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The X/Ka-band (8.4/32 GHz) 2023a 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 75% as well as adding the much needed north-south geometry from Japan to Australia. The latest solutions have median formal precisions of 45 μas in α cosδ and 65 μas in δ.

The large spherical harmonic distortions seen in the ICRF3-XKa are greatly improved with the Z-dipole term reduced from 314 μas to a nearly statistically insignificant -85 +- 44 μas and with the quadrupole 2,0 magnetic term reduced to 158 +- 16 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 over 80% 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.

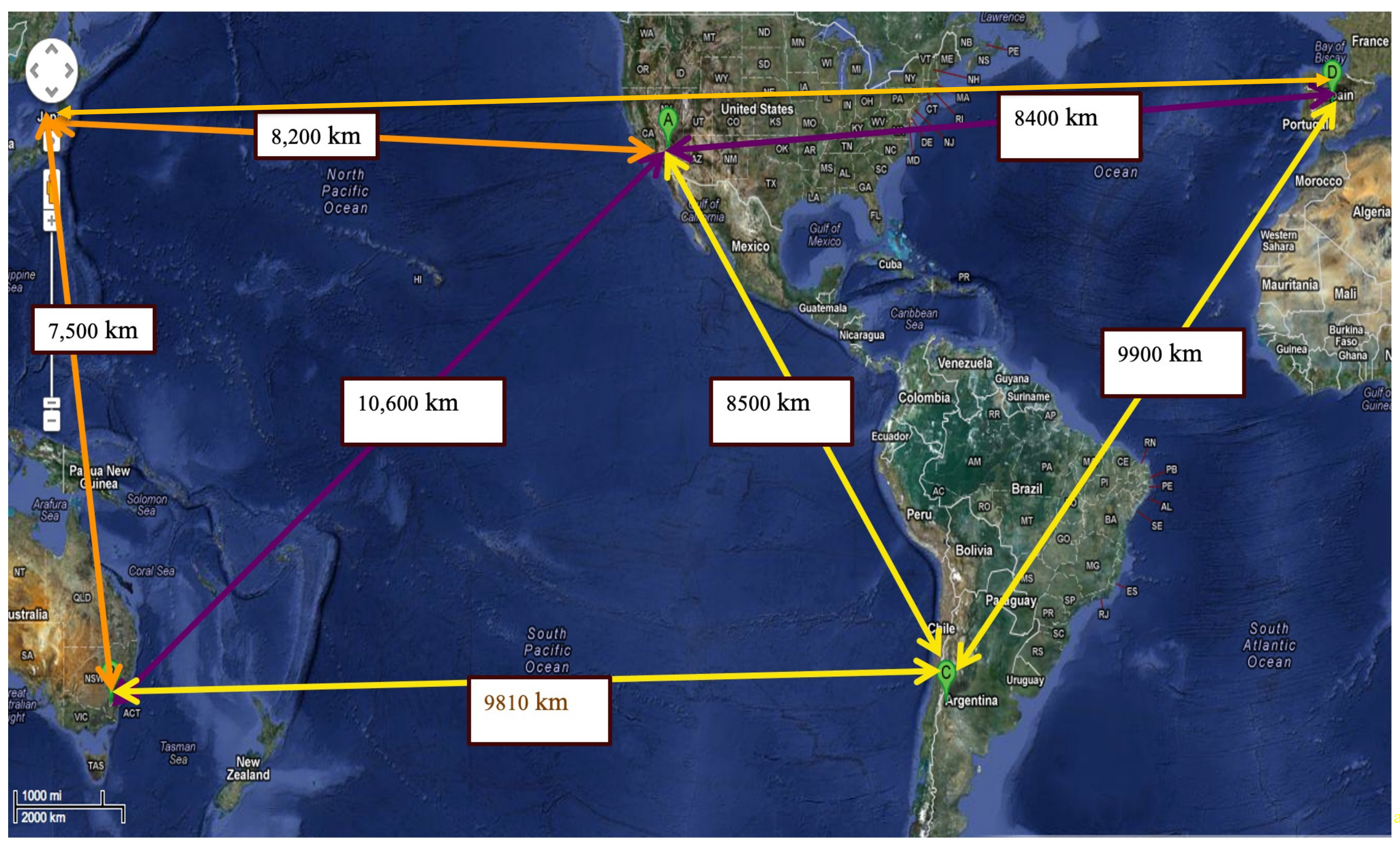

Fig. 1 NASA-ESA-JAXA Ka-band network. The addition of Argentina & Japan adds 6 baselines & Full Sky coverage. For δ = +45 to +90 deg, only single California-=Spain baseline. For δ -45 to -90 deg, only Australia-Argentina baseline,

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.

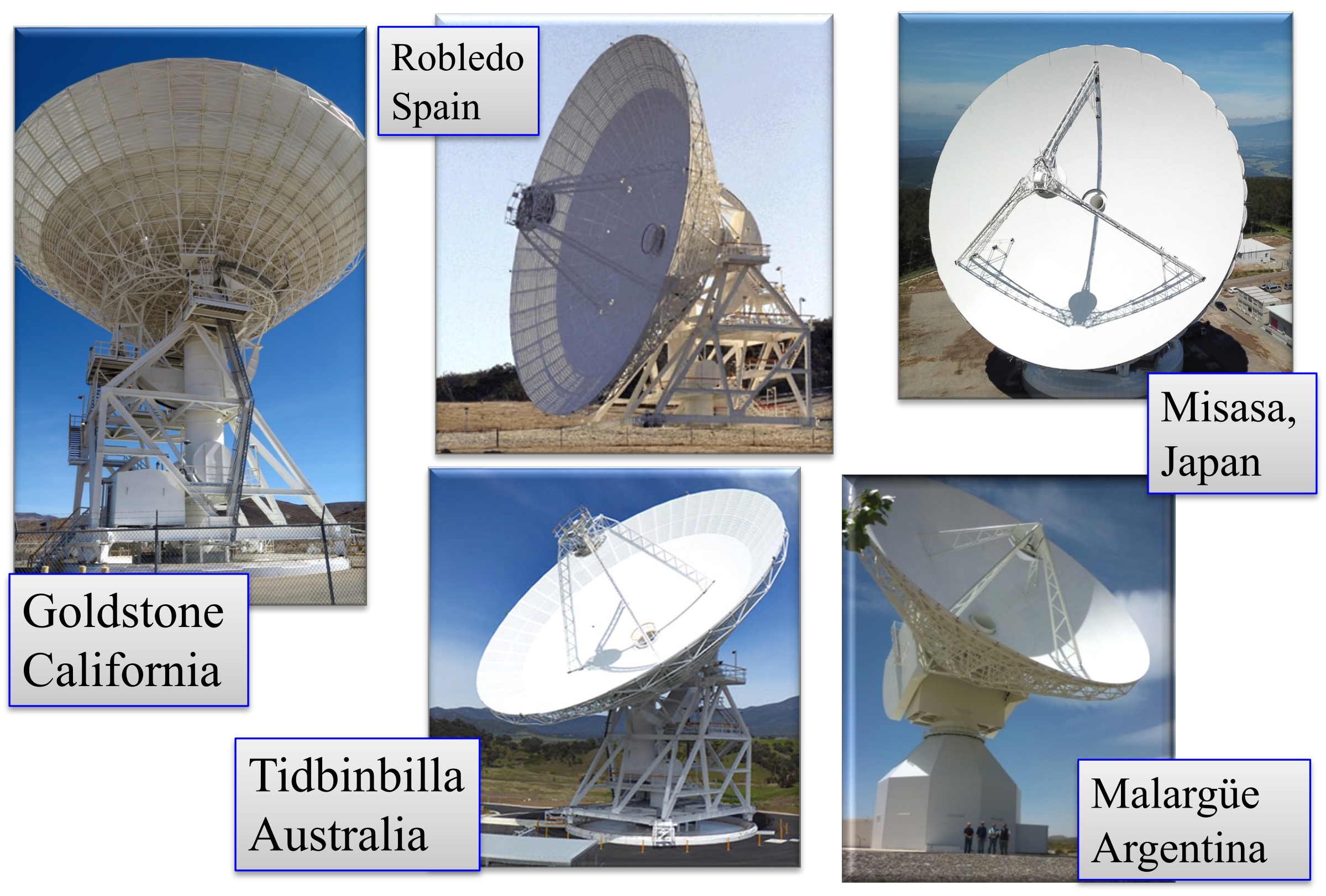

Fig. 2. Antennas of combined NASA-ESA-JAXA X/Ka-band network. Antenna diamters: Goldstone, Robledo, & Tidbinbilla are 34m, Malargüe is 35m, Misasa is 54m.

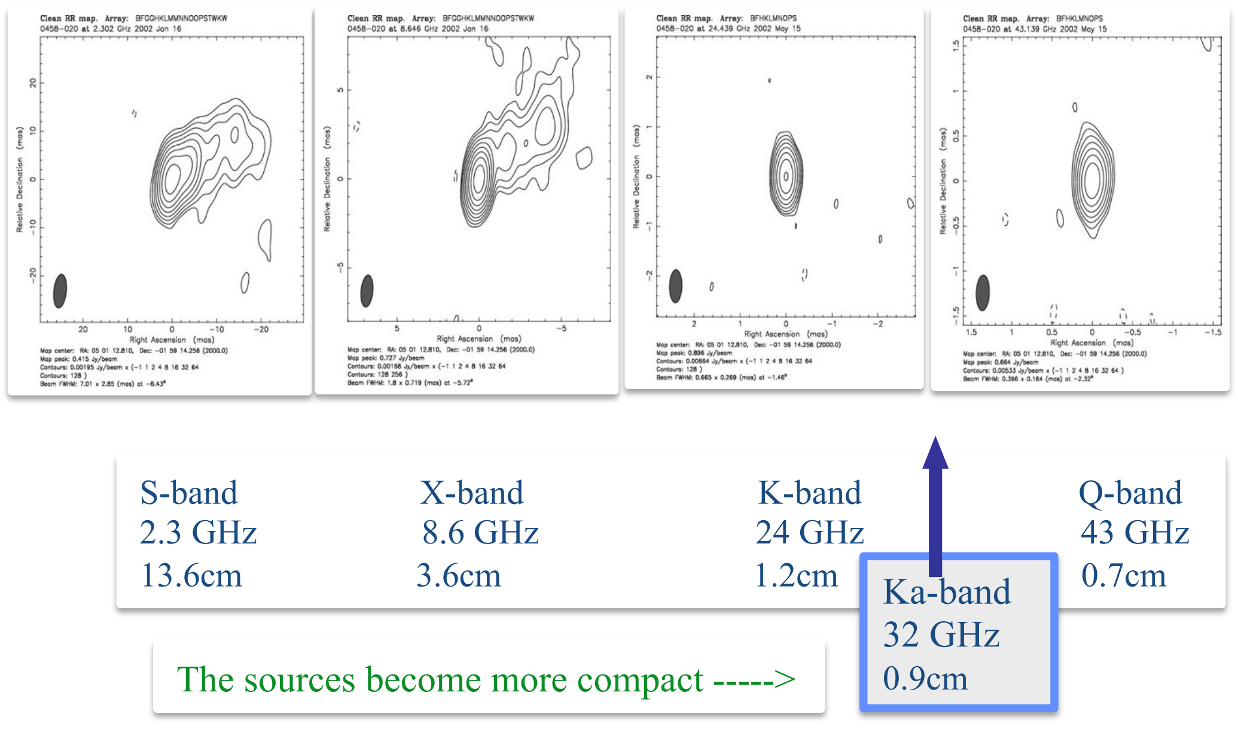

Fig. 3: Source structure & compactness vs. wavelength (Charlot+, 2010; Pushkarev+, 2012)

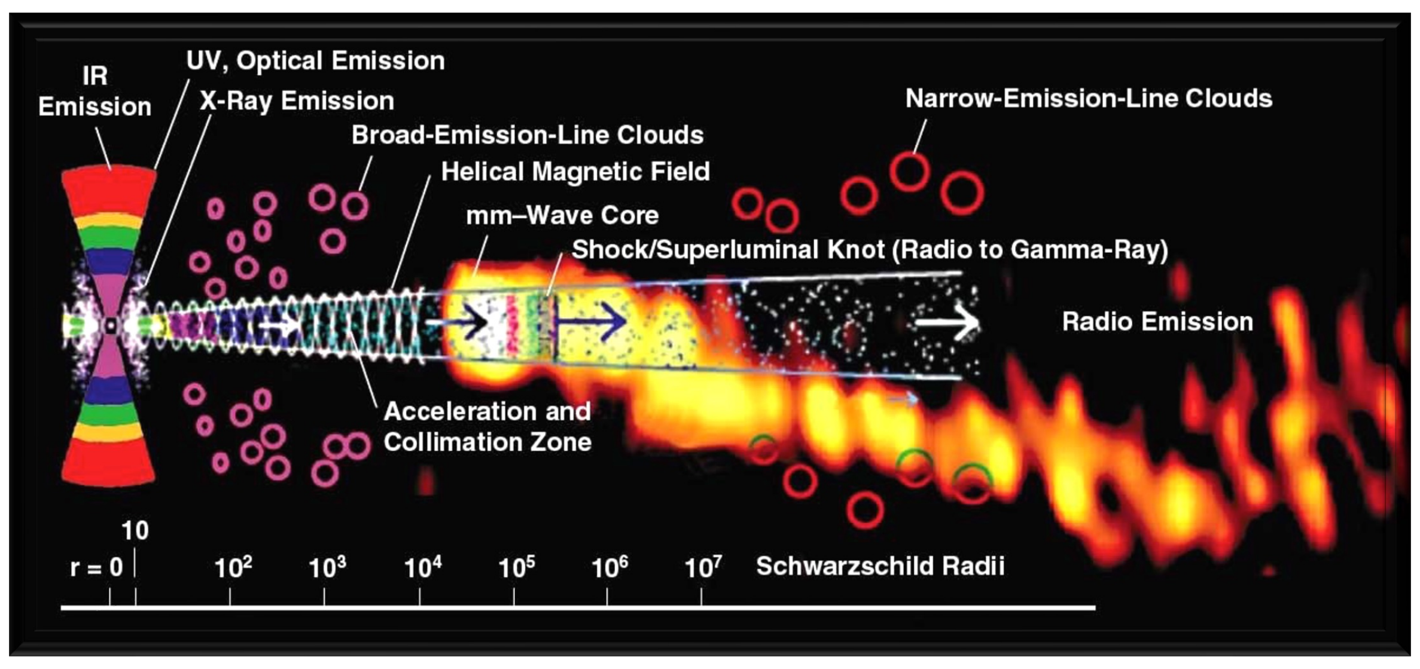

Fig. 4: Schematic of Active Galactic Nuclei (Marscher, 2006, Krichbaum, 1999, Wehrle, 2010)

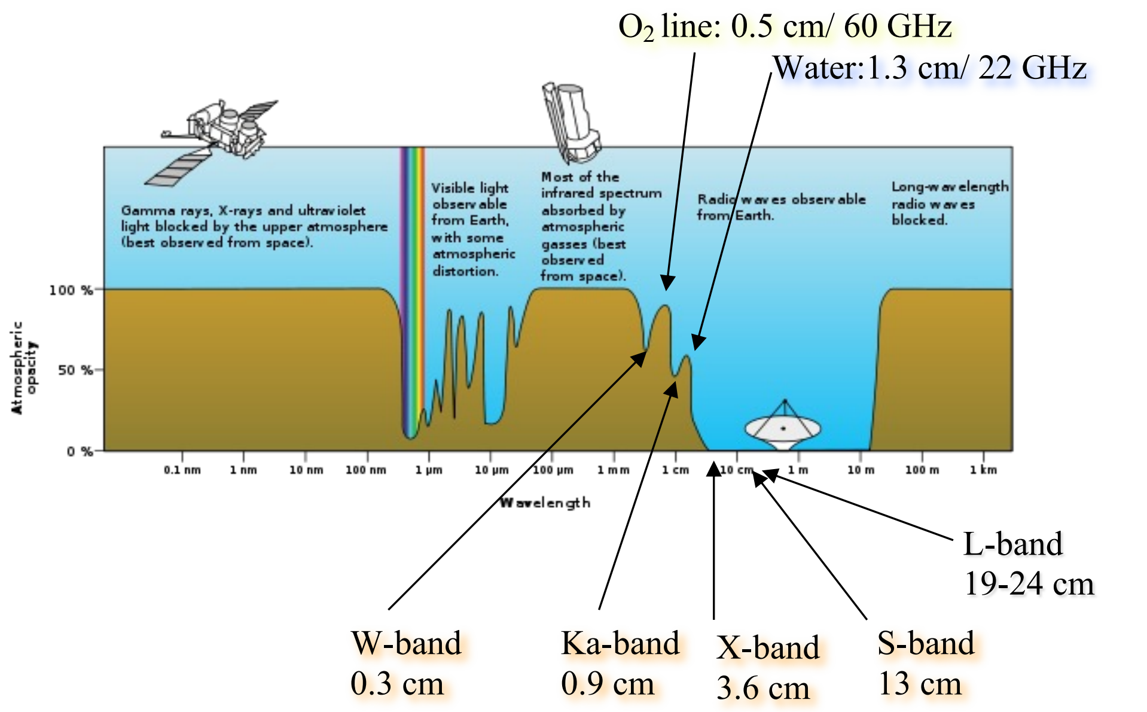

Fig. 5: The radio "window" is transparent compared to most of the spectrum (credit: NASA) Ka-band (32 GHz) is in the saddle point between H_20 (22 GHz) and O_2 (60 GHz) lines.

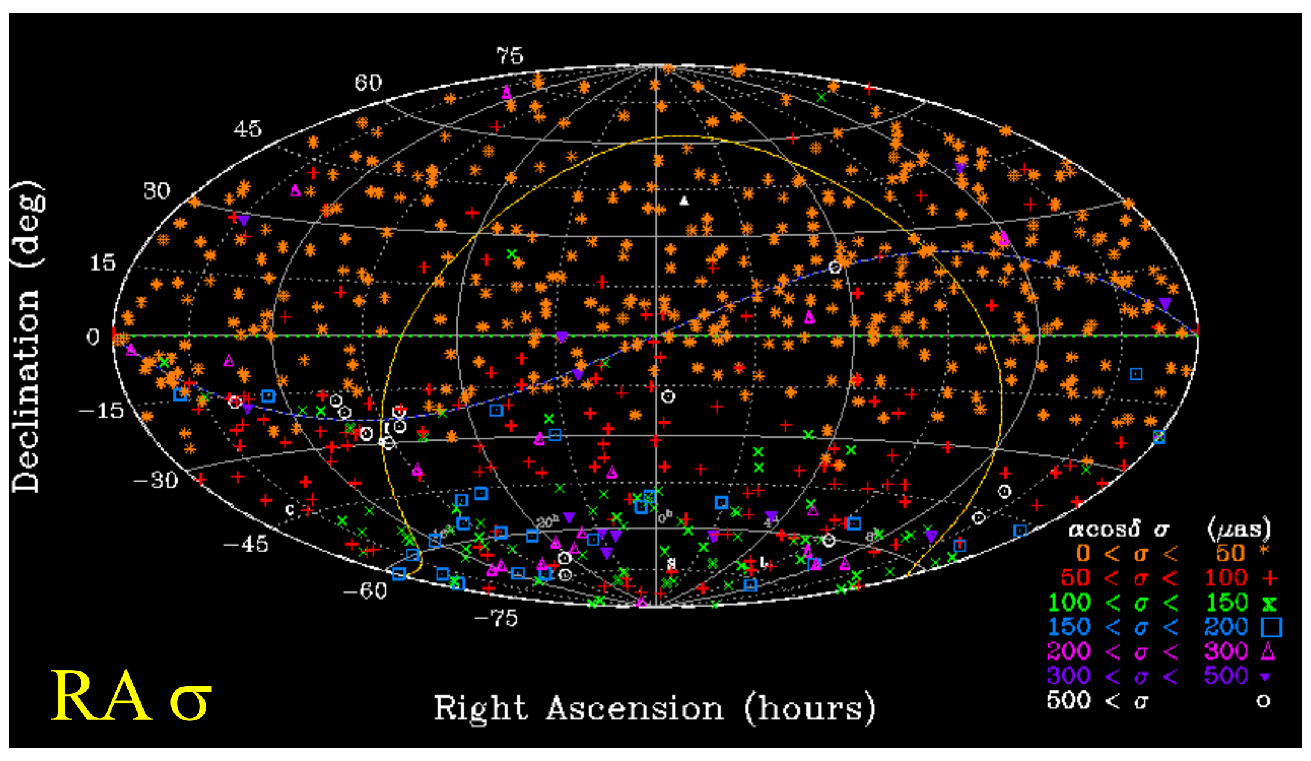

Fig. 6 RA* (arc) precision: Median σ 45 μas for 680 sources. Median 126 μas for Dec < -45 deg.

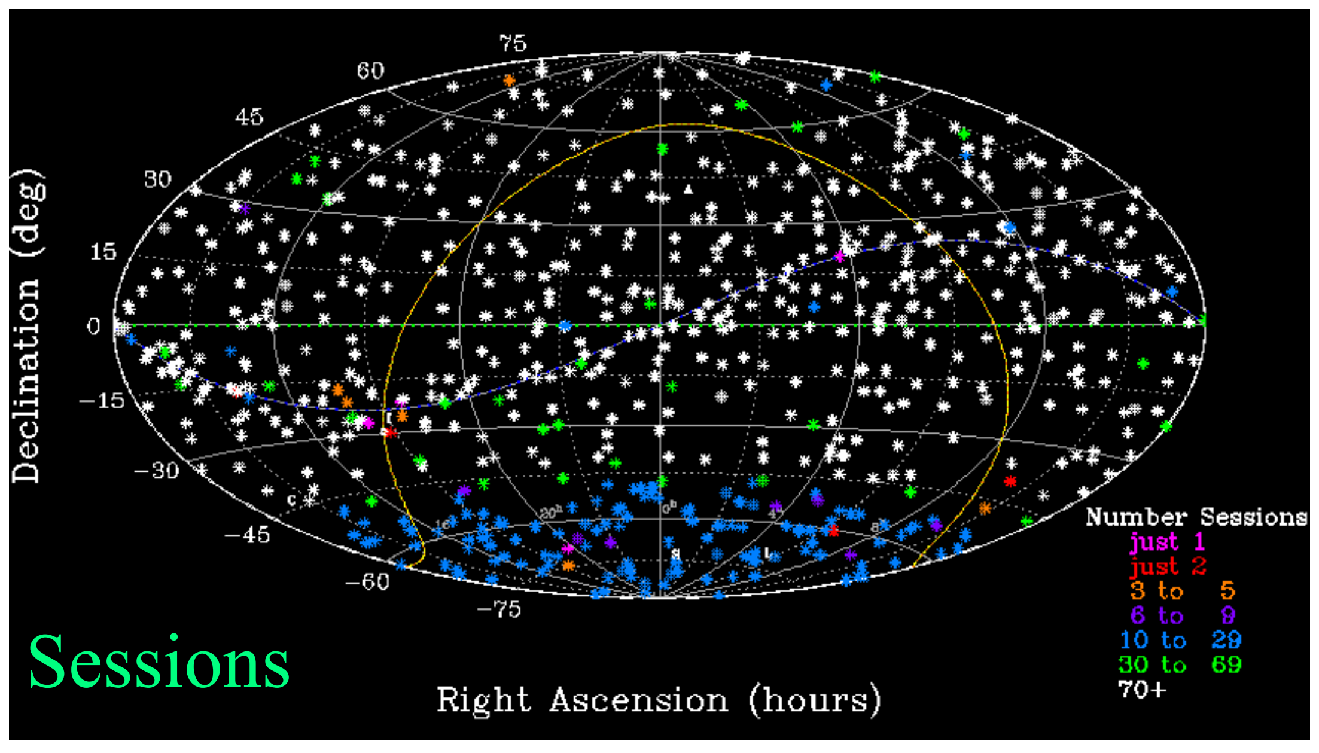

Fig. 8: Number of sessions: Median number of sessions is 132, but only 15 in far south

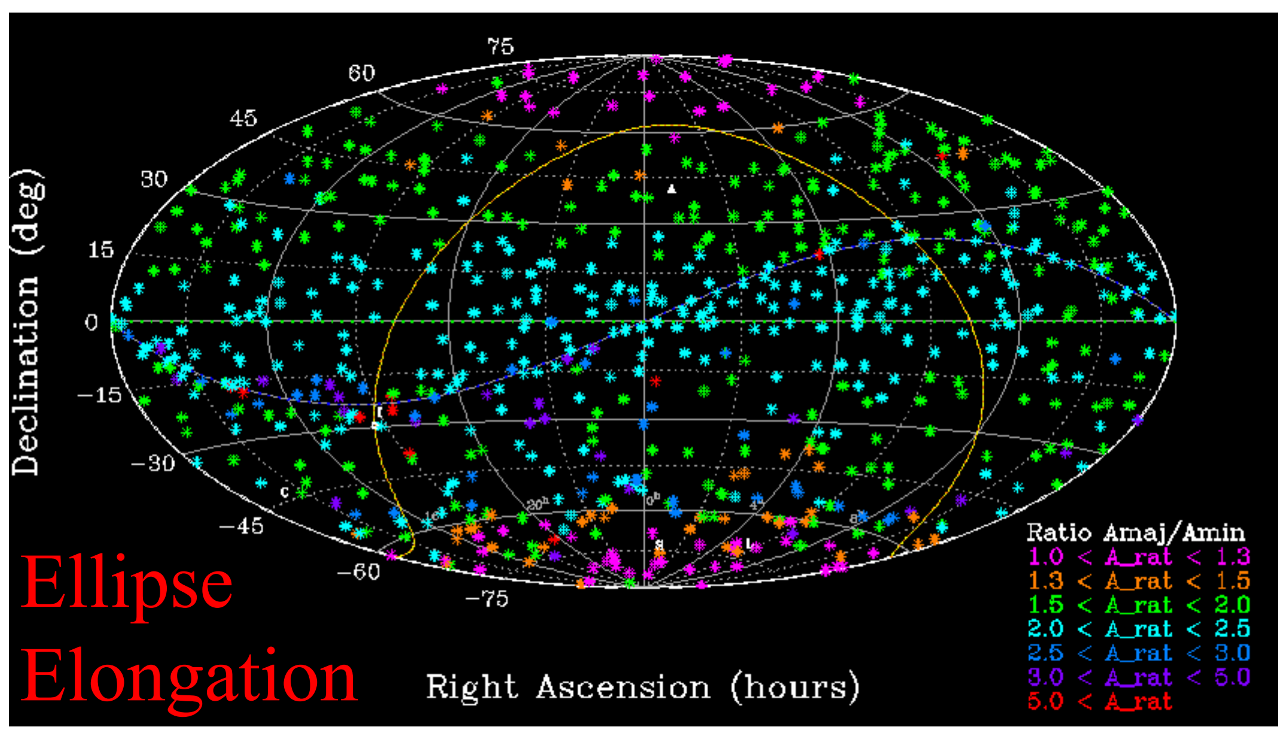

Fig. 10: : Error Ellipse ratio A_{maj}/A_{min} shows steady elongation from δ +90 to -45 deg.

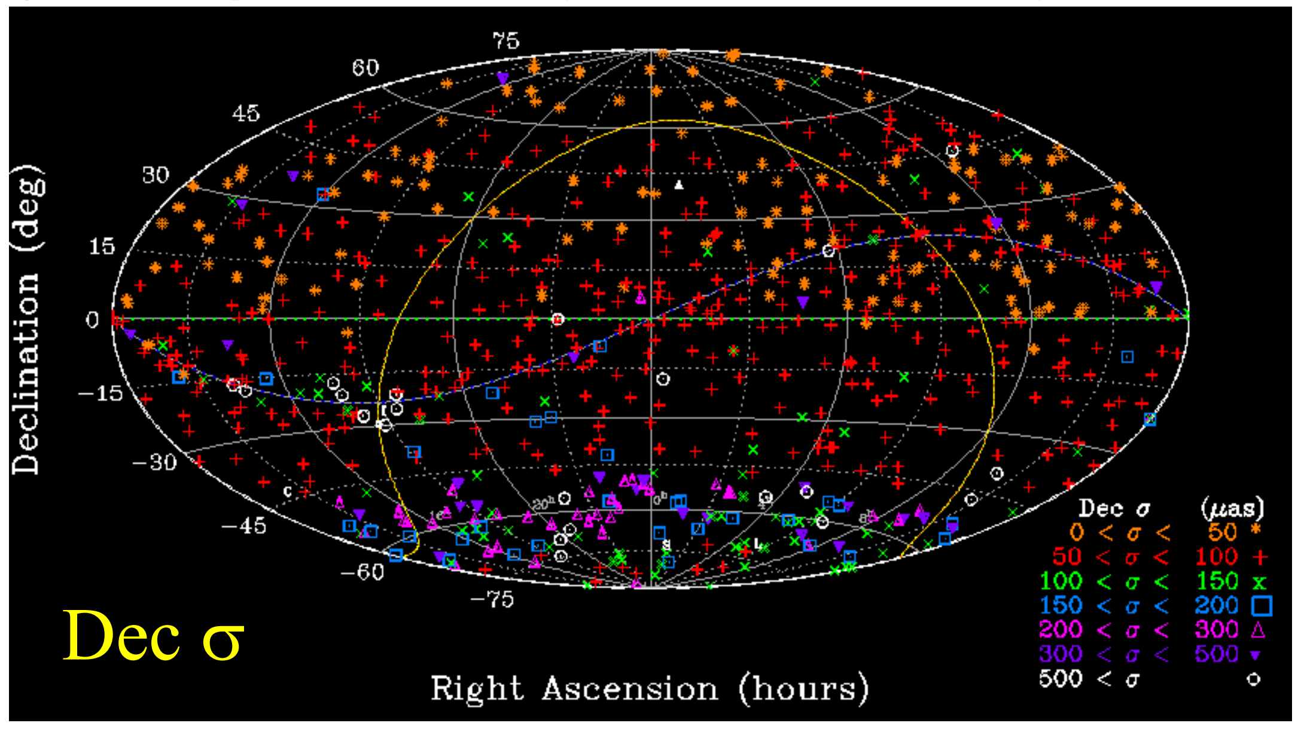

Fig. 7: Dec precision: Median σ is 65 μas for 680 sources. Median = 180 μas for Dec < -45 deg.

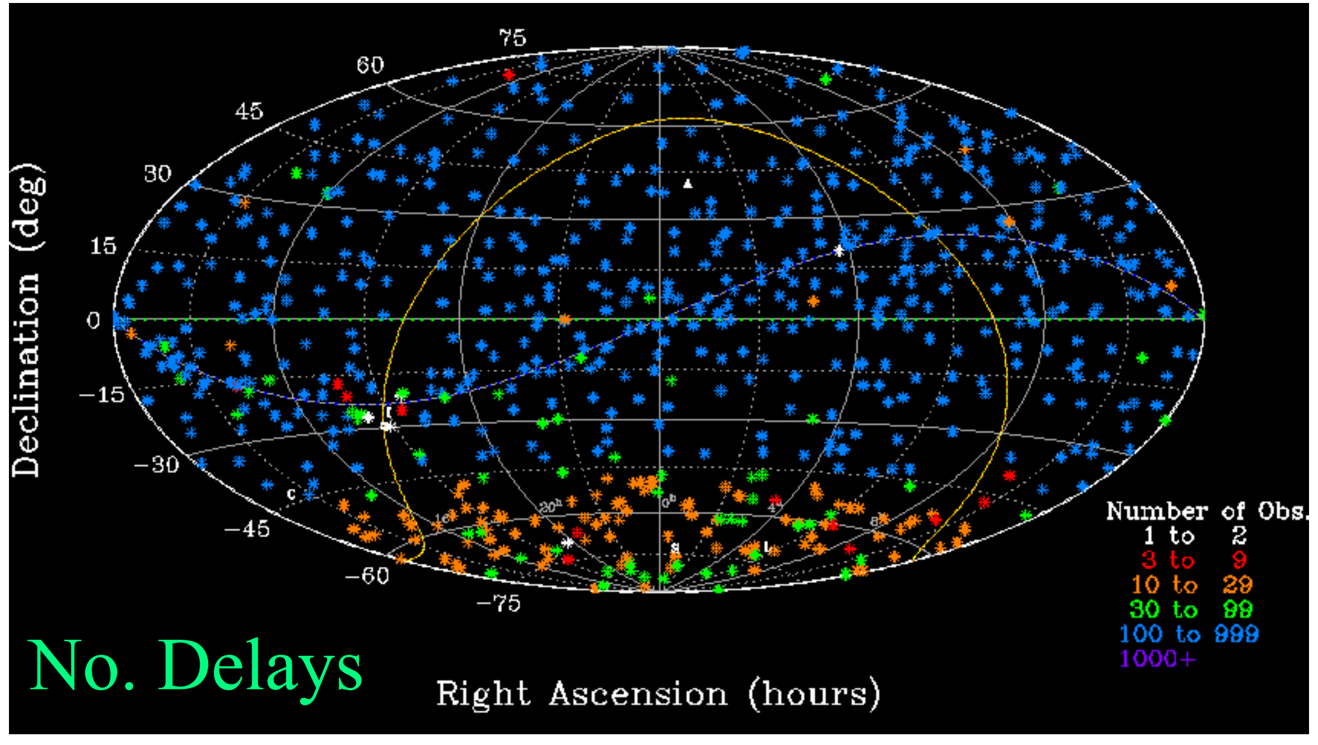

Fig. 9: Number of Delay Observations: Median = 208. South of -45 deg, median = 24.

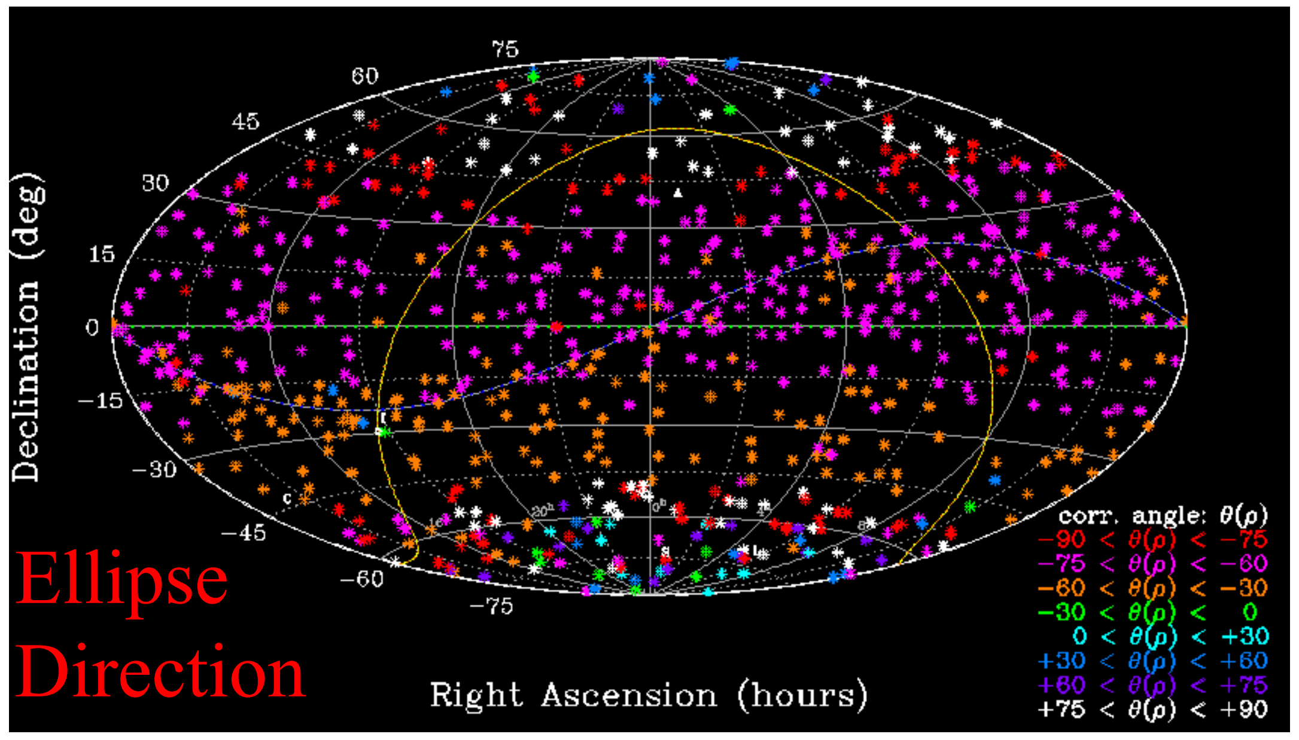

Fig. 11: Direction of Error Ellipses: semi-major axes are mostly North-South i.e. δ weaker than α

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

Comparison of XKa solution dated 230523 to the current ICRF3-S/X (Charlot+, 2020), after removing outliers > 5-σ, leaves 541 sources in common. The wRMS agreement is 134/ 142 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 -85 +- 44 μas and a quadrupole 2,0 Magnetic term at 158 +- 16 μas. More California-Argentina data should control these 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 will include more than 500,000 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), 461 sources are detected in both the optical and XKa-band radio---after removing 63 of the sources as outliers >= 5-σ. Rotational alignment is made with ~17 μas precision (1-σ, per 3-D component). wRMS scatter is 212 μas in αcosδ and 230 μas in δ. The largest Vector Spherical Harmonic difference term out to degree and order 2 is 171 +- 22 μas in quadrupole 2,0 mag, indicating better than one part per billion level of global agreement of the two frames.

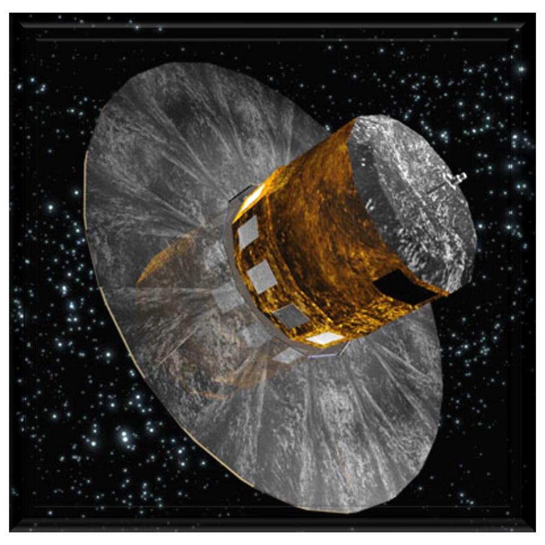

Fig. 12: Gaia launched in Dec 2013 toward L2 (www.esa.int/esaSC/120377_index_1_m.html#)

IV. Goals for the Future:

1. Number: 700 to 1000 sources. Greater density along ecliptic plane.
2. Precision: <= 50 μas (1-σ) to match/exceed Gaia
3. Uniformity: Improve south with baselines from Malargüe and Misasa to Australia, California, Spain.

V. Conclusions: The X/Ka-band CRF has 680 sources covering the full sky and is making rapid improvements in the precision. The median precision is 45 / 65 μas in αcosδ / δ. Spherical harmonic differences vs. ICRF3-S/X are <= 158 μas and scatter vs. Gaia are <= 230 μas. Improving accuracy depends on controlling systematics via increased observations using a North-South baseline geometry.

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