The X/Ka-band (8.4/32 GHz) 2018b Celestial Reference Frame

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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 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 176 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 0.67 µas in αcosδ and 95 µas in δ.

Comparison of 529 XKa sources in common with the S/X-band (2.3/8.4 GHz) ICRF3 produced wRMS agreement of better than 165 µas. There is evidence for systematic errors at the 100 µas level. Known errors include limited SNR, lack of phase calibration, tropospheric mismodeling, 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.

**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.

**Fig. 1:** NASA-ESA Ka-band network. The addition of ESA’s Argentina station adds 3 more stations to full sky coverage.

**Fig. 2:** Antenna of the combined NASA-ESA X/Ka-band network. Diameters are about 5 meters.

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

**Fig. 4:** Schematic of Active Galactic Nuclei (Marchetti, 2008; Kochanek, 1997; Wrobel, 2015).

**Fig. 5:** The radio “wobbles” is transparent compared to most of the spectrum (credit: NASA).

**Fig. 6:** RA of Active Galactic Nuclei: Large scale pattern of the K-band.

**Fig. 7:** Dep. position: Median 0.5-3 µas for 678 sources. Note source position at Dec. ~ 30 deg.

**Fig. 8:** Number of sessions: Median number of sessions is 30, but only 17 or 20 in some.

**Fig. 9:** Optical magnitudes: Median V vs. XKa. About 30% sources bright for Gaia, (V < 13).

**Fig. 10:** Error Ellipse size: α/δ, there is only an elongation from 24 h to 45 deg.

**Fig. 11:** Direction of Error Ellipse: some large rms are mostly North-South, α ≈ 90 deg than.

**Fig. 12:** Elliptical Polarimetry: Median V vs. XKa. About 30% sources bright for Gaia, (V < 13).

**Fig. 13:** Data: Launched in 2013 (European VLBI Network/ESAC) + data from 2013 onwards (European Space Agency/ESAC).

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

Comparison of XKa-band (solution date 1809x) to the current ICRF3-S/X, after removing outliers > 5σ, leaves 529 sources in common. The wRMS agreement is 151/163 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 -183 ± 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. cross-correlation. As a result Gaia provides the most independent check of accuracy available today. With Gaia Data Release 2 (Mignard, 2018), 490 sources are detected in both the optical and XKa-band radio—after removing 9% (45) of the sources as outliers > 5 σ. Rotational adjustment is made with ~20 µas precision (1σ, per 5-D component). Scatter is ~270 µas wRMS. Vector Spherical Harmonics difference terms out to degree and order 2 are all 210 µas or less, indicating good global agreement of the two frames.

**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 67 / 95 µas in αcosδ / δ. Spherical harmonic differences vs. ICRF3-S/X are ≈210 µas and Gaia are ≈210 µas. Improving accuracy will depend on controlling systematics via increased observations using a North-South baseline geometry.

**IV. Goals for the Future:**

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