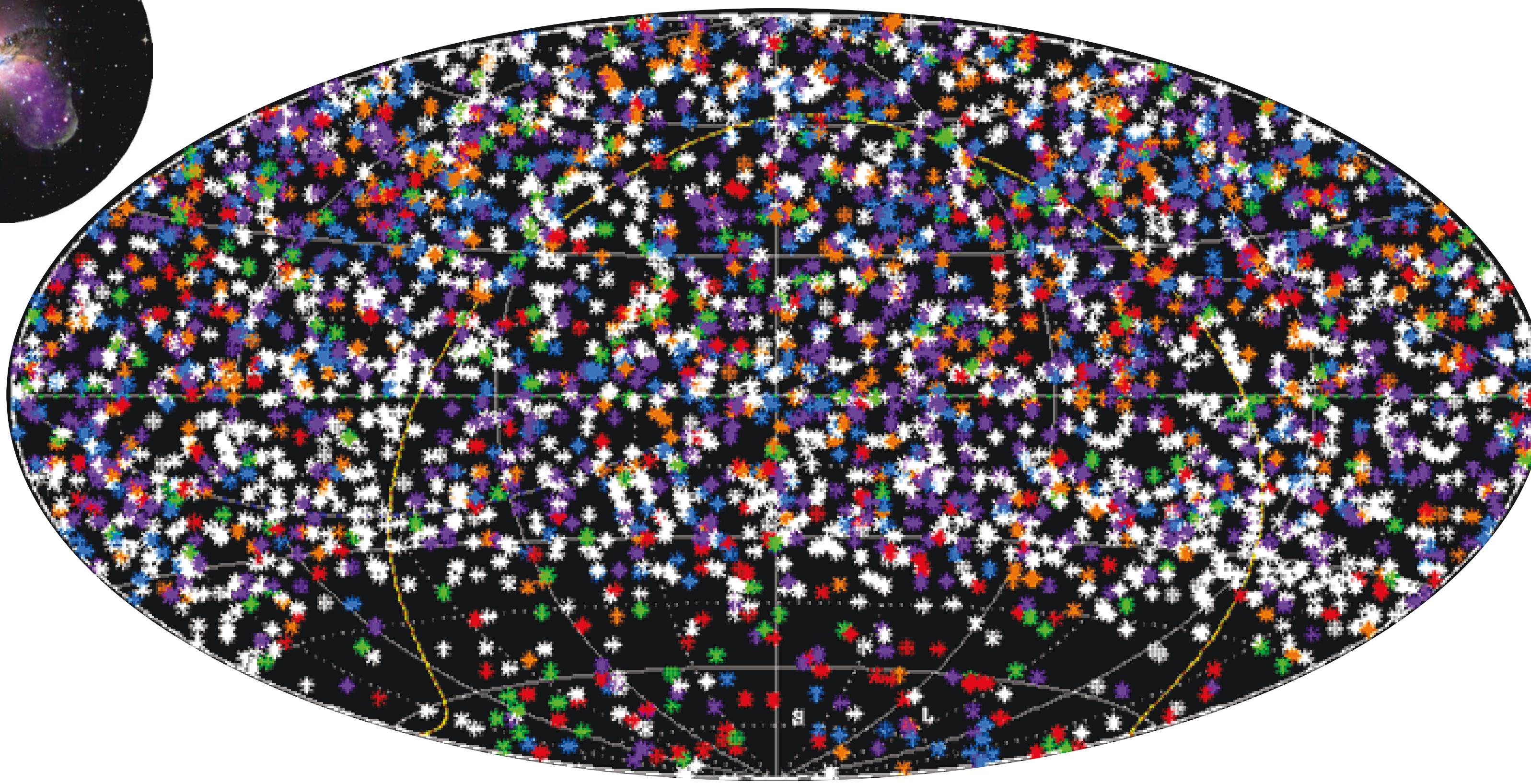
IERS DB Retreat, Paris, France, 23 May 2013

ICRF-3 Overview



Ralph Gaume USNO & Chopo Ma, GSFC (presenters)

Prepared by Christopher S. Jacobs, (ICRF-3 WG chair)

Jet Propulsion Laboratory, California Institute of Technology

On behalf of the IAU's ICRF-3 Working Group

23 May 2013

Formation of IAU WG

- International Astronomical Union (IAU) is international governing body for the Celestial Reference Frame
  - ICRF accepted as fundamental CRF effective 01 Jan 1998
  - ICRF2 accepted as fundamental CRF effective 01 Jan 2010
    - Previously endorsed by IERS and IVS DBs
- Discussions were held at XXVIII GA of the IAU in Beijing concerning next generation ICRF
  - Discussions within Division I (now Division A) = Fundamental Astronomy
  - Organizing Group met in Beijing (Aug 2012)
  - Subsequent meeting in October in Bordeaux (Oct 2012)
    - Charter completed, WG chair selected (Chris Jacobs)
      - Submitted to and accepted by IAU Division A

ICRF-3 working group members

- Felicitas Arias, France
- David Boboltz, USA
- Johannes Boehm, Austria
- Sergei Bolotin, USA
- Geraldine Bourda, France
- Patrick Charlot, France
- Aletha de Witt, South Africa
- Alan Fey, USA
- Ralph Gaume, USA
- David Gordon, USA
- Robert Heinkelmann, Germany
- Christopher Jacobs, USA
- Sebastien Lambert, France
- Chopo Ma, USA
- Zinovy Malkin, Russia
- Axel Nothnagel, Germany
- Manuela Seitz, Germany
- Elena Skurikhina, Russia
- Jean Souchay, France
- Oleg Titov, Australia

http://www.iau.org/science/scientific_bodies/working_groups/192/members/

Overview of 2nd International Celestial Reference Frame

Brief description of how the current ICRF-2 was realized:

- S/X data (2.3/ 8.4 GHz or 13/ 3.6 cm) for 3414 sources
- 6.5 Million group delay observations 1979 to 2009
- No-Net-Rotation relative to ICRF-1
- Estimate TRF and EOPs internally from VLBI data
  Constrain to VTRF-2008 (VLBI part of ITRF-08: *Böckmann et al, JGeod, 84, 2010*)
  as ITRF-2008 was not yet released.
  4 constraints: XYZs: No-Net-Translation, No-Net-Rotation
  Velocities: No-Net-Translation, No-Net-Rotation
- Produced from a single monolithic fit.
  Verified with solutions from multiple independent software packages.

Details in ICRF-2 Technical Note: Ma et al, IERS, 2009.

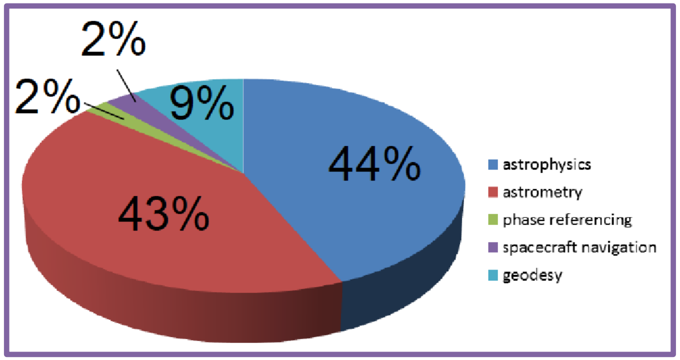
http://adsabs.harvard.edu/abs/2009ITN....35....1M

ICRF-3

The 3rd generation International Celestial Reference Frame

Assessment of needs for ICRF-3

1. VLBA Cal Survey is most (2/3) of ICRF-2
   but positions are 5 times worse than rest of ICRF-2
2. ICRF-2 is weak in the south
3. High frequency frames have more point-like sources
   but also fewer sources at present.
   As with S/X, high frequency CRFs are weak in the south.



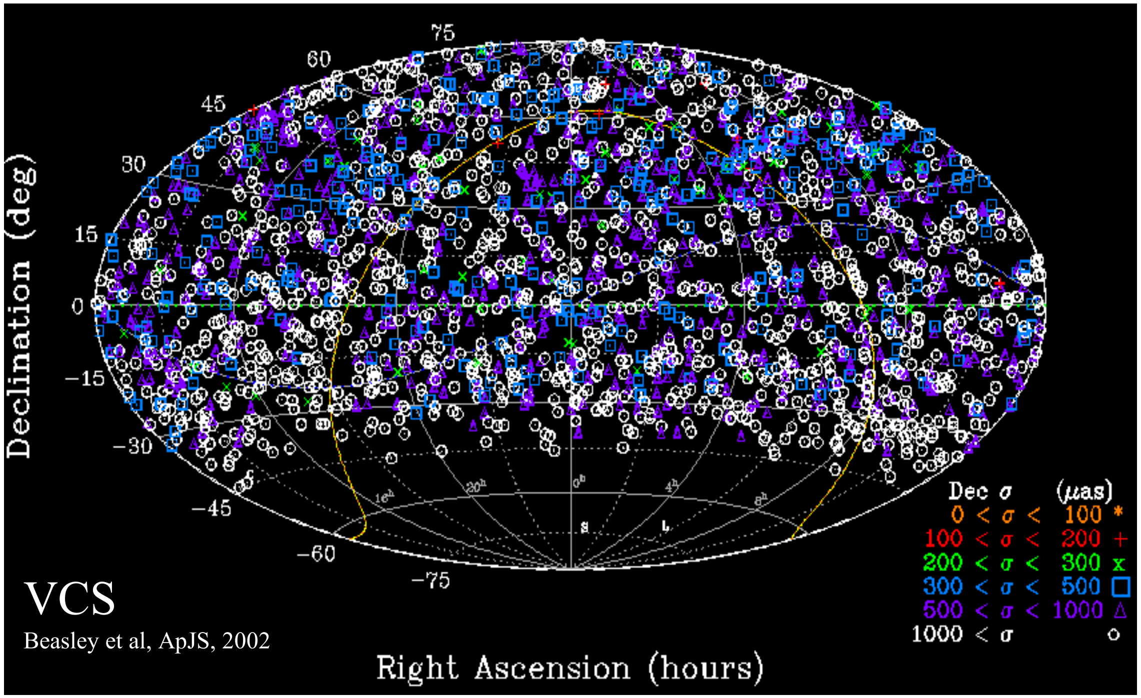
ICRF-1 users: Distribution of ~400 citations
Credit: R. Heinkelmann, ICRF-3 work group

Goals:

1. Complete ICRF-3 by 2018
   in time for comparisons with Gaia optical frame
2. Competitive accuracy with Gaia ~ 70 μas (1-sigma RA, Dec)
3. Uniform precision for all sources. Implies improving VLBA Cal Survey positions.
4. Uniform spatial coverage. Implies improving southern observations.
5. High frequency frames 24, 32, 43? GHz (K, X/Ka, Q?)
   Improve number, accuracy, and southern coverage
6. Improve set of optical-radio frame tie sources for use with Gaia (Bourda et al)

Assessment of ICRF-3 Needs

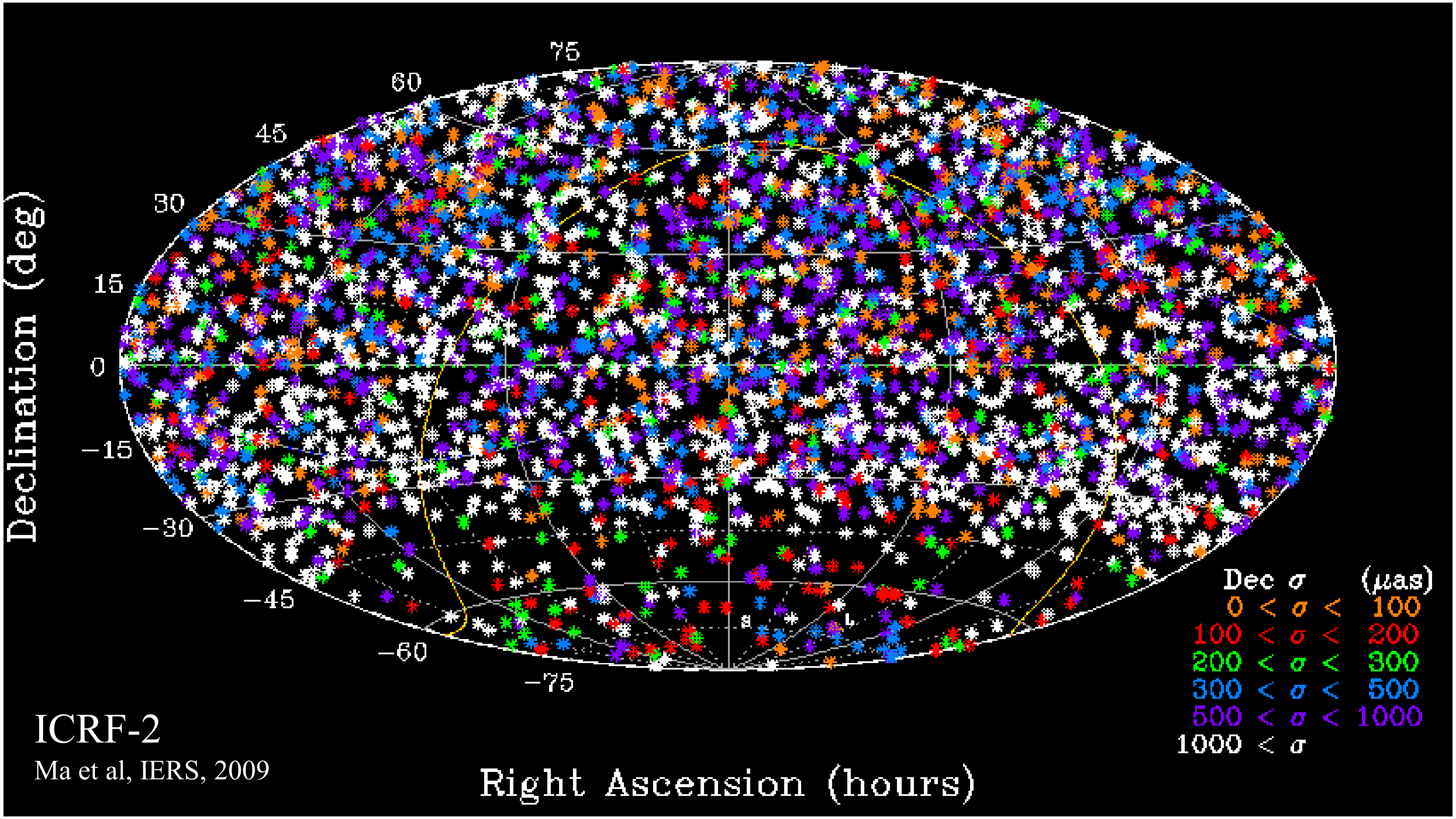
- Uneven precision of current ICRF-2 VCS's 2200 sources (2/3 of the ICRF-2)
  VCS precision is typically 1,000 µas or 5 times worse than the rest of ICRF2.



ICRF-2 Item	VCS	non-VCS	factor
N_src	2197	1217	VCS 1.8X better
median sessions	1	13	VCS 13X worse
median observations	45	249	VCS 5.5X worse
median time span	0	13 years	VCS arbitrarily worse
median RA sigma	621	130 µas	VCS 4.8X worse
median Dec sigma	1136	194 µas	VCS 5.9X worse

- VLBA just approved 8 x 24-hour sessions to re-observe VLBA Cal Survey!!

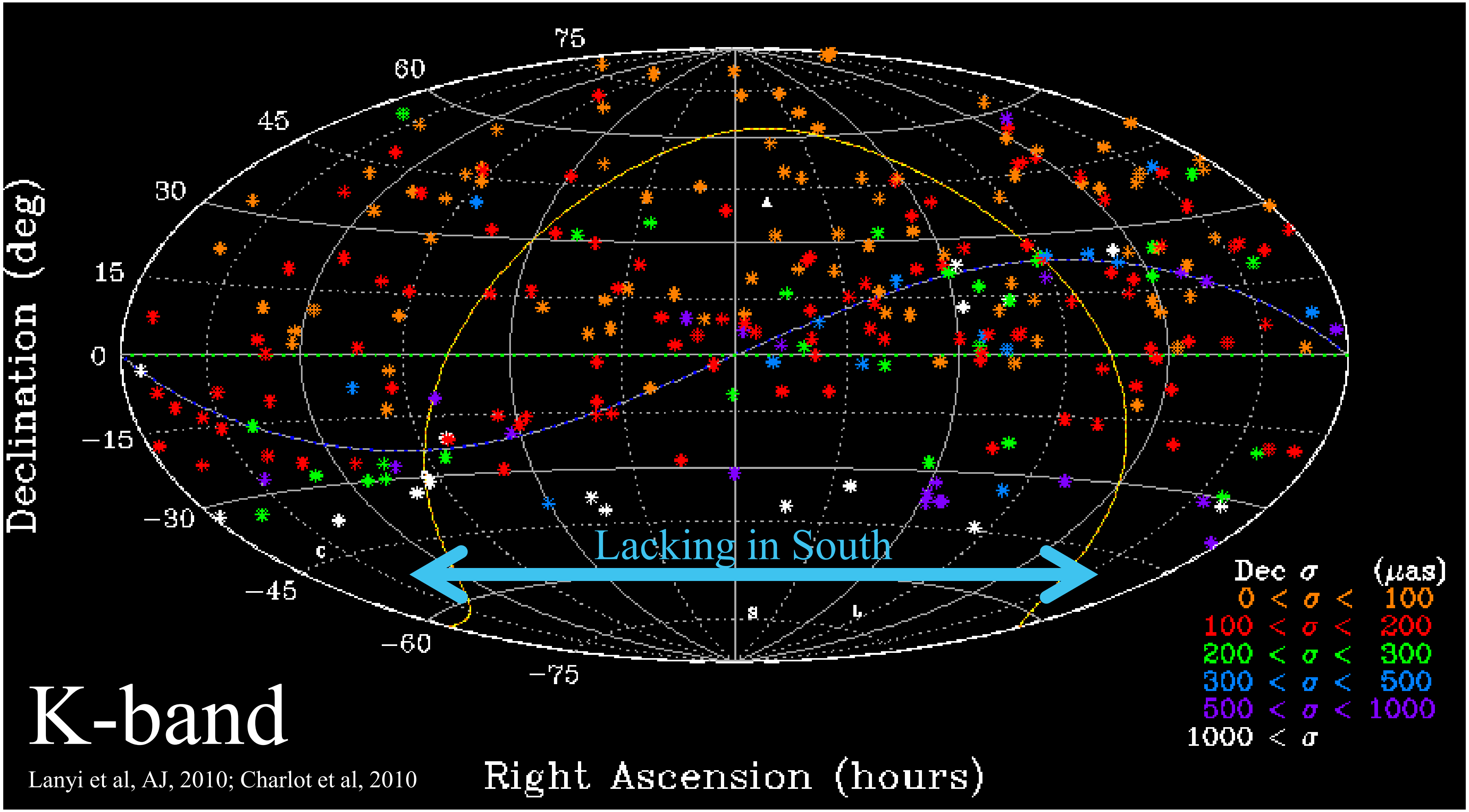
S/X-band (8 GHz) ICRF-2



3414 Sources of which ~2200 are single session survey sources.

VLBI in general and ICRF-2, specifically, **is sparse south of about -40 deg.**

K-band (24 GHz) CRF: 275 sources



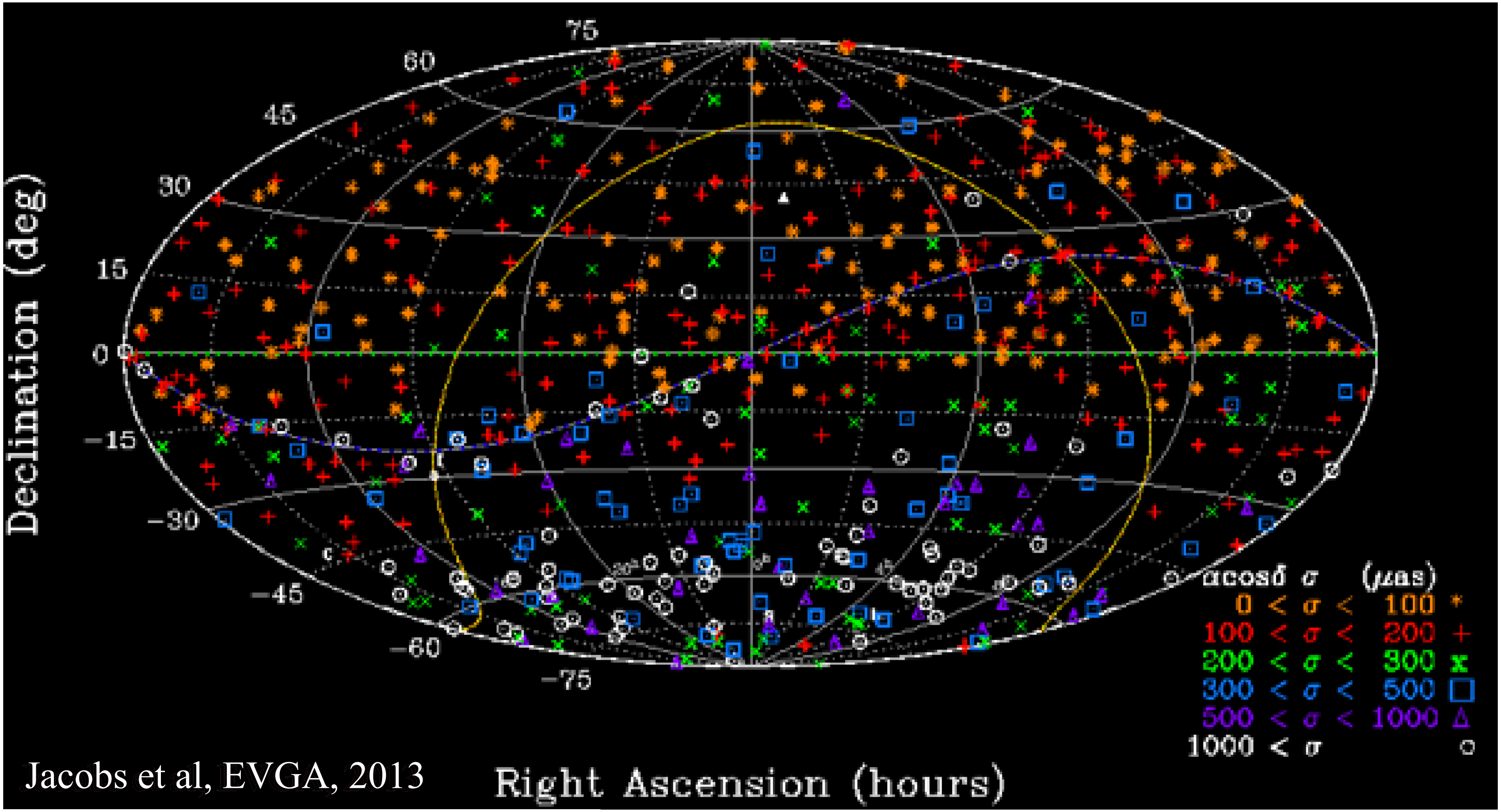
High frequency frames a K (24 GHz), XKa (32 GHz), and Q (43 GHz) lacking in the south

K-band: Goal to add baseline: HartRAO, S. Africa to Australia (Hobart/Tidbinbilla?)

XKa: recently added Malargüe, Argentina to Tidbinbilla, Australia

X/Ka: 610 sources from joint NASA-ESA

Full sky coverage, but weak in the south



Goldstone, CA to Madrid & Australia + **Argentina to Australia**.

South cap 128 (dec<-45); 25 ICRF2 Defining; 2/3 of cap non-ICRF2

- What are the most demanding applications?
  - Spacecraft Navigation: greatest demands on *consistent* set of frames:
    CRF, EOP, TRF, planetary ephemeris consistent at < 100 µas level
  - Relative astrometry: demands stability of small part of CRF
    at 10 µas for Δ VLBI parallax/proper motion, Galactic masers, SgrA*, pulsars
  - Gaia optical: understanding of frequency dependent systematics < 70 µas
  - Geodesy: 1mm goal is equivalent to averaging over several sources to 20 µas

- Who are the users of the ICRF?
  - Astronomers: need highest spatial density, most frequent ones citing ICRF
  - Geodesists: do most of data collection in terms of no. delay measurements
    to produce EOPs (**VLBI uniquely determines UT1-UTC, nutation**) and TRF
  - Navigators: most demanding consistency of frames; ecliptic density
  - Gaia: will use radio ICRF for external technique verification at ~70µas
    and frame alignment

- What are the user requirements for:
  - Precision: 50-100 µas
  - Stability: relative astrometry may need 10 µas stability
  - Accuracy: systematics 10s of µas e.g. ICRF-2 noise floor 40 µas
  - Latency: About once per decade for official ICRF **releases (adopted by IAU resolution)** individual institutes densify several times per year for internal use

- How is the current ICRF-2 made consistent with the ITRF and EOPs and what is the current level of consistency?

  Consistency is enforced by the usual global constraints:
  CRF No-Net-Rotation for 295 defining sources
  TRF No-Net-Translation, No-Net-Rotation, No-Net-velocity & NN-Vel. Rot.
  EOPs estimated

- Needed level of consistency from the ICRF user applications' point of view?

  CRF Axes stable at 10 μas level (0.05 ppb)
  Individual sources known to < 100 μas (< 0.5 ppb)
  Wavelength dependence < 70 μas in time for Gaia comparisons circa 2020

- Does the current practice meet the user need and requirements? Are there weaknesses to mitigate?

In general, position precision requirements are met. The sources are *very* stable.

Weaknesses:

Source morphology (structure) can cause apparent motions at a significant level for a small subset of sources (> 1.0 ppb).

- Parameterize with time varying positions on scales ~month
- Move to higher frequency (> 8 GHz) where sources are more compact.

Non-uniform coverage especially in south and near Galactic plane

Lack of multi-wavelength: Add 24 and 32 GHz (and 43 GHz?) data.

Geometry: poor southern coverage allows zonal errors e.g. ΔDec vs. Dec

- What are the plans for the next ICRF realization?
  - Underway: extend observation programs e.g. South, high freq., VCS
  - By 2015 IAU GA publish roadmap for work.
  - By 2018 deliver ICRF-3 to the IAU.
  - 70-100 μas precision (1-sigma per coordinate)
  - More uniform spatial coverage—improve the southern hemisphere
  - More uniform wavelength coverage–improve 24 and 32 GHz CRFs
  - Improve set of source for radio-optical frame tie with Gaia focusing on increasing number of optically bright sources (V< 18 mag)

- Do we need to include the ICRF in the ITRF combinations that already include EOPs? What is the opinion of the ICRF WG?

  The ICRF-3 working group is just starting to study combinations. It is too early to express an opinion.

- Is there a utility for daily (or weekly) ICRF products, and if yes, how best to achieve that?

  NO. At present VLBI does not have the data collection resources needed to create daily or weekly solutions at the ppb level of interest. Exploratory monthly positions characterize sources with known structure problems. *However,* weekly single dish monitoring for flaring sources might have some value as an indicator of changing source structure and/or core shift and could be used to alter observing schedule to avoid sources in unstable states.

Combination Issues

- EOP and TRF combination Effects on CRF
  Seitz et al show that multi-technique data combinations have very little effect (10 μas = 0.05 ppb) on CRF
  Only for poorly observed ~100 of 3400 sources is effect larger.

- Plan: Re-observe these 100 sources in order to de-sensitize CRF to EOP and TRF.

  However, VLBI contribution to TRF must be made consistent with ICRF.

- CRF solution combinations
  SINEX level combinations of CRF, TRF, EOP

  Also simple pairwise comparisons of CRFs during formulation stages to expose outliers, analyst errors, etc.

Summary of ICRF-3 Goals:

- ICRF-3 completed by August 2018 in time for comparisons with & alignment of Gaia optical frame

- Competitive accuracy with Gaia ~ 70 μas (1-sigma RA, Dec)
- Improve set of optical-radio frame tie sources for Gaia.

- Uniform precision for all sources.
  Implies improving VLBA Cal Survey's 2000+ positions.
- Uniform spatial coverage.
  Implies improving southern observations.

- High frequency frames 24, 32, 43? GHz (K, X/Ka, Q?)
  Improve number, accuracy, and southern coverage
  to enable characterization of frequency dependent effects

Other issues: Status of VLBA

- Inclusion of VLBA observations made the most significant difference between ICRF and ICRF2
  - RDV experiments 24 hrs every 2 months (VLBA+)
  - VCS sources
- VLBA needed to improve ICRF2
- VLBA at risk for closing
  - Judged as providing poor scientific return on dollar
  - Definite risk for ICRF3
  - USNO providing financial support
    - VLBA EOP series
    - Continued CRF observations
    - Backup operations for USNO Correlator
  - IAU Division A, IVS and IERS DBs have written letters of support
  - Additional Partners welcome

Backup slides

Charter for IAU Division A Working Group on the Third Realization of the International Celestial Reference Frame

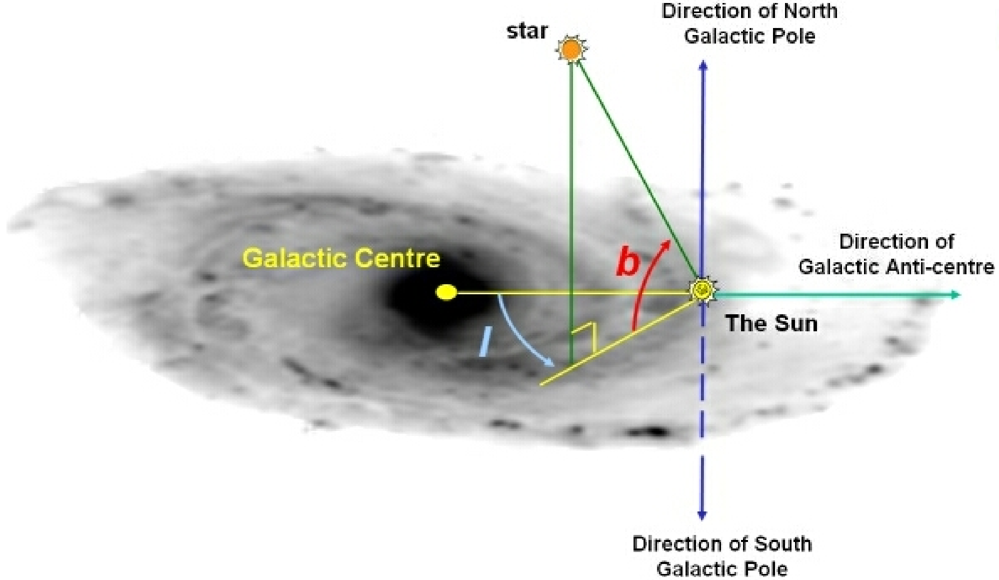
The purpose of the IAU Division A Working Group on the Third Realization of the International Celestial Reference Frame (ICRF) is to produce a detailed implementation and execution plan for formulation of the third realization of the ICRF and to begin the process of executing that plan.

The implementation plan along with execution progress will be reported to IAU Division A at the XXIX General Assembly of the IAU in 2015.

Targeted completion of the third realization of the ICRF will be the XXX General Assembly of the IAU in 2018.

Derived from VLBI observations of extragalactic radio sources, the third realization of the ICRF will apply state-of-the-art astronomical and geophysical models and analysis strategies, and utilize the entire relevant astrometric and geodetic data set. The Working Group will examine and discuss new processes and procedures for formulating the frame along with the potential incorporation of new global VLBI arrays, and new observing frequencies offering the potential for an improvement over ICRF2. The Working Group will provide oversight and guidance for improving the relevant data sets.

Galactic Acceleration



http://astronomy.swin.edu.au/cosmos/N/North+Galactic+Pole

- ICRF-2 is in the Frame of the Solar System Barycenter (SSB)

- SSB has unmodelled accelerations in direction of galactic center (200 Myr period around SgrA*) plus other smaller accelerations

- SSB orbit *velocity* around Galactic center causes a large aberration which is mostly constant on decade scales
  This is currently absorbed as ~constant distortion in reported positions.

- SSB orbit *acceleration* causes changes of 5 μas/yr (times projection factor)

- IAU's ICR**S** working group (not ICR**F**-3 wg) is charged with setting standard
- We anticipate the need for a default model in the Gaia era to account for motion between mean epochs of sources in Gaia & VLBI frames

<u>Gaia-Optical *vs.* VLBI-radio</u>:

Celestial Frame tie
and
Accuracy Verification

Gaia frame tie and accuracy verification

Gaia: 10^9 stars

- 500,000 quasars V< 20
  20,000 quasars V< 18
- radio loud 30-300+ mJy
  and
  optically bright: V<18
  ~2000 quasars
- Accuracy
  70 µas @ V=18
  25 µas @ V=16

Launch in Fall 2013

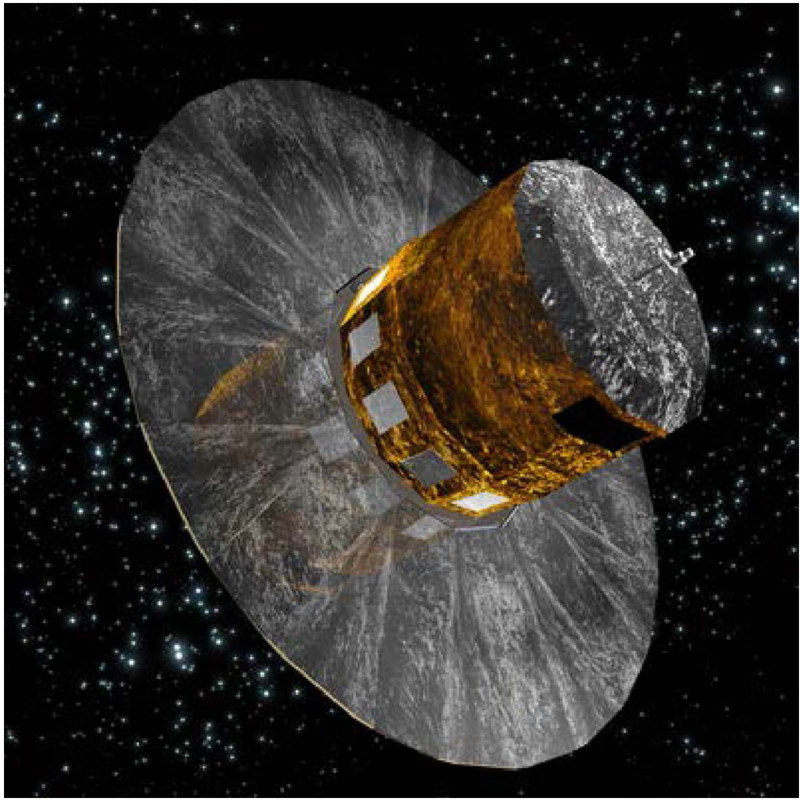


Figure credit: http://www.esa.int/esaSC/120377_index_1_m.html#subhead7

References:

Lindegren et al, IAU 248, 2008
http://adsabs.harvard.edu/abs/2008IAUS..248..217L

Mignard, IAU, JD-7, 2012
http://referencesystems.info/uploads/3/0/3/0/3030024/fmignard_iau_jd7_s3.pdf

Optical vs. Radio positions

Positions differences from:

- Astrophysics of emission centroids

  - radio: synchrotron from jet

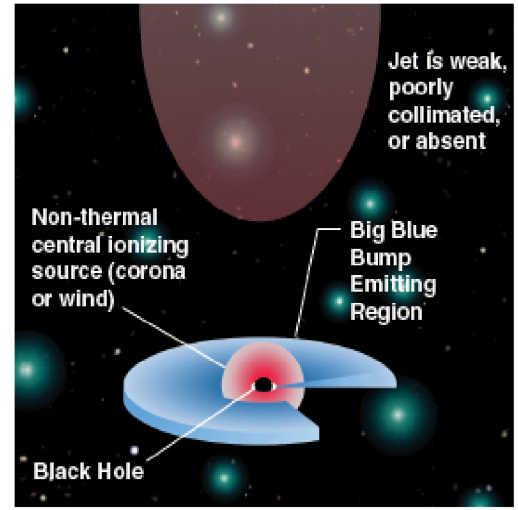
  - optical: synchrotron from jet?
    non-thermal ionization from corona?
    “big blue bump” from accretion disk?

  - optical centroid biased by host galaxy?

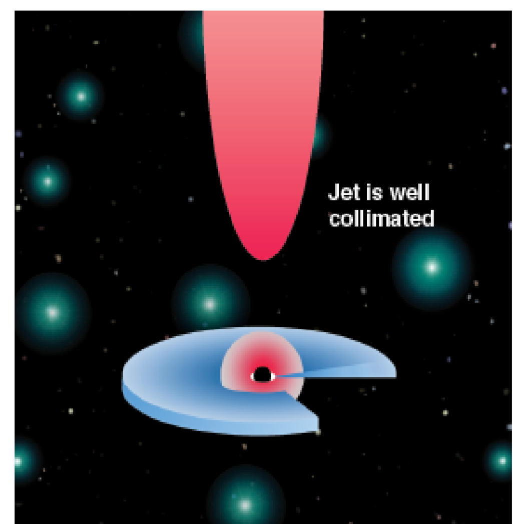
- Instrumental errors both radio & optical

- Analysis errors

Radio-quiet Quasar

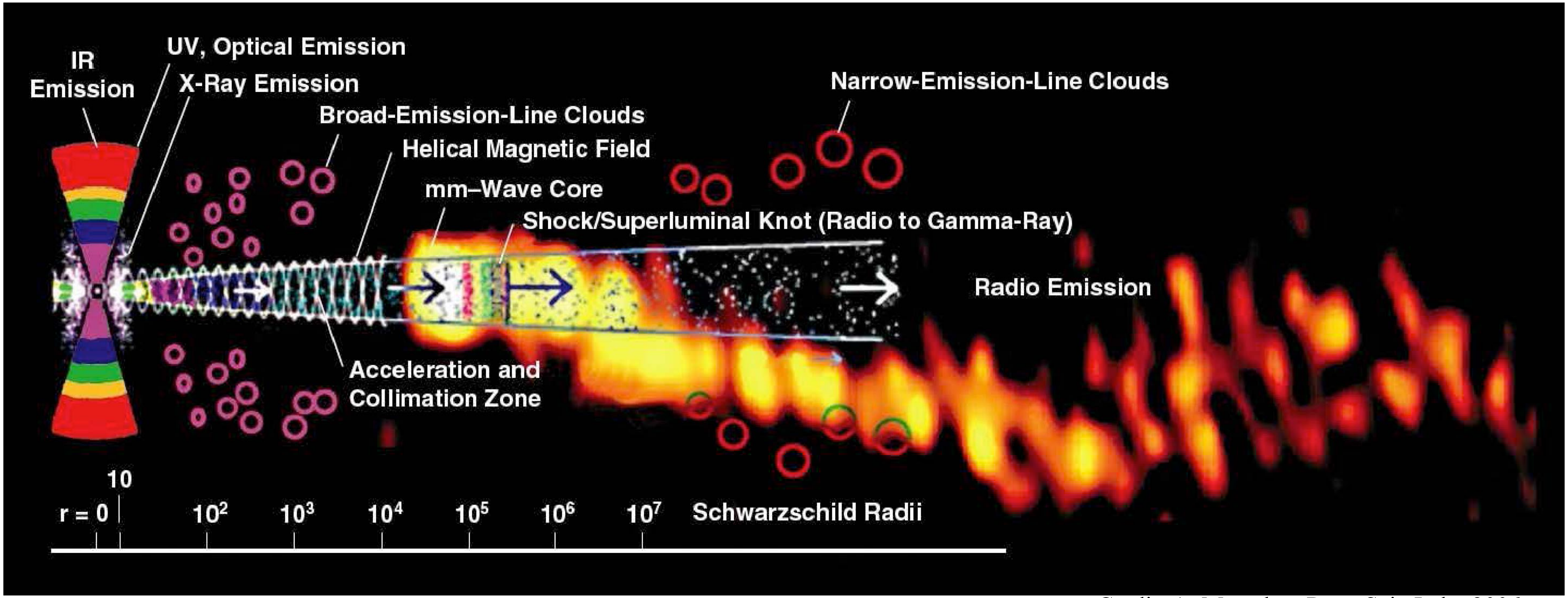


Radio-loud Quasar



Credit: Wehrle et al, μas Science, Socorro, 2009

9mm vs. 3.6cm? Core shift & structure



R~0.1-1 μas 1mas

Credit: A. Marscher, Proc. Sci., Italy, 2006.
Overlay image: Krichbaum, et al, IRAM, 1999.
Montage: Wehrle et al, ASTRO-2010, no. 310.

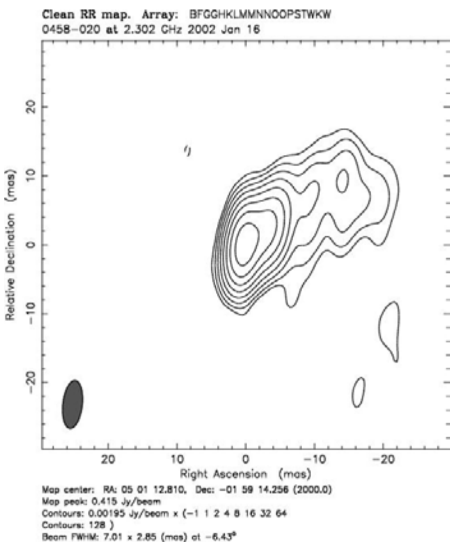
Positions differences from ‘core shift’

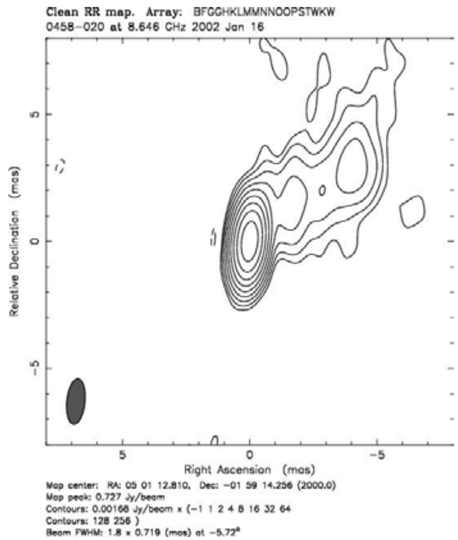
- wavelength dependent shift in radio centroid.
- *3.6cm to 9mm core shift:*

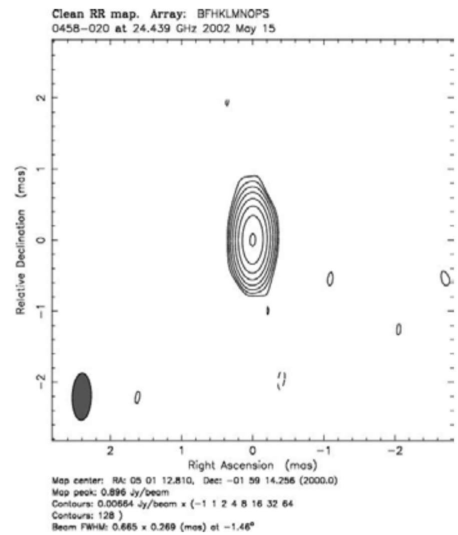
  100 μas in phase delay centroid?

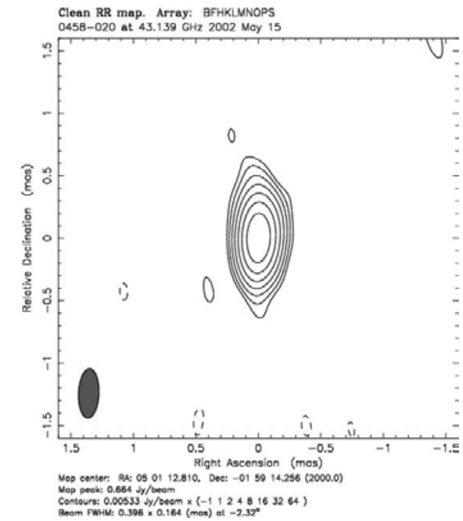
  <<100 μas in group delay centroid? (*Porcas, AA, 505, 1, 2009*)
- shorter wavelength closer to Black hole and Optical: 9mm X/Ka better

Source Structure vs. Wavelength









S-band
2.3 GHz
13.6cm

X-band
8.6 GHz
3.6cm

K-band
24 GHz
1.2cm

Q-band
43 GHz
0.7cm

The sources become better ----->

Ka-band
32 GHz
0.9cm

Image credit: P. Charlot et al, AJ, 139, 5, 2010