13th International VLBI Service General Meeting, Tsukuba, Japan, 4-9 March 2024

The X/S-Band (8.4/2.3 GHz) Celestial Reference Frame

Executive Summary: Celestial angular coordinates (α,δ) of 5707 sources are derived from VLBI measurements at 8.4 and 2.3 GHz (3.6 and 13 cm) of Active Galactic Nuclei. Agreement with the ICRF3-XS and Gaia-EDR3 is at the part per billion level.

David Gordon[1], Christopher S. Jacobs[2]

(1) U.S. Naval Observatory, Washington, D.C. (2) Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California

Abstract:

The X/S-band (8.4/2.3 GHz) Celestial Reference Frame is the largest of the three components of the ICRF3 released in 2018. In the nearly six years since, the X/S-band data set has increased by ~25% to 5707 sources, based on ~7100 VLBI sessions and ~18.4 million observations—a 40% increase since ICRF3. Observations using the VLBA have been key to densifying the frame. In particular, the density of sources near the ecliptic has been greatly improved making the frame more useful for spacecraft navigation. The latest solutions have median formal precisions of 107 μas in α cosδ and 189 μas in δ. Median number of sessions per source is 6, but with a much higher number for sources used regularly in geodesy.

The spherical harmonic distortions seen in the recent X/S-band CRF vs. ICRF3-X/S with the largest terms: Y-rotation -13 +- 2 μas, quadrupole 2,0 Mag 8.1 +- 1.8 μas and the quadrupole 2,0 electric term of 11.5 +- 2.2 μas. We note that the X/S-band frame is dominated by the all northern geometry of the VLBA. This results in some weakness in sources from the equator to -40 deg declination. Future improvements include the potential for increasing the VLBA data rates from 2 Gbps to 4 Gbps.

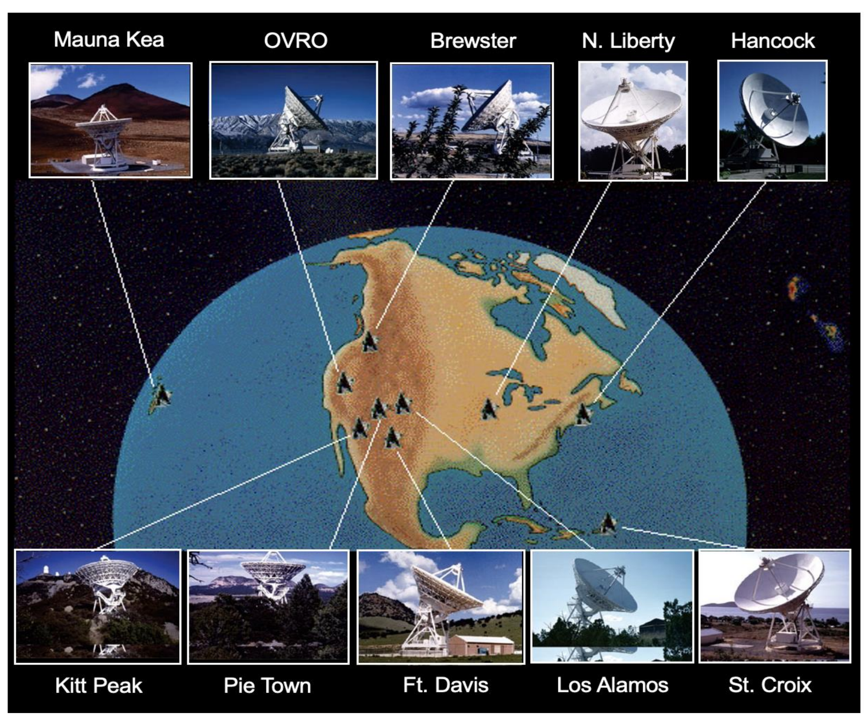

Fig. 1 . Beyond a core of ~1800 geodetic sources observed under the IVS, most of the remaining ~3900 sources have been observed only with the Very Long Baseline Array (VLBA) of ten 25-meter telescopes which form 45 baselines with the longest East-West baseline being over 8000 km. The longest North-South baseline is about 3000 km leading to significantly lower declination precision. We are grateful to the NRAO, the NSF and USNO for sponsoring this time.

I. Frequency Dependence of Radio Frames:

As radio frequencies decrease, sources tend to be less core dominated due to increased extended jet structure (Fig. 3 & 4). The spatial offset of the emissions from the AGN engine due to opacity effects ("core shift") increases as frequency decreases.

Advantages of X/S-band compared to K and Ka-band:

- Less weather sensitive (Fig. 5).
- Longer coherence times.
- Increased source flux strength.
- Antenna pointing and surface accuracy less demanding.
- Combined effect is greater sensitivity resulting in much greater source density.

Disadvantages of X/S-band vs K and Ka-band.:

- Sources are less compact and less stable (Fig. 3, 4).
- Greater opacity effects: "core shift".
- Plasma effects limit scans near Sun & galactic center.

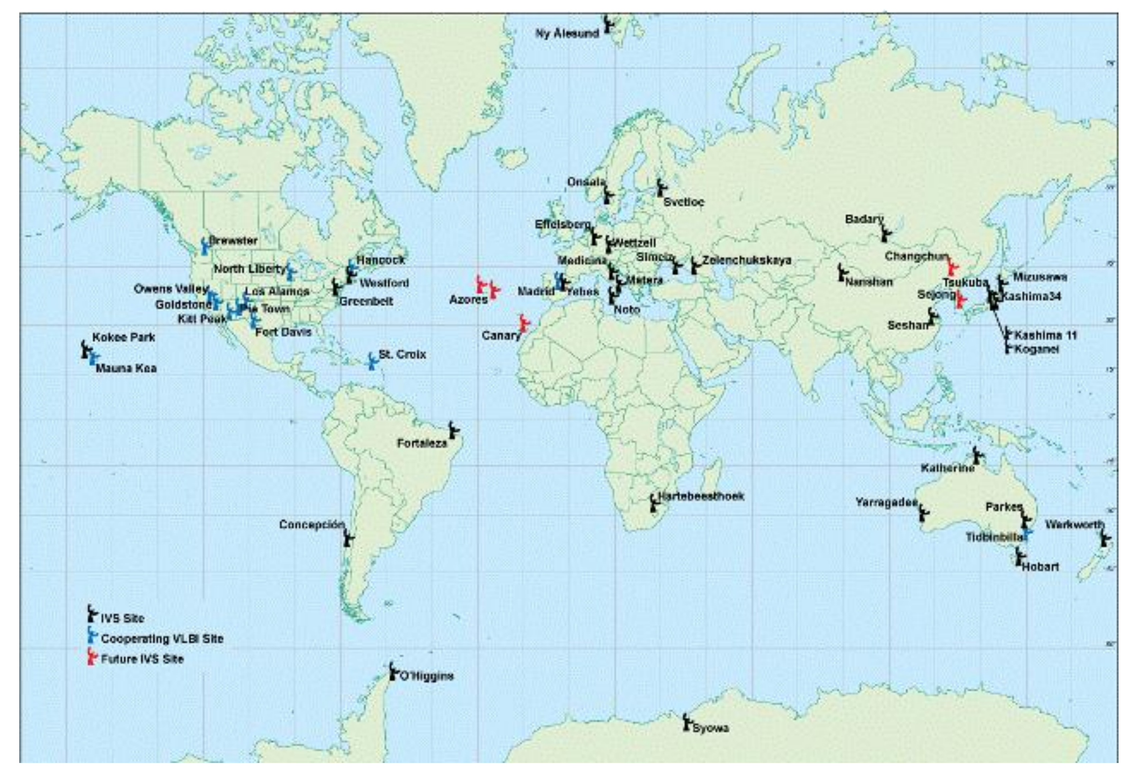

Fig. 2. Antennas of the combined International VLBI Service (IVS) Network used to do geodesy, earth orientation and celestial frame work at X/S band. All these programs contribute to the X/S Celestial Reference Frame. Figure credit: IVS.

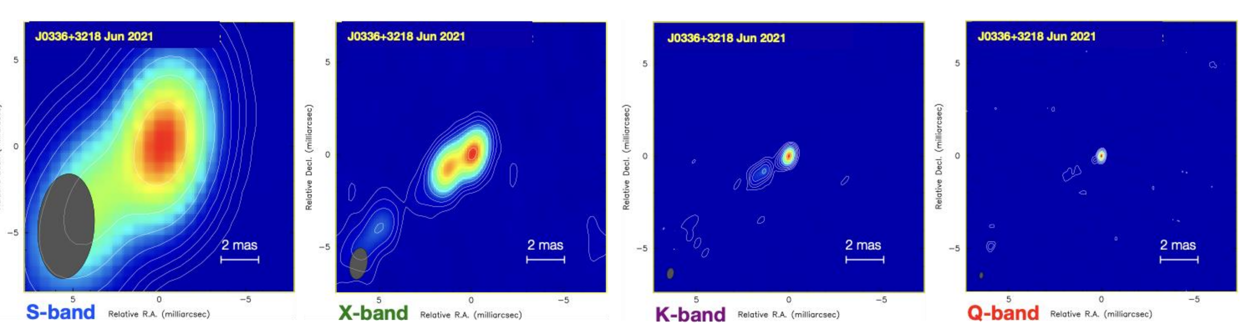

Fig. 3: Near-simultaneous S (2.3 GHz), X (8.4 GHz), K (22 GHz) and Q-band (43 GHz) images from VLBA observations of 453 ICRF sources between April - June 2021 (*Hunt et al, 2022, de Witt et al, 2022*) demonstrate that VLBI calibrator sources get more compact with increasing frequency. In particular, 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. So X/S has a disadvantage in source compactness, but a significant advantage in sensitivity and duration of observing programs. This results in a frame with ~6 times more sources than K-band and ~8 times more than X/Ka-band.

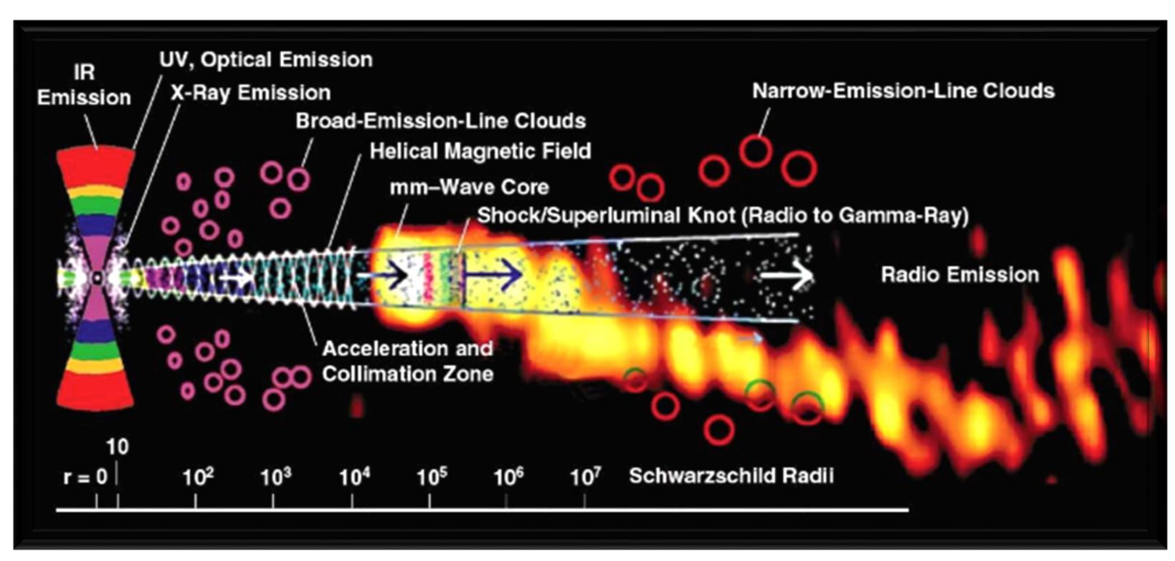

Fig. 4: Schematic of Active Galactic Nuclei (Marscher, 2006, Krichbaum, 1999, Wehrle, 2010)

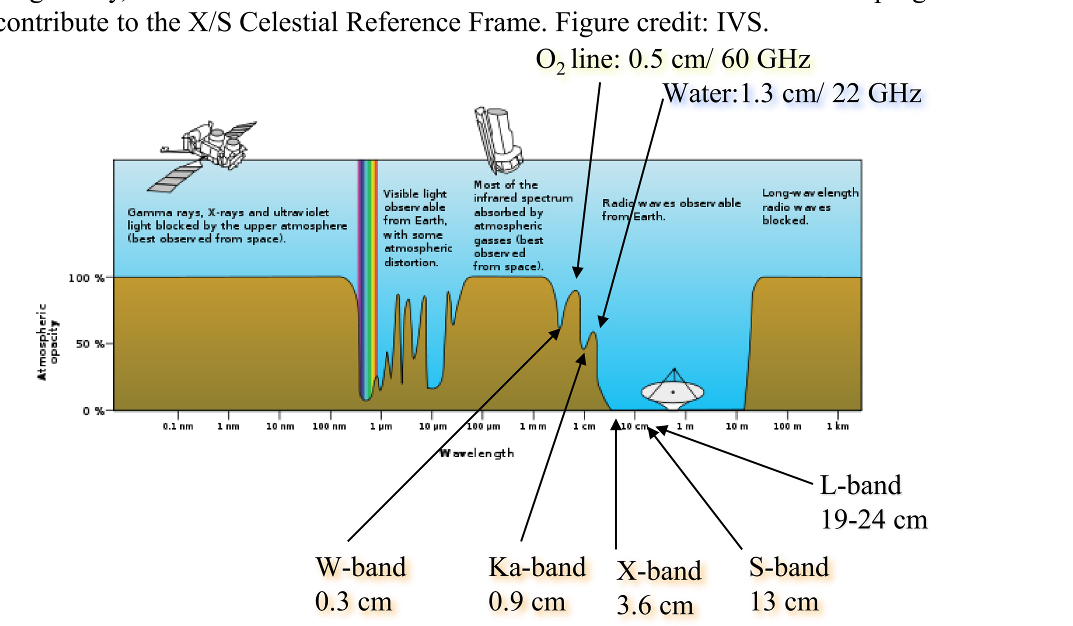

Fig. 5: The radio "window" is transparent compared to most of the spectrum (credit: NASA). S and X-bands are in a very transparent region well below the H_2O line at 22 GHz.

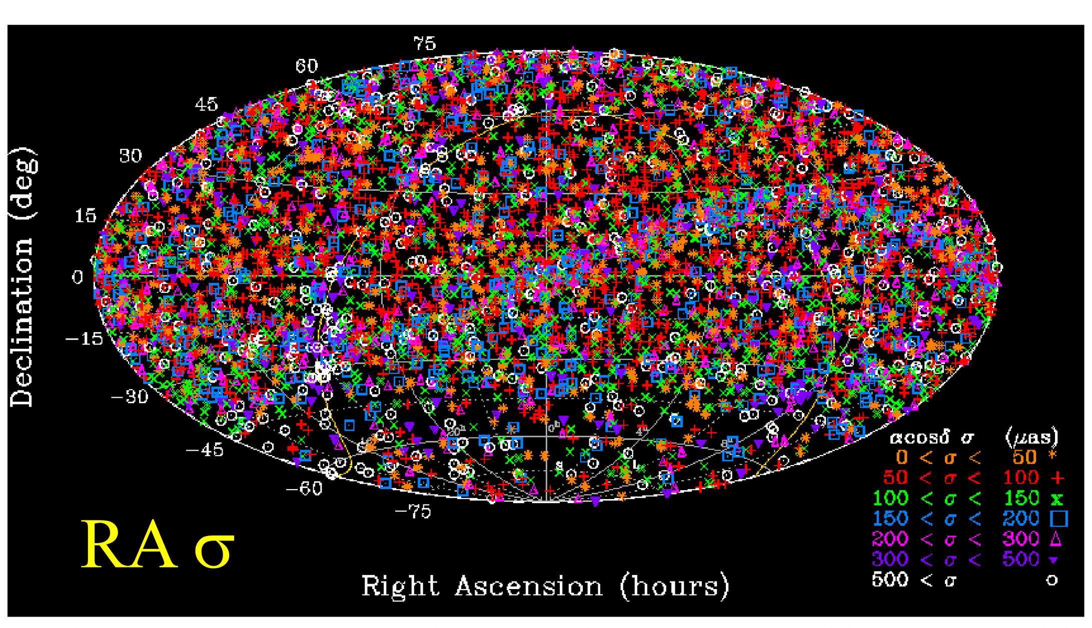

Fig. 6: RA (arc) precision: Median 107 μas for 5707 sources. Median 126 μas for Dec < -45º.

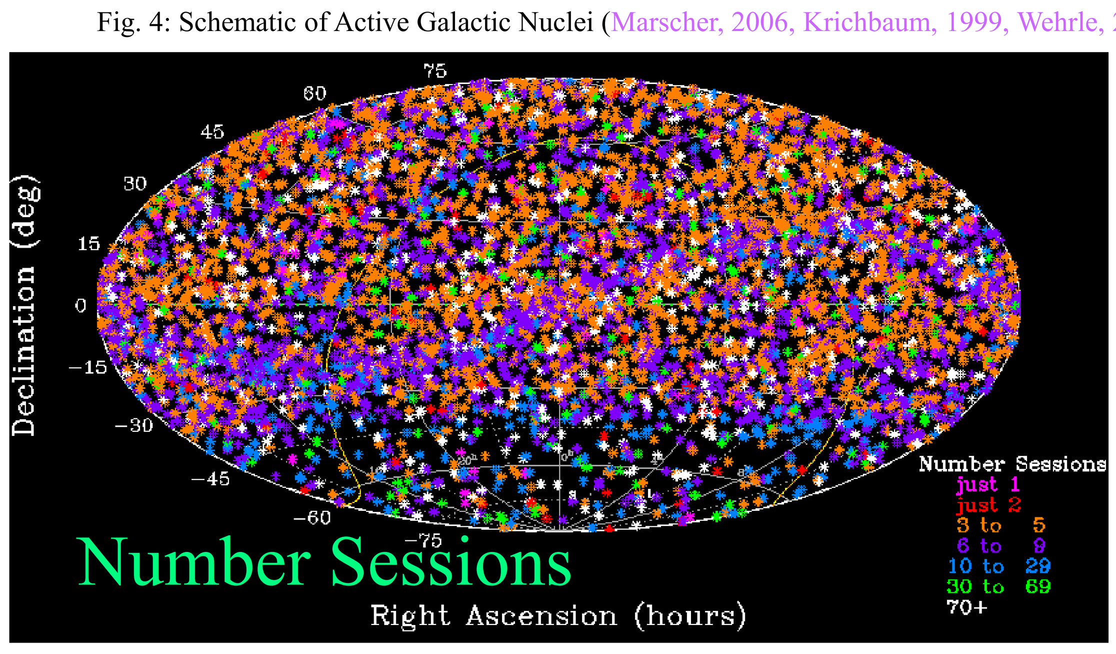

Fig. 8: Number of sessions: Median sessions is 6. For Dec south of -45º, median = 10.

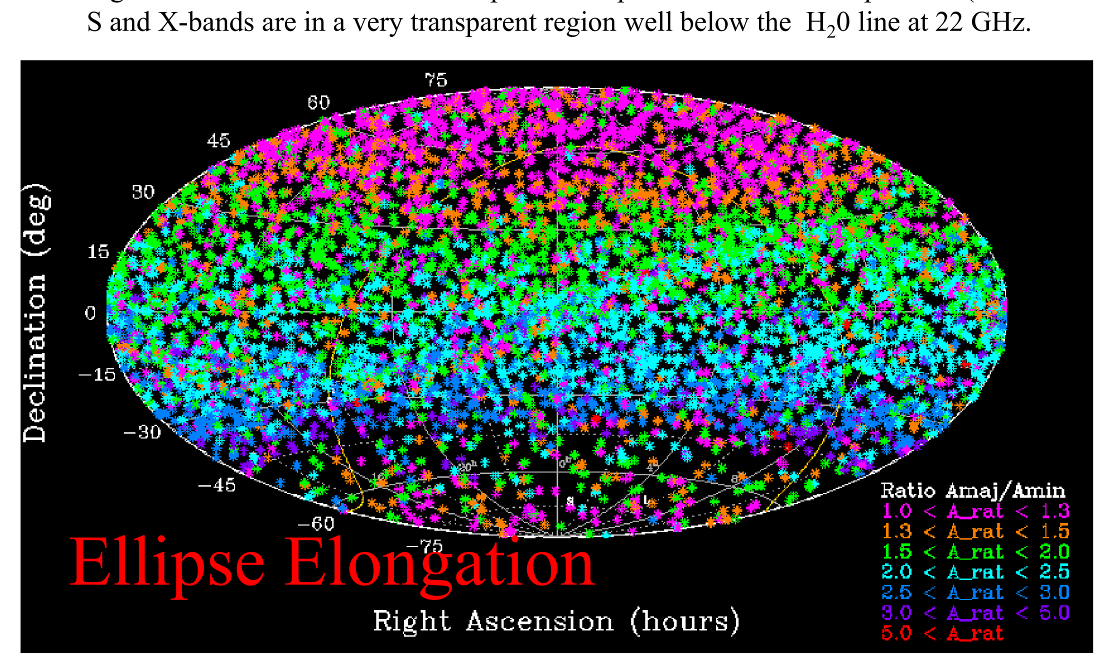

Fig. 10: : Error Ellipse ratio A_{major}/A_{minor} shows steady elongation from δ +90º to -45º.

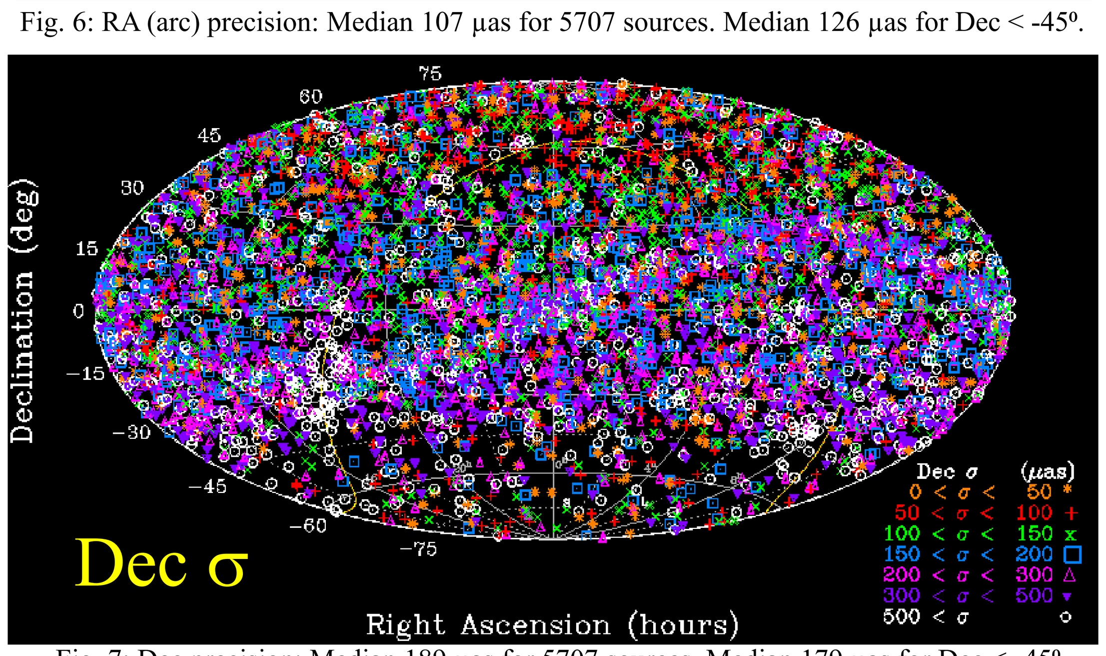

Fig. 7: Dec precision: Median 189 μas for 5707 sources. Median 179 μas for Dec < -45º.

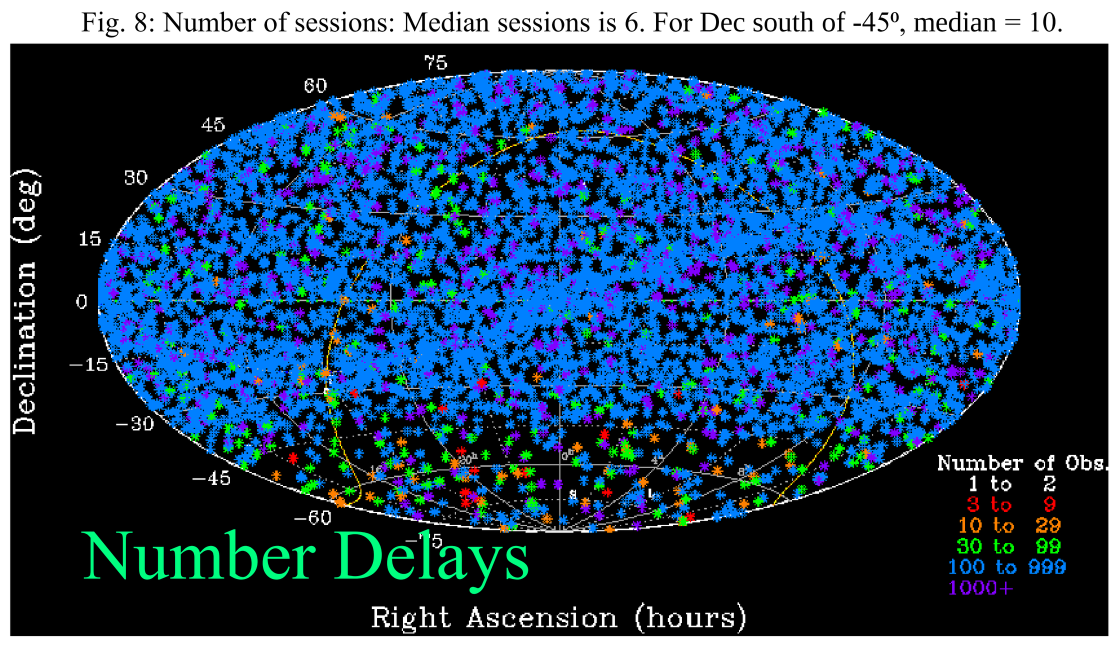

Fig. 9: Number of Delay Observations: Median = 391. South of -45º, median = 136.

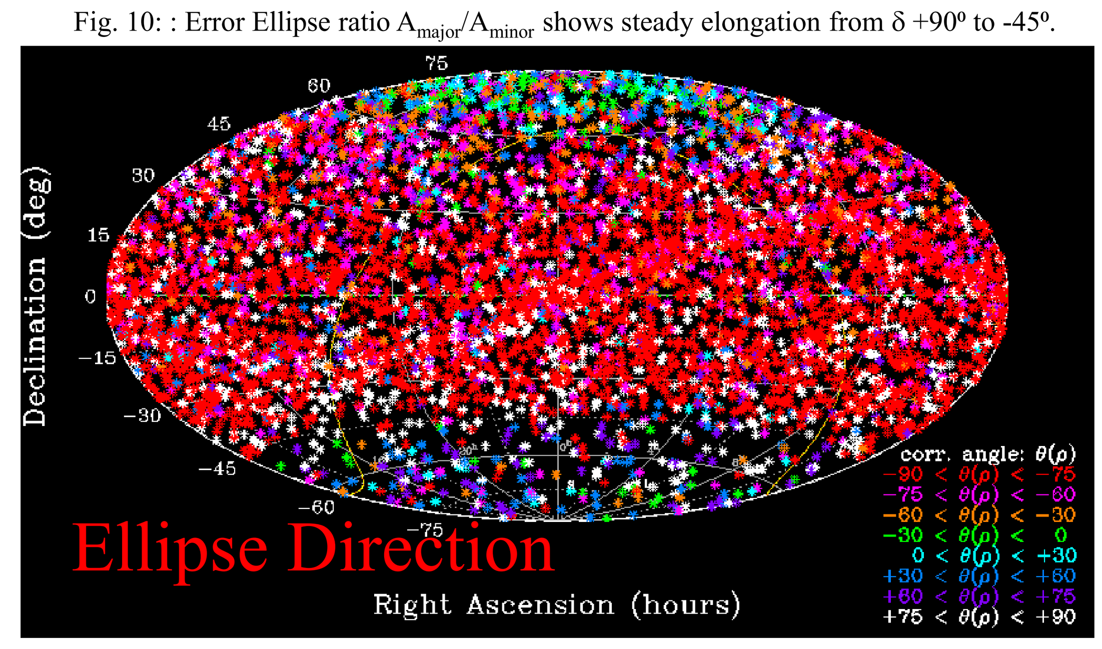

Fig. 11: Direction of Error Ellipses: semi-major axes are mostly North-South, σ_δ weaker than σ_α.

II. Accuracy: X/S vs. ICRF3-XS

Comparison of X/S solution dated 2024/01/19 to the current ICRF3-XS (Charlot et al, 2020), after removing 26 outliers > 5-σ, leaves 4350 sources in common. The wRMS agreement is 83/97 μas in αcosδ and δ, respectively. Vector spherical harmonics (Mignard & Klioner, 2012) to degree and order 2 were estimated. Y-rotation = -13 +- 2 μas and a quadrupole 2,0 Mag. = 8.1+- 1.8; quadrupole 2,0 Elec. = 11.5 +- 2.2 μas. More north-south baseline data should help 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 1.6 million AGN, of which ~20,000 will be optically bright (V < 18 mag).

Comparison: The Gaia celestial frame is independent from X/S-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), 2436 sources are common to both the optical and X/S-band radio---after removing 468 of the sources as outliers >= 5-σ. Rotational alignment is made with ~7 μas precision (1-σ, per 3-D component). wRMS scatter is 252 μas in αcosδ and 267 μas in δ. The largest Vector Spherical Harmonic differences are in quadrupole 2,0 elec. = 34 +- 8 μas and quadrupole 2,1 elec. = 29 +- 10. Thus the two frames agree to about 1.3 parts per billion in scatter and 0.1 ppb in global alignment.

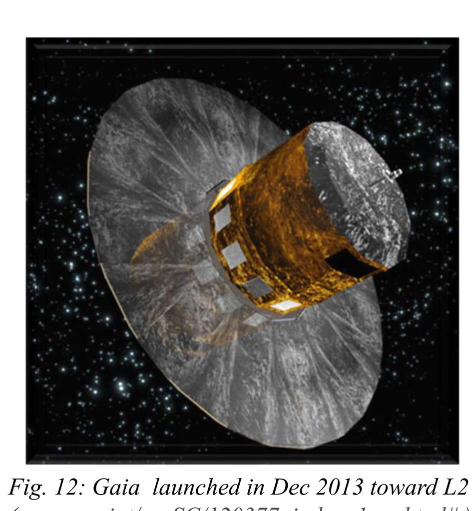

Fig. 12: Gaia launched in Dec 2013 toward L2 (www.esa.int/esaSC/120377_index_1_m.html#)

IV. Goals for the Future:

1. Precision: < 75 μas (medians)

2. Uniformity: More southern observations for improved southern source precisions, especially in Dec.

3. Observations: > 5 sessions all sources.

V. Conclusions: The X/S-band CRF has 5707 sources covering the full sky and is making rapid improvements in the precision. The median precision is 107 / 189 μas in αcosδ / δ. Spherical harmonic differences vs. ICRF3-XS are <= 35 μas and scatter vs. Gaia is <= 260 μas. Improving accuracy depends on controlling systematics via increased observations using a North-South baseline geometry.

Acknowledgements: *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).*