ICRF-3: ROADMAP TO THE NEXT GENERATION ICRF

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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 as well as the 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 631 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 hemisphere 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.

1. 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 (Ma *et al*, 2009), uses 295 fiducials to define the axes and then densifies the frame with additional AGN for a total of 3414 sources (Fig. 1). The axes are claimed to be stable at the 10 μas level. The noise floor of individual coordinates is estimated to be 40 μas.

About 2/3 of the sources are from the VCS survey (Fig. 2; Beasley *et al*, 2002) 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 $-30°$, the approximate limit of the reach of northern arrays. To remedy these weaknesses, southern antenna arrays are being coordinated for VLBI observations (Fig. 3).

2. ASSESSMENT OF NEEDS for ICRF-3

A review of the needs for a next generation celestial frame revealed the following areas of concern:

1. More uniform precision: VLBA Calibrator Survey (VCS) is ∼2/3 of the ICRF-2 but VCS positions are 5 times worse than the rest of ICRF-2.

2. Weak southern hemisphere: The ICRF-2 and all VLBI frames are weak in the south due to a lack of southern stations and observations.

3. Reduction of source structure and core shift effects: Many sources at the standard S/X-bands have systematic errors due to non-pointlike nature of sources.

4. Extend reference frame to higher frequencies: 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 celestial frames are weak in the south.

3. ICRF-3 GOALS

Having reviewed the needs for the proposed ICRF-3, we set goals to address these needs within estimated resources constraints:

1. Date: Complete a radio-based candidate catalog for ratification by IAU as ICRF-3 by 2018
   to be ready for comparisons before Gaia optical frame release 2021.
2. Accuracy: 70 μas or better (1-σ RA, Dec) to match Gaia's precision.
3. Uniform precision for all sources: 2nd generation VLBA Cal Survey (8 x 24 hr)
   now approved for VLBA observations will help to solve precision uniformity problems.
4. Uniform spatial coverage: Implies improving southern observations.
   S/X: increase number of observations between Australia and South Africa (e.g. Titov *et al*, 2013)
   K: Observations amongst South Africa, Australia, and 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)
   Increase number of sources to more than 500 at K-band and more than 700 at X/Ka-band.
   Accuracy: better than 70 μas
   Southern coverage: make southern accuracy comparable to northern accuracy.
6. Optical-radio frame tie: add more than 100 optically bright sources to radio frame
   to improve the frame tie to the Gaia optical frame (Bourda *et al*, 2011)

4. HIGH FREQUENCY RADIO FRAMES

As radio frequencies increase, sources tend to become more core dominated as the extended structure in the jets tends to fade away with increasing frequency. Also the spatial offset of the radio emissions from the AGN's central black hole due to opacity effects ("core shift") is reduced with increasing observing frequency. For applications lacking dual frequency observations for plasma calibrations, moving to higher frequencies quickly reduces charged particle effects. All these factors motivate the creation of celestial frames above the standard 8.4 GHz frequency.

While the astrophysics is better at higher frequencies, the presence of a rotational water line at 22 GHz makes observations at K and Ka-bands more weather sensitive and combined with the shorter wavelengths leads to shorter coherence times. Furthermore, sources are often weaker and antenna pointing is more difficult. The combined effect is lower sensitivity, but advances in recording technology are rapidly compensating with higher data rates. For example, both the VLBA and JPL's Deep Space Network are moving to 2 Gbps operations.

Lanyi *et al* (2010) and Charlot *et al* (2010) did pioneering work to develop a high precision celestial frame at 24 GHz. They used the VLBA to observe about 270 sources (Fig. 4) with precision better than 200 μas. This work showed that there were a sufficient number of compact sources with sufficient flux density for creating a celestial frame at 24 GHz.

Since 2005, the two baselines of NASA's Deep Space Network have been making observations at X/Ka-band of about 500 sources down to −45° south. Recently they have been joined by ESA's DSA03 station in Malargüe, Argentina resulting in full sky coverage at Ka-band (Horiuchi *et al*, 2013). The X/Ka work now includes 630 sources (Fig. 5).

We also note that work is underway to explore combinations of S/X and X/Ka catalogs using the full parameter covariances in an effort to create a strengthened catalog product.

5. 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 at $V = 18$ mag and 25 μas at $V = 16$ mag.

Tie sources: Bourda *et al* (2011) estimate that over 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-σ, per 3-D component, [Horiuchi *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.

6. 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.

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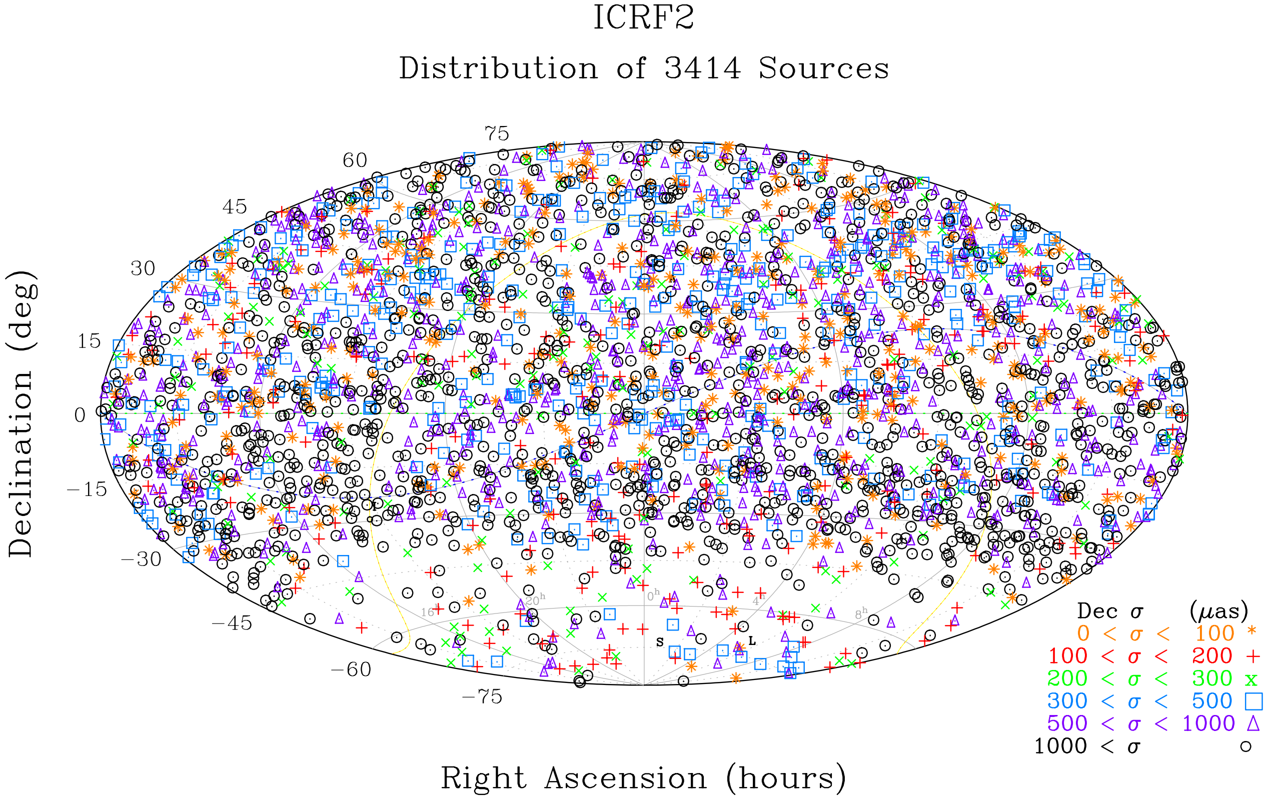

Figure 1: ICRF-2: the current IAU standard frame consists of 3414 sources (Ma *et al*, 2009). Note the lower spatial density of sources south of −30°. About 2/3 of the sources, originating from the VCS survey have 5 times lower precision than the well observed sources.

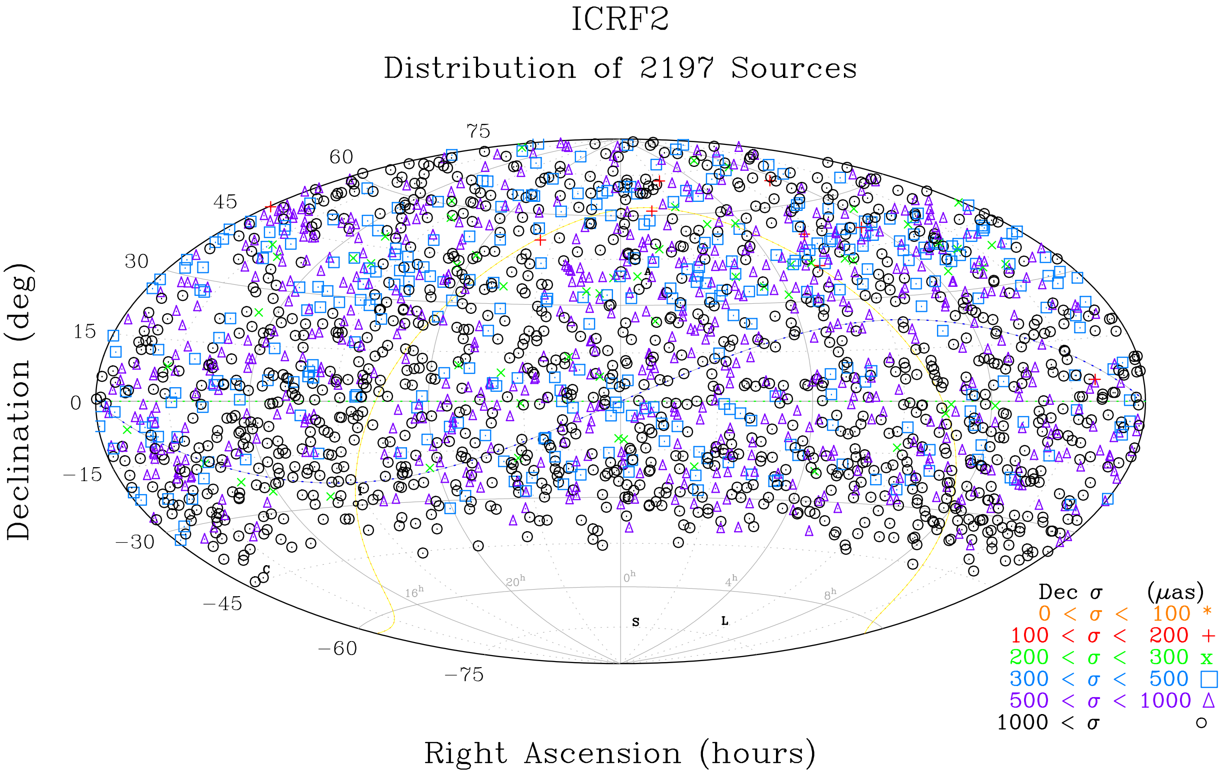

Figure 2: ICRF-2 survey sources. These 2197 sources are typically observed in only 1 or 2 sessions resulting in a median precision of ∼ 1 mas—5 times lower precision than non-VCS sources (Beasley *et al*, 2002). The lack of sources south of −45° is due to the geometric limits of the all-northern VLBA. No comparable mas-level survey was available in the south at the time the ICRF2 was constructed. The LBA Calibrator Survey work now underway will help to rectify this gap.

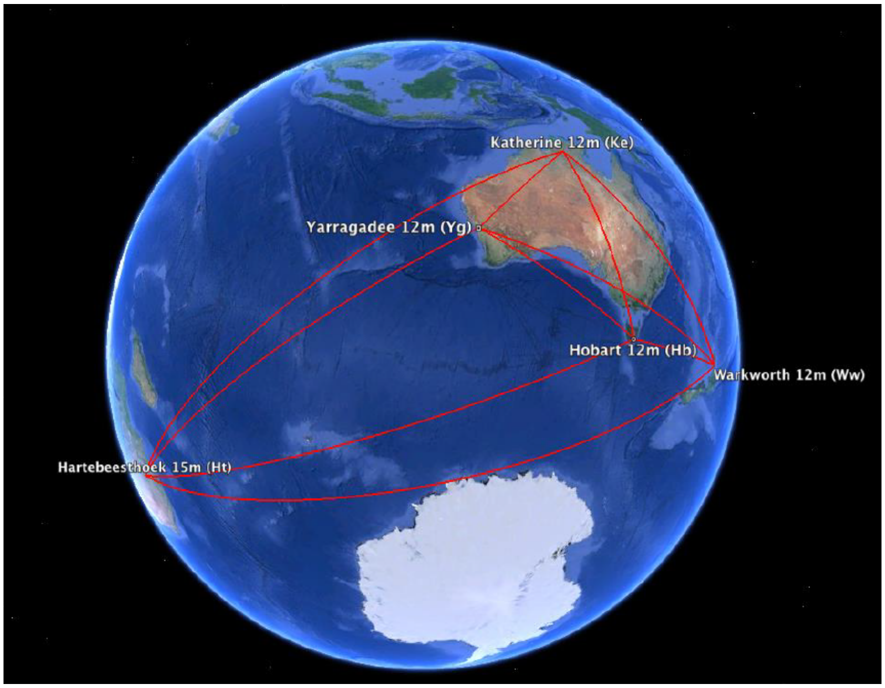

Figure 3: Southern stations: These new, fast southern stations are expected to improve the ICRF in the south. Because the newer stations are 12–15 meters in diameter, larger antennas such as Parkes, DSS45, Hobart-26m, and Hart-26m will need to be added in order to detect weaker sources (Titov *et al*, 2013).

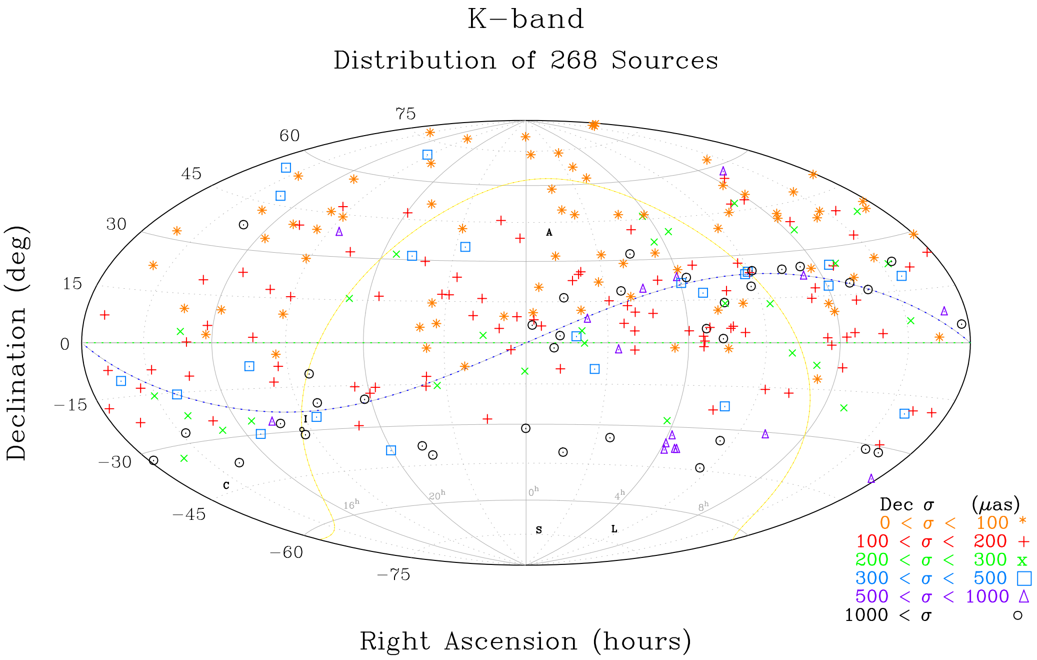

Figure 4: K-band Frame: Positions of 268 sources at 24 GHz were measured with the VLBA (Lanyi *et al*, 2010 and Charlot *et al*, 2010). Most with a precision better than 200 μas. The work of Bertarini *et al* is seeking to fill in the far south.

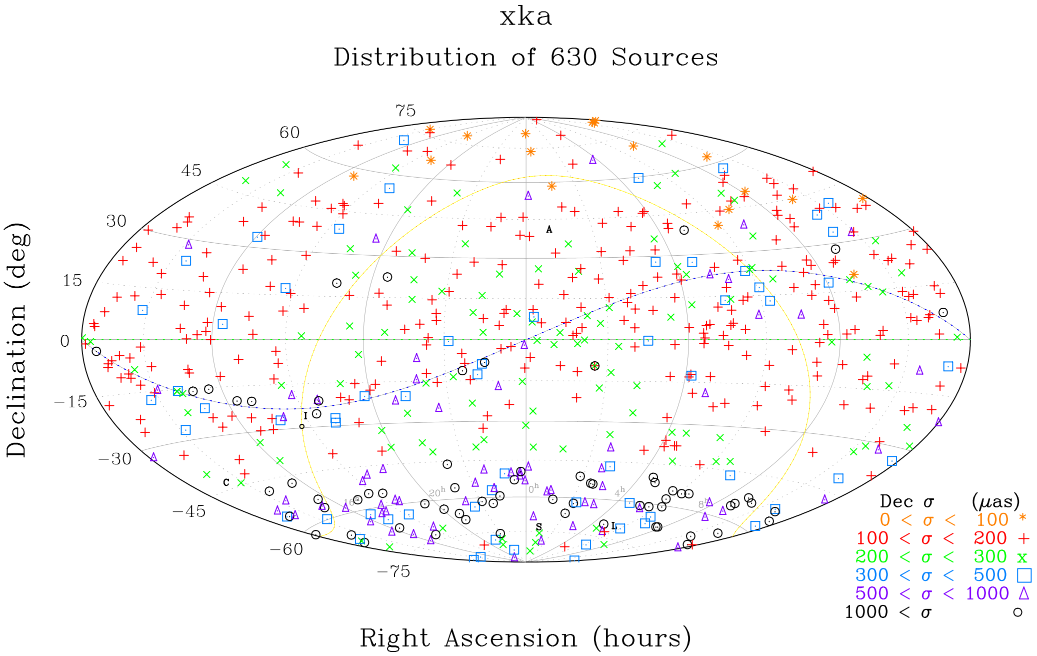

Figure 5: X/Ka Frame: Positions of 630 sources have been measured at 8.4/32 GHz using the combined NASA and ESA Deep Space Networks (Horiuchi *et al*, 2013).