The 24th EVGA Meeting, Las Palmas, Gran Canaria, Spain, 17-20 March 2019

The K-band (24 GHz) 2019a Celestial Reference Frame

Can it be more accurate than SX (8 GHz)?

Executive Summary: Celestial angular coordinates (α, δ) are derived from VLBI measurements at 24 GHz (1.2 cm) of Active Galactic Nuclei. Agreement with S/X is at approximately the 100 μas level. K-band has reduced astrophysical systematics vs. S/X.

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Abstract: A K-band (24 GHz) celestial reference frame of 918 sources covering the full sky has been constructed using 0.68 million observations from 69 observing sessions from the VLBA and HartRAO-Hobart. Observations at K-band are motivated by their access to more compact source morphology and reduced core shift relative to observations at the historically standard S/X-band (2.3/8.4 GHz). The factor of three increase in interferometer resolution at K-band should resolve out source structure which is a concern for AGN centroid stability. K median precision is comparable to S/X precision (for common sources) thereby raising the question of which frame is more accurate. The accuracy of the K CRF is quantified by comparison of 783 sources in common with the current (2019 Jan) S/X-band producing wRMS agreement of 78 µas in α cos(δ) and 133 µas in δ. There is evidence for systematic errors below the ~60 µas level. The success of Gaia optical astrometry motivates work to tie the radio and optical frames. K-band data and Gaia Data Release-2 data give a frame tie precision of ~15 µas (1-σ, per 3-D rotation component). If K-band precision can be pushed below ~20-30 μas, the K frame has potential to produce a tie to Gaia that is superior to S/X due to reduced astrophysical systematics at K relative to S/X. The K-band 2019a frame is an incremental update to the ICRF-3's K-band component thereby answering the IAU's call for maintenance of the ICRF-3.

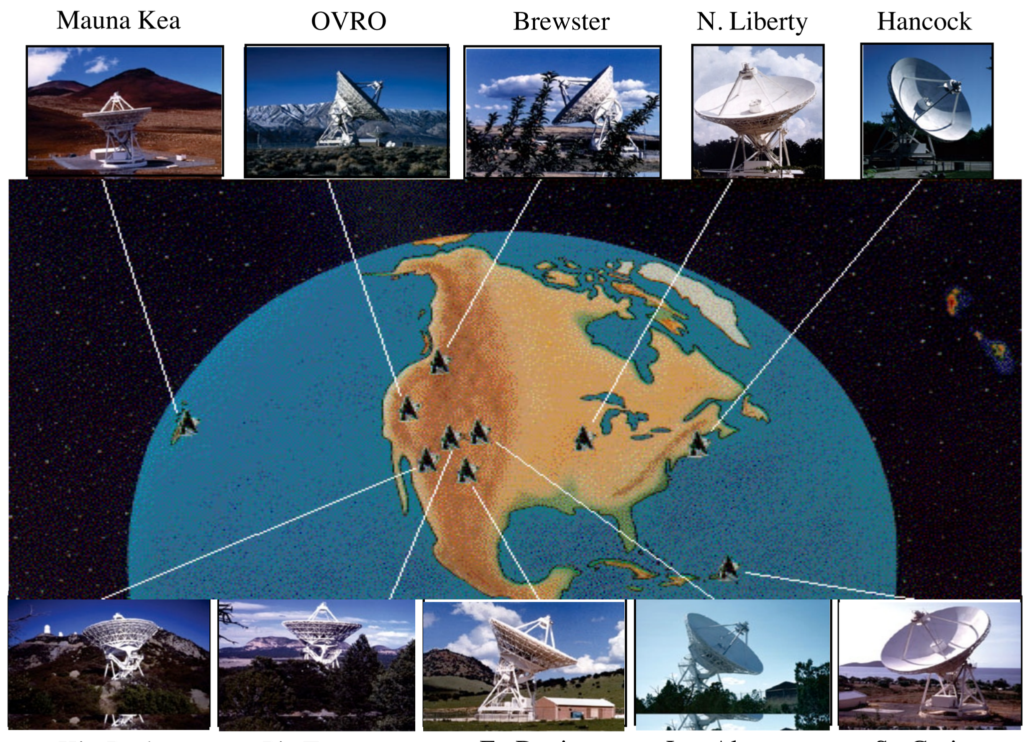

Fig. 1 Very Long Baseline Array of 25m antennas observed from δ +90 to about -40 deg. credit: NRAO/AUI

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, and *LeBail+ paper*)
- Reduced opacity effects: "core shift"
- Ionosphere & solar plasma reduced by 9X (see *Soja+ paper*).

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 operational rate to 2 Gbps has compensated.
4 Gbps VLBA 7-station Mk6 test ran on 2019 Mar 05.

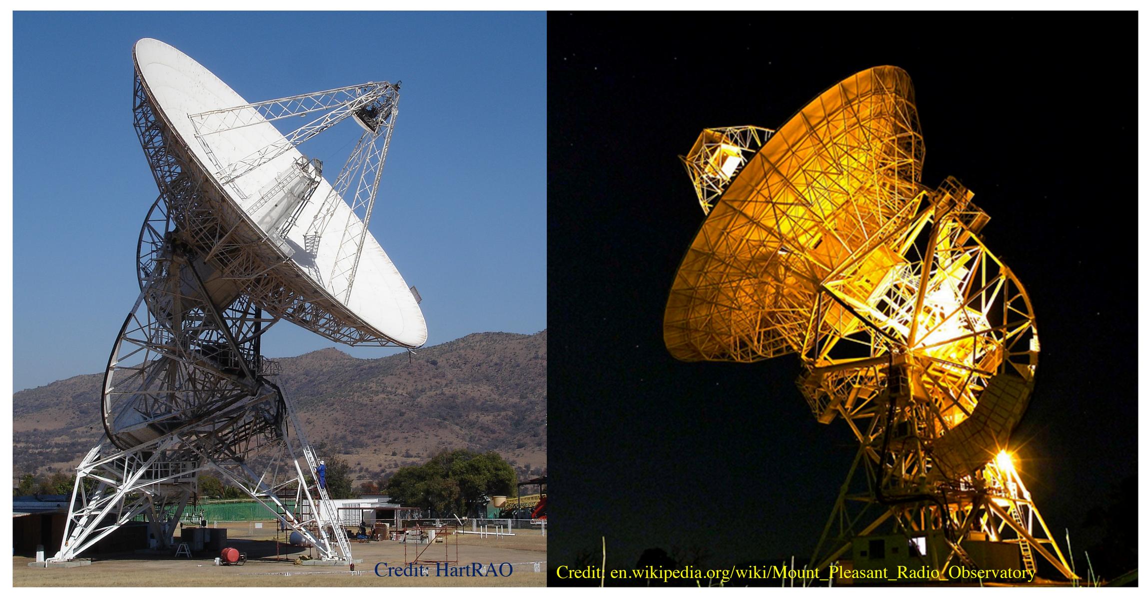

Fig. 2 HartRAO, South Africa 26-m to Hobart, Tasmania 26-m completes coverage in the South.

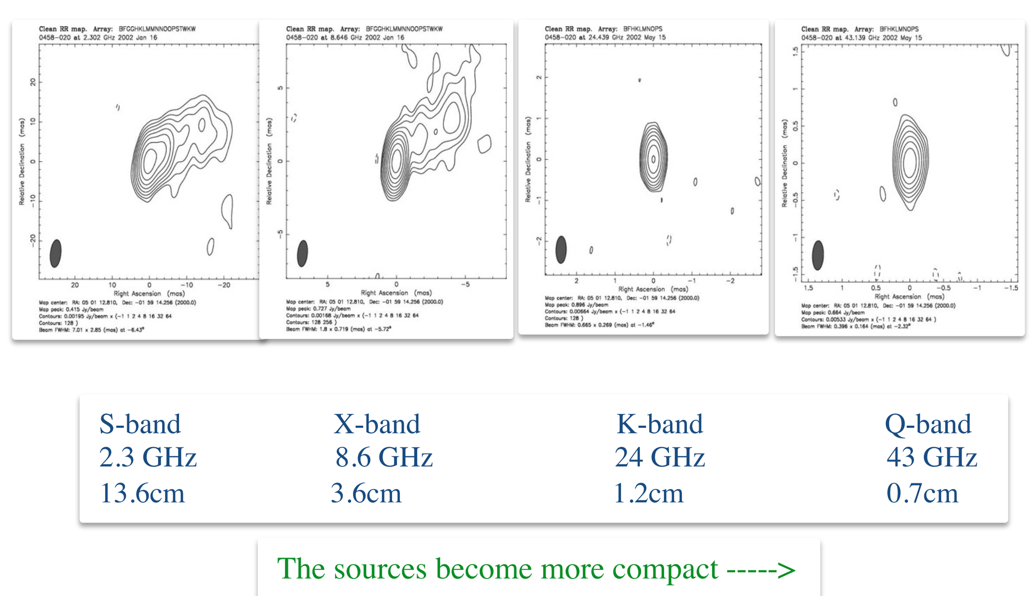

Fig. 3: Source structure & compactness vs. wavelength (Charlot+, 2010; Pushkarev+, 2012)

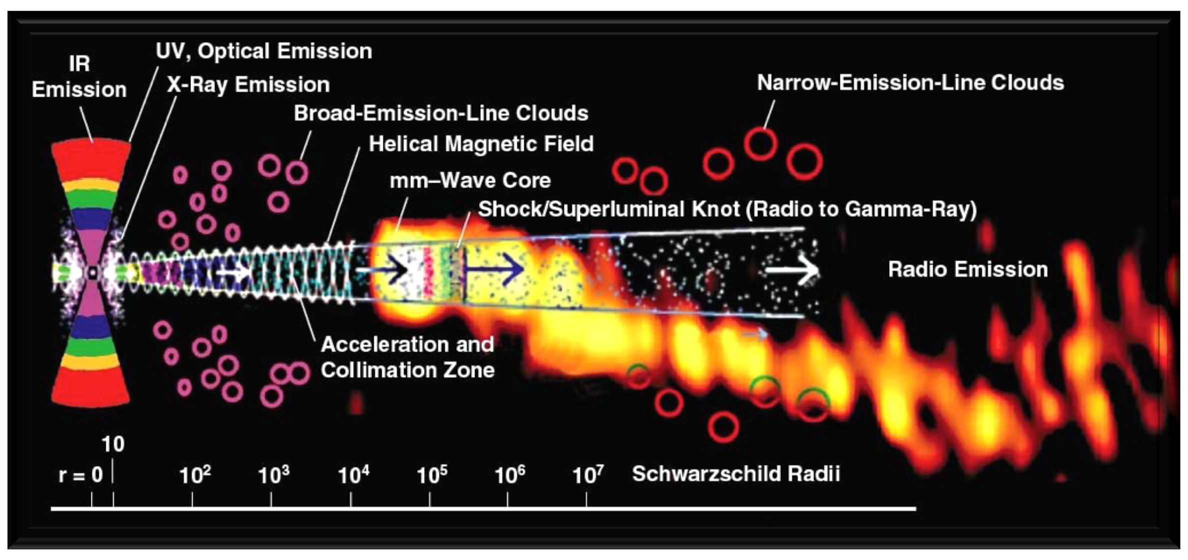

Fig. 4: Schematic of Active Galactic Nuclei (Marscher, 2006, Krichbaum, 1999, Wehrle, 2010)

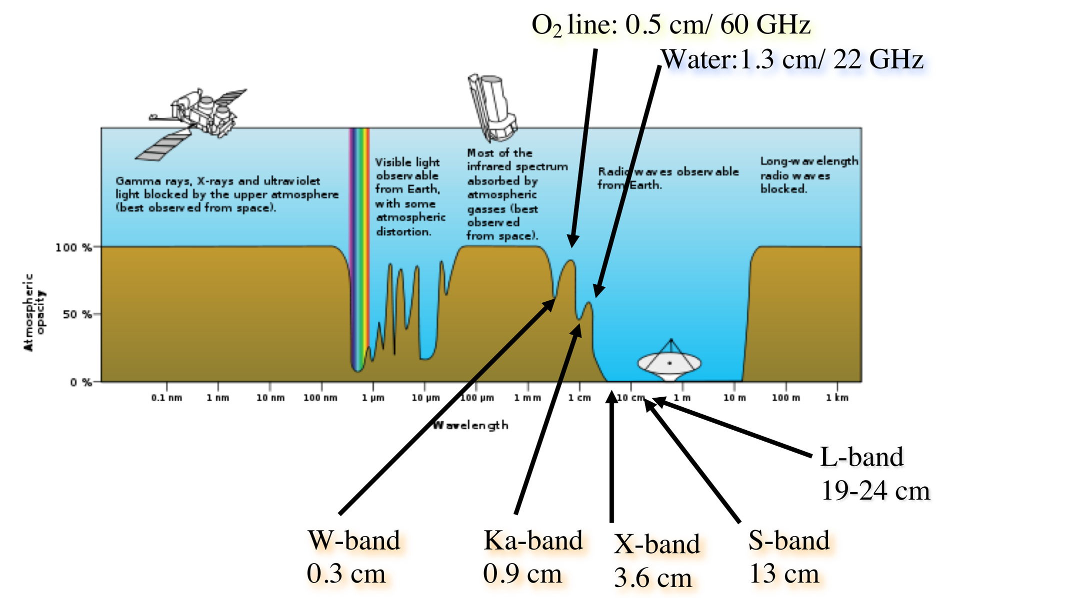

Fig. 5: The radio "window" is transparent compared to most of the spectrum (credit: NASA) K-band (24 GHz) is just above the H_2O line at 22 GHz. credit: NASA: http://en.wikipedia.org/wiki/Radio_window

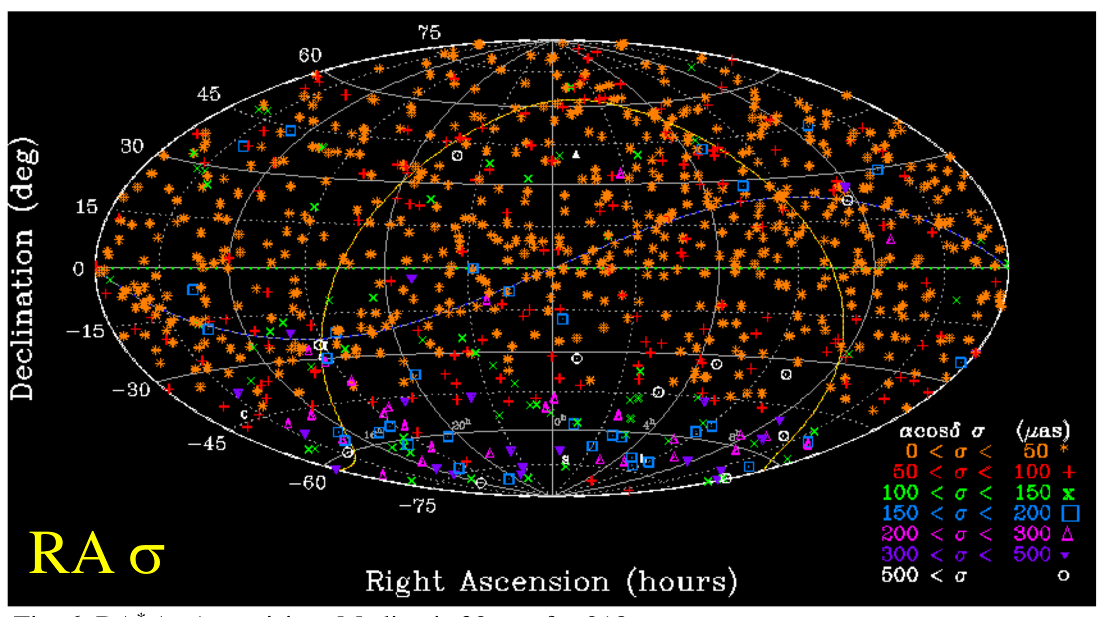

Fig. 6 RA* (arc) precision: Median is 39 μas for 918 sources.

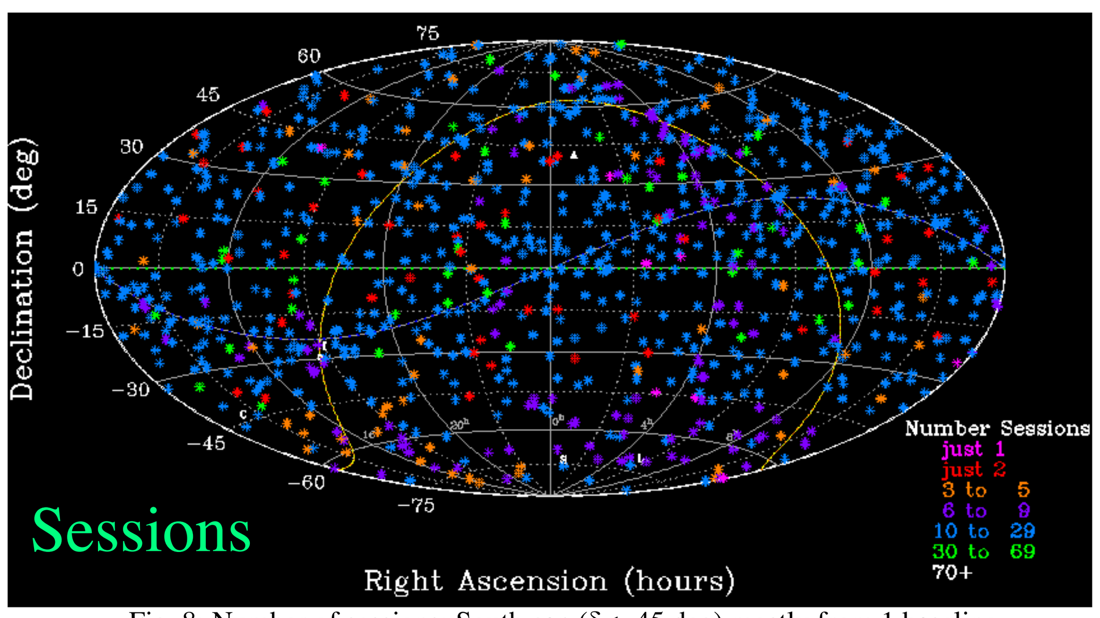

Fig. 8: Number of sessions: South cap (δ< -45 deg) mostly from 1 baseline

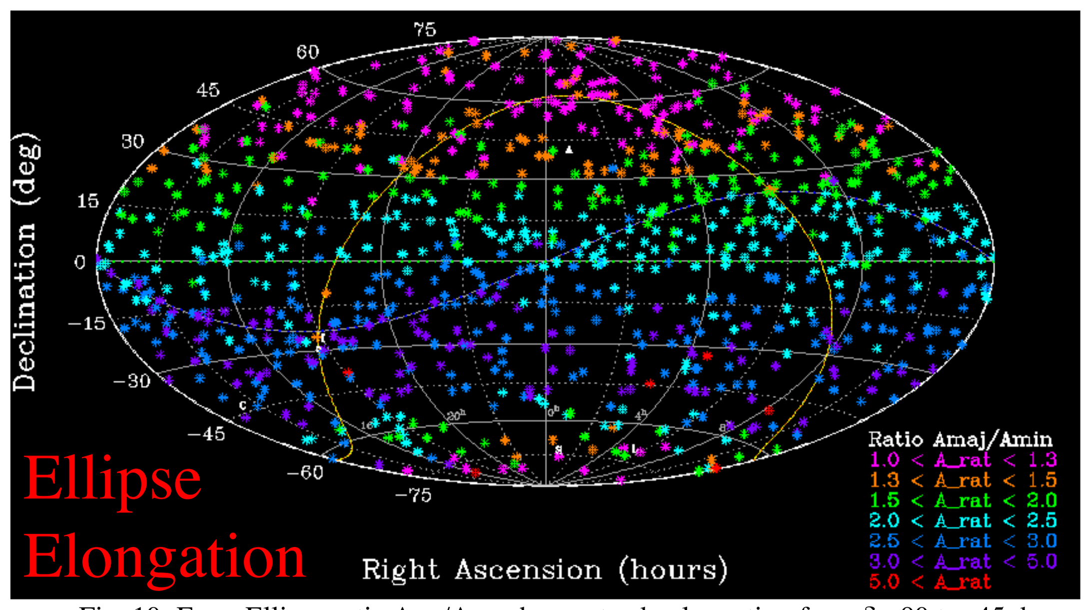

Fig. 10: Error Ellipse ratio A_{maj}/A_{min} shows steady elongation from δ +90 to -45 deg

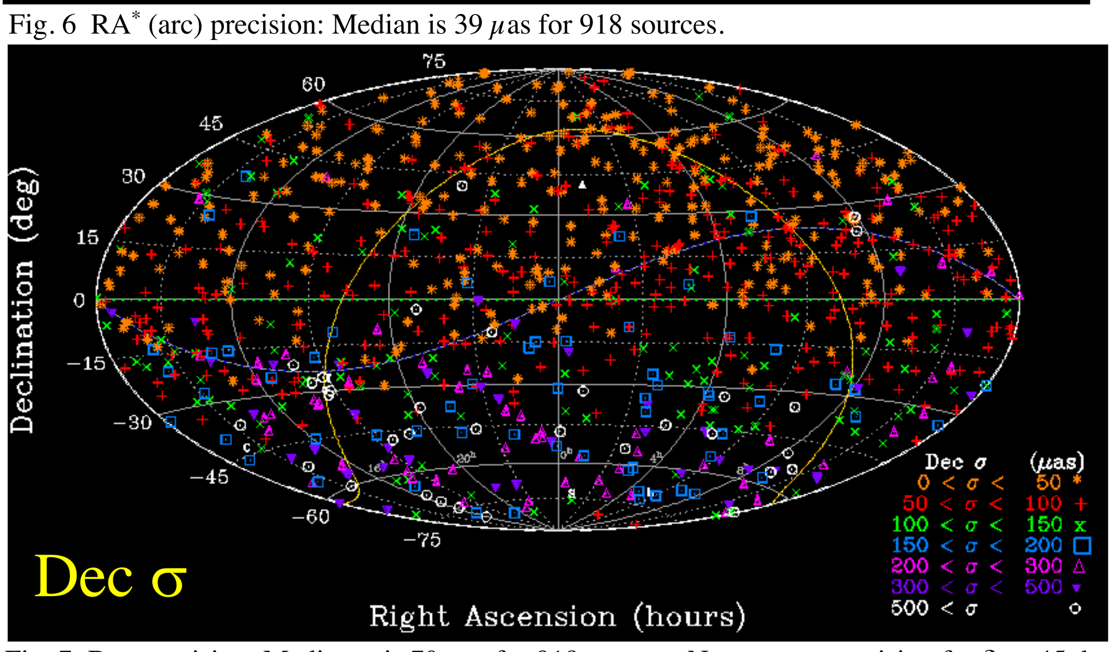

Fig. 7: Dec precision: Median σ is 70 μas for 918 sources. Note worse precision for δ < -45 deg.

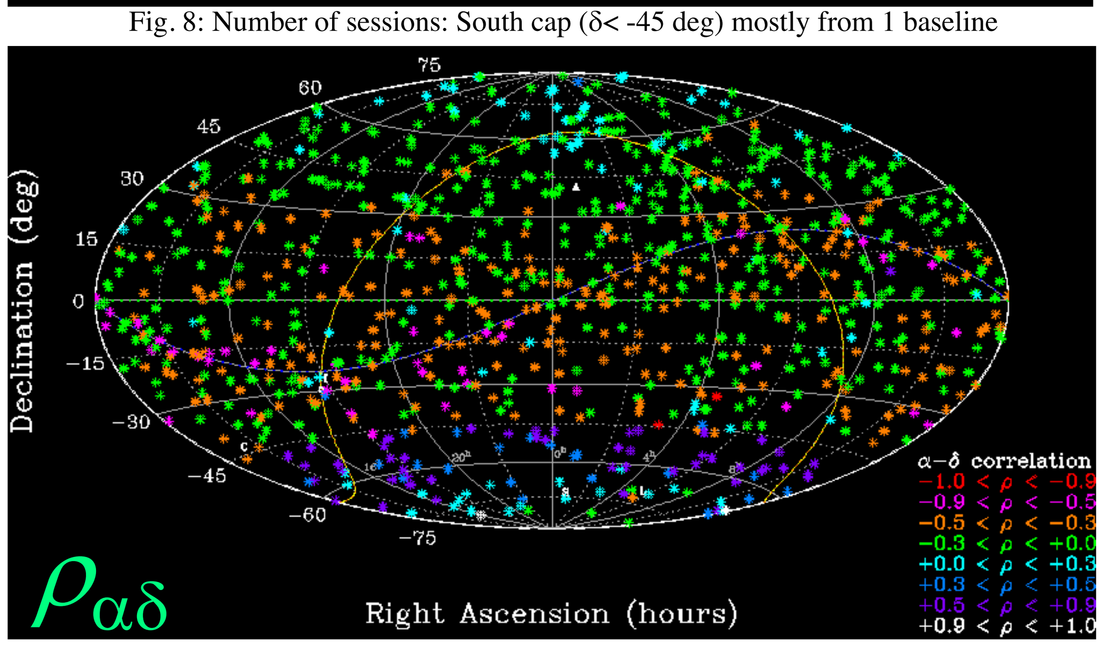

Fig. 9: RA-Dec correlations: Error ellipses are less circular in the south.

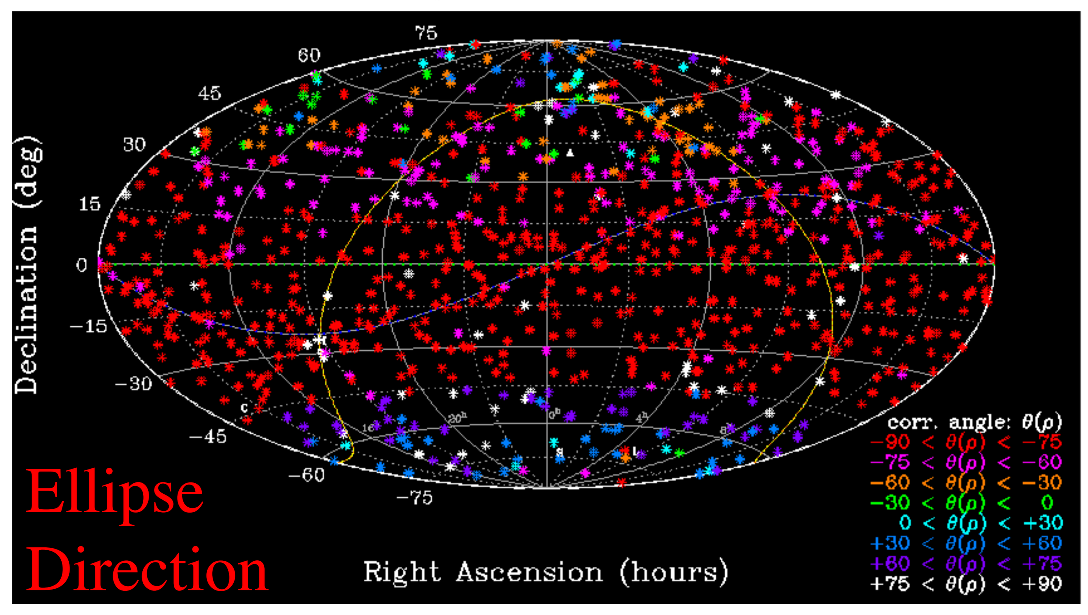

Fig. 11: Direction of Error Ellipses: semi-major axes are mostly North-South i.e. δ weaker

II. Accuracy: K vs. S/X

Comparison of K-band to the current (1901121) S/X, after removing 97 outliers > 5-σ, leaves 783 sources in common. The wRMS agreement is 78/133 μas in αcosδ and δ, respectively. We tested for spatially correlated differences by estimating vector spherical harmonics (Mignard& Kiloner, 2012) to degree and order 2. Z-dipole was 58 μas, all other terms were <= 28 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 1.7 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 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 K-band accuracy available today. With Gaia Data Release-2 (Mignard+, 2018), 569 sources are detected in both the optical and K-band radio---after removing 11% of the sources as outliers >= 5-σ. Rotational alignment is made with ~15 μas precision (1-σ, per 3-D component). Scatter is ~220 μas wRMS. Vector Spherical Harmonics difference terms out to degree and order 2 reveal a Z-dipole of 56 μas with all other terms <= 35 μas, indicating excellent global agreement.

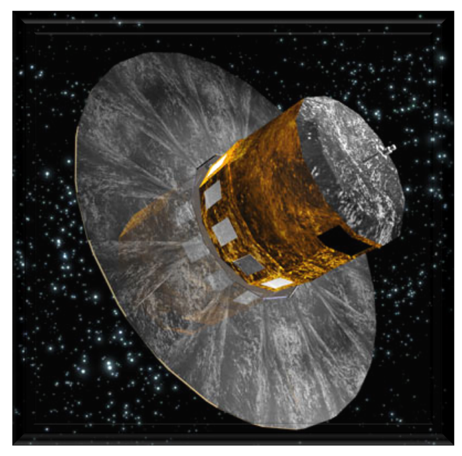

Fig. 12: Gaia launched in Dec 2013 toward L2 (www.esa.int/esaSC/120377_index_1_m.html#)

IV. Goals for the Future:

1. Number: >= 1000 sources. Greater density along ecliptic plane.
2. Precision: <= 30 μas (1-σ) to match/exceed S/X
3. Uniformity: Improve south with baselines from HartRAO to Hobart.
4. Imaging & Sensitivity: Dual polarization (RCP, LCP), 4 Gbps

V. Conclusions: The K-band CRF has 918 sources covering the full sky and is making rapid improvements in the precision. The K-band CRF now has comparable precision to the current SX frame in RA. Spherical harmonic differences vs. S/X are <= 58 μas and vs. Gaia are <= 56 μas. Improving accuracy will depend on controlling systematics from ionosphere and adding North-South baseline geometry.

 U.S. Government sponsorship acknowledged for work done at JPL-Caltech under a contract with NASA. The VLBA is managed by NRAO, funded by the National Science Foundation, and operated under cooperative agreement by Associated Universities. The authors gratefully acknowledge use of the VLBA under the USNO's time allocation. This work supports USNO's ongoing research into the celestial reference frame and geodesy. HartRAO is a facility of the National Research Foundation (NRF) of South Africa. The Hobart telescope is operated by the University of Tasmania and this research has been supported by AuScope Ltd., funded under the National Collaborative Research Infrastructure Strategy (NCRIS). HK works within the project T 697-N29 funded by the Austrian Science Fund (FWF).