The X/Ka-band (8.4/32 GHz) 2024a Celestial Reference Frame

Executive Summary: Celestial angular coordinates (α,δ) are derived from VLBI measurements at 8.4/ 32 GHz (36/ 9 mm) of Active Galactic Nuclei. Agreement with S/X is at the part per billion level. X/Ka has reduced astrophysical systematics vs. S/X.

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Abstract:

The X/Ka-band (8.4/32 GHz) Celestial Reference Frame became one of three components of the ICRF-3 in 2018. In the five years since, the X/Ka data set has increased by about 93% as well as adding the much needed north-south geometry from Japan to Australia. The latest solutions have 686 sources with median formal precisions of 43 µas in α cosδ and 62 µas in δ.

The large spherical harmonic distortions seen in the ICRF3-X/Ka are greatly improved with the Z-dipole term reduced from 314 µas to a statistically insignificant -49 +- 40 µas and with the quadrupole 2,0 magnetic term of 186 +- 15 µas and a quadrupole 2,0 electric term of 80 +- 24 µas. We note that the X/Ka frame is derived from a limited geometry of only five observing sites of which the two DSN baselines dominate with 85% of the total data thus creating a susceptibility of this frame to geometric distortions. The prospects for future improvements are bright and we expect the distortions to be reduced as more data from the ESA Malargüe and JAXA Misasa stations are added.

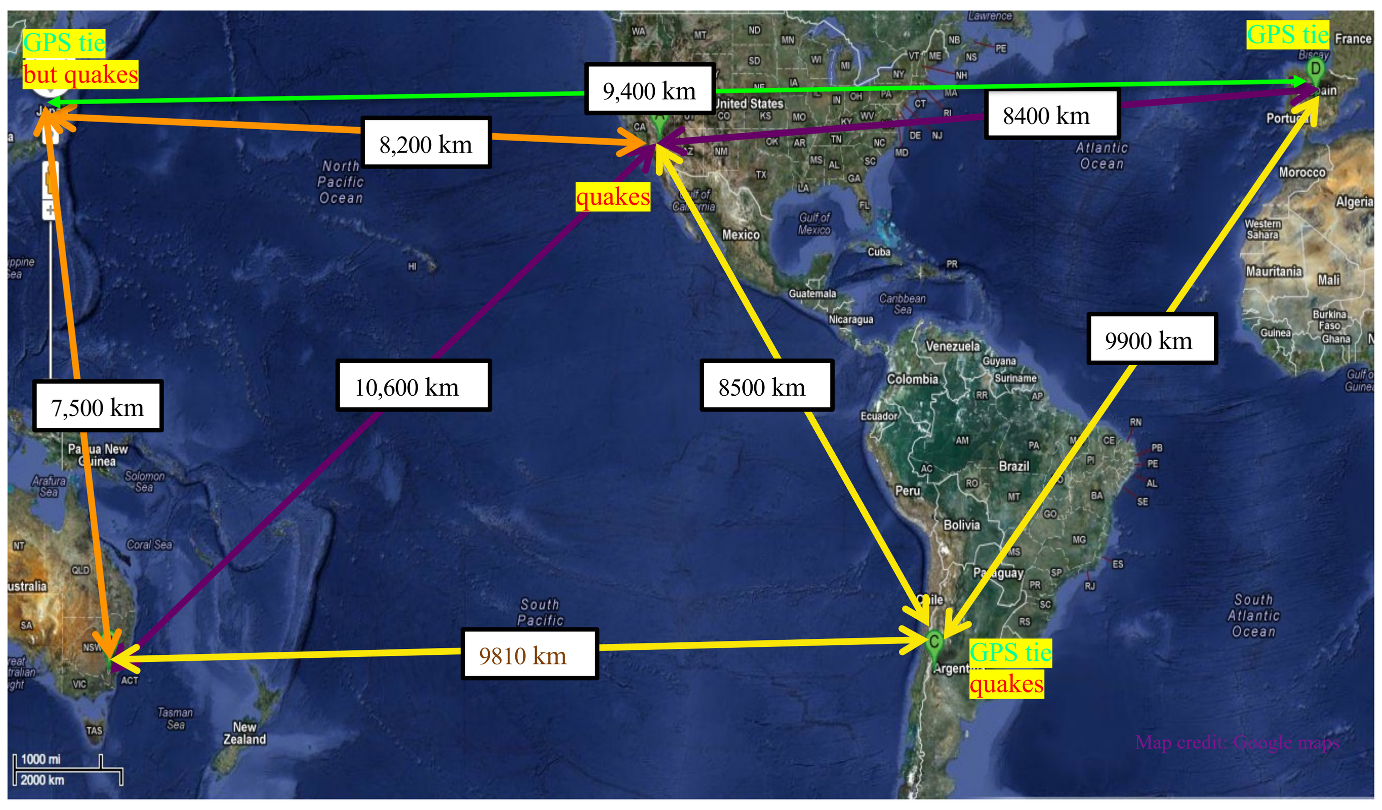

Fig. 1 NASA-ESA-JAXA Ka-band network. The addition of Argentina & Japan adds 6 baselines & Full Sky coverage. For δ = +45 to +90 deg coverage is from California-=Spain and Japan-Spain baselines. For δ -45 to -90 deg, coverage is only from the Australia-Argentina baseline. Three sites are susceptible to earthquakes.

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 Ka-band compared to S/X-band:
- More compact, stable sources (Fig. 3,4)
- Reduced opacity effects: "core shift"
- Ionosphere & solar plasma effects reduced by 15X.

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

But increasing data rates are rapidly compensating. We have increased JPL operations to 2.0 Gbps.

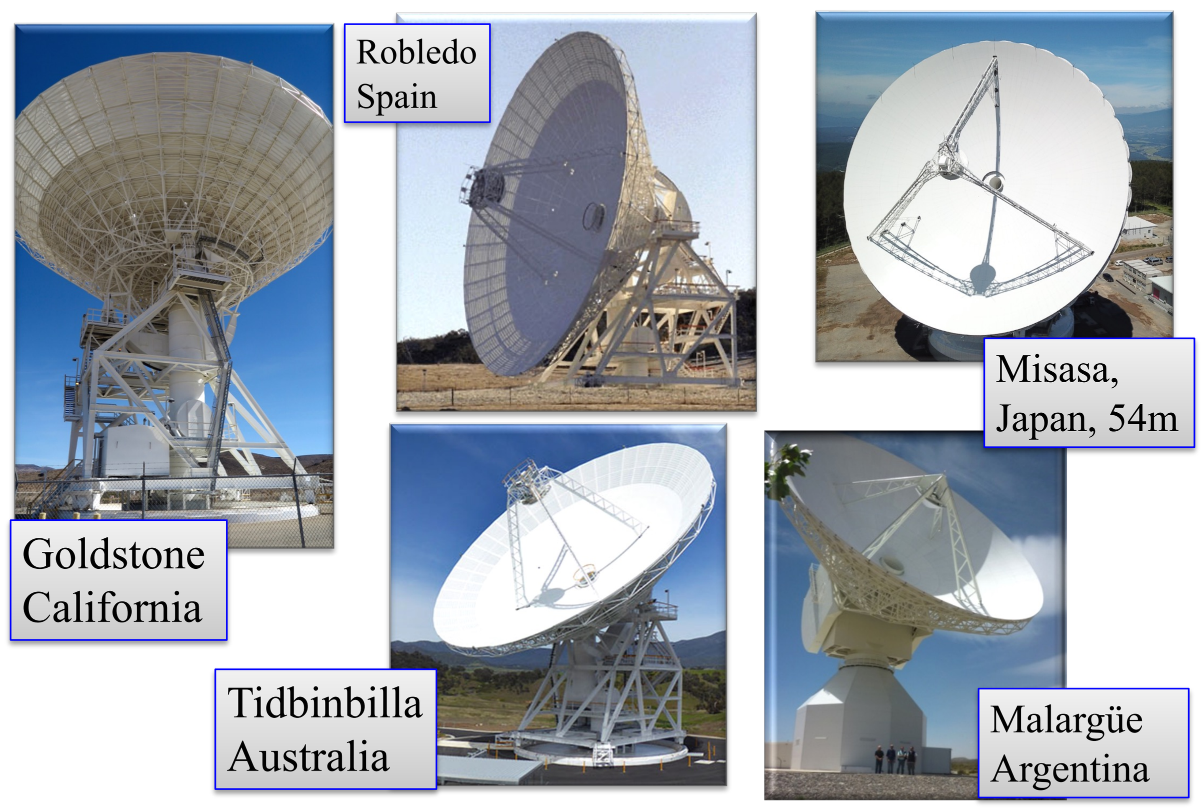

Fig. 2. Antennas of combined NASA-ESA-JAXA X/Ka-band network. Antenna diameters: Goldstone, Robledo, & Tidbinbilla are 34m, Malargüe is 35m, Misasa is 54m.

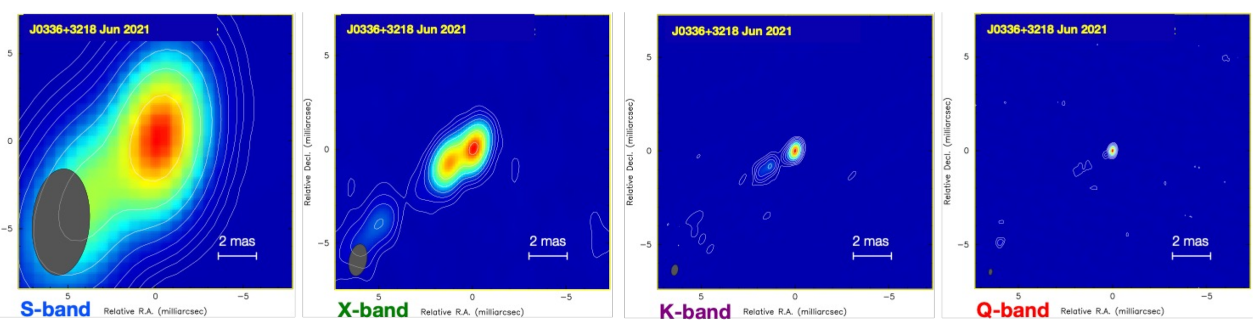

Fig. 3: Near-simultaneous S (2.3 GHz), X (8.4 GHz), K (22 GHz) and Q-band (43 GHz) images based on VLBA observations of 453 ICRF sources between April - June 2021 (*Hunt et al, 2022, de Witt et al, 2022*) demonstrate that VLBI calibrator sources get more compact with increasing frequency. In particular, 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.

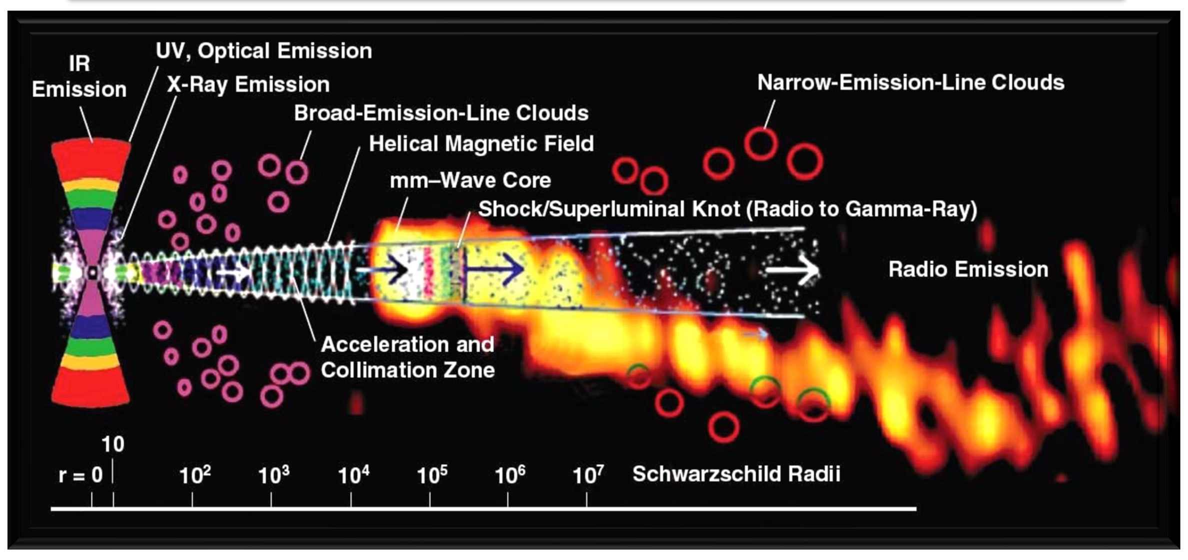

Fig. 4: Schematic of Active Galactic Nuclei (Marscher, 2006, Krichbaum, 1999, Wehrle, 2010)

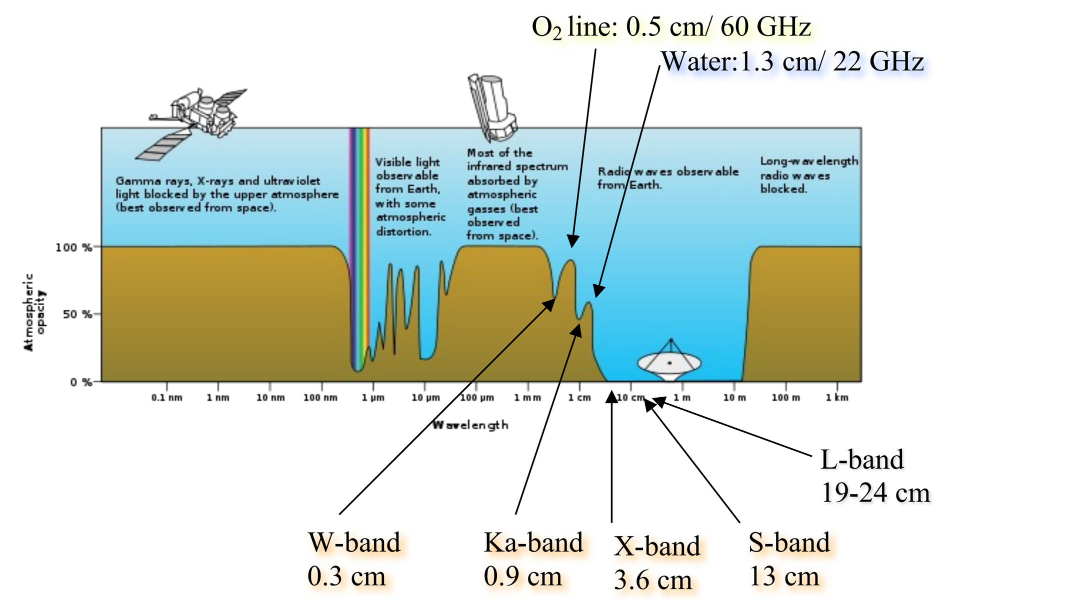

Fig. 5: The radio "window" is transparent compared to most of the spectrum (credit: NASA) Ka-band (32 GHz) is in the saddle point between H_20 (22 GHz) and O_2 (60 GHz) lines.

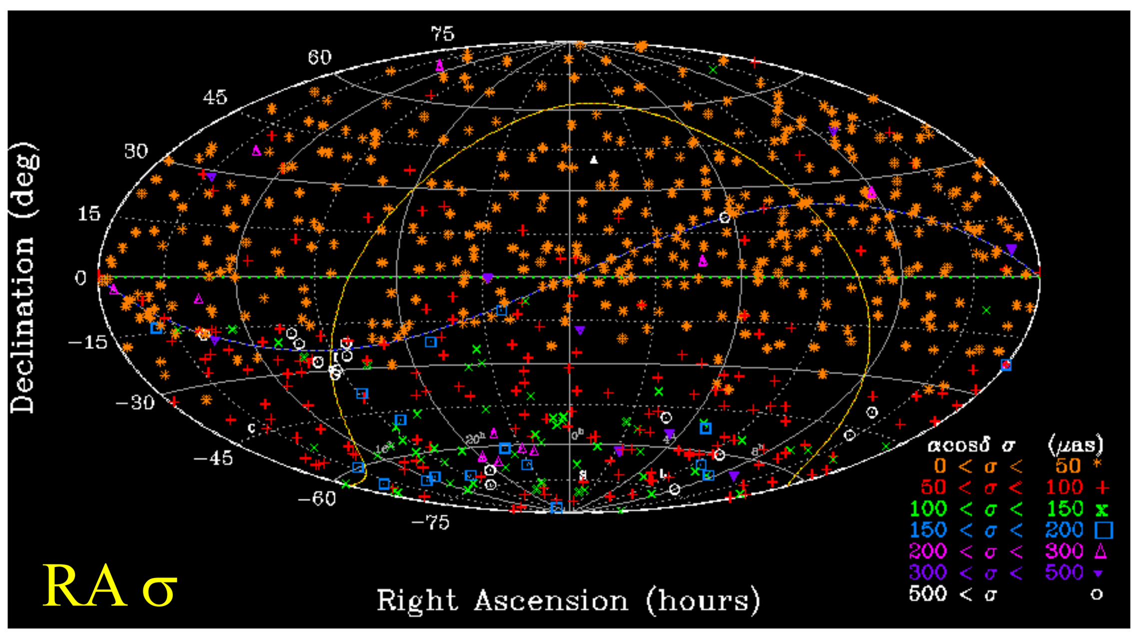

Fig. 6 RA* (arc) precision: Median σ 43 µas for 686 sources. Median 107 µas for Dec < -45 deg.

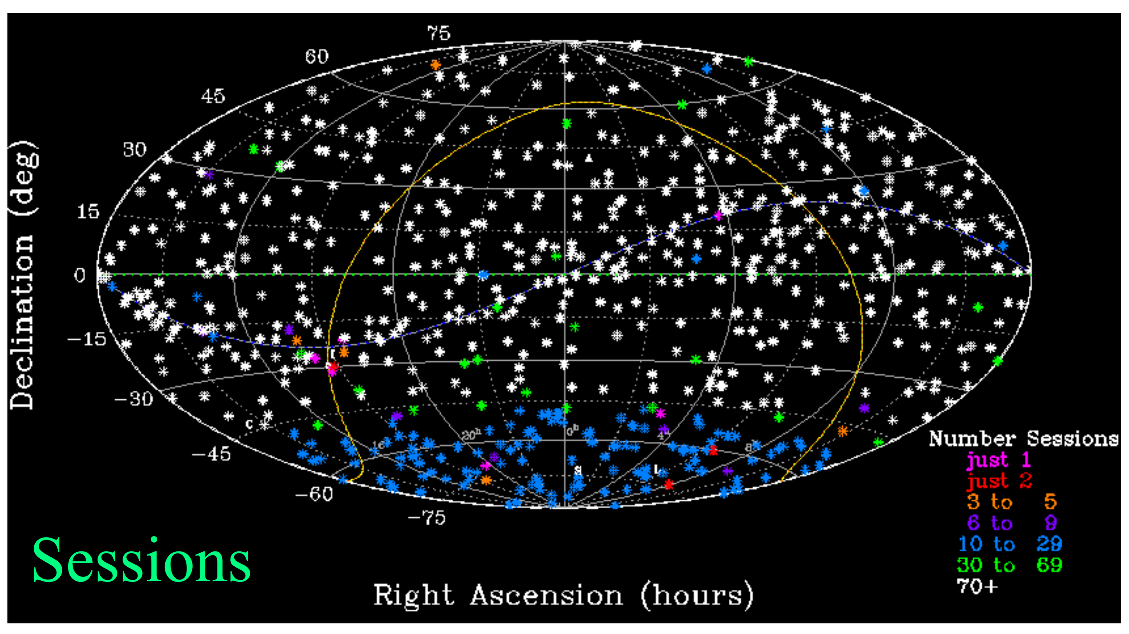

Fig. 8: Number of sessions: Median number of sessions is 139, but only 18 in far south

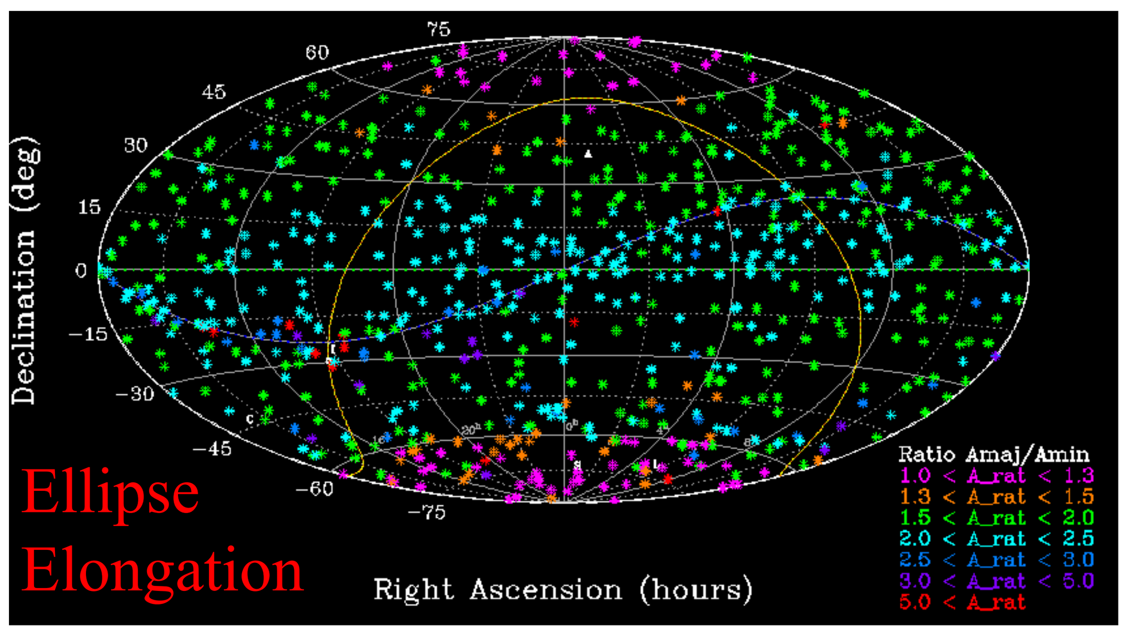

Fig. 10: : Error Ellipse ratio A_{maj}/A_{min} shows steady elongation from poles to equator.

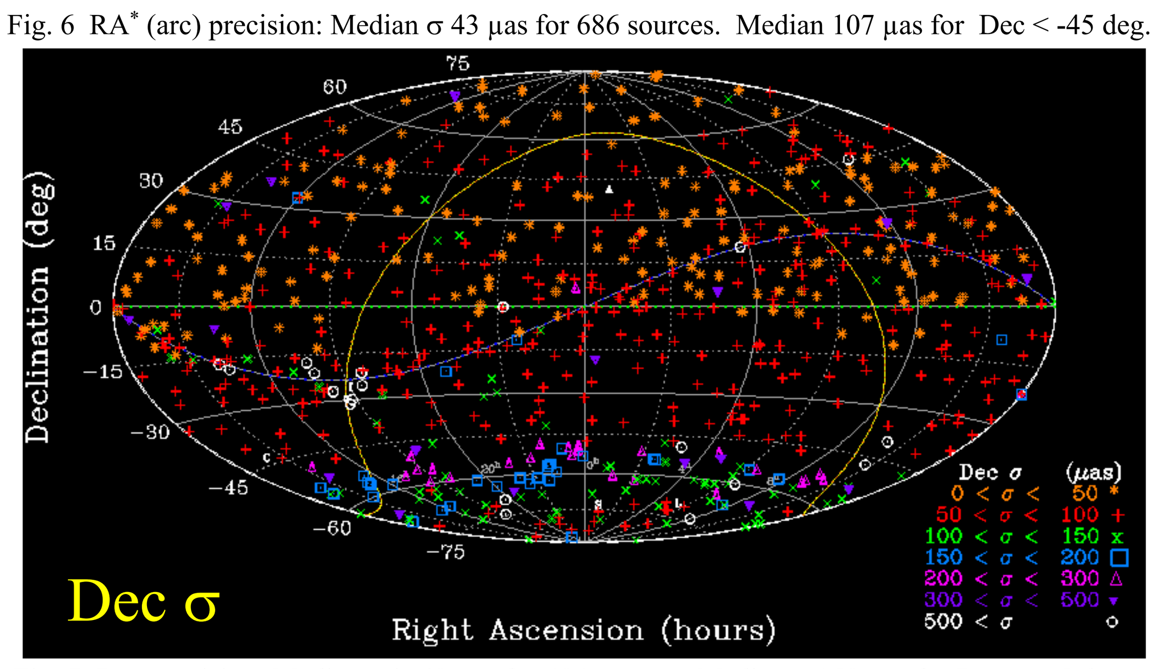

Fig. 7: Dec precision: Median σ is 62 µas for 686 sources. Median = 150 µas for Dec < -45 deg.

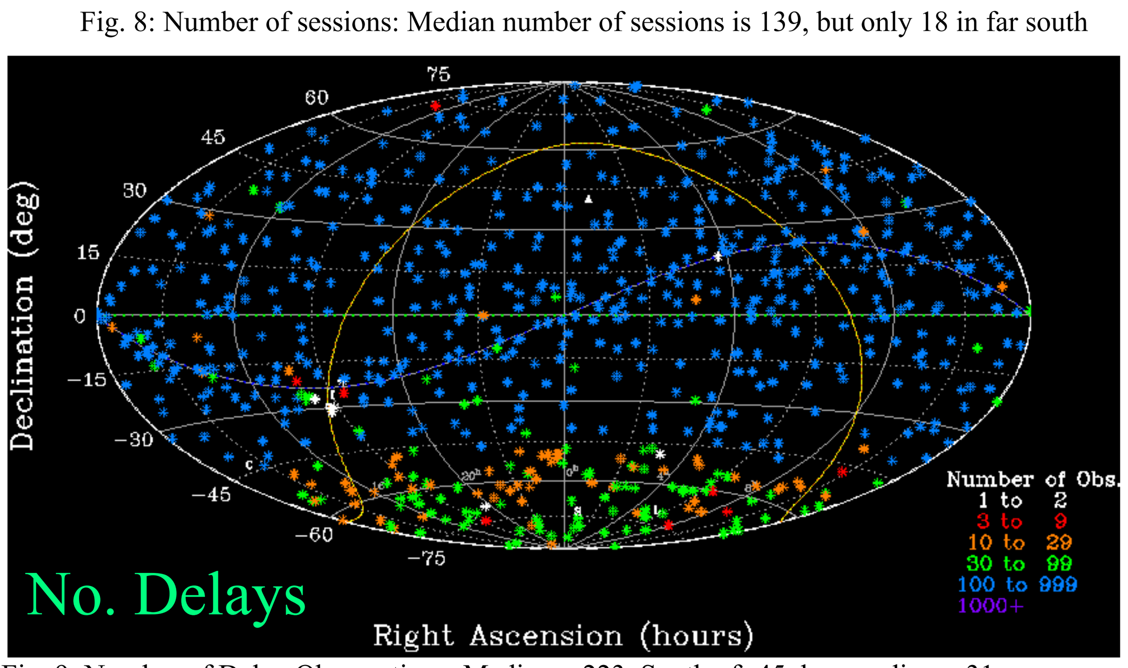

Fig. 9: Number of Delay Observations: Median = 223. South of -45 deg, median = 31.

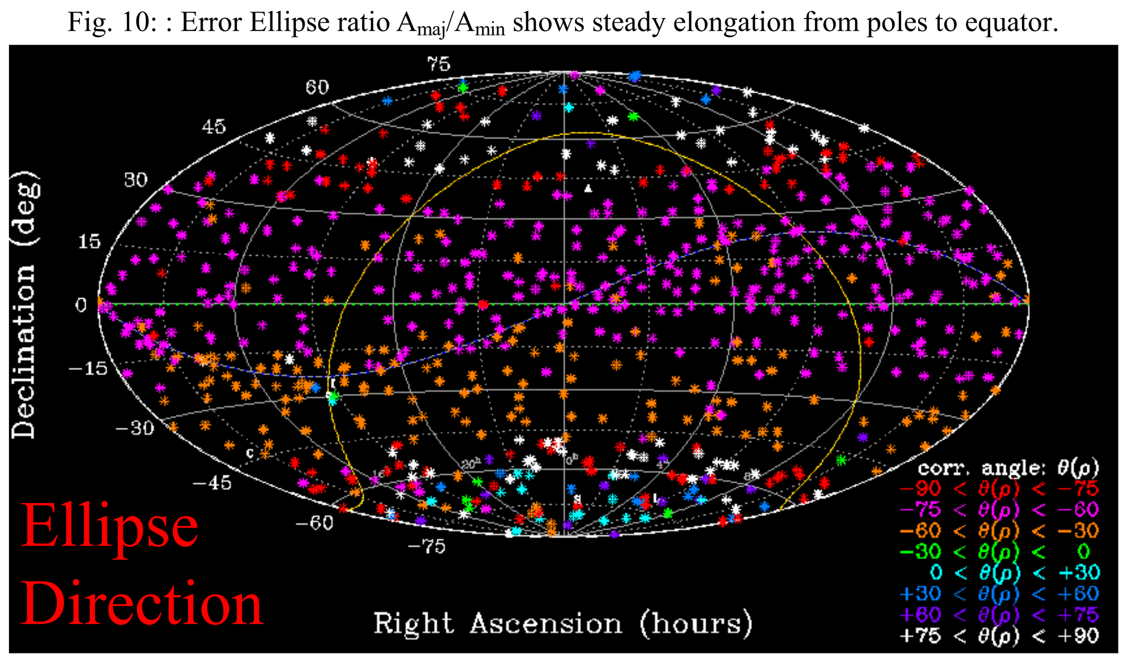

Fig. 11: Direction of Error Ellipses: semi-major axes are mostly North-South i.e. δ weaker than α

II. Accuracy: X/Ka vs. S/X

Comparison of XKa solution dated 2024/02/21 to the current ICRF3-S/X (Charlot+, 2020), after removing 86 outliers > 5-σ, leaves 534 sources in common. The wRMS agreement is 144 / 135 µas in αcosδ and δ, respectively. We tested for spatially correlated differences by estimating vector spherical harmonics (Mignard & Klioner, 2012) to degree and order 2. The largest terms were a Z-dipole at -49 +- 40 µas, quadrupole 2,0 Magnetic term at 186 +- 15 µas and a quadrupole 2,0 electric term of 80+- 24 µas.

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 will include more than 1.6 million AGN of which ~20,000 will be optically bright (V < 18 mag).

Comparison: The Gaia celestial frame is independent from XKa-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. With Gaia Early Data Release-3 (Gaia collab.+, 2022), 438 sources are detected in both the optical and XKa-band radio---after removing 69 of the sources as outliers >= 5-σ. Rotational alignment is made with ~16 µas precision (1-σ, per 3-D component). wRMS scatter is 230 µas in αcosδ and 230 µas in δ. The largest Vector Spherical Harmonic difference term out to degree and order 2 is 210 +- 21 µas in quadrupole 2,0 mag, indicating better than one part per billion level of global agreement of the two frames.

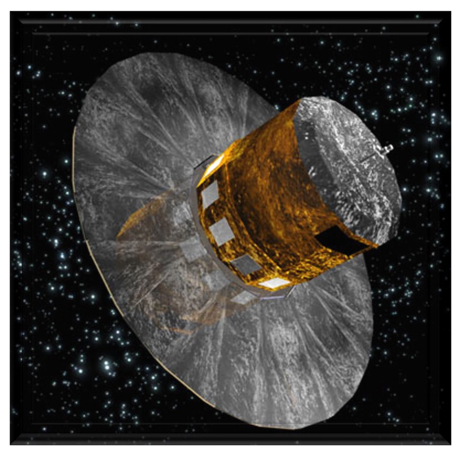

Fig. 12: Gaia launched in Dec 2013 toward L2 (www.esa.int/esaSC/120377_index_1_m.html#)

IV. Goals for the Future:

1. Number: 700 to 1000 sources. Greater density along ecliptic plane.
2. Precision: <= 50 µas (1-σ)
3. Uniformity: Improve south with baselines from Malargüe and Misasa to Australia, California, Spain.
4. Add X/Ka to the VLBA (Kooi et al, 2023)

V. Conclusions:

The X/Ka-band CRF has 686 sources covering the full sky and is making rapid improvements in the precision. The median precision is 43 / 62 µas in αcosδ / δ. Spherical harmonic differences vs. ICRF3-S/X are <= 190 µas. wRMS scatter vs. Gaia is ~230 µas. Improving accuracy depends on controlling systematics via increased observations using a North-South baseline geometry.

 This research was carried out in part at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration (80NM0018D0004).