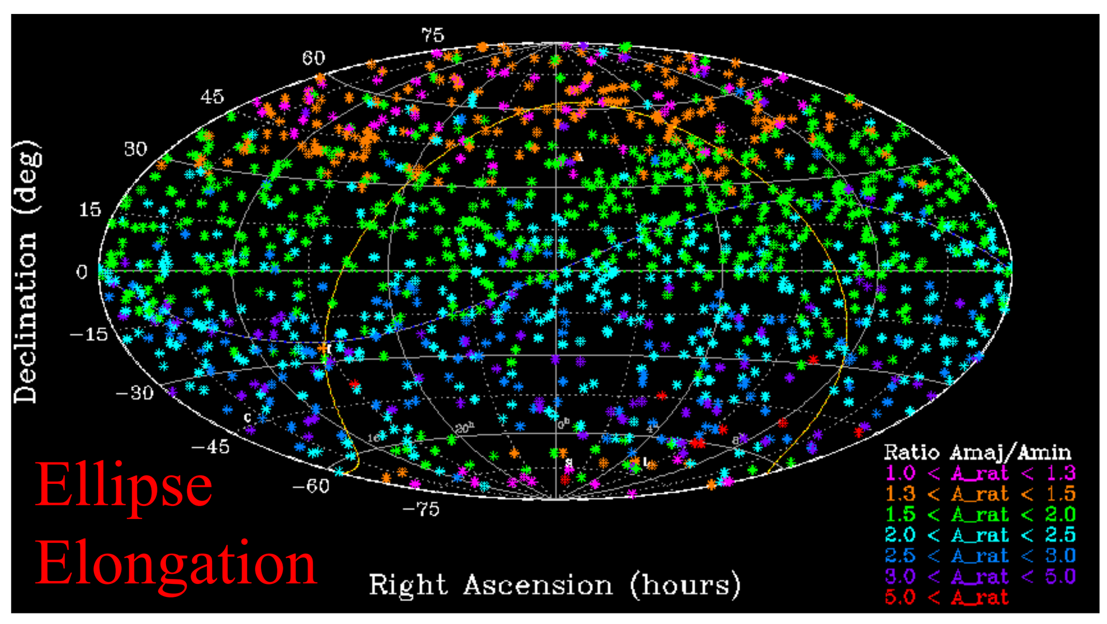

Fig. 10: : Error Ellipse ratio A_{maj}/A_{min} shows steady elongation from δ +90 to -45 deg.

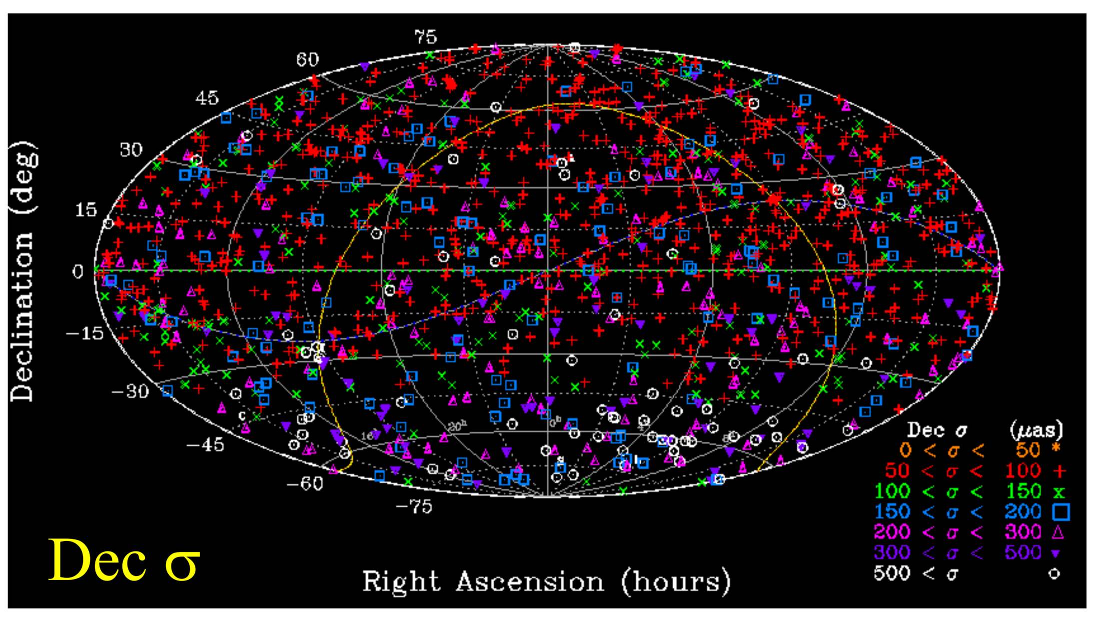

Fig. 7: Dec precision: Median σ is 91 μas for 1315 sources. Median = 324 μas for Dec < -45 deg.

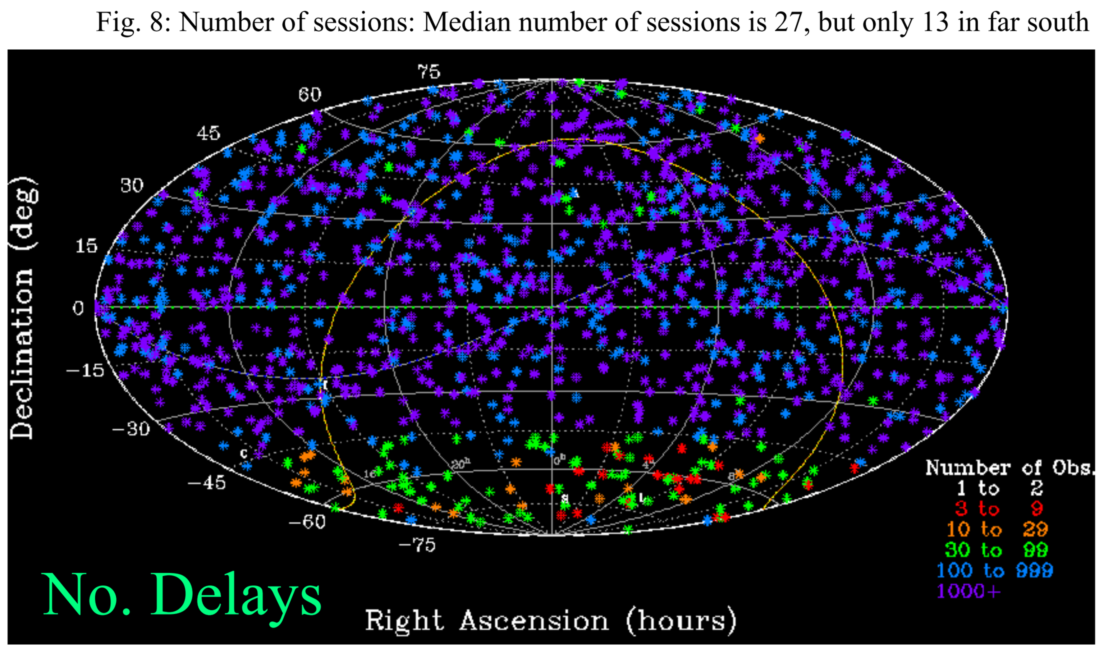

Fig. 9: Number of Delay Observations: Median = 1579. South of -45 deg, median = 40.

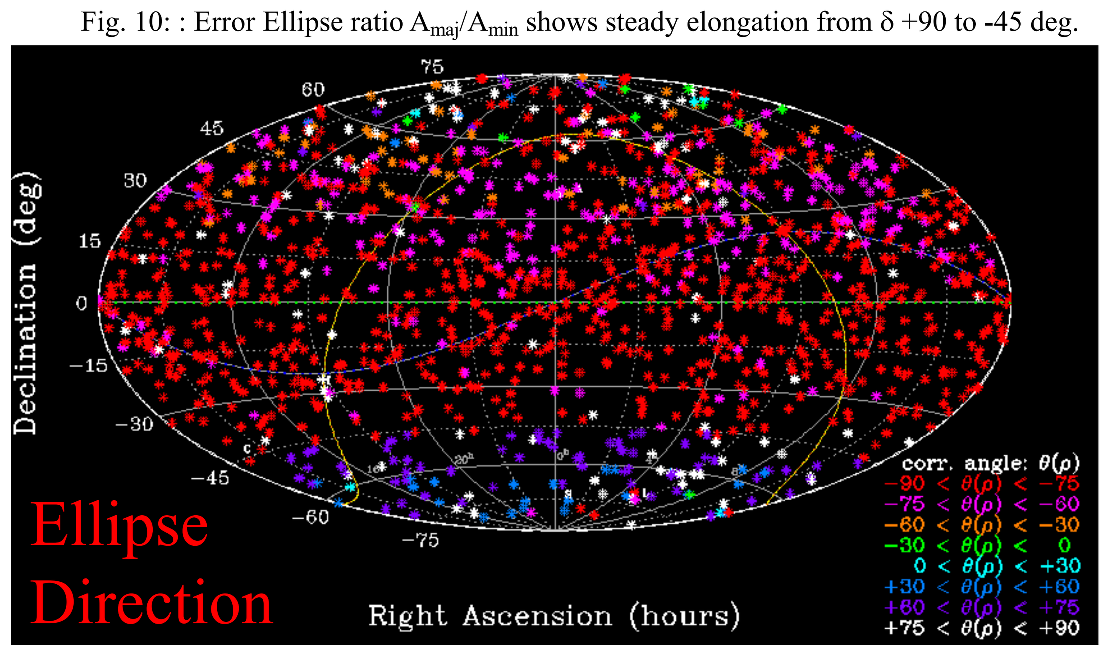

Fig. 11: Direction of Error Ellipses: semi-major axes are mostly North-South i.e. δ weaker than α

II. Accuracy: K vs. S/X

Comparing K-band (2024/01/19) to the ICRF3-S/X (Charlot et la, 2020), after removing sources with $\sigma_{\alpha\cos\delta}$, σ_δ > 2 mas and 57 outliers > 5-σ leaves 1175 common sources. wRMS agreement is 112/ 162 μas in αcosδ and δ, respectively. Vector Spherical Harmonic differences (Mignard & Klioner, 2012) to degree and order 2 largest terms were Y-rotation = -46 +-6 μas, and quadrupole 2,0 Magnetic/electric terms of -26 +- 4 and -36 +- 7 μas. More north-south baseline data is expected to help control the quadrupole errors.

III. Gaia Optical-Radio Frame Tie and Accuracy Verification:

Background: Launched in Dec. 2013, ESA's Gaia mission measures positions, proper motions and parallaxes of 1.8 billion objects down to 21st magnitude---as well as photometric and radial velocity measurements. Gaia's observations include more than 1.6 million AGN of which ~20,000 are optically bright:V < 18 mag (Klioner, Gaia-CRF3, A&A, 2022).

Comparison: The Gaia celestial frame is independent from K-band in three key respects: optical vs. radio, space vs. ground, pixel centroiding vs. interferometry. As a result Gaia provides the most independent check of accuracy available today.

Gaia Early Data Release-3 (Gaia collab.+, 2022): 946 sources are detected in both the optical and K-band radio---after removing 119 outliers >= 5-σ (~11%). Rotational alignment is made with ~12 μas precision (1-σ, per 3-D component). wRMS scatter is 216 μas in αcosδ and 245 μas in δ. Vector Spherical Harmonic differences are dominated by quadrupole 2,1 mag real/imaginary of 70+-14 and 46+-15 μas. Thus overall, global agreement of the two frames is at the part per billion level.

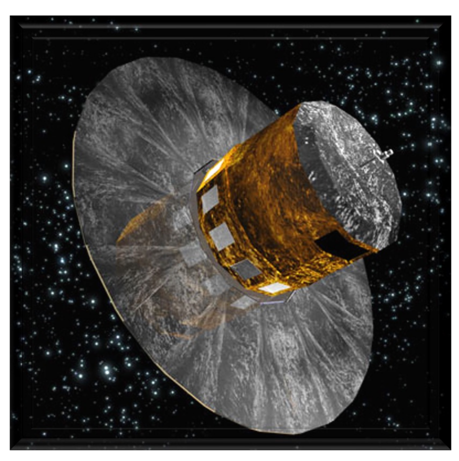

Fig. 12: Gaia launched in Dec 2013 toward L2 (www.esa.int/esaSC/120377_index_1_m.html#)

IV. Goals for the Future:

1. Number: > 1500 sources.
   - Increase ecliptic density for spacecraft.
   - More sources in deep south add LBA ? CART, Argentina 40m?
2. Precision: <= 30 μas (1-σ)
3. Sensitivity: VLBA 4 to 8 Gbps KVN/Hart/Yebes 2 to 4 Gbps
3. Improve Declination accuracy: Spain-South Africa, Korea-Australia. Global proposal: VLBA + KVN + EVN

V. Conclusions: The K-band CRF has 1315 sources covering the full sky and is making rapid improvements in the precision. The median precision is 52 / 12 μas in α cosδ / δ. Spherical harmonic differences vs. ICRF3-S/X are <= 46 μas and vs. Gaia VSH are <= 70 μas. Improving accuracy depends on controlling systematics via increased observations using a North-South baseline geometry.

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