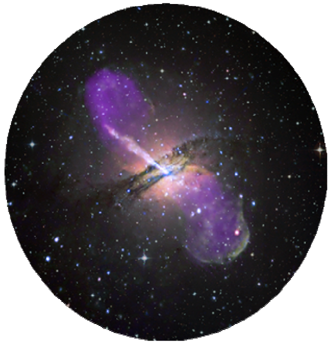
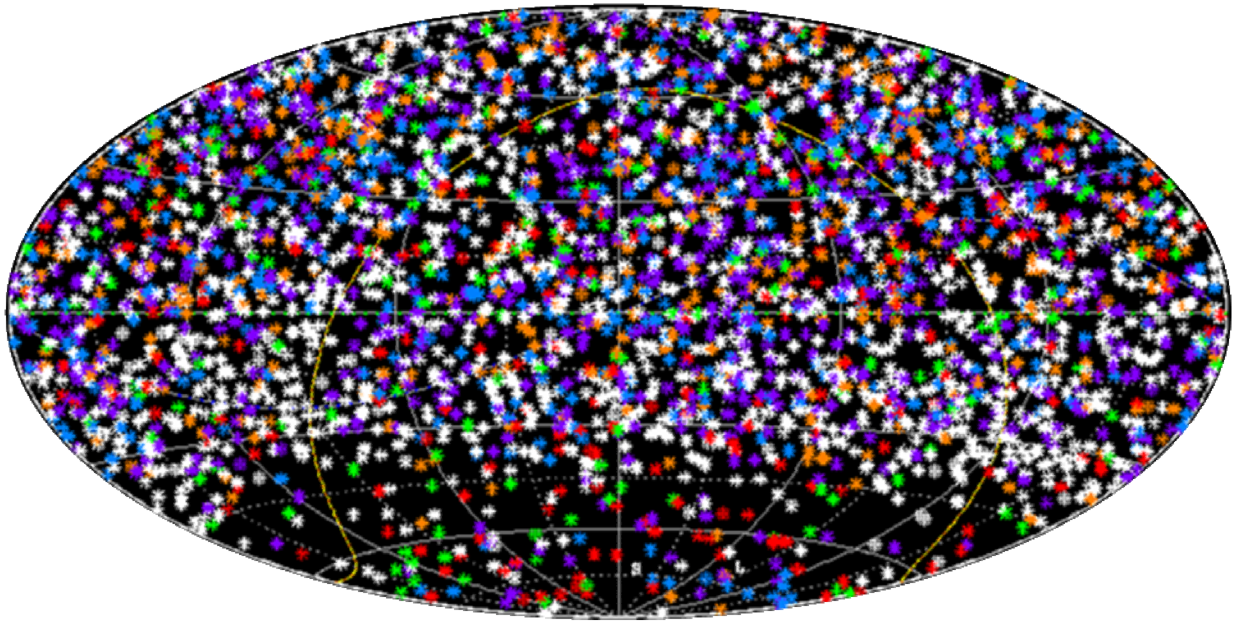
The ICRF-3:
Proposed Roadmap to the next generation International Celestial Reference Frame





Christopher S. Jacobs,
ICRF-3 Working Group chair
Jet Propulsion Laboratory, California Institute of Technology

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

16 September 2013

Overview of ICRF-3 Roadmap

- Formation of ICRF-3 working group
- ICRF-2 history and benefits vs. ICRF-1
- Assessment of needed improvement in ICRF-3
- Plans for improving the ICRF
  more uniform precision: VCS-II
  more uniform spatial coverage: southern CRF
  improved frequency coverage: K, X/Ka
- Gaia: radio-optical frame tie
  Wavelength dependent systematic errors in CRFs

Formation of IAU Working Group

- International Astronomical Union (IAU) is international governing body for the Celestial Reference Frame
  - ICRF1 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)

IAU 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 (chair)
- 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/

1st ICRF-3 working group meetin

- Together with IAG Sub-Commission 1.4 (chair: Johannes Boehn
- At Aalto University, Espoo, Finland (Mar 2013)

Aalto University

IERS Directing Board meeting

- IERS Directing Board meeting concerning Reference Frames (May 2C

2nd ICRF-3 working group meeting

l'Observatoire de Paris

- At Observatoire de Paris, France (mid Sep 2013)

Overview of 2nd International Celestial Reference Frame

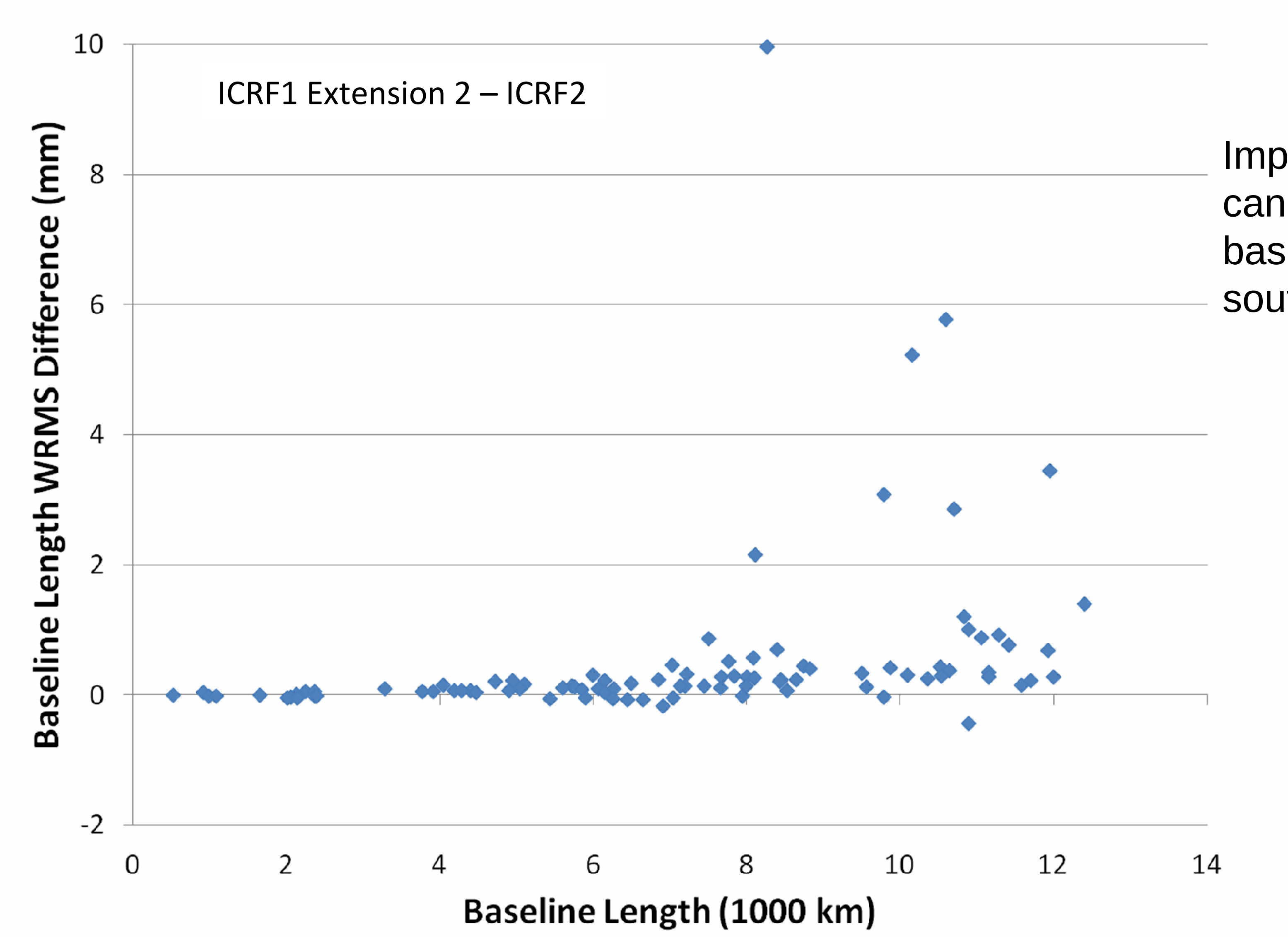
Brief description of how the current ICRF-2 was realized:

- 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 VTRF2008 (VLBI part of ITRF-08: *Böckmann et al, JGeod, 84, 2010*)
  as ITRF2008 was not yet released.
  4 constraints: Positions: No-Net-Translation, No-Net-Rotation
  Velocities: No-Net-Translation, No-Net-Rotation
- Produced from a single monolithic fit.
  Verified with solutions from various groups using independent software packages.

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

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

Geodetic impact by the switch from ICRF1-ext.2 to



Improvements can be found for baselines including southern stations!

Courtesy D. MacMillan, GSFC

Geodetic impact by the switch from ICRF1-ext.2 to ICRF2

Table: EOP differences w.r.t. IGS

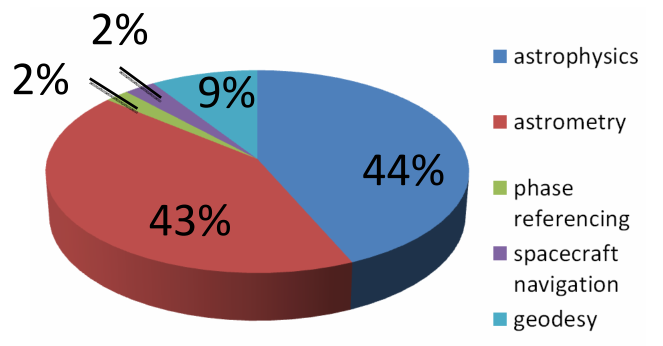
EOP	ICRF1 Ext.2 fixed		ICRF2 fixed	
	WRMS	Chi2/dof	WRMS	Chi2/dof
x-pole	123.4	3.3	113.5	2.8
y-pole	113.3	3.1	109.6	2.9
X-pole rate	318.9	2.1	305.0	1.9
Y-pole rate	315.1	2.1	302.7	1.9
LOD	19.6	3.7	18.9	3.4

Courtesy of D. MacMillan, GSFC

All EOPs improved with ICRF2!

ICRF-3 assessment of Needs

Assessment of users for ICRF-3

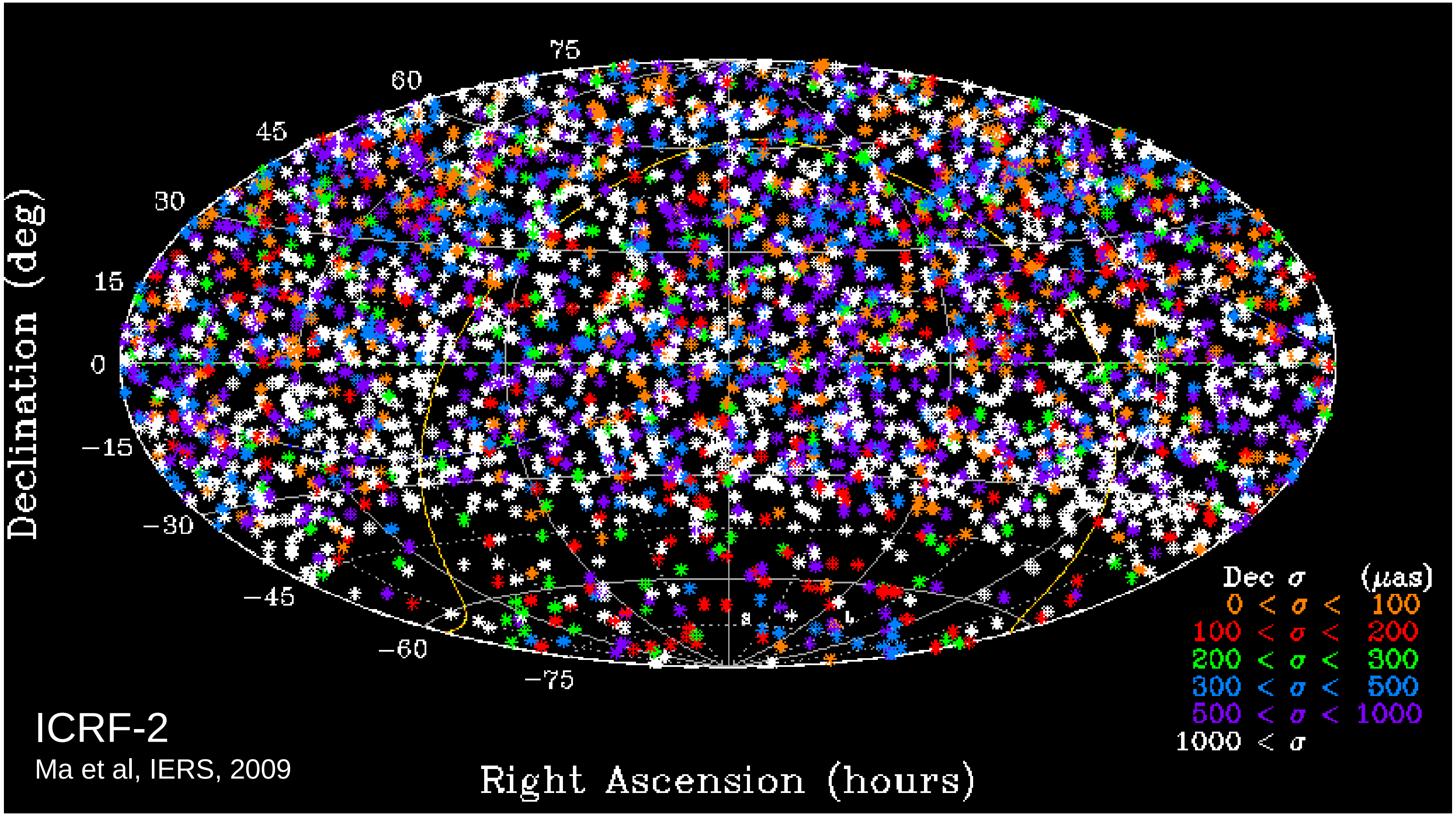


ICRF-1 users: Distribution of ~400 citations

Assessment of user relevant deficiencies

1. VLBA Calibrator Survey (VCS) is most (2/3) of ICRF-2
   but positions are 5 times worse than the rest of ICRF-2
2. ICRF-2 is weak in the south especially below -40 deg Declination.
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.

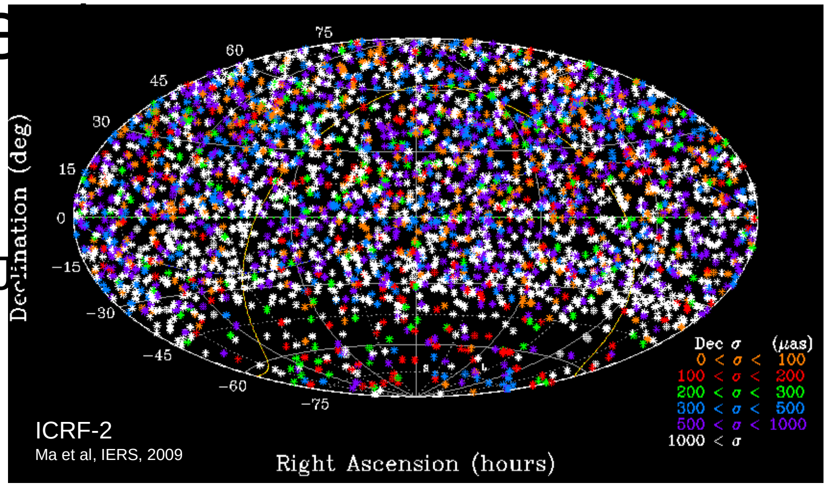
S/X-band (2/8 GHz) ICRF-2



- 3414 Sources in ICRF2. Huge improvement over ICRF1's 608 sources
- ~2200 are single session survey sources (VLBA Calibrator Survey).

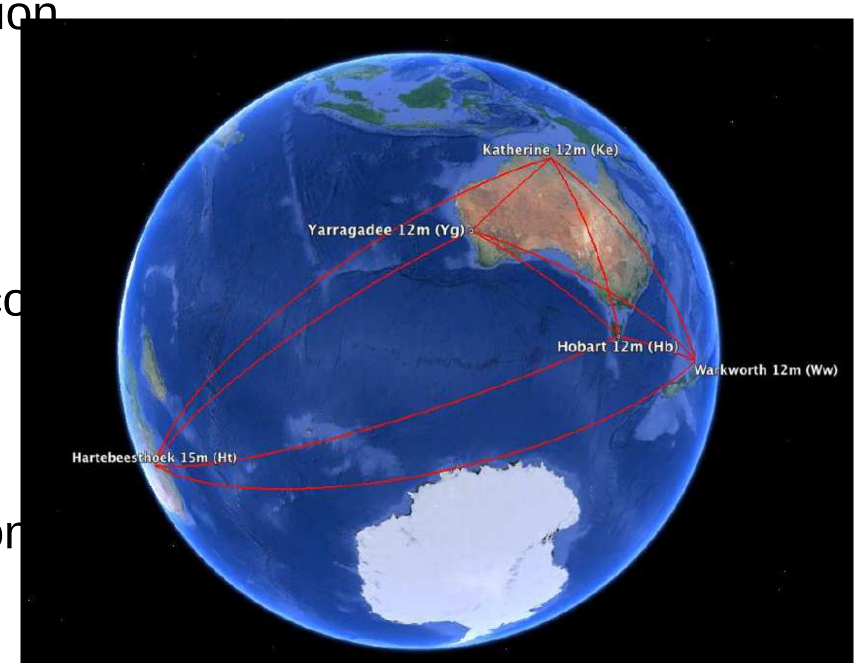
S/X-band Plan for Southern Improveme

- Plans from Titov et al, IAG, 2013



- 2013-15: Observe 100-200 **strong** (> 400 mJ sources using the small, fast stations of the southern CRF Network at S/X-bands.

- Goal > 100 scans per source, 50 μas precision



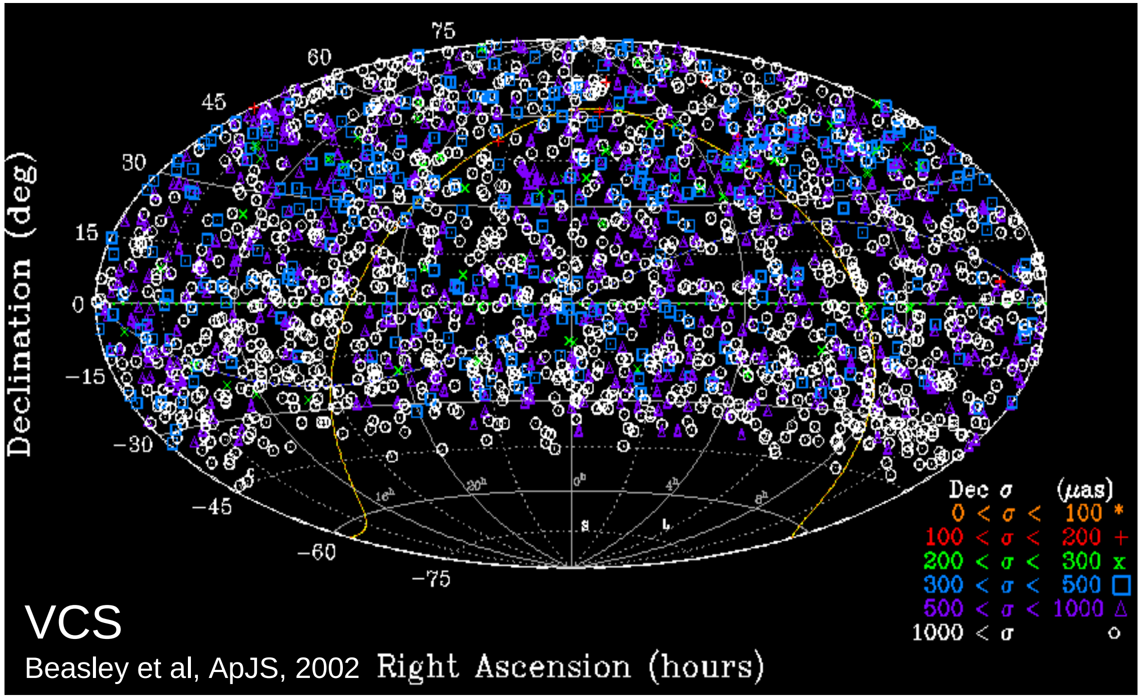
- **Weaker sources** observed with large telesco Parkes, DSS45, Hobart26, HartRAO 100-200 sources over 2 years,

- Goal 20 scans/source, 100-150 μas precision

Southern Hemisphere CRF stations
Credit: Titov el al, IAG, 2013

S/X Survey sources (VCS)

- VCS precision is typically 1,000 μas or 5 times worse than the rest of ICRF-2



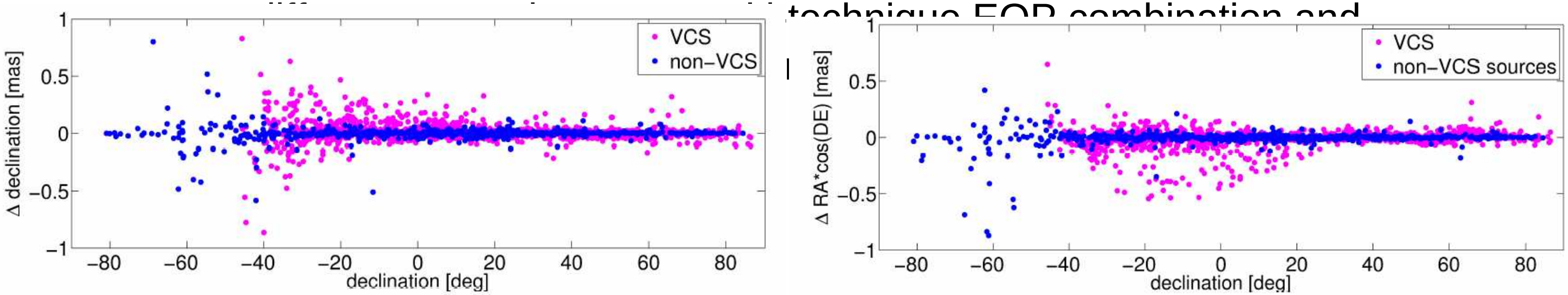
ICRF-2	Item	VCS	non-VCS	factor
	N_src	2197	1217	VCS 1.8X better
	median sessions	1	13	VCS 13X worse
	median observations	45	249	VCS 5.5X worse
	median time span	0	13 yrs	VCS arbitrarily worse
	median RA sigma	621	130 μas	VCS 4.8X worse
	median Dec sigma	1136	194 μas	VCS 5.9X worse

- Deficiency: Uneven precision of ICRF-2 VCS's 2200 sources (2/3 of the ICRF-2)

  Plan: Re-observe VCS sources with VLBA
- VLBA approved 8 x 24-hour sessions to re-observe VCS sources.
- PI: David Gordon. First pass scheduled and waiting in the VLBA queue

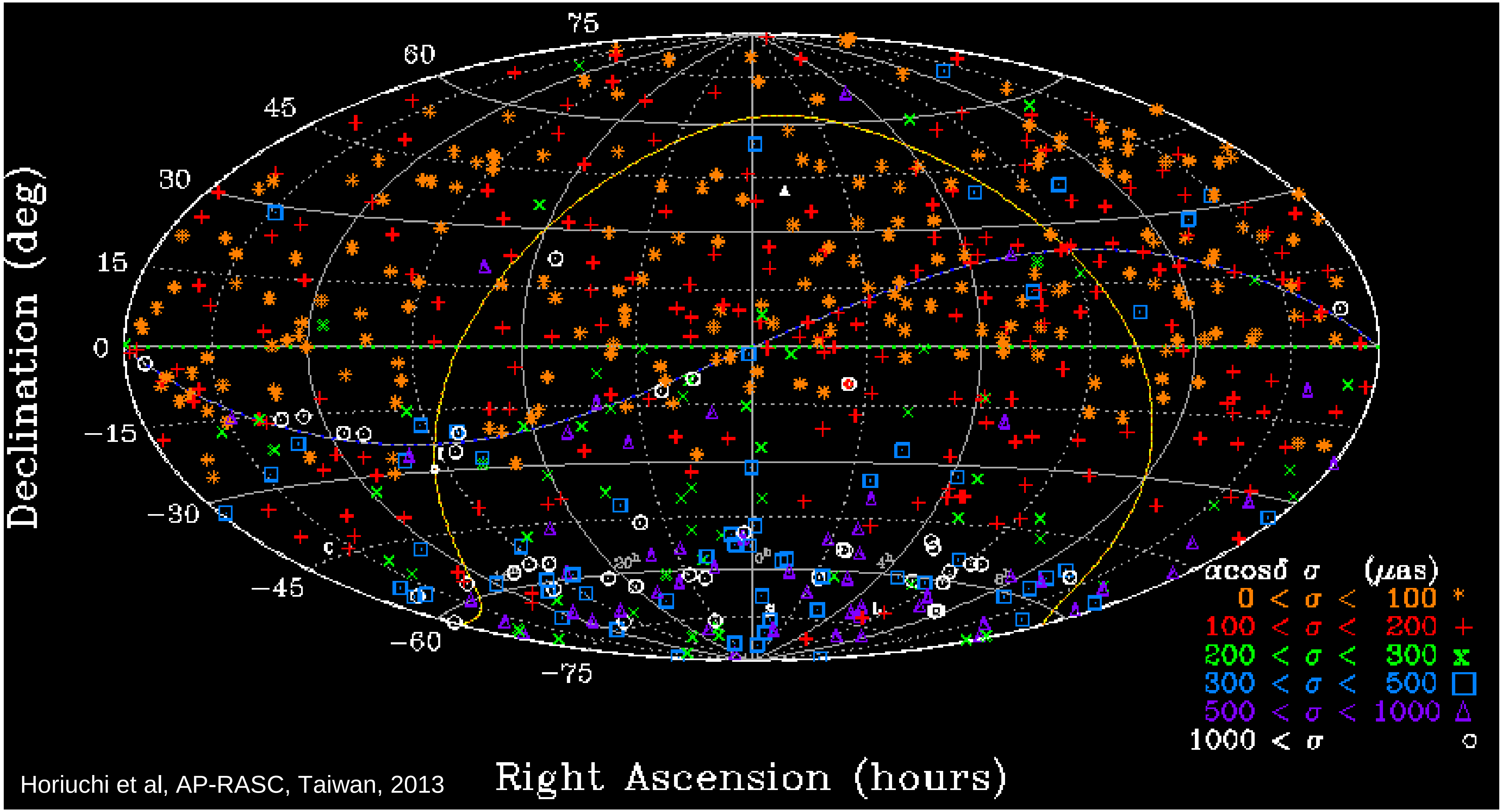
Consistency between ICRF, EOP, and ITRF

- IUGG Res. 3 (2011): *„… highest consistency between the ICRF, the International Terrestrial Reference Frame (ITRF), and the Earth Orientation Parameters (EOP) as observed and realized by the IAG and its components such as the IERS should be a primary goal in all future realizations of the ICRS."*
- ICRF-2: consistency by NNR/NNT constraints
  - CRF: NNR for defining sources, TRF: NNR/NNT for datum sites, EOP: estimated
  - After the catalogue was determined it was rigidly rotated (small angles) onto ICRS
- ICRF3 WG started to investigate combinations of multiple VLBI solutions (cf. *Bachmann, Iddink*)
- The IAU WG ICRF-3 is starting to study EOP & TRF multi-technique combinations



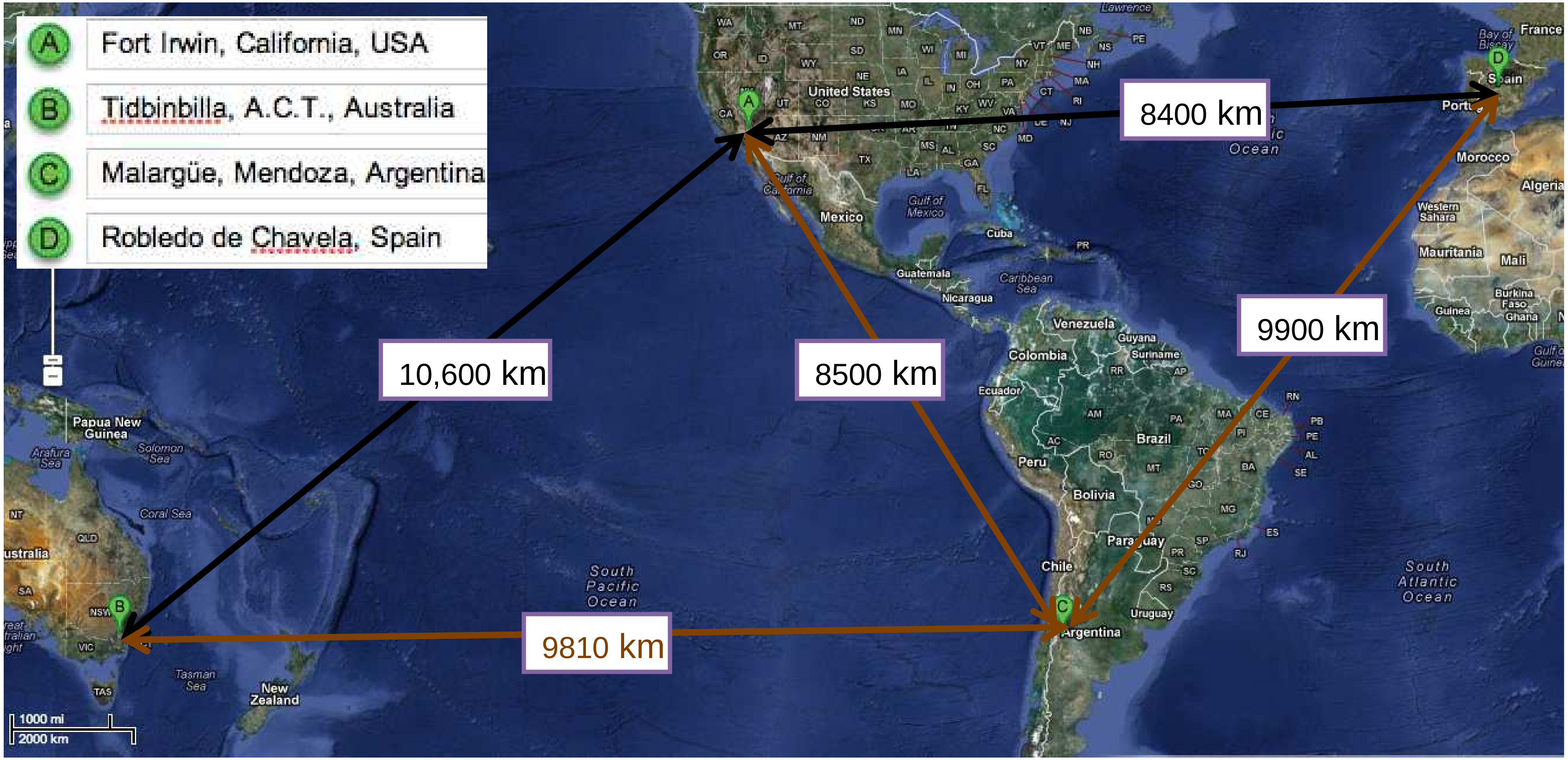
- Plan: VCS-II collaboration of Gordon et al will re-observe VCS sources to de-sensitize their positions to EOP errors

X/Ka-band (8/32 GHz) CRF



- Deficiency: Weak in the south. S. cap 134 sources (dec< -45); 27 ICRF2 Defi
- Full sky coverage (627 sources): NASA baselines CA to Madrid & Australia
  + recently added ESA Malargüe, Argentina to Tidbinbilla, Australia, PI: Jacob

Plan to improve X/Ka: baselines to Argentina

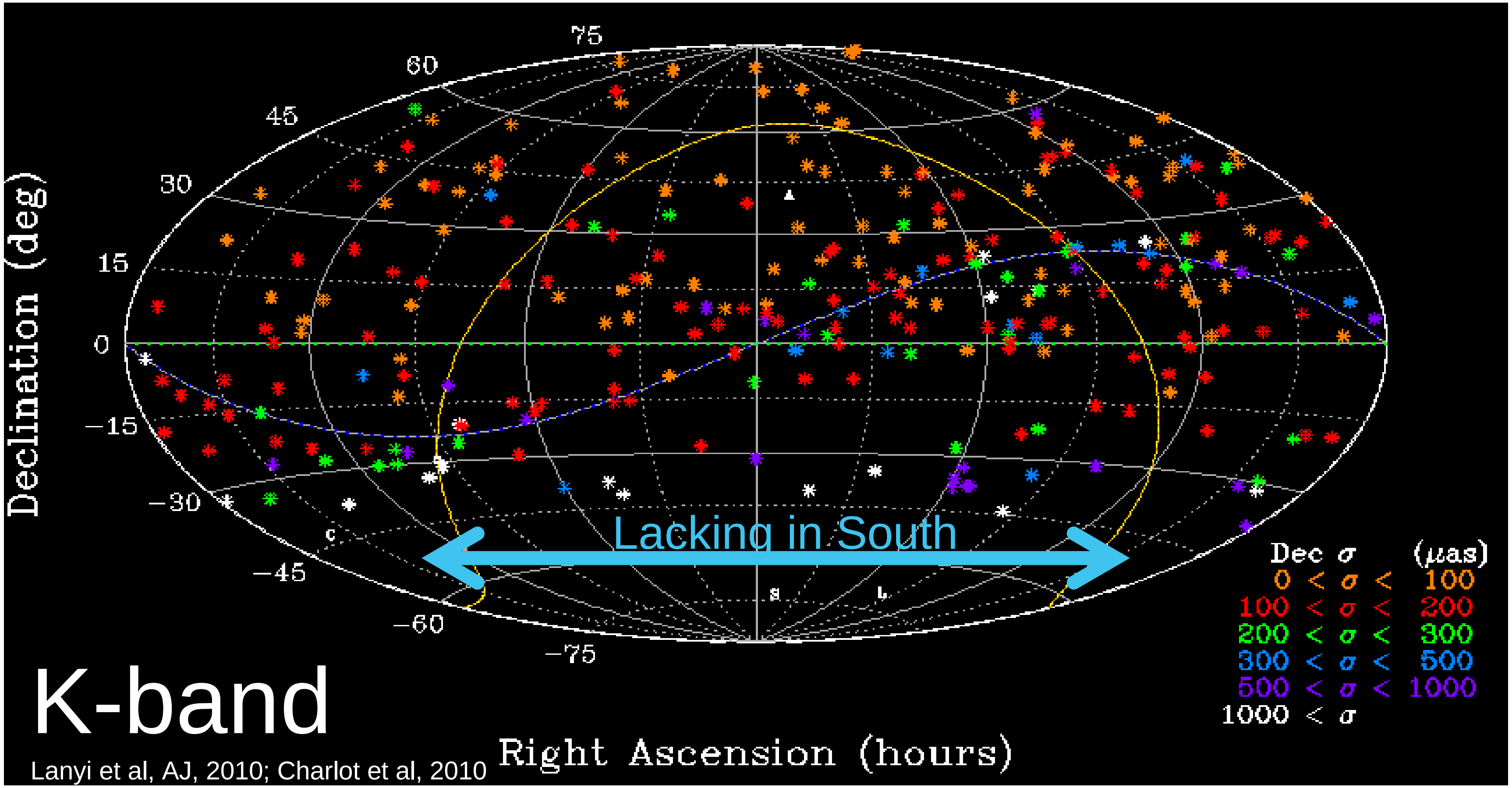


Maps credit: Google maps

ESA's Argentina 35-meter antenna **adds 3 baselines** to DSN's 2 ba

- Full sky coverage by accessing south polar cap
- near perpendicular mid-latitude baselines: CA to Aust./Argentin

K-band (24 GHz) CRF: 275 sources



- Deficiency: lacking in the south

Plan: New K-band full sky coverage collaboration: *Bertarini et al., de Witt et al*

- First 5h K-band session carried out (23 Aug 2013)
- First results will be shown at Journees in Paris, France (Sep 2013)

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

Celestial Frame tie
and
Accuracy Verification

Gaia/VLBI frame tie & Accuracy test

<u>Gaia: 10^9 stars</u>

- 500,000 quasars V< 20 mag
  20,000 quasars V< 18 mag
- radio loud 30-300+ mJy
  and optically bright: V<18 mag
  ~2000 quasars (*Mignard, this meeti*

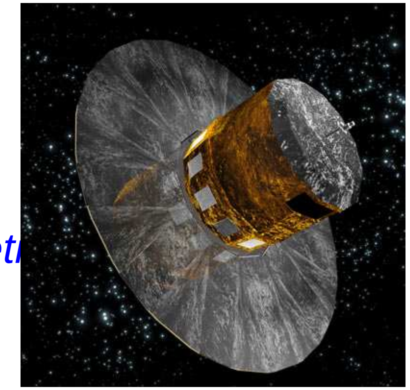


Figure credit: http://www.esa.int/esaSC/120377_index_1_m.html#subhead7

- Quasar Precision
  70 µas @ V=18
  25 µas @ V=16

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

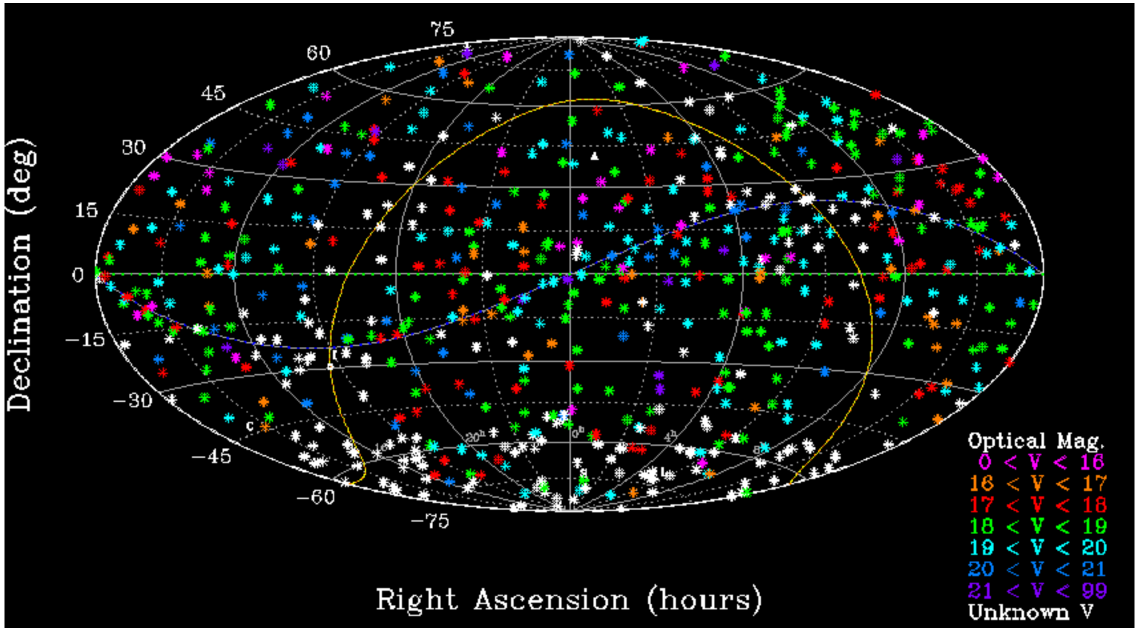
Mignard, IAU, JD-7, 2012
http://referencesystems.info/uploads/3/0/3/0/3030024/fmignard_iau_jd7_s3.

- S/X frame tie Strategy:
  Bring new optically bright quasars into the radio frame (*Bourda, EVN, Bordeaux, 2012*)

- X/Ka frame tie:
  Measured X/Ka precision and simulated Gaia optical precision yields frame tie alignment of
  ~ 10 µas per 3-D rotation angle
  Limited by X/Ka precision, but improving as more data arrives.

- Titov *et al* are measuring optical properties for yet-to-be identified sources ('white' in figure to right)

http://arxiv.org/abs/1305.3017 http://arxiv.org/abs/1109.1034



XKa: 136 optically bright counterparts: V< 18mag

(optical V magnitudes: Veron-Cetty & Veron, 2010)

Optical vs. Radio positions

Positions differences from:

- Astrophysics of emission centroids

  - radio: synchrotron from jet

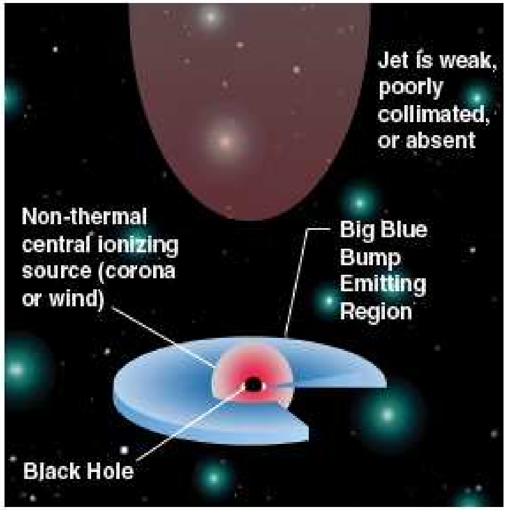
  - optical: synchrotron from jet?
    non-thermal ionization from corona?
    “big blue bump” from accretion disk?

  - optical centroid biased by host galaxy?

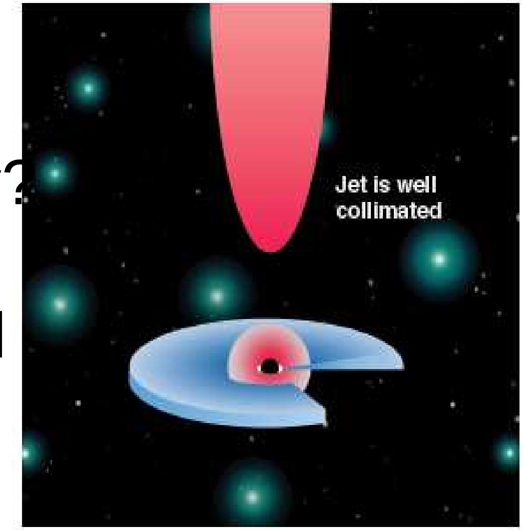
- Instrumental errors both radio & optical

- Analysis errors

Radio-quiet Quasar

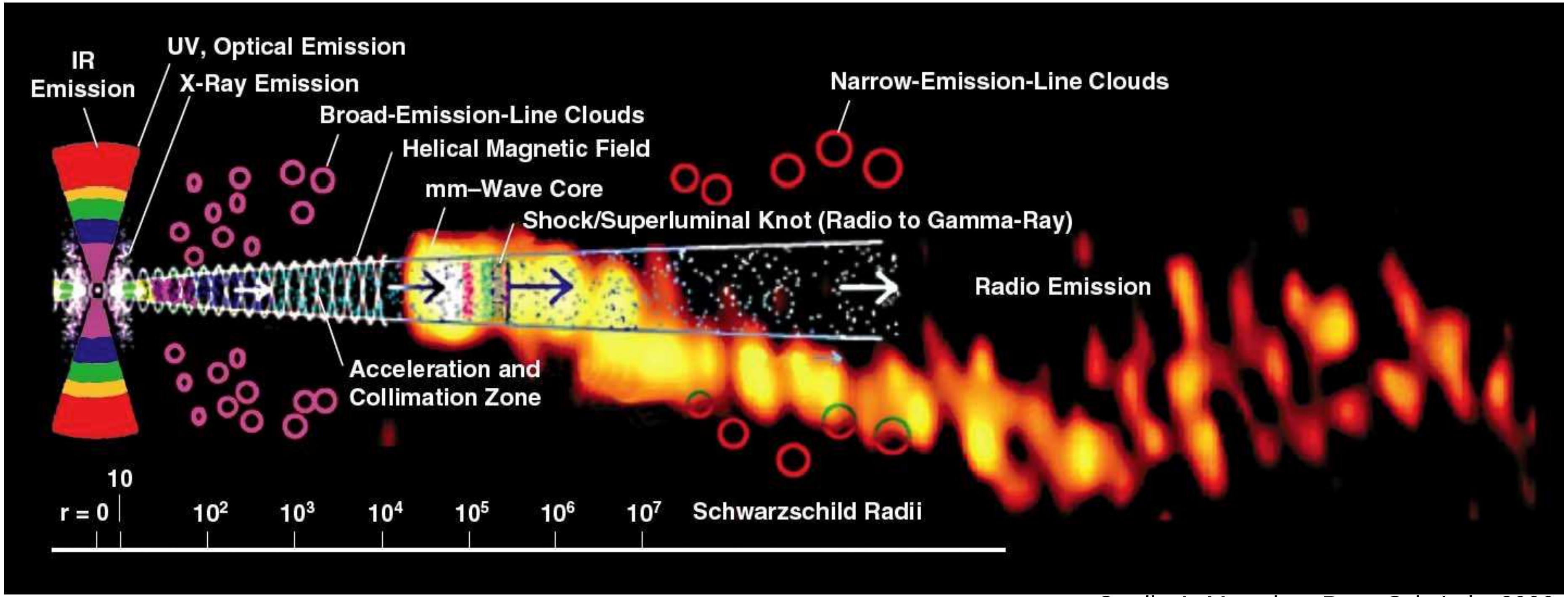


Radio-loud Quasar



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'

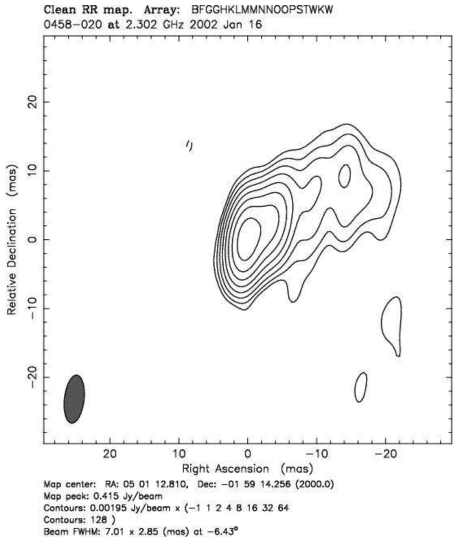
- wavelength dependent shift in radio centroid.
- *3.6cm to 9mm core shift:*

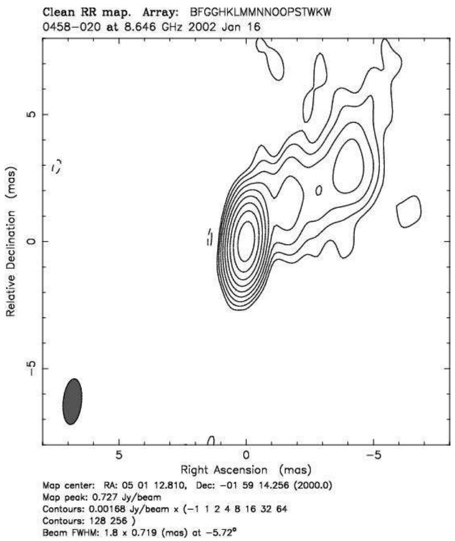
100 μas in phase delay centroid?

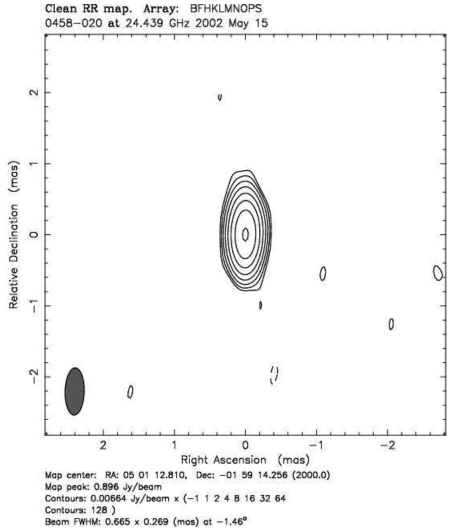
<<100 μas in group delay centroid? (*Porcas, AA, 505, 1, 2009*)

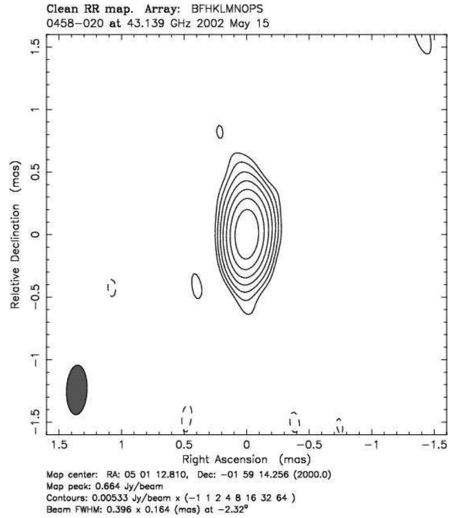
- Shorter wavelength closer to Black hole and Optical: 9mm X/Ka

Source Structure vs. Wavelength









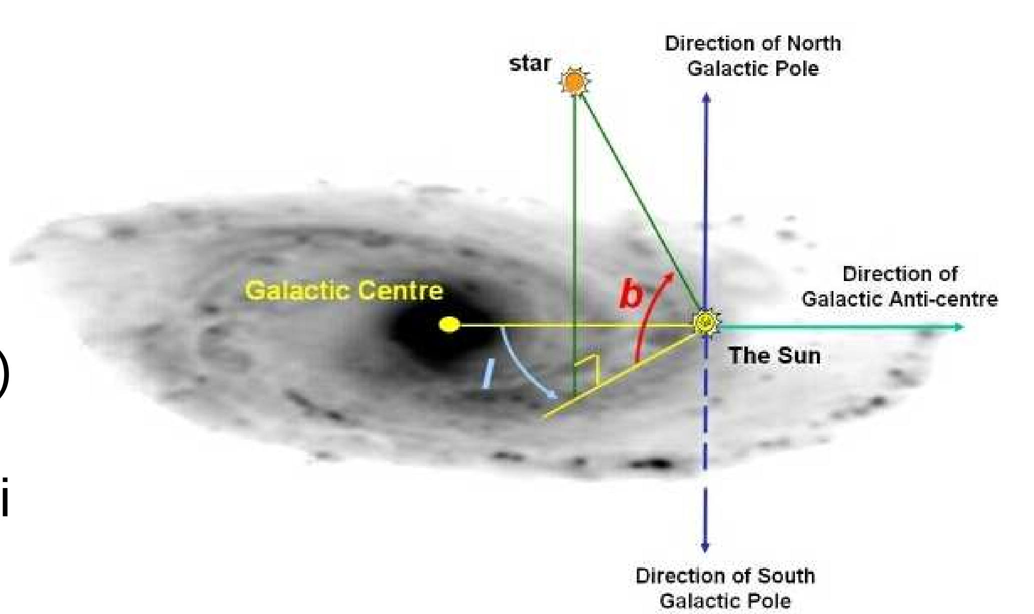
S-band	X-band	K-band	Q-bar
2.3 GHz	8.6 GHz	24 GHz	43 GH
13.6cm	3.6cm	1.2cm	0.7cm

Ka-band
32 GHz
0.9cm

The sources become better ----->

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

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 accelerati 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

Summary of ICRF-3 goals:

•Improving **VLBA Cal Survey's** 2000+ positions

→ More uniform precision for all sources

•Improving **southern observations**

→ More uniform spatial coverage

•Improving number, accuracy, and southern coverage of **high frequency frames** 24, 32, 43? GHz (K, X/Ka, Q?)

→ Improved frequency coverage

•ICRF-3 completed by **Aug 2018 in time for** comparisons & alignment with **Gaia** optical frame

•Competitive accuracy with Gaia ~ 70 µas (1-sigma RA, Dec)

•Improving set of **optical-radio frame tie** sources for Gaia

Thank you for attention!

Backup slides

Status of VLBA

- Inclusion of VLBA observations made the most significant difference between ICRF and ICRF2
  - RDV experiments 24 hrs every 2 months (VLB/
  - VLBA Calibrator Survey (VCS) sources
- VLBA needed to improve ICRF2
- VLBA at risk for closing
  - Judged as providing poor scientific return on dc
  - 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

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.