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The X/Ka-band (8.4/32 GHz) 2019a 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: Observations at X/Ka-band are motivated by their ability to access more compact source morphology and reduced core shift relative to observations at the historically standard S/X-band. In addition, the factor of four increase in interferometer resolution at Ka-band should resolve out some extended source structure. Given these motivations, an X/Ka-band (8.4/32 GHz) celestial reference frame has been constructed using a combined NASA and ESA Deep Space Network. In 179 observing sessions we detected 678 sources covering the full 24 hours of right ascension and the full range of declinations. The resulting XKa median precision is now 66 μas in αcosδ and 94 μas in δ.

Comparison of 541 X/Ka sources in common with the S/X-band (2.3/8.4 GHz) ICRF3 produced wRMS agreement of 153/ 161 μas in αcosδ/ δ. There is evidence for systematic errors at the 200 μas level. Known errors include limited SNR, lack of phase calibration, troposphere mismodelling, and terrestrial frame distortions. Actions are underway to reduce all of these errors. In particular, a collaboration between NASA and the ESA deep space antenna in Malargüe, Argentina is reducing weaknesses in the southern hemisphere. By comparing coordinate estimates, we probe the accuracy limits of current celestial frames in an effort to understand the advantages of each frame.

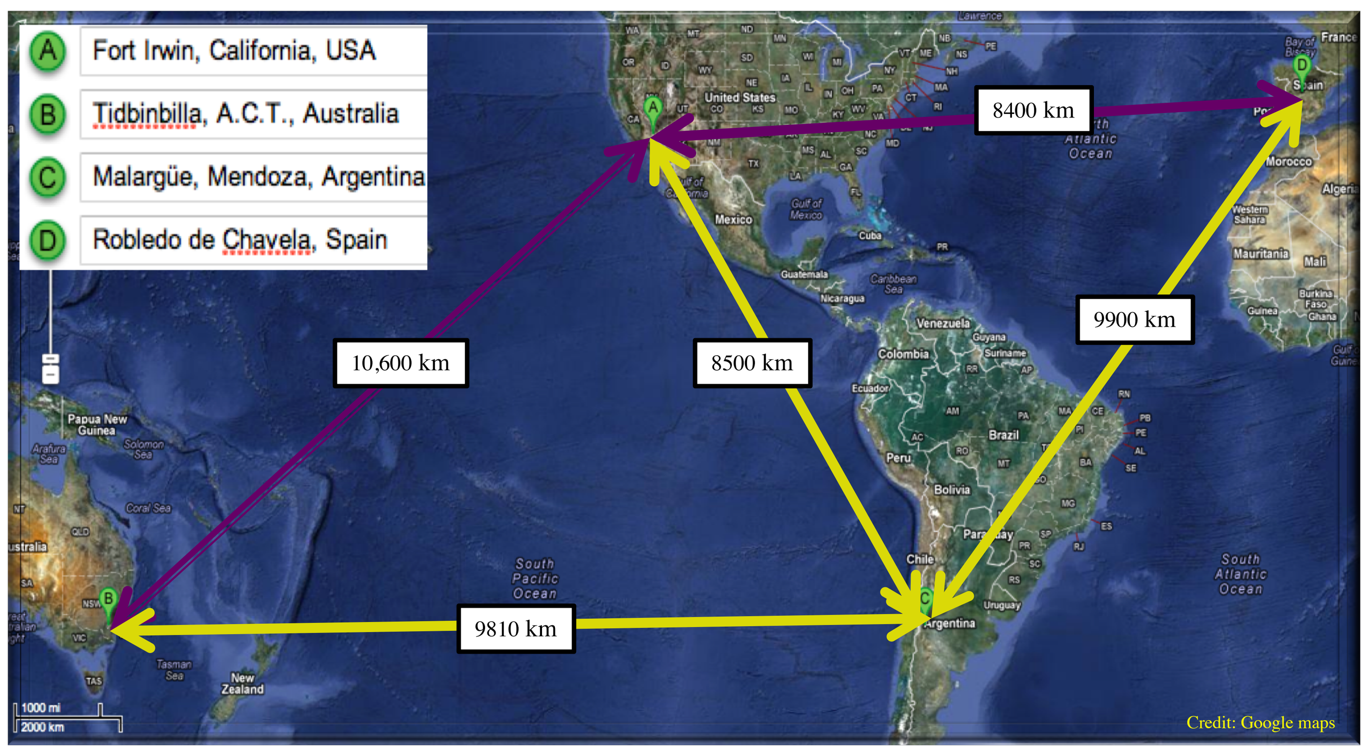

Fig. 1 NASA-ESA Ka-band network. The addition of ESA's Argentina station adds 3 baselines & Full Sky coverage. For δ = +45 to +90 deg, only single California-=Spain baseline. For δ -45 to -90 deg, only Australia-Argentina baseline,

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.

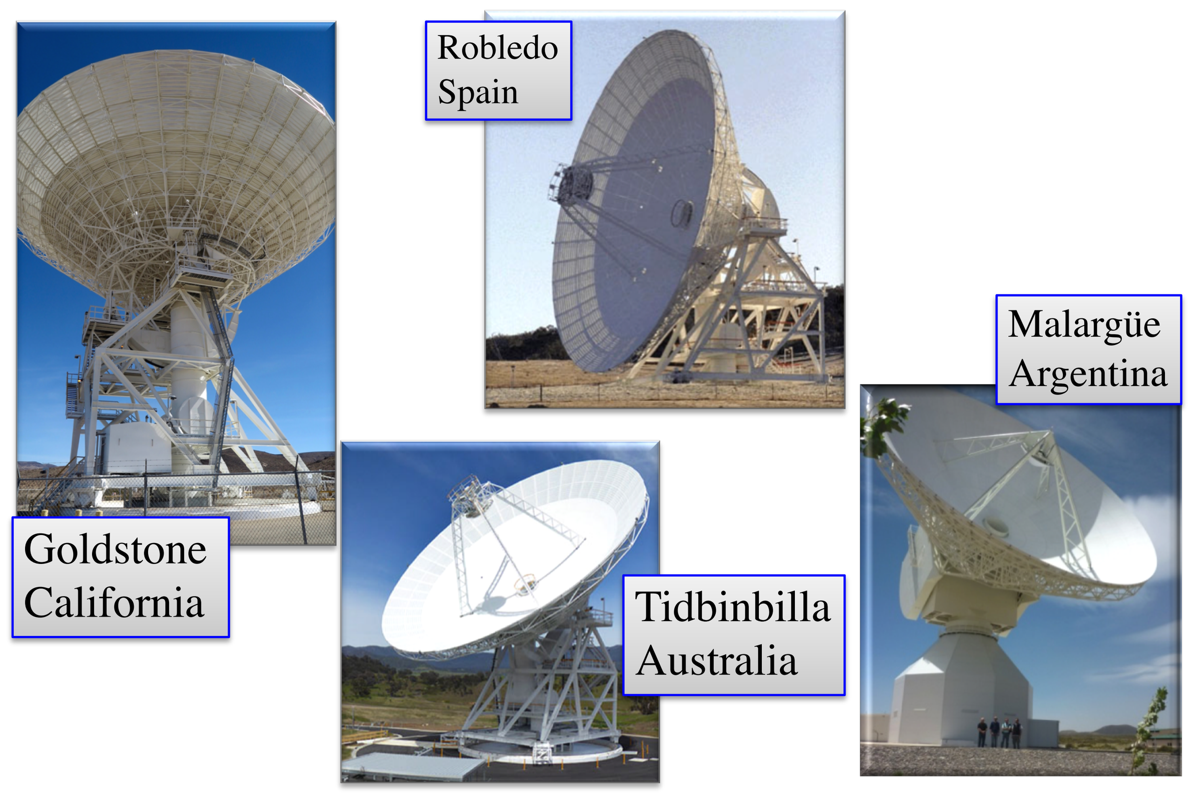

Fig. 2. Antennas of the combined NASA-ESA X/Ka-band network. Diameters are about 34meters.

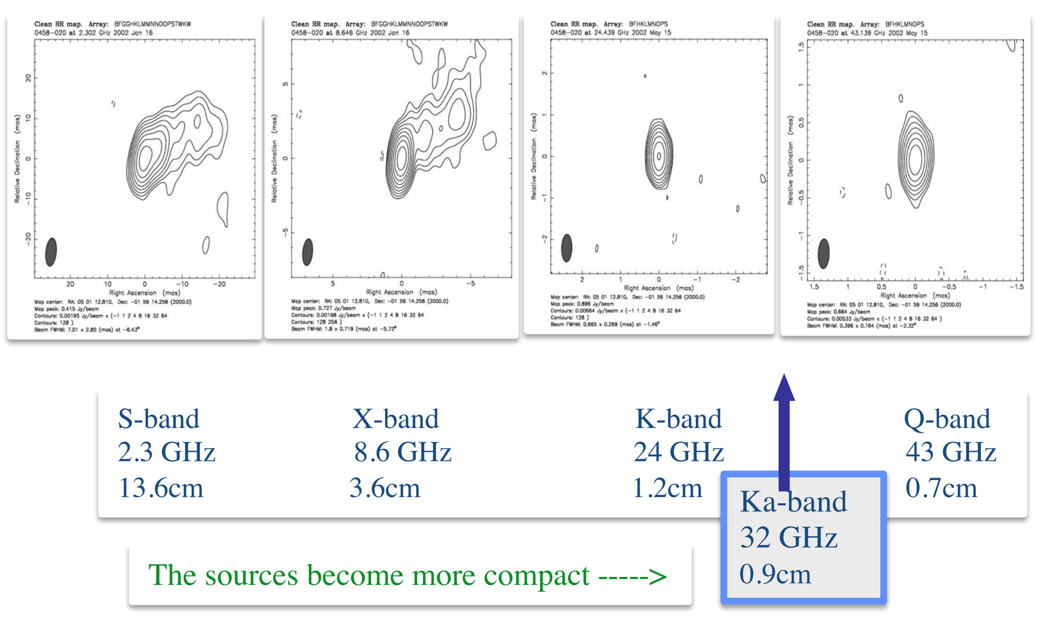

Fig. 3: Source structure & compactness vs. wavelength (Charlot+, 2010; Pushkarev+, 2012)

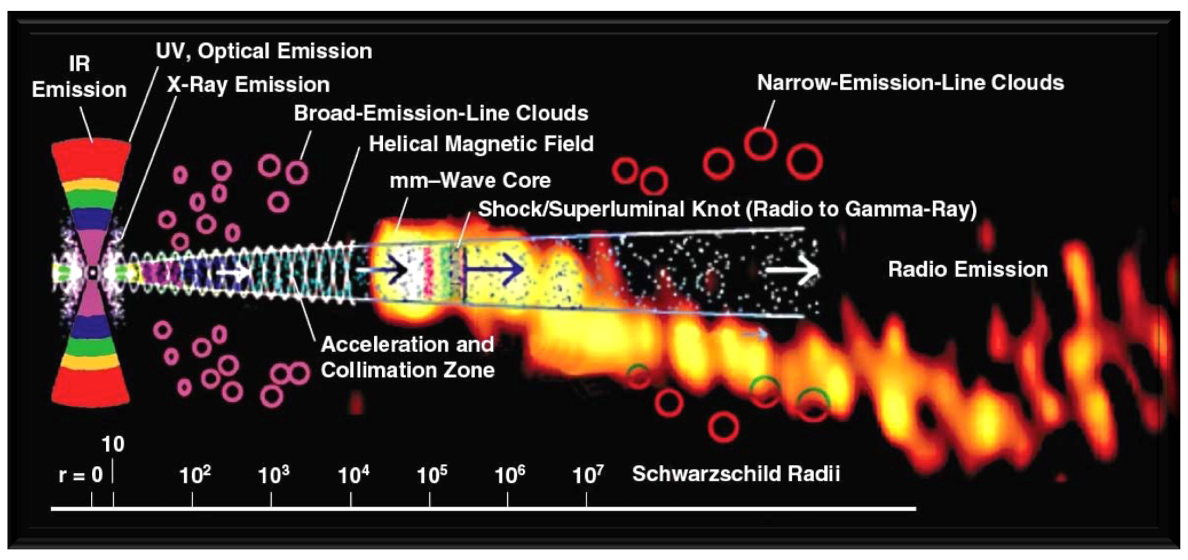

Fig. 4: Schematic of Active Galactic Nuclei (Marscher, 2006, Krichbaum, 1999, Wehrle, 2010)

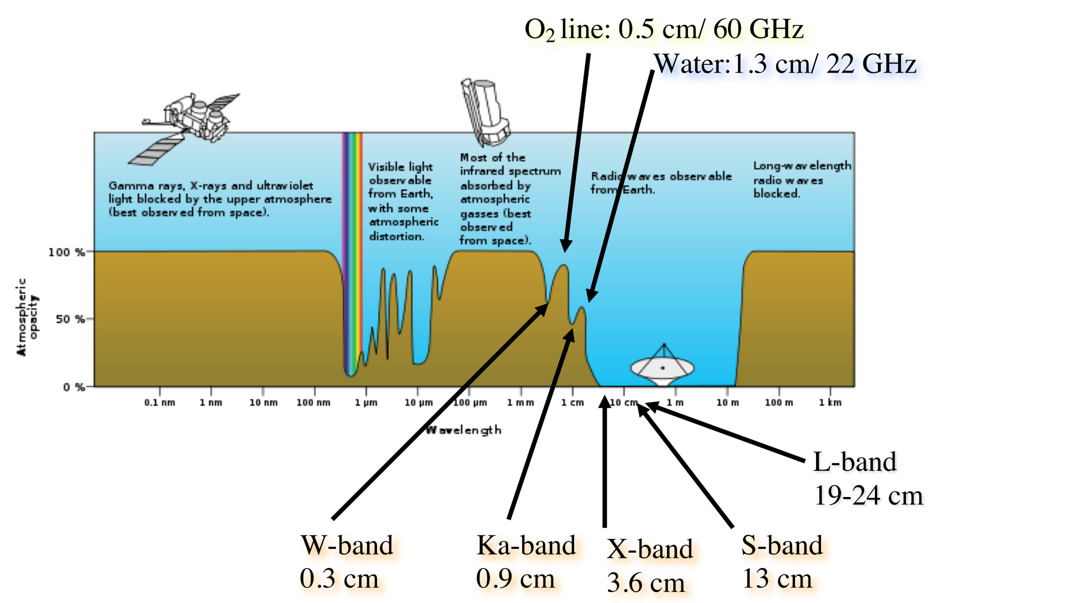

Fig. 5: The radio "window" is transparent compared to most of the spectrum (credit: NASA) Ka-band (32 GHz) is in the saddle point between H_2O (22 GHz) and O_2 (60 GHz) lines.

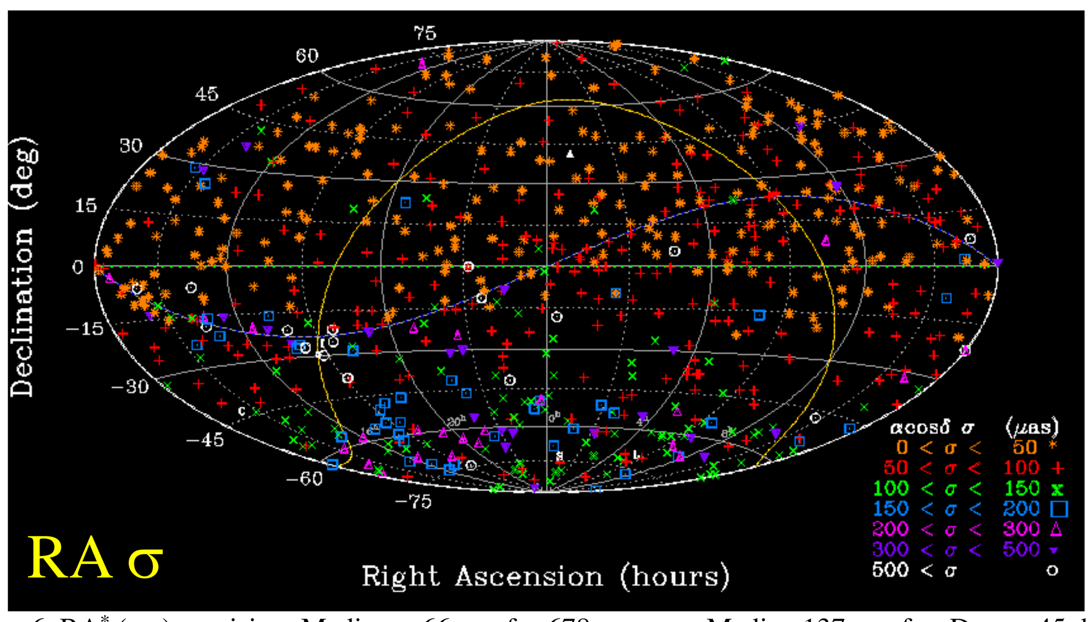

Fig. 6 RA* (arc) precision: Median σ 66 μas for 678 sources. Median 137 μas for Dec < -45 deg.

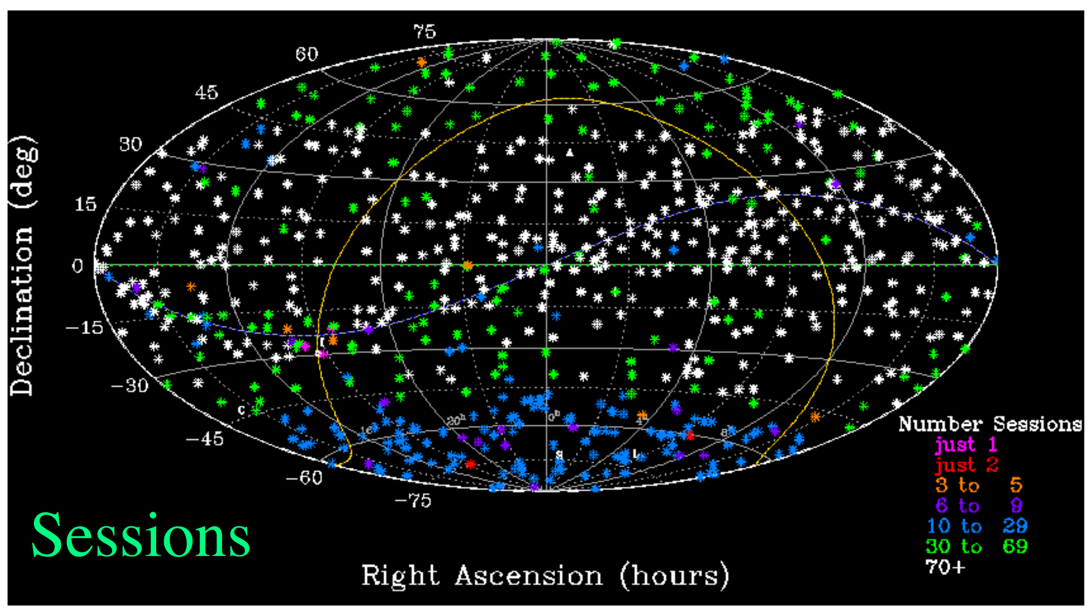

Fig. 8: Number of sessions: Median number of sessions is 77, but only 13 in far south

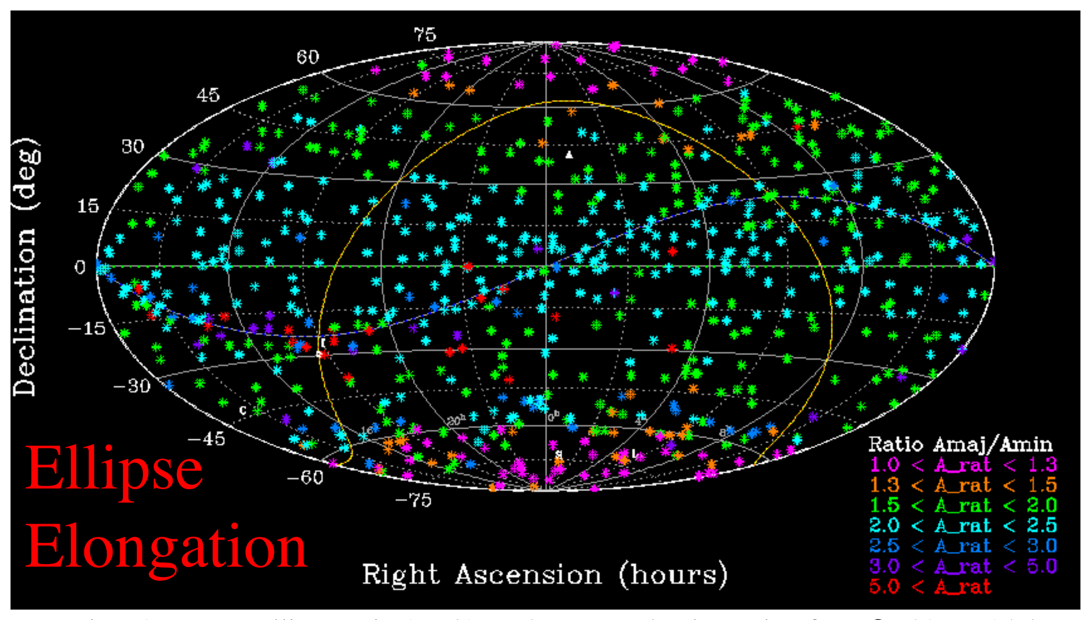

Fig. 10: : Error Ellipse ratio A_{maj}/A_{min} shows steady elongation from δ +90 to -45 deg.

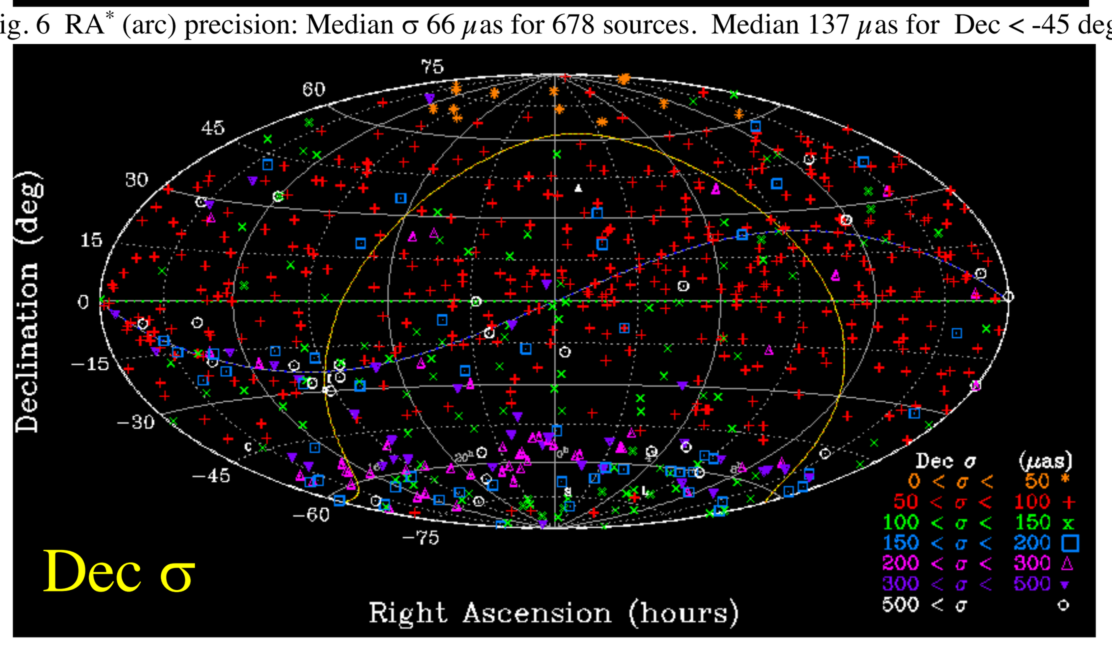

Fig. 7: Dec precision: Median σ is 94 μas for 678 sources. Median = 195 μas for Dec < -45 deg.

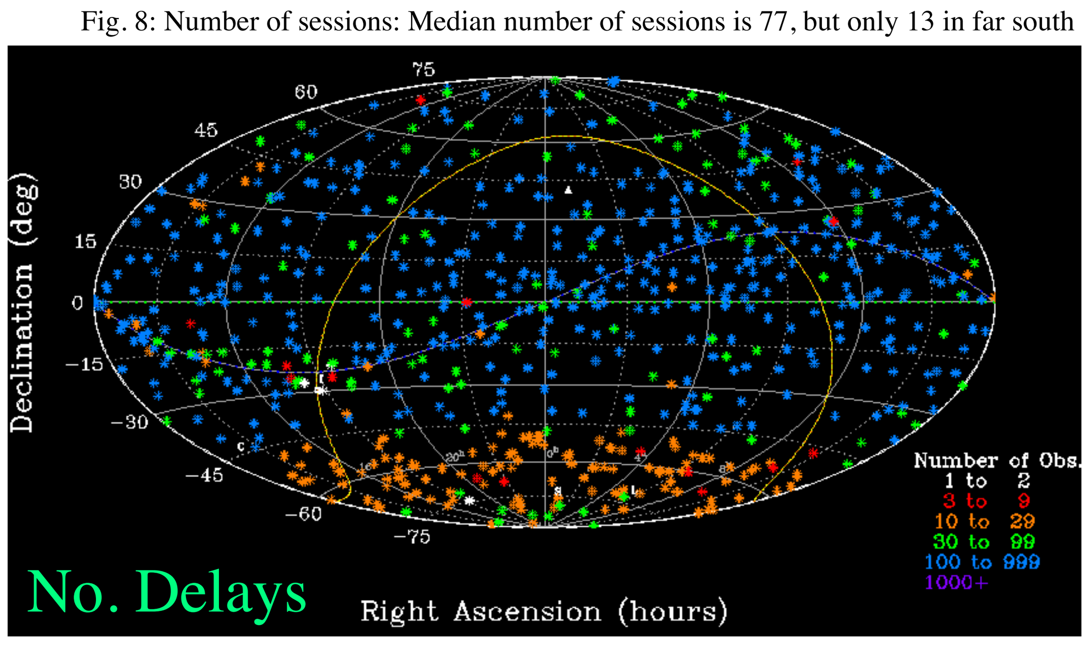

Fig. 9: Number of Delay Observations: Median = 119. South of -45 deg, median = 21.

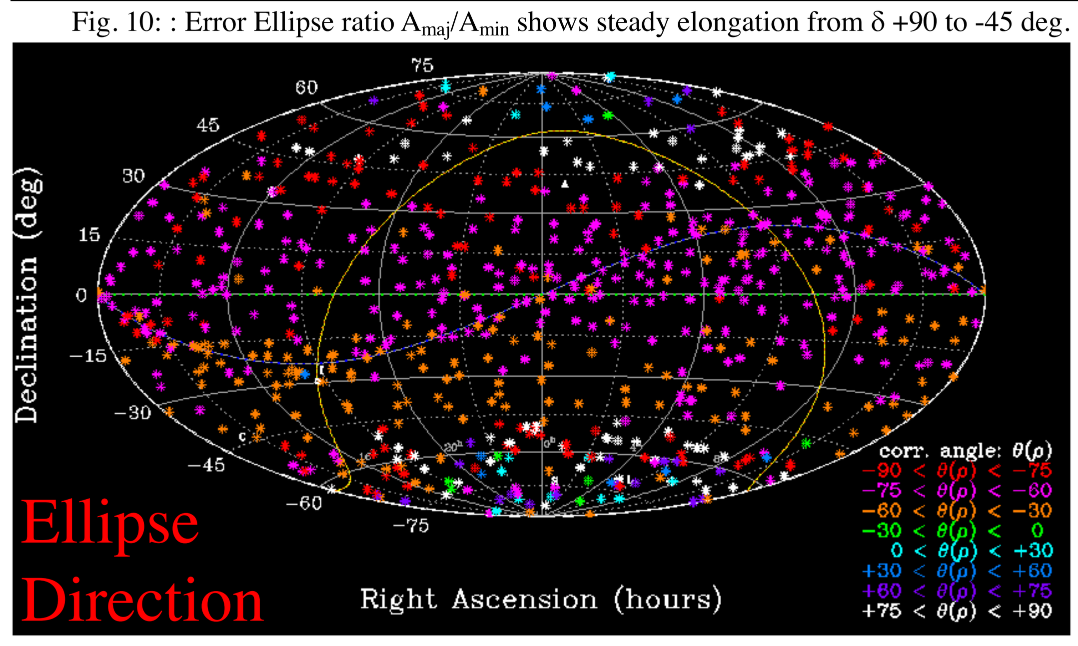

Fig. 11: Direction of Error Ellipses: semi-major axes are mostly North-South i.e. δ weaker than α

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

Comparison of XKa solution dated 190305 to the current ICRF3-S/X (Charlot+, 2019), after removing outliers > 5-σ, leaves 541 sources in common. The wRMS agreement is 153/ 161 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 -141 +- 55 μas and a quadrupole 2,0 Magnetic term at 208 +- 20 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 1.7 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 Data Release-2 (Mignard+, 2018), 499 sources are detected in both the optical and XKa-band radio---after removing 10% (48) of the sources as outliers >= 5-σ. Rotational alignment is made with ~20 μas precision (1-σ, per 3-D component). Scatter is ~265 μas wRMS. Vector Spherical Harmonic difference terms out to degree and order 2 are all 220 μas or less, indicating the one part per billion level of global agreement of the two frames.

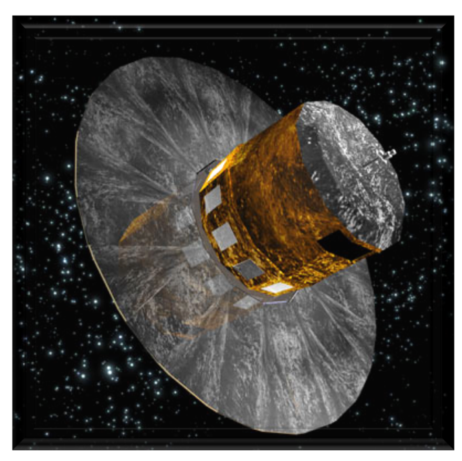

Fig. 12: Gaia launched in Dec 2013 toward L2 (www.esa.int/esaSC/120377_index_1_m.html#)

IV. Goals for the Future:

1. Number: 700 to 1000 sources. Greater density along ecliptic plane.
2. Precision: <= 70 μas (1-σ) to match/exceed Gaia
3. Uniformity: Improve south with baselines from Malargüe, Argentina to Australia, California, Spain.
4. Optical-radio frame tie: Add 30+ optically bright sources.

V. Conclusions: The X/Ka-band CRF has 678 sources covering the full sky and is making rapid improvements in the precision. The median precision is 66 / 94 μas in αcosδ / δ. Spherical harmonic differences vs. ICRF3-S/X are <= 208 μas and vs. Gaia are <= 220 μas. Improving accuracy will depend on controlling systematics via increased observations using a North-South baseline geometry.

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