Astronomía Dinámica en Latino-América (ADeLA), Santiago, Chile, 29 Sep to Oct 01, 2014

ICRF-3: Roadmap to the next generation International Celestial Reference Frame

Executive Summary: Celestial angular coordinates (RA, Dec) are defined by axes derived from positions of 295 Active Galactic Nuclei measured using the VLBI technique at 8 GHz (3.6 cm). We propose improving this current IAU standard, the ICRF-2, in several ways.

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Abstract: We propose a 3rd generation radio-based International Celestial Reference Frame (ICRF-3) to improve upon the highly successful ICRF-2. Our goals are to improve the precision, spatial and frequency coverages relative to the ICRF-2 by 2018. This date is driven by the desire to create radio frames early enough to test the Gaia optical frame during its construction. Several specific actions are underway. A collaboration has been started to improve S/X-band precision of the 2200+ VLBA Calibrator Survey sources which are typically 5 times less precise than the rest of the ICRF-2. S/X-band southern precision improvements are planned from observations with southern antennas such as the AuScope and HartRAO, S. Africa. We seek to improve radio frequency coverage with X/Ka and K-band work. An X/Ka frame of 654 sources now has full sky coverage from the addition of a 2nd southern station in Argentina which should strengthen the southern hemisphere in general. A K-band collaboration has formed with similar coverage and southern precision goals. On the analysis front, special attention will be given to combination techniques both of VLBI catalogs and of multiple data types (e.g. VLBI+GPS). Finally, work is underway to identify and pinpoint sources bright enough in both radio and optical to allow for a robust frame tie between VLBI and Gaia optical frames.

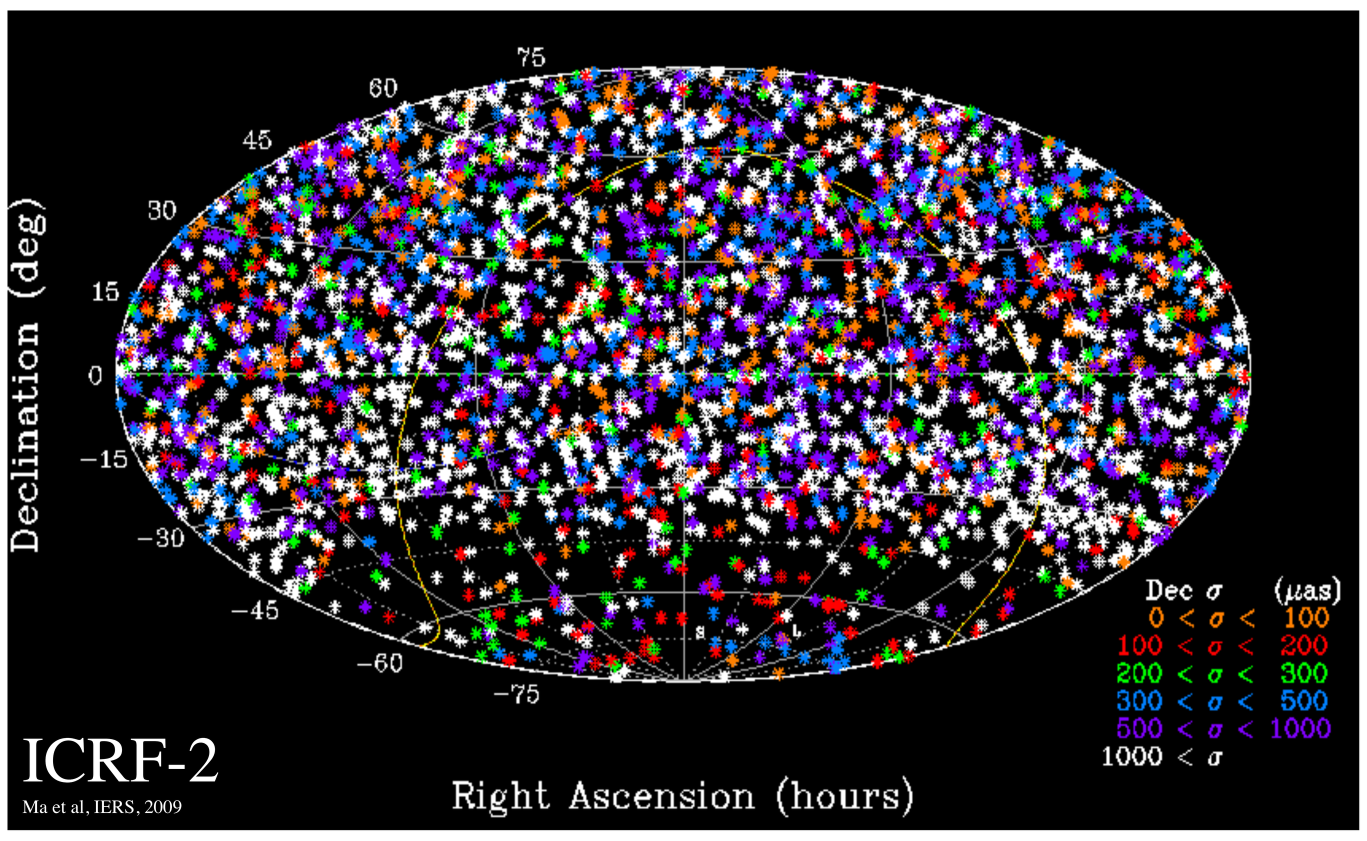

Fig. 1 The 2nd International Celestial Reference Frame (ICRF-2): Distribution of 3414 AGN over the celestial sphere.

I. Introduction

Since the adoption of the ICRF-1 (Ma et al, 1998) on 1998 Jan 01, the IAU has defined angular coordinates on the sky using axes defined from VLBI observations at S/X-bands (2.3/8.4 GHz) of a few hundred Active Galactic Nuclei (AGN). The current standard, ICRF-2, uses 295 fiducials to define the axes densified by additional AGN for a total of 3414 sources (Fig. 1). The noise floor is estimated at about 40 μas.

About 2/3 of the sources are from the VLBA Calibrator Survey (VCS) series of observations (fig. 2) which have about 5 times worse precision than the remaining 1/3 of the sources. Both the VCS and the ICRF-2 in general are weak south of declination -30 deg —the limit of the reach of northern baselines.

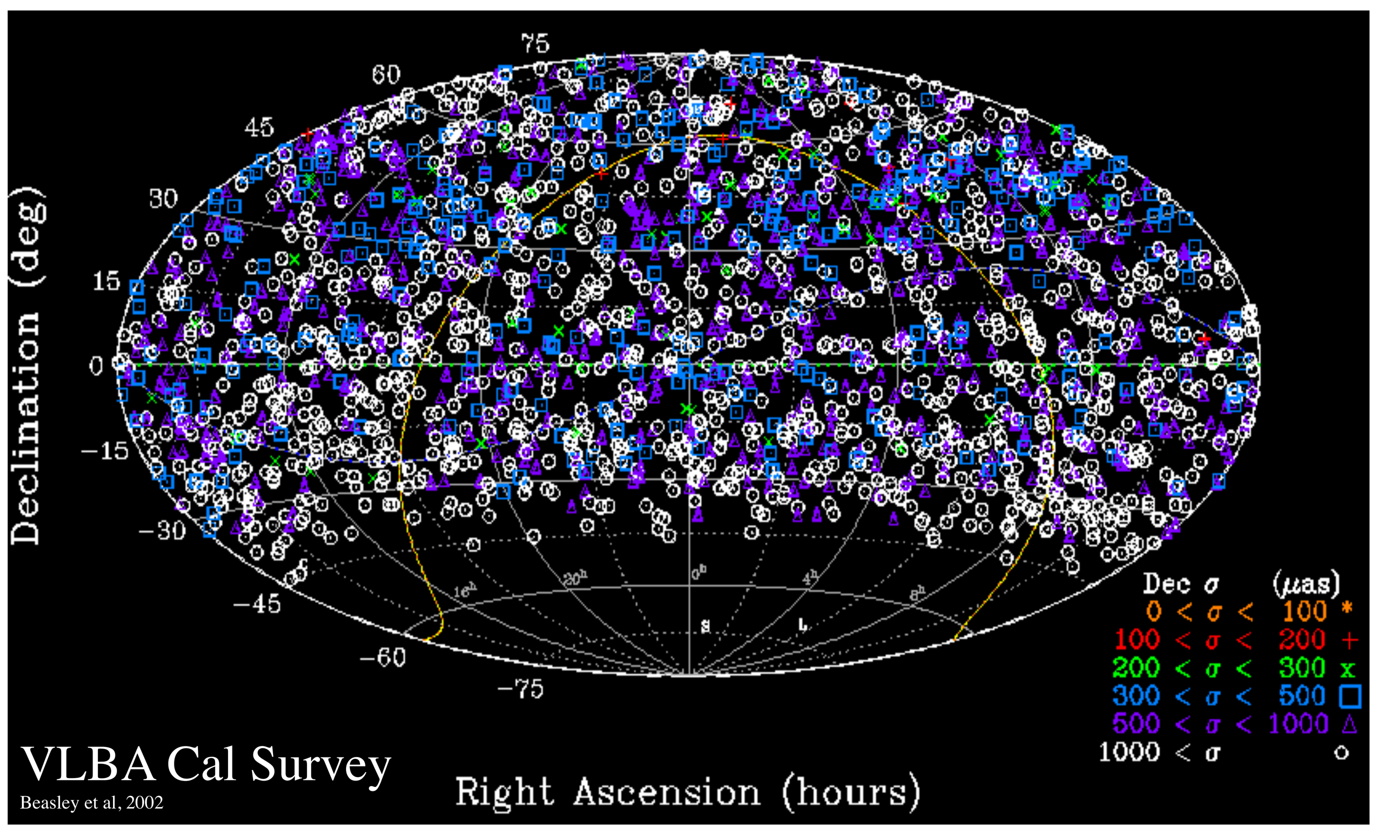

Fig. 2 VLBA Calibrator Survey: Distribution of ~2200 sources (Beasley et al, 2002). Precision is 5X worse than rest of ICRF-2

II. Assessment of Needs for ICRF-3

1. More uniform precision: VLBA Cal Survey is ~2/3 of the ICRF-2 but VCS positions are 5 times worse than rest of ICRF-2
2. Southern hemisphere: The ICRF-2 and all VLBI frames are weak in the south due to a lack of southern stations & observations.
3. Reduced source structure and core shift: Many sources at the standard S/X-bands have systematic errors due to non-pointlike nature of sources.
4. High frequency frames at K (22-24 GHz) and Ka-band (32 GHz) have more point-like structure, but also fewer sources at present. Also, as with S/X, high frequency CRFs are weak in the south.

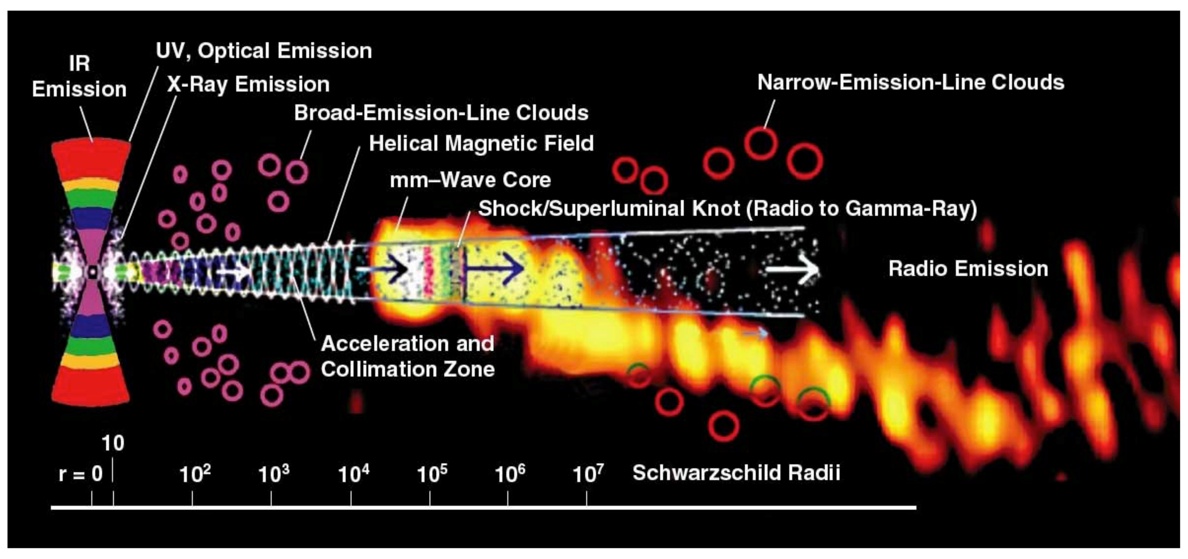

Fig. 3: Schematic of Active Galactic Nuclei (Marscher, 2006, Krichbaum, 1999, Wehrle, 2010)

III. Goals for a Candidate ICRF-3:

1. Date: Complete a radio-based candidate for the ICRF-3 by 2018 to be ready for comparisons before Gaia optical frame release ~2021.
2. Accuracy: 70 μas or better (1-sigma RA, Dec) to match Gaia's precision.
3. Uniform precision for all sources: 2nd generation VCS (8 x 24 hr) now underway with projections for 3 times improvement from initial data.
4. Uniform spatial coverage: Implies improving southern observations.
   - S/X: increase observation between Australia & S. Africa (e.g. Titov 2013)
   - K: Observations amongst S. Africa, Australia,& Korea (Bertarini et al 2013)
   - X/Ka: Baselines from Malargüe, Argentina to Australia, California & Spain
5. High Frequency Frames: K (22-24 GHz), Ka (32 GHz)
   - Improve number: 500+ K-band sources, 700+ X/Ka sources
   - Accuracy: better than 70 μas
   - Southern coverage: make southern accuracy comparable to northern
6. Optical-radio frame tie: add 100+ optically bright sources to radio frame to improve the frame tie to the Gaia optical frame (Bourda et al, 2012)

IV. High Frequency Radio Frames:

As radio frequencies increase, sources tend to be more core dominated because the extended structure in the jets tends to fade away with increasing frequency (Figs. 3 & 5). Also the spatial offset of the emissions from the AGN engine due to opacity effects ("core shift") is reduced with increasing observing frequency.

- Fig. 4a: K-band distribution of 275 sources. K-band (22-24 GHz, 1.2cm) is near the 22 GHz water line.
- Fig. 4b: X/Ka distribution of 654 sources. Ka-band (32 GHz, 9mm) lies between the 22 GHz water line and the 60 GHz O_2 line (Fig. 6).

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

- More compact, stable sources (Fig. 5)
- Reduced opacity effects: "core shift"
- Ionosphere & solar plasma observing effects down by 15X.

Disadvantages of K & Ka-band:

- More weather sensitive
- Shorter coherence times
- Weaker sources, many resolved
- Antenna pointing is more difficult,.
- Combined effect is lower sensitivity, but advances in recording technology are rapidly compensating with higher data rates.

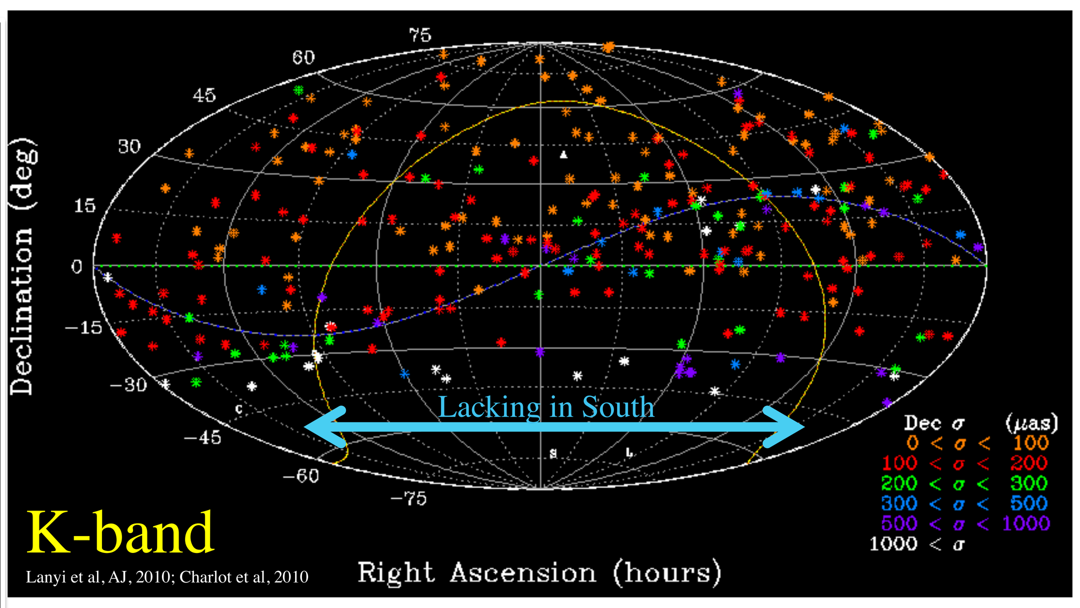

Fig. 4a: K-band distribution of 275 sources. Note the lack of sources below -40 deg Dec

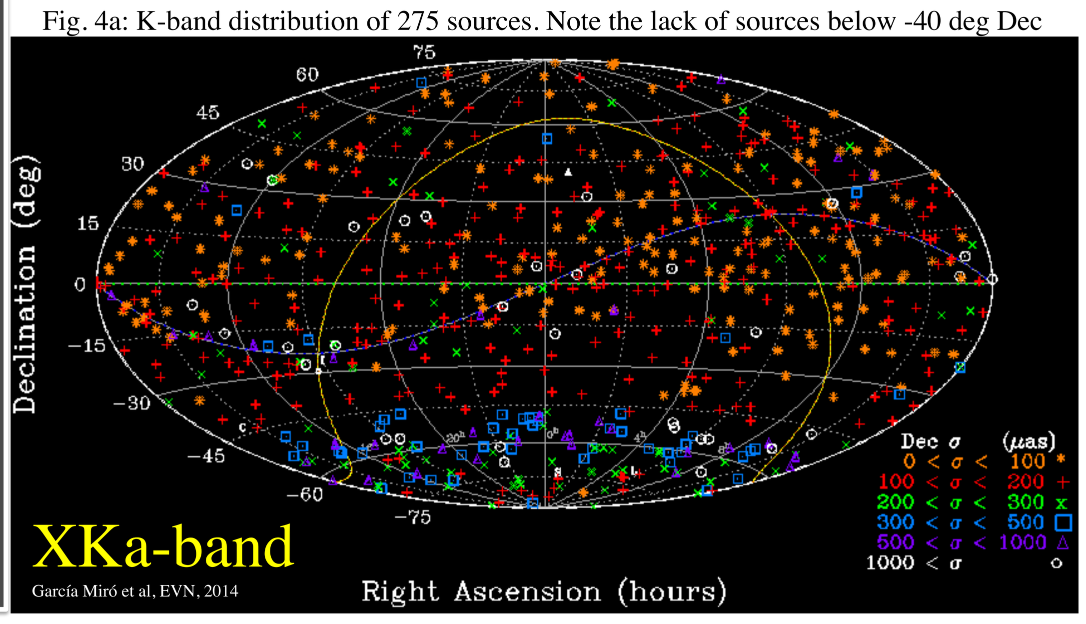

Fig. 4b: X/Ka distribution of 654 sources. Note lower precision in south (Dec < -45 deg)

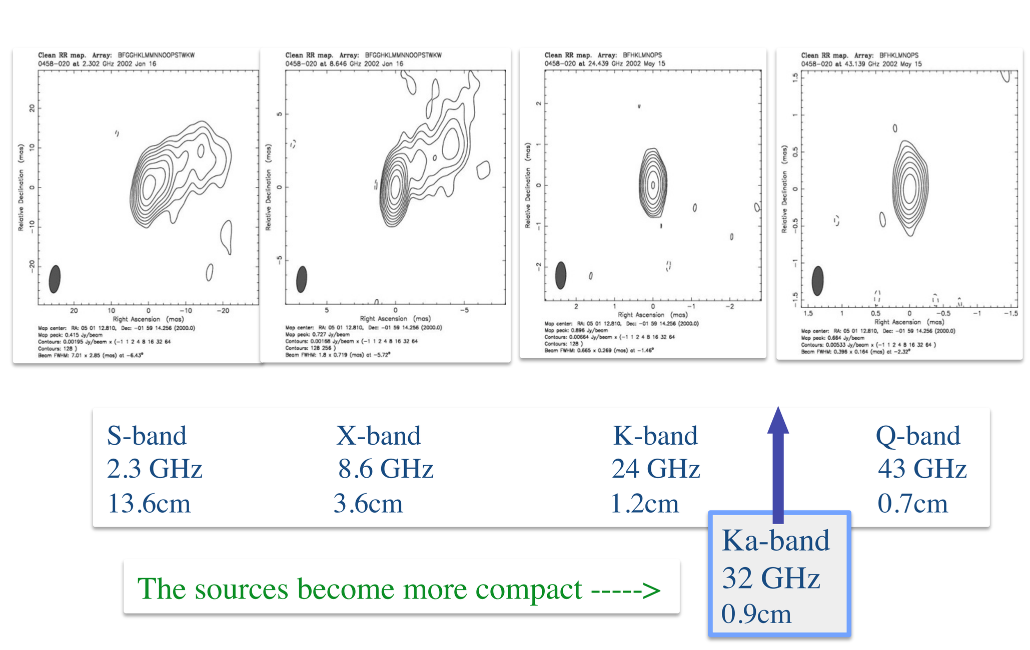

Fig. 5: Source structure & compactness vs. wavelength (Charlot et al, AJ, 2010)

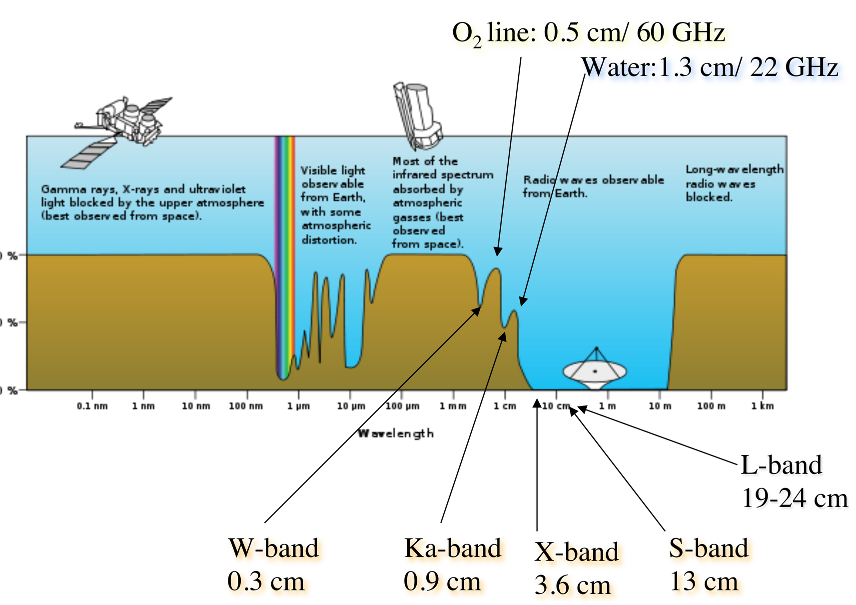

Fig. 6: Frequencies in relation to the Radio Window (credit: NASA)

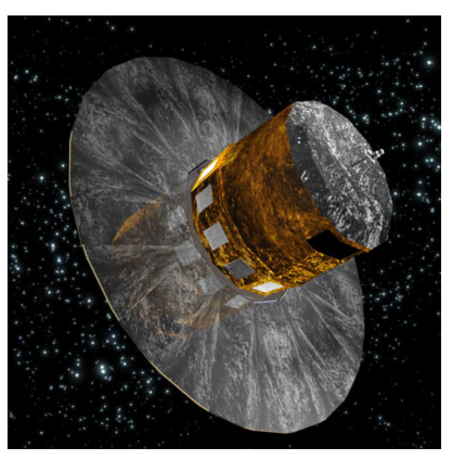

Fig. 7: Gaia launched in Dec 2013 toward L2 (http://www.esa.int/esaSC/120377_index_1_m.html#)

V. Gaia Optical-Radio Frame Tie and Accuracy Verification:

Background: Launched in Dec. 2013, ESA's Gaia mission is designed to make state-of-the-art astrometric measurements (positions, proper motions and parallaxes) of a billion objects as well as photometric and radial velocity measurements (Lindegren, 2008; Mignard, 2013). Gaia's observations will include approximately 500,000 AGN of which ~20,000 will be optically bright (V < 18 mag) thus enabling very high precisions: 70 μas @V=18 mag and 25 μas @V=16 mag.

Tie sources: Bourda et al (2012) estimate that 300+ AGNs should be both bright in the optical and bright and compact in the radio thus enabling both Gaia and VLBI to make very precise position measurements of a common set of sources which should allow the Gaia Optical and VLBI radio frames to be rotationally aligned to better than 10 μas precision (1-sigma, per 3-D component, [Jacobs et al 2013]). After making the optical-radio alignment, position offsets between the two techniques can be studied to characterize systematic errors. Having multiple radio frames (S/X, K, X/Ka) should be of great value in characterizing frequency dependent effects e.g. core shift.

VI. Conclusions:

The great success of the ICRF-1 and ICRF-2 in providing the IAU with a standard celestial reference frame has encouraged us to pursue improvements to enable a 3rd generation ICRF, the ICRF-3. We believe that further significant progress is achievable by 2018 by leveraging sensitivity improvements from higher data rates, improved geometry including greater use of southern hemisphere stations, and quantifying frequency dependent astrophysical effects from higher radio frequency observations at K and Ka-bands which in turn are expected to benefit tying the radio-based frames to a future optical frame based on the Gaia mission. *Accordingly, we have begun a program of observations to create a candidate ICRF-3.*

Acknowledgements: Thanks the the International VLBI Service (IVS) and its members for decades of dedication to the collection of the data used in this research (Schuh & Behrend, J. Geodynamics, 61, 68–80, Oct. 2012. DOI 10.1016/j.jog.2012.07.007)
Research done in part under NASA contract. Sponsorship by U.S. Government, our respective institutes & funding agencies acknowledged.