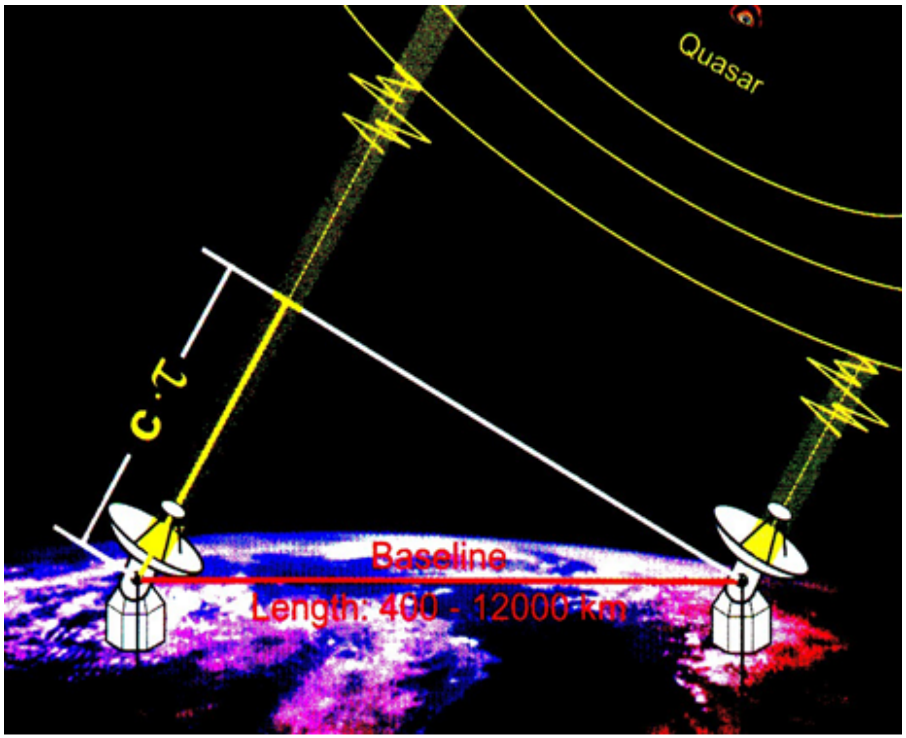
The International Celestial Reference Frame (ICRF) from VLBI

David Gordon

NVI Inc., Code 61A

June 22, 2017

Very Long Baseline Interferometry (VLBI)



- Multiple radio telescopes observe the same distant radio sources simultaneously.
- Quasar signals arrive at different times at each antenna.
- Signals (+ noise) are recorded on disks independently at each station.
- Disks are sent to a VLBI correlator where the recorded data streams are cross-correlated to extract the VLBI observables (delays, delay rates, fringe phases, and fringe amplitudes).

VLBI is an astronomical technique that can be used for astronomy, astrometry (absolute and relative), precise geodesy, spacecraft navigation. The GSFC VLBI group uses VLBI for geodesy and absolute astronomy.

Geodetic/Astrometric VLBI sessions:

- Sessions are usually 24-hrs in length.
- Most sessions have been dual frequency at X (~8.5 GHz) and S (~2.3 GHz) bands to allow correcting for the ionosphere.
- Typically ~50-100 different quasars observed.
- Data correlated/fringed to get observed delays and delay rates.
- Observed delays and theoretical delays used in least squares solutions to determine site positions, Earth orientation parameters, source positions, etc. using the GSFC Calc/Solve and µSolve software packages.

Why do we need a precise celestial reference frame for geodesy?

VLBI operates between two reference frames.
VLBI antennas are 'fixed' in a rotating terrestrial reference frame (TRF).
Quasars are 'fixed' in an inertial celestial reference frame (CRF).

The TRF and the CRF are connected by a set of 5 Earth orientation angles (EOP's: X_{pole}, Y_{pole}, UT1, X_{nut}, Y_{nut}).

A very precise celestial reference frame is needed by VLBI in order to determine a very precise terrestrial reference frame and very precise Earth orientation parameters.

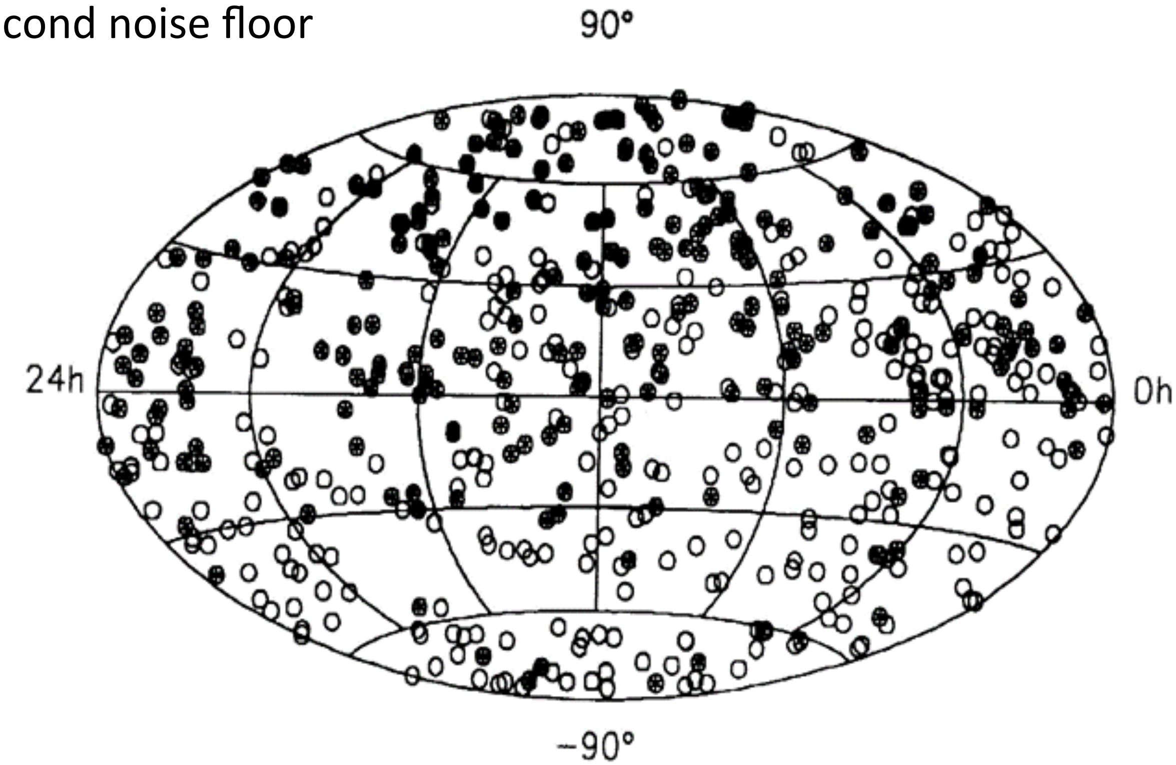
International Celestial Reference Frames – ICRF1:

In January 1998, the IAU adopted the VLBI X/S celestial reference frame as the **International Celestial Reference Frame** - **ICRF1**, replacing the FK5 optical frame. ICRF1 was composed of the celestial coordinates of 608 compact radio sources and had an estimated noise floor of 250 μ-arc-seconds. Although an international effort, the ICRF1 catalog was generated here at GSFC. The axes of ICRF1 were defined by the coordinates of a set of 212 'defining' sources thought to be stable and well-observed. Axis stability was estimated at ~20 μ-arc-sec.

In later solutions, the defining sources were held to a no-net-rotation constraint from their ICRF1 coordinates. The other sources were to be freely adjusted in the least-squares solutions. Two extensions to ICRF1 were made, ICRF-ext1 and ICRF-ext2, which added additional sources.

ICRF1: Adopted by the IAU in Jan. 1998.

- X/S frequencies
- 608 total sources
- 212 defining sources
- 250 μ-arc-second noise floor



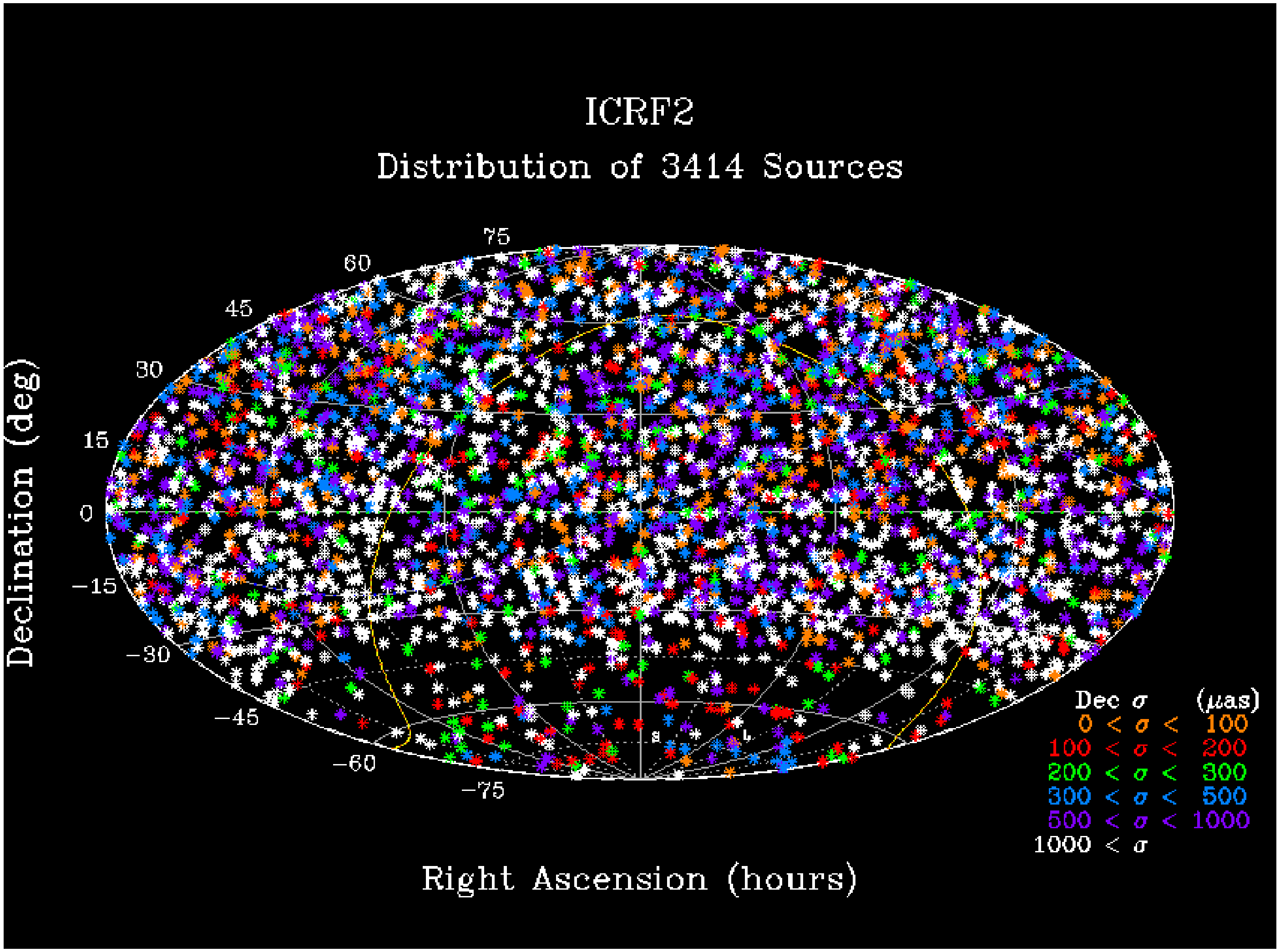
Weaknesses of ICRF1:

- Few defining sources in the far-south.
- Several defining sources found to be unstable.
- Few overall sources in the far-south. (Most VLBI antennas are in the northern hemisphere.)

International Celestial Reference Frames – ICRF2:

A second realization of the International Celestial Reference Frame, **ICRF2**, was generated by an IAU/IVS Working Group in 2009, and adopted by the IAU in January 2010**.** ICRF2 had precise coordinates of 3414 sources and an estimated noise floor of 40 µ-arc-sec (*equivalent to a quarter as seen from ~125,000 km aw*ay). The solution used to construct ICRF2 was also generated here at GSFC. The axes of ICRF2 were defined by 295 'defining' sources. Axis stability was estimated at ~10 µ-arc-sec.

The main reason for the large increase in sources is that ~2200 additional sources were observed in 24 VLBA Calibrator Survey (VCS1-VCS7) sessions (1994-2007), which were run to densify the phase referencing calibrator catalog for astronomical VLBI.



ICRF2: Adopted by the IAU Jan. 2010.

- X/S bands
- 3414 total sources
- 295 defining sources
- 40 µ-arc-sec noise floor

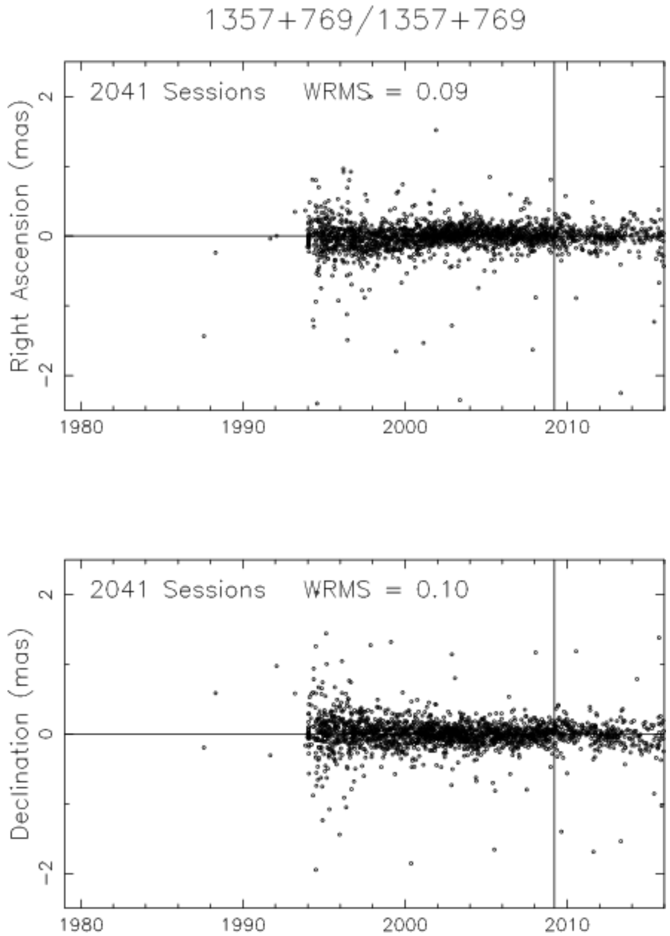
Weaknesses of ICRF2:

- ~2/3 of the sources were observed in only one session, the VLBA Calibrator Surveys (VCS), and had position uncertainties ~5 times greater than the other 1/3.
- Scarcity of sources south of ~-30° declination. (VLBA limit is ~-40°.)

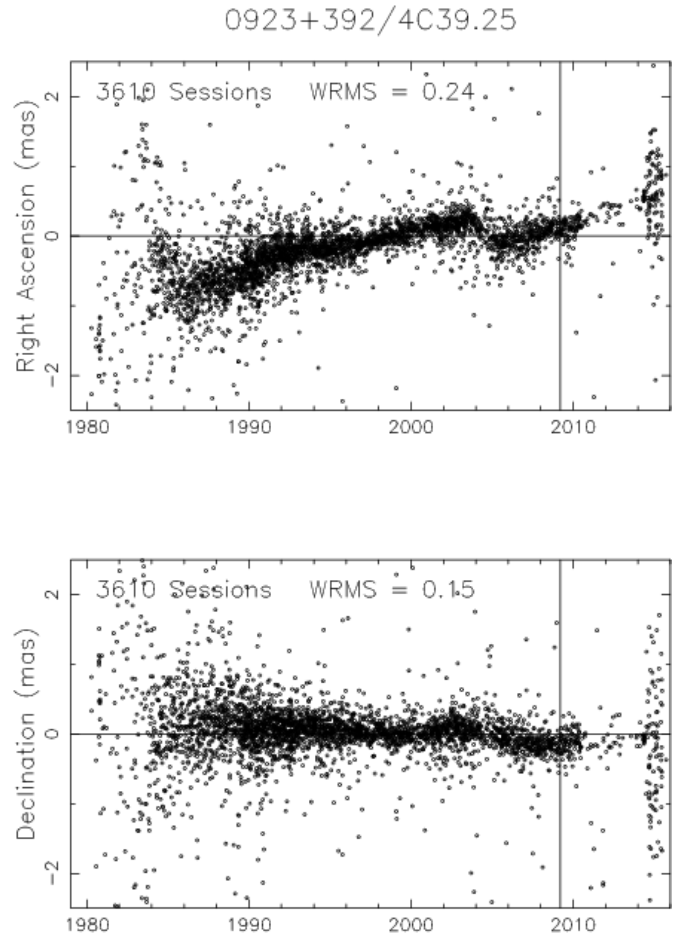
The Nature of Quasar Radio Sources:

At the radio frequencies, many quasars show structures (jets, etc.) which can vary in intensity. This produces shifts in their apparent positions. Some are very stable, some very unstable, most are somewhere in-between. Some of the ICRF1 defining sources were found to show fairly large position variations. For ICRF2, considerable efforts were made to identify and use the most stable and least structured sources as defining sources.

A Stable Source



An Unstable Source



Uses of the ICRF:

- VLBI geodesy. For improved UT1 and precession/nutation leading to improved geophysical modeling.
- Phase reference calibrators. For VLBI imaging of compact sources, measurements of parallaxes and proper motions (masers, pulsars, radio stars) improving the understanding of galactic structure.
- Spacecraft navigation.
- Alignment of the planetary ephemerides.
- Gaia optical alignment and comparisons. Gaia can detect most of the ICRF2 (and future ICRF3) sources. Radio and optical reference frames need to be aligned. Can lead to accurate measurements of core-shifts.
- Studies of galactic aberration.

ICRF-3: Work towards ICRF3 began with the creation of an IAU Working Group in 2012. Goals were:

- Improve upon the precision of ICRF2, especially for the 'VCS' sources.
- Increase the number of sources.
- Provide for a frame tie and accuracy comparisons with the anticipated Gaia optical catalog.
- Present it to the IAU for approval at the August 2018 General Meeting.

Three GSFC code 61A personnel are members of the ICRF3 Working Group (David Gordon, Chopo Ma, Sergei Bolotin).

Current work towards ICRF3:

ICRF3 will have catalogs at three different frequencies.

X/S-band: Many of the single epoch sources have now been observed in 3 or more sessions, and have much smaller formal errors. Most have been re-observed in VLBA sessions. Also, ~860 additional sources have been added, mostly from VLBA sessions and southern hemisphere astrometry sessions.

Source position time-series plots and VLBI maps will be examined to find the best defining sources, with emphasis on uniform sky distribution. The X/S catalog will probably be a combination from ~7 different groups using several independent software packages (Calc/Solve, VieVS, OCCAM, QUASAR).

Current work towards ICRF3: (continued)

K-band: An earlier K-band (24 GHz) astrometry program was restarted in 2014. Now ~30 K-band sessions (VLBA and South Africa-Australia) and 788 sources. Formal errors nearly as good as at X/S. Using GPS ionosphere maps for ionosphere corrections.

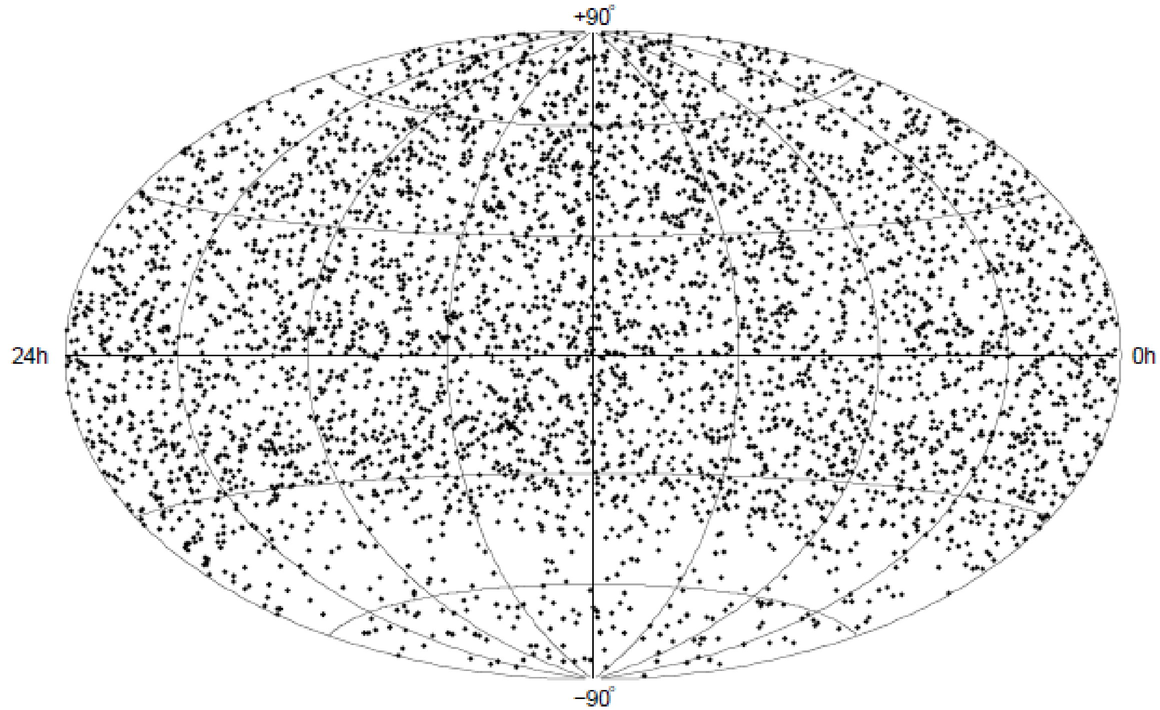
Ka/X-band: Observations being made by Chris Jacobs (JPL) using DSN antennas. Mostly single baseline sessions, ~700 sources. The Ka (~34 GHz) and X (~8.4 GHz) frequencies allow for ionosphere corrections. Future spacecraft navigation work will shift to Ka band so a Ka/X catalog will be very important.

Source structure generally decreases with increasing frequency. Therefore, the higher frequency catalogs (K-band and X/Ka band) can be more stable. The VLBI position can also move closer to the quasar's core. The sources generally become weaker though, so fewer sources can be detected.

ICRF1 vs. ICRF2 vs. ICRF3 Comparison

Parameter	ICRF1 (Jan. 1998)	ICRF2 (Jan. 2010)	ICRF3 (2018/2019)
Data Span:	Aug 1979 - July 1995 (16 years)	Aug 1979 – March 2009 (29.5 years)	X/S: Aug 1979 - ~Dec 2017 (38.4 years) K: 2002 – 2017 (15 yrs) Ka/X: 2012 – 2017 (~5 yrs)
# Observations (data points)	1.6 million X/S band	6.5 million X/S band	~15 million X/S band ~400,00 K band ~100,000 Ka/X band
# Defining Sources	212	295	~300
Total # Sources	608	3414	~4300 X/S band ~800 K band ~700 Ka/X band
Noise Floor	~250 μ-arc-sec	~40 μ-arc-sec	~30 μ-arc-sec
Axis Stability	~20 μ-arc-sec	~10 μ-arc-sec	≤10 μ-arc-sec

Preliminary ICRF3 X/S source distribution
June 12, 2017 solution



4274 Sources

VLBI web page:
https://lupus.gsfc.nasa.gov/

Latest ICRF2 compliant solution:
https://gemini.gsfc.nasa.gov/solutions/2016a_astro/2016a_astro.html

Latest source time series:
https://gemini.gsfc.nasa.gov/solutions/2016a_astro/2016a_ts.html