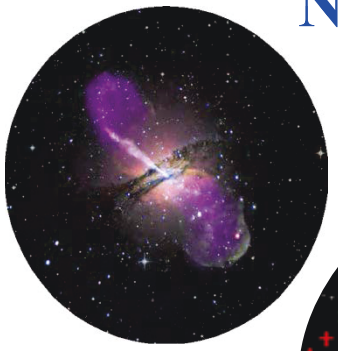
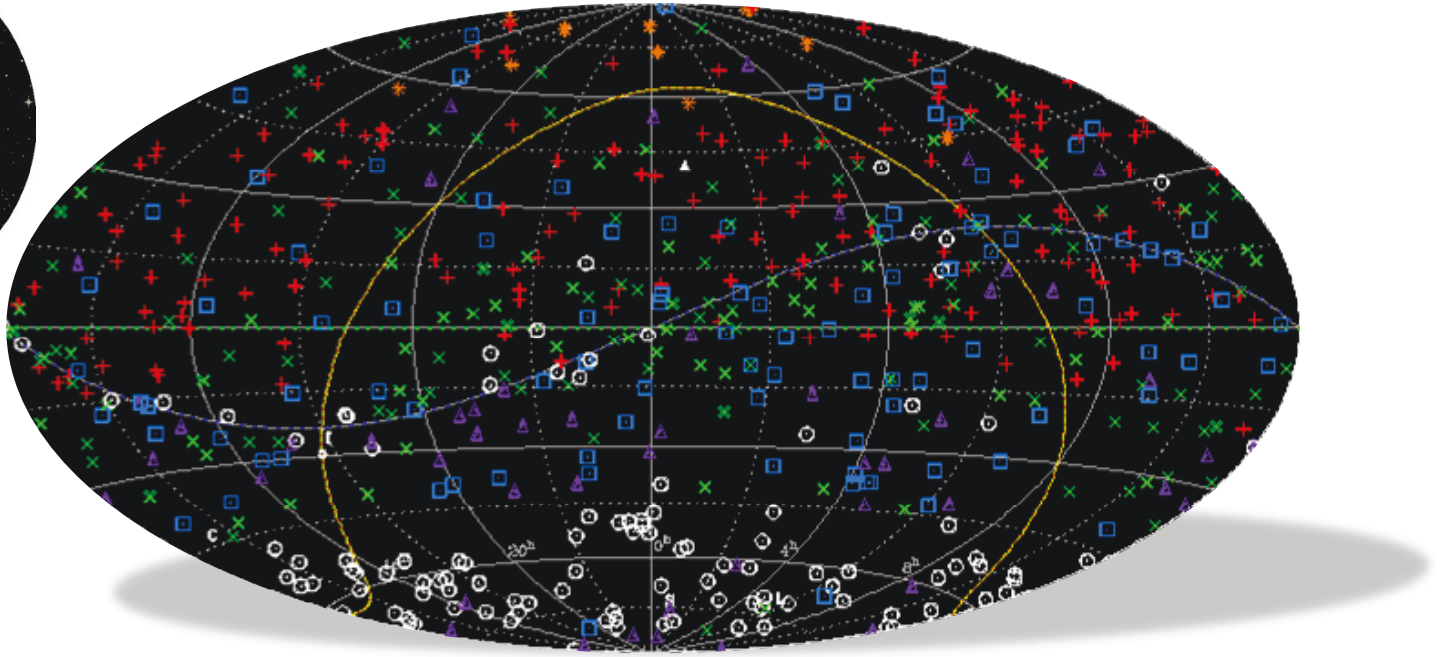
Extending the X/Ka Celestial Reference Frame to the South Polar Cap: Results from combined NASA-ESA baselines to Malargüe, Argentina





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J.E. Clark, J. de Vicente, M. Dugast, C. García-Miró, C.E. Goodhart, S. Horiuchi, S.T. Lowe, R. Madde, M. Mercolino, C.J. Naudet, L. Snedeker, I. Sotuela, L.A. White

7 March 2013

Overview

- How do astrometric sources change with wavelength? Why Ka-band?

- X/Ka in the context of other Celestial Frames: S/X, K, Q

- Prospects for Improvements:

  SNR, Instrumentation, Troposphere

- Southern Geometry:
  - Our plan to reduce the largest error is a NASA collaboration with ESA's X/Ka 35-m in Malargüe, Argentina
  - First fringes Malargüe to Australia, California, Spain
  - South Polar Cap first results: 95 sources detected! 2/3 non-ICRF2

- Optical frames: tying to ESA's Gaia mission at 10 μas level

VLBI wavelength dependence?

- **Sensitivity worsens** at shorter wavelength/high frequency

  Higher system temperature: atmosphere H_20 (22 GHz), O_2 (60 GHz)

  Antenna pointing more difficult

  Antenna surface shape control more difficult

  Atmospheric absorption

  Resolved sources

- **Quasar astrophysics gets better for astrometry**

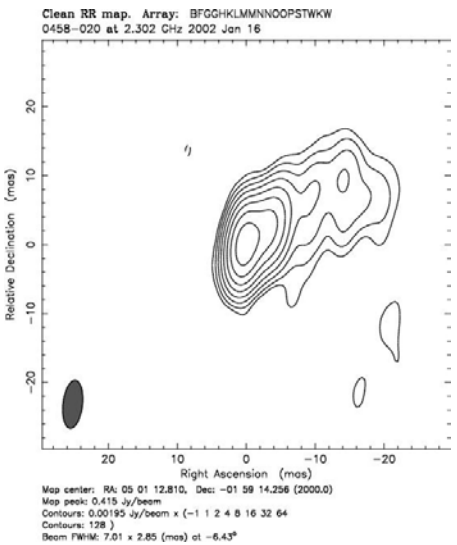
  Sources more compact at shorter wavelength (higher frequency)

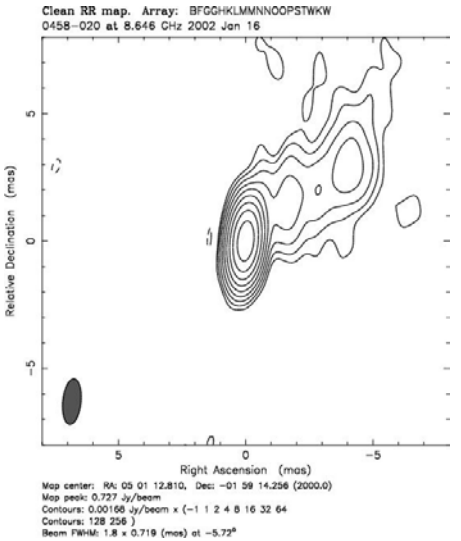
  More sources resolved at higher frequency-> less sources

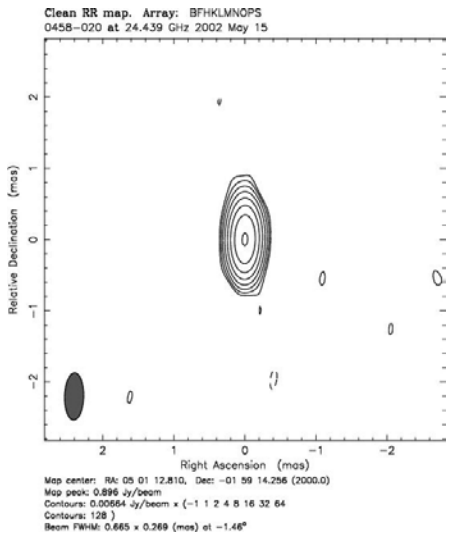
  Less extended structure: plume is steep spectrum

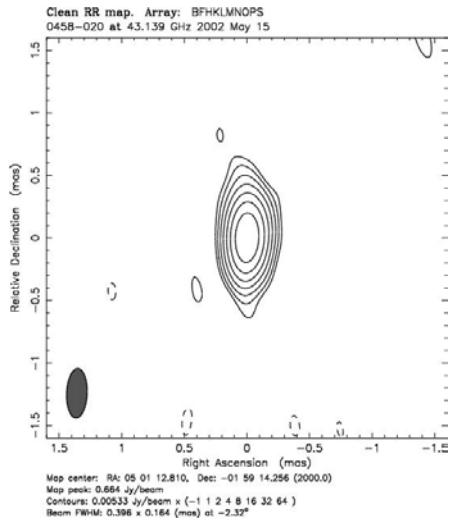
  Core shift reduced at short wavelength/high frequency

Source Structure vs. Wavelength









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

The sources become better ----->

Ka-band
32 GHz
0.9cm

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

Celestial Reference Frames

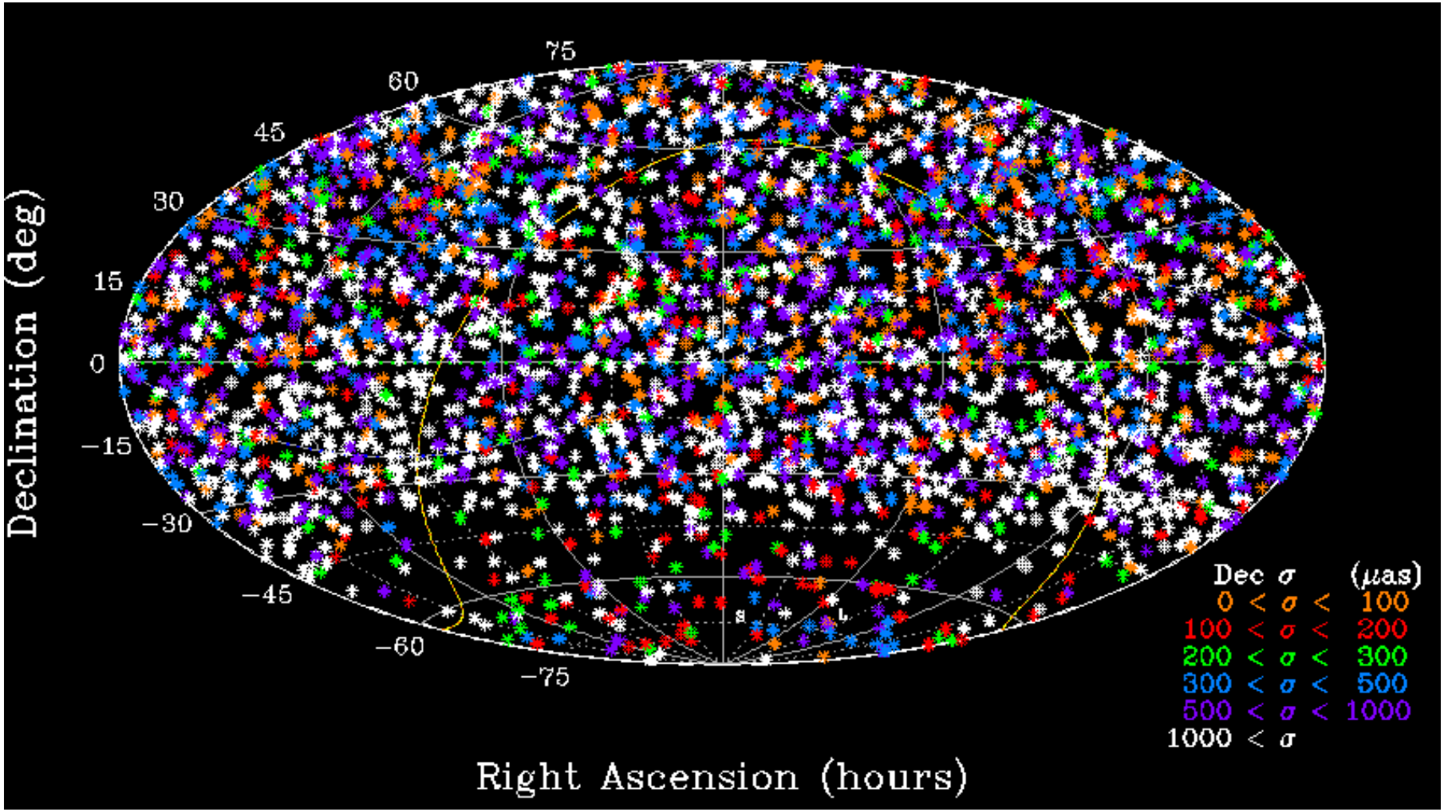
CRF Context for X/Ka

S/X ICRF2: 3.6cm, 8 GHz (Ma et al, IERS, 2009)

K-band: 1.2cm, 24 GHz (Lanyi et al, AJ, 2010)
(Charlot et al, AJ, 2010)

X/Ka-band: 9mm, 32 GHz (Jacobs et al, ISSFD, 2012)

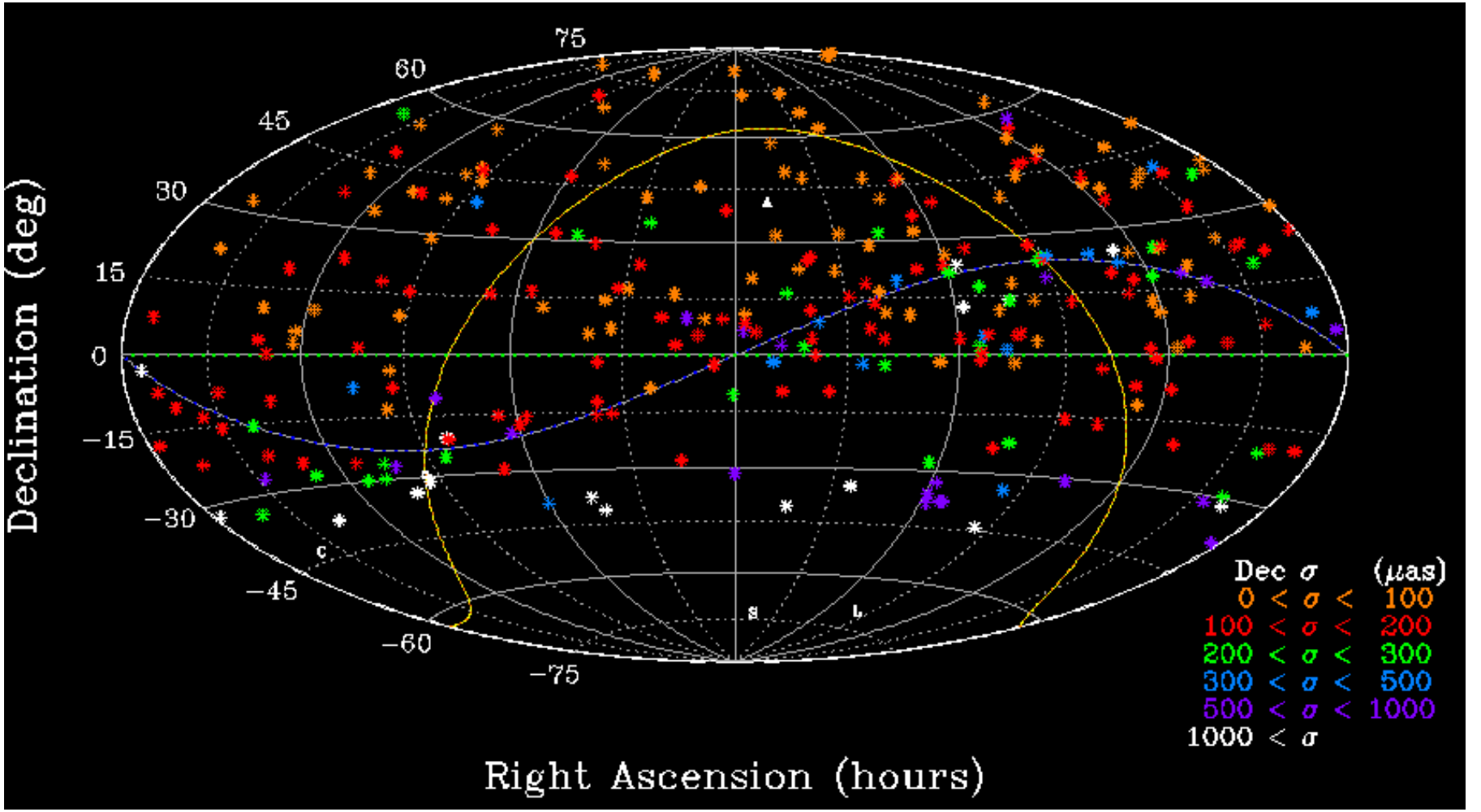
ICRF2 S/X: 8.4 GHz, 3.6cm: 3414 sources



40 μas floor. ~1200 obj. well observed, ~2000 survey session only

Credit: Ma et al, eds.: Fey, Gordon, Jacobs, IERS Tech. Note 35, Germany, 2009

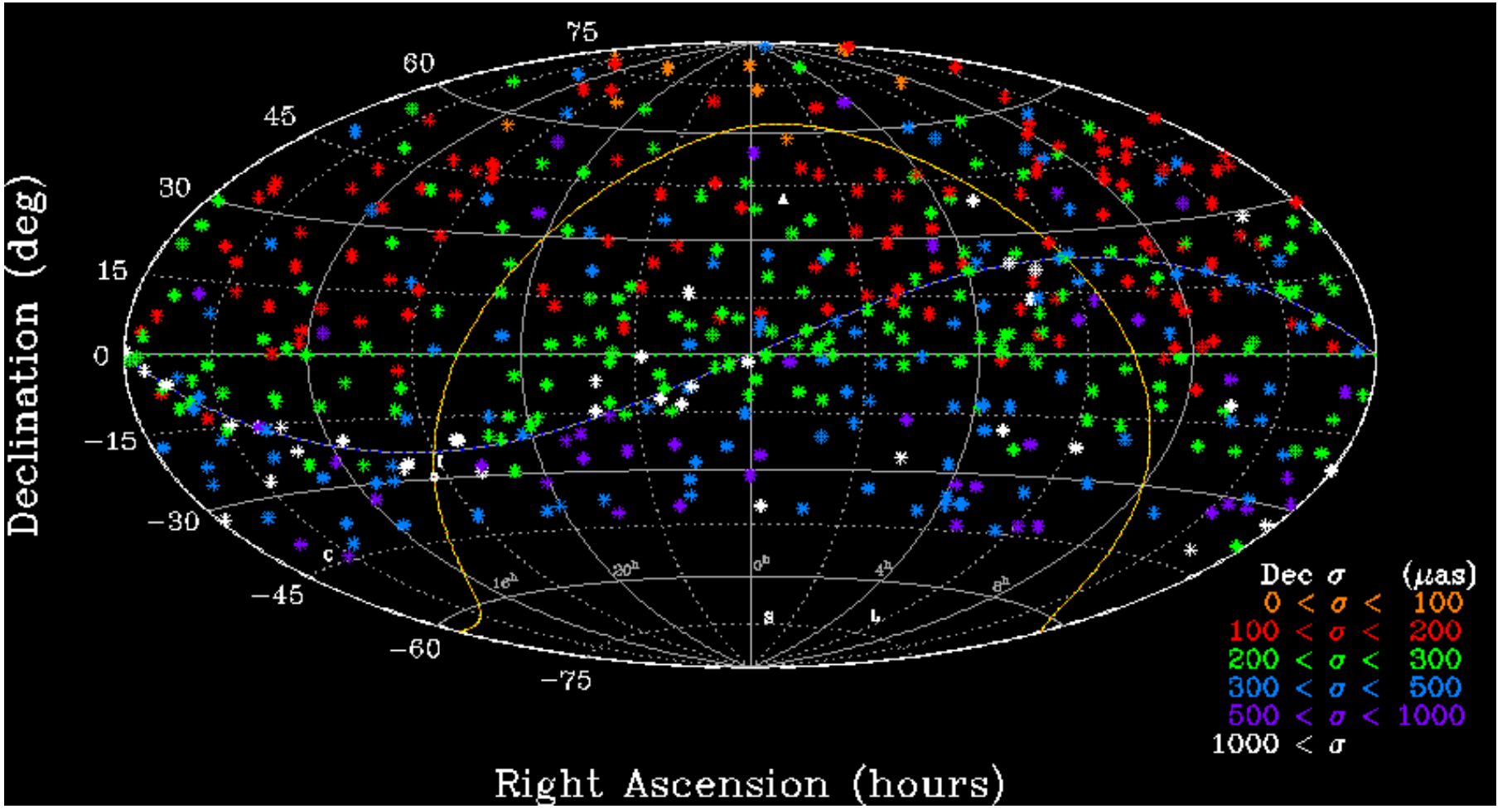
K-band 24GHz, 1.2cm: 278 Sources



VLBA all northern, poor below Dec. -30˚. ΔDec vs. Dec tilt= 500 μas

Credit: Lanyi et al, AJ, 139, 5, 2010; Charlot et al, AJ, 139, 5, 2010

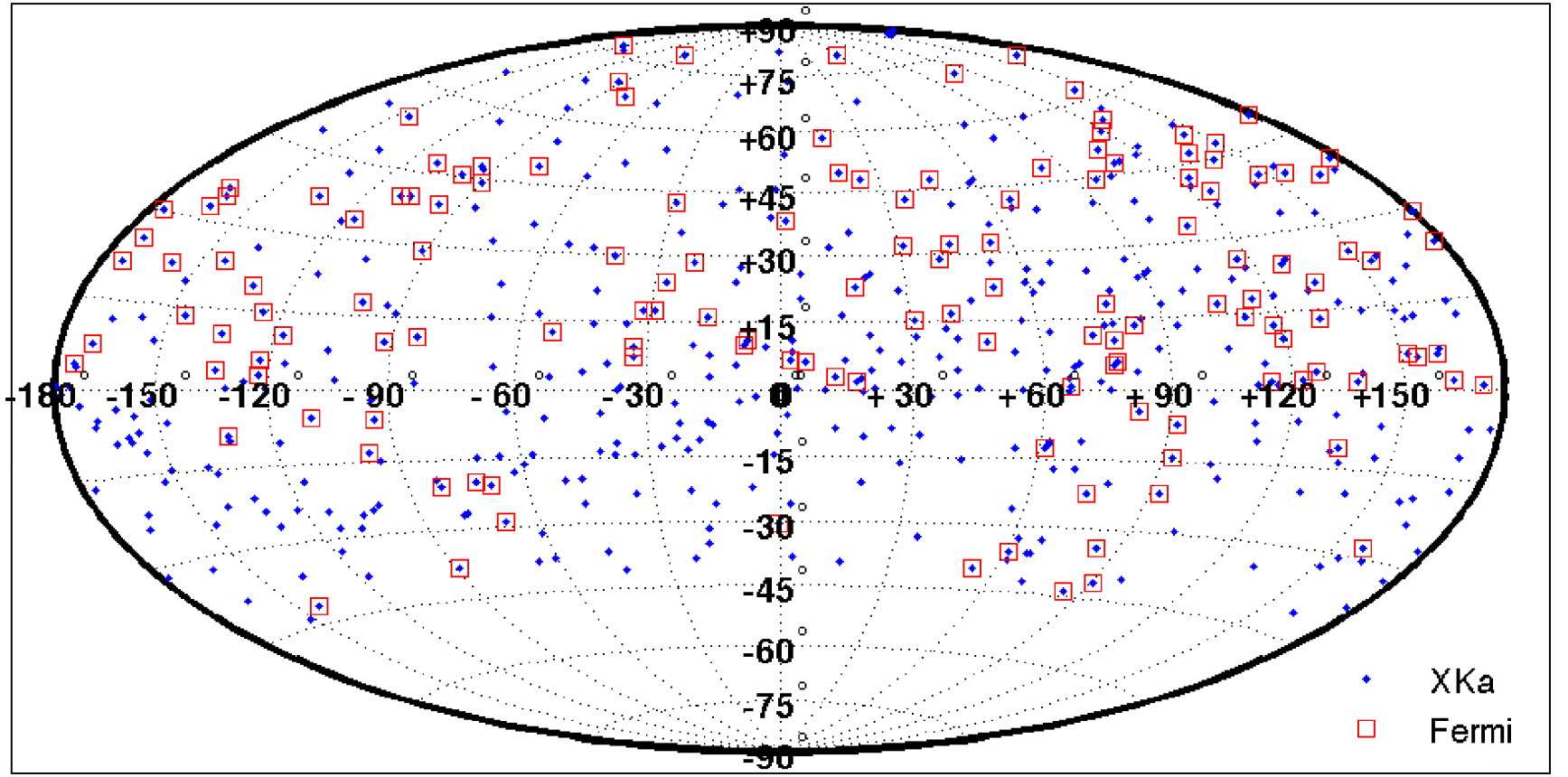
X/Ka 32GHz, Dec results: 482 Sources



Cal. to Madrid, Cal. to Australia. Weakens southward. No ΔDec tilt

Credit: Jacobs et al, ISSFD, Pasadena, 2012

X/Ka FERMI gamma-ray correspondance



X/Ka sources (blue) which are surrounded by Red squares are also in the Fermi 2FGL gamma-ray point source catalog. Over 1/3 of X/Ka sources (~175) have gamma-ray detections.

Credit: Majid et al, IVS, Madrid Spain, 2012

Attacking the X/Ka Error budget

- **SNR**: low cost disk drives -> more bits!

- **Instrumentation**: Ruszczyk et al, IVS, 2012; Tuccari, IVS, 2012

  Digital Back Ends: Baseband Conversion, Filters García-Miró et al, IVS, 2012

  Phase calibration for X/Ka-band Hamell, Tucker, Calhoun, 2003

- **Troposphere cals:**

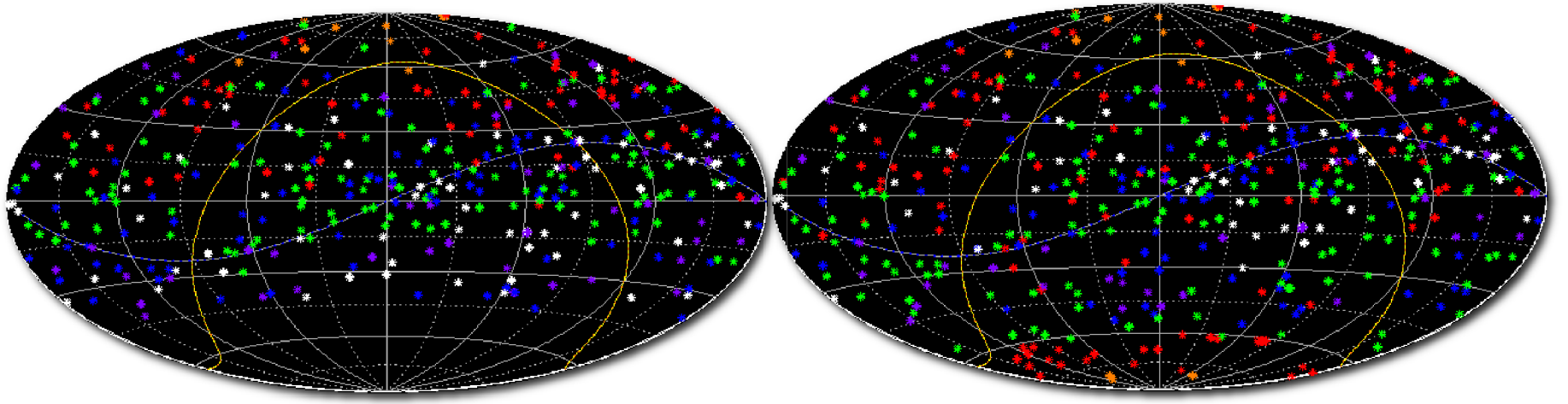
  JPL Advanced WVR: 1 mm accuracy Tanner et al, R.Sci, 2003;

  Bar-Sever et al, IEEE, 2007

- **Southern Geometry**

  Collaborate with ESA's X/Ka station in Malargüe, Argentina

Simulation: 9800km all-Southern baseline



50 sessions, No Sim. Southern Data *Adding Simulated data*

Credit: Bourda, Charlot, Jacobs, ELSA Conf., 2010

- 50 real X/Ka sessions augmented by simulated data
  simulate 1000 group delays, SNR = 50
  ~9000 km baseline: Australia to Argentina

- Completes Declination coverage: cap region -45 to -90 deg
  144 south polar candidate sources (*Sotuela et al, Porto, 2011*)
  200 µas (1 nrad) precision in south polar cap,
  mid south 200-1000 µas, all with just a few days observing.

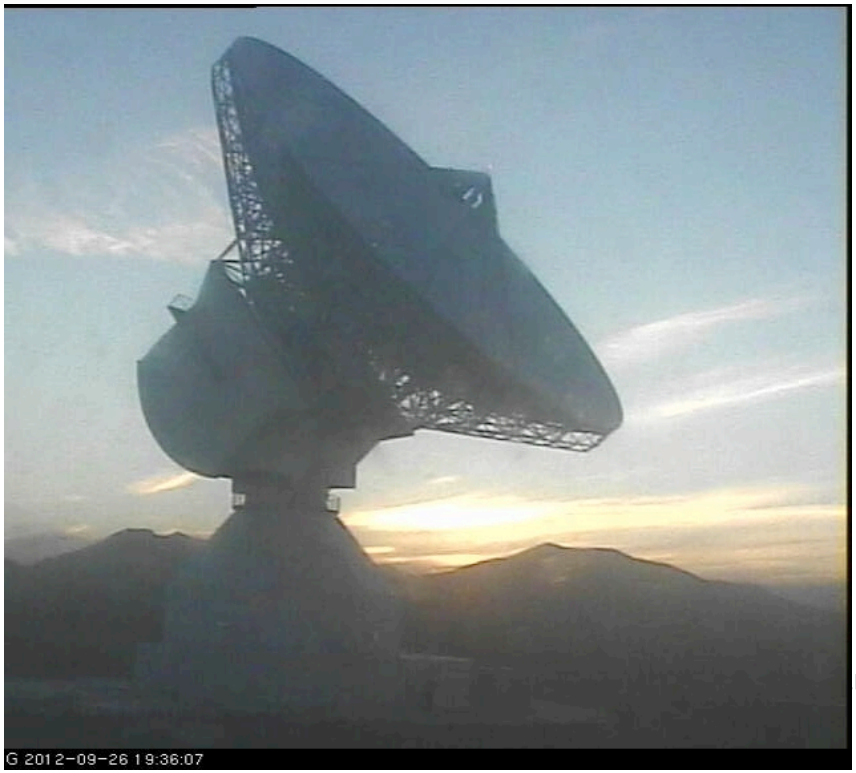
Declination Sigma

Orange: < 100 µas
Red: < 200
Green: < 300
Blue: < 500
Purple: < 1000
White: > 1000

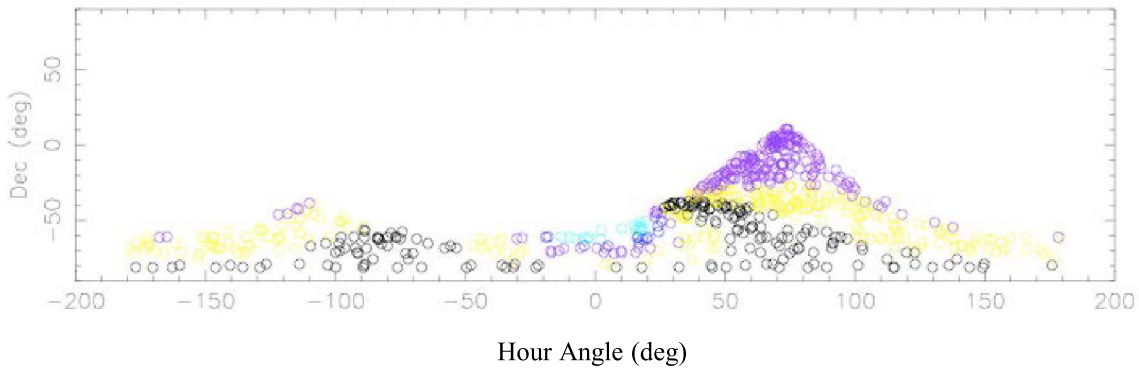
Malargüe: The Next X/Ka VLBI Station

X/Ka: ESA Deep Space Antenna DSA 03

- **Malargüe, Argentina**
- Fall-2012 NASA/ESA collaboration
- 35-m, X/Ka-band, 9,500 km baseline
  Argentina-Australia covers south polar cap
  Full sky coverage for X/Ka!!
- Argentina-California & Australia-California orthogonal baselines for mid-latitudes
- High (1.5km), dry desert site: good for Ka-band
- HA-Dec coverage: Tidbinbilla to Malargüe:



Malargüe, Argentina 35-meter as of 26 Sept. 2012
Photo credit: European Space Agency
http://www.esa.int/Our_Activities/Operations/Malarguee_-_DSA_3



ESA Deep Space Antenna
X/Ka-band capable

Malargüe: The Next X/Ka VLBI Station

Malargüe, Argentina

ESA's DSA 03 35-meter

Dec 2012

Photos credit: Leslie A. White

Malargüe: The Next X/Ka VLBI Station

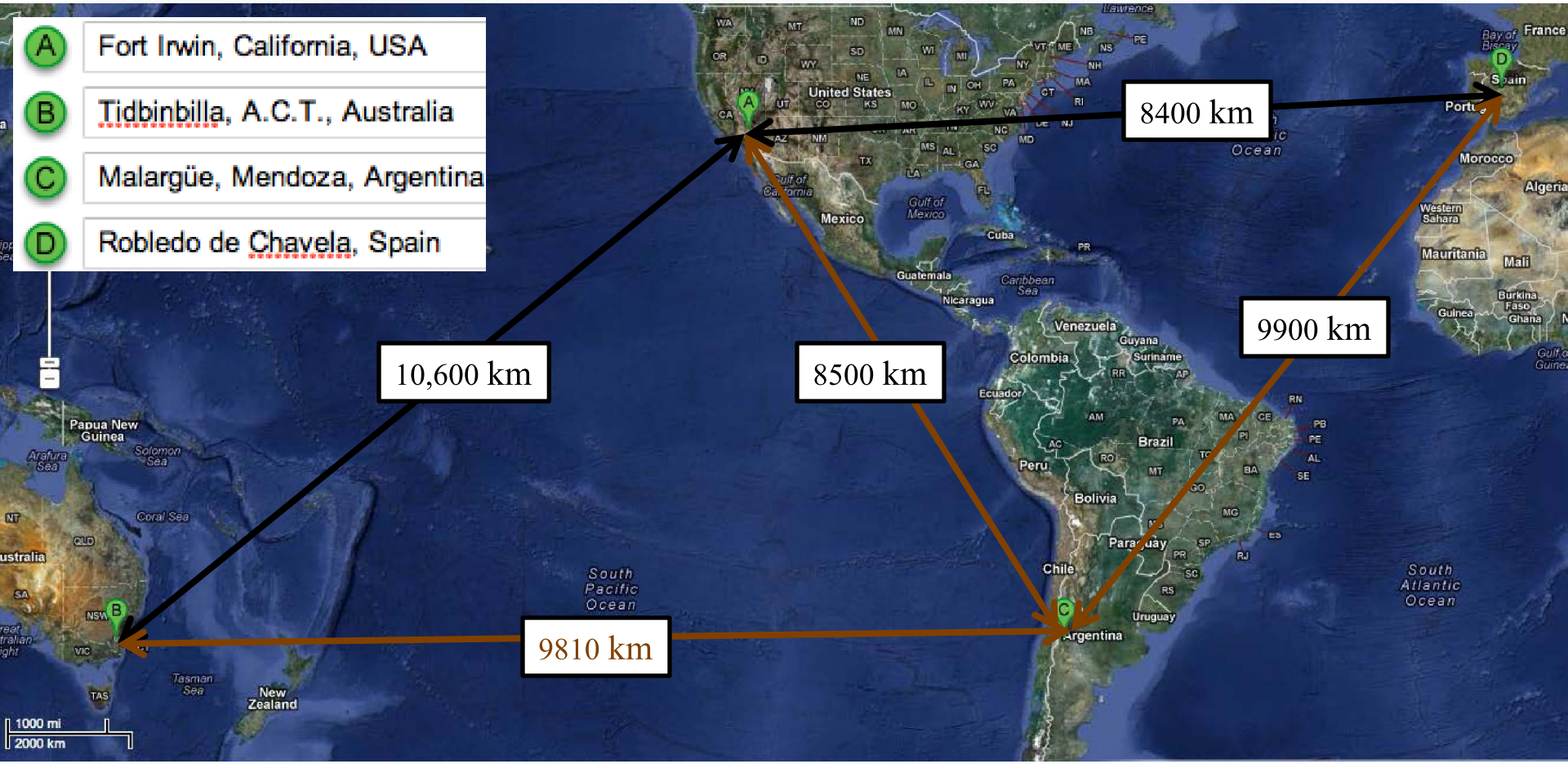
Malargüe, Argentina

ESA's DSA 03 35-meter

Dec 2012

Photos credit: Leslie A. White

X/Ka stations for Celestial Frame



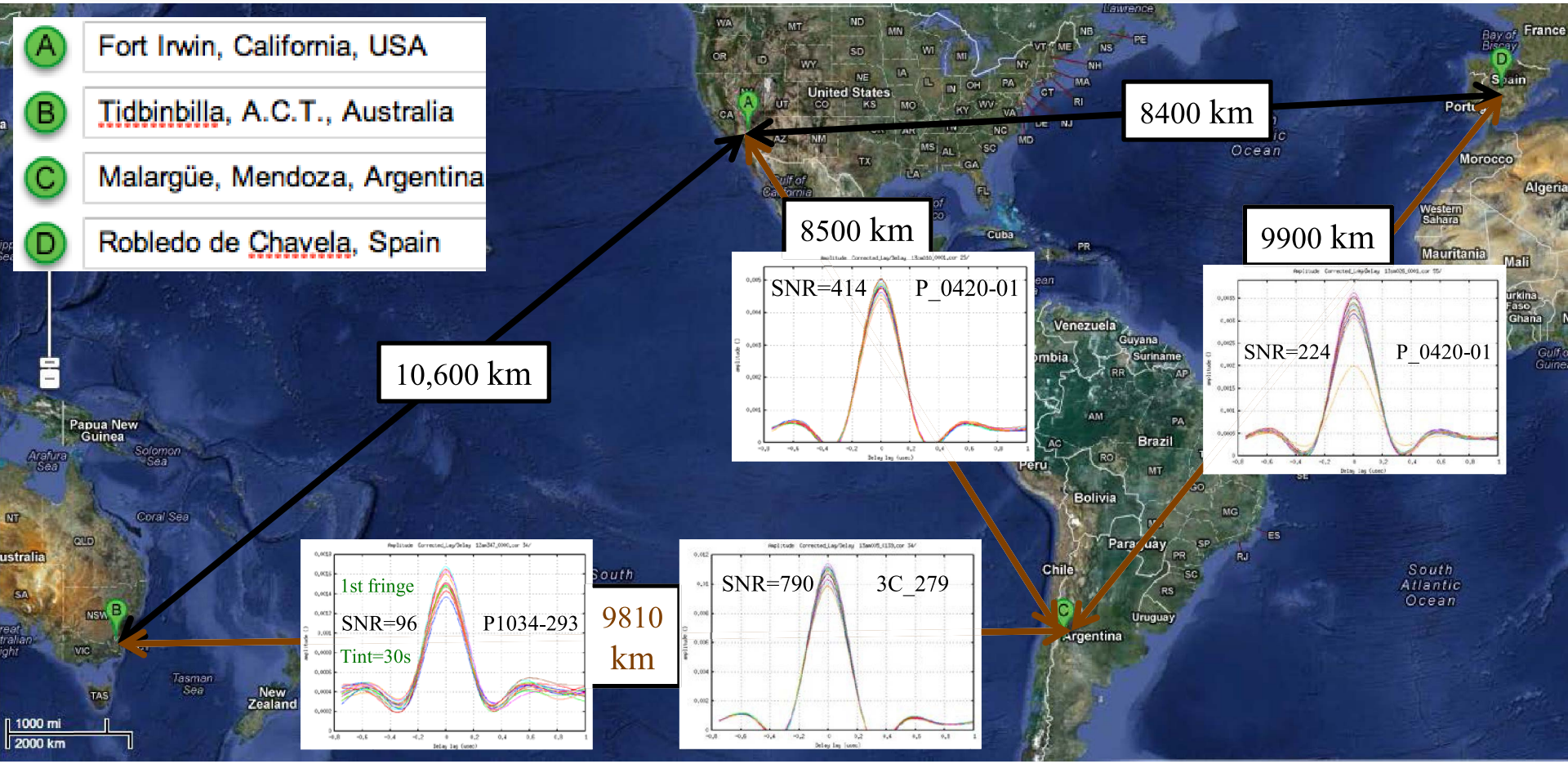
Maps credit: Google maps

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

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

1st Ka fringes NASA to ESA-Malargüe

60 sec integrations, 256 Mbps (16 channels, 4 MHz, I/Q, @2bit)



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

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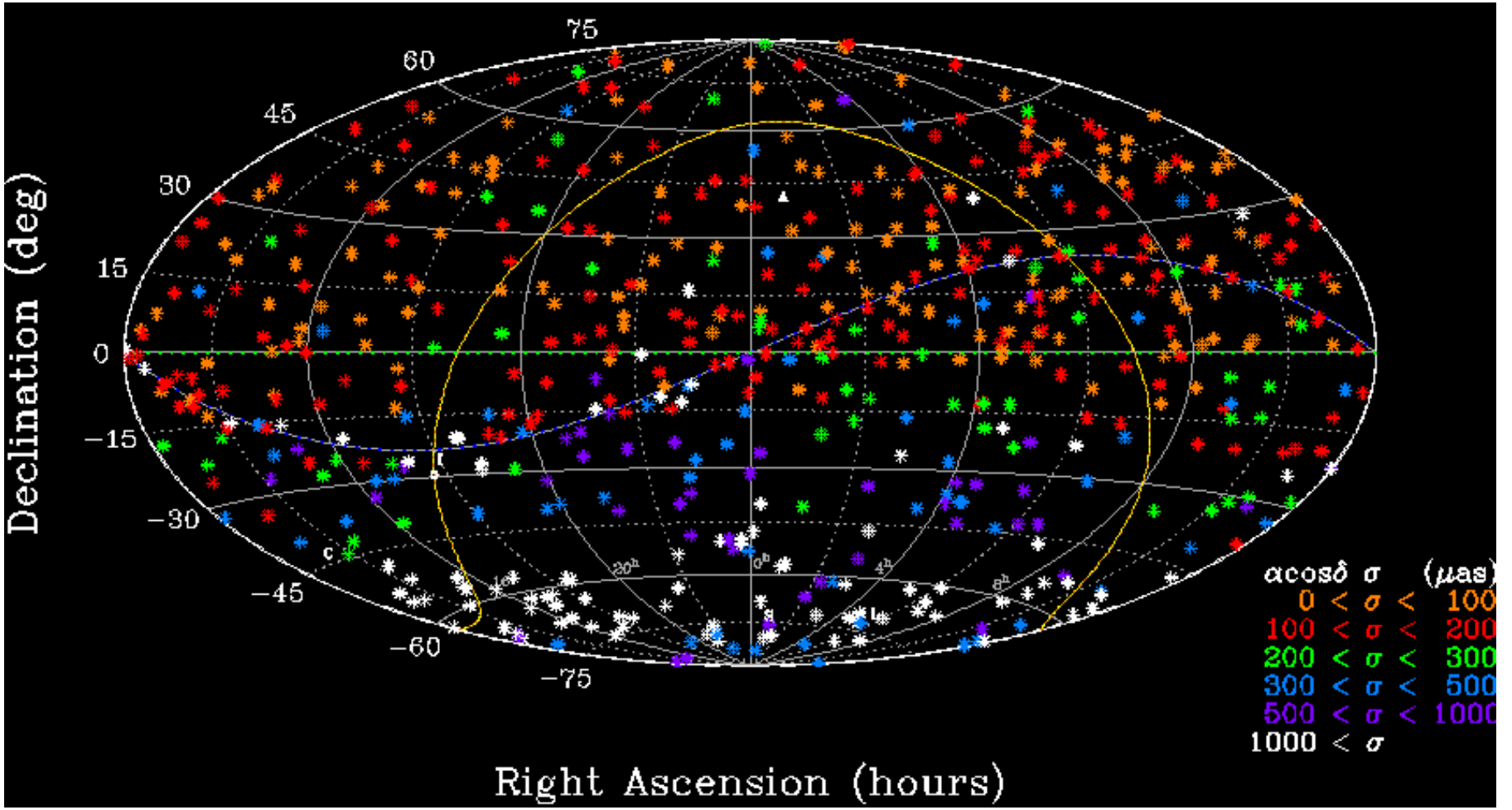
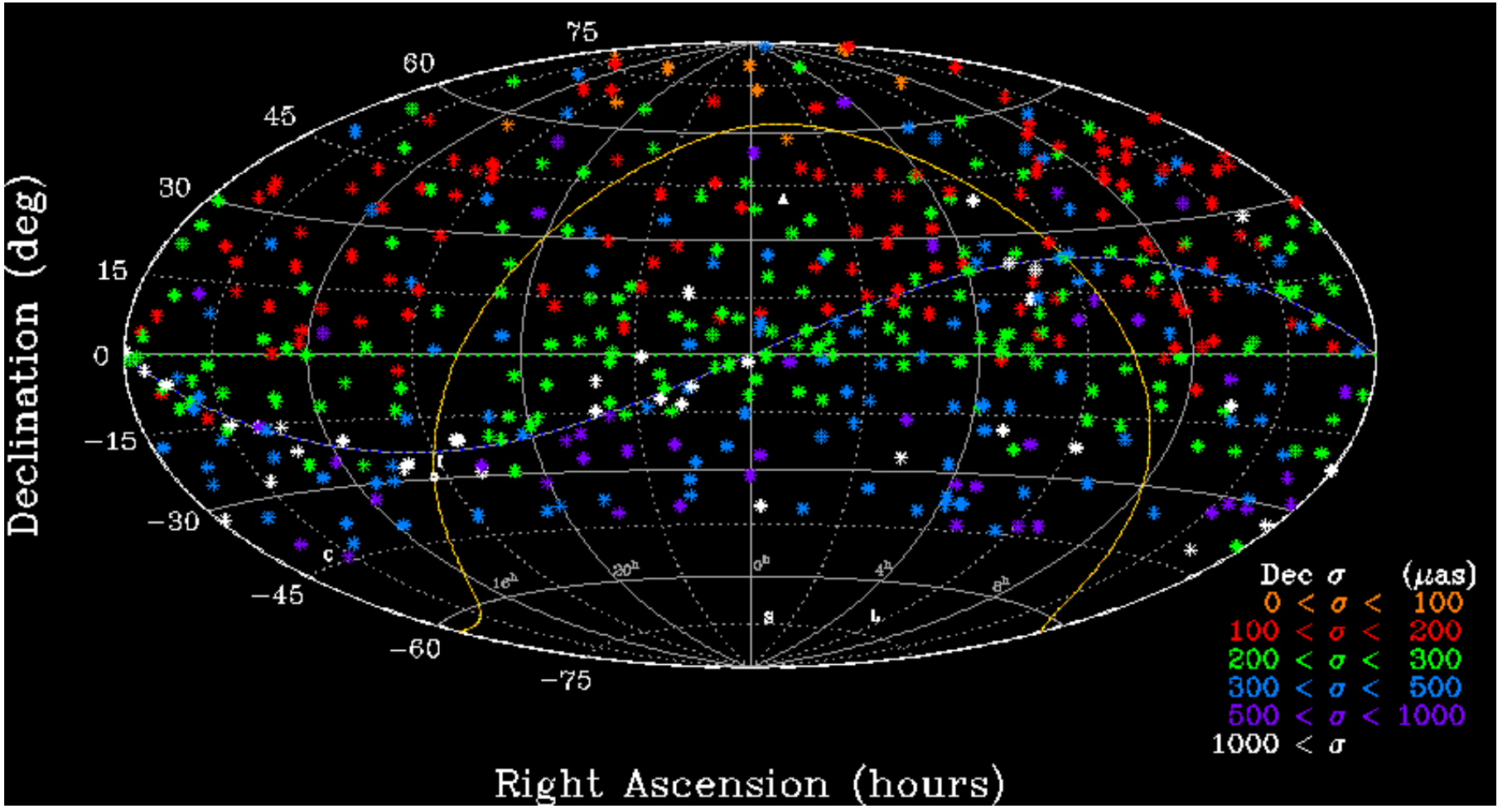
NASA-ESA 32GHz RA results: 577 sources



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

95 in south cap (dec<-45); 19 ICRF2 Defining; 2/3 of cap non-ICRF2

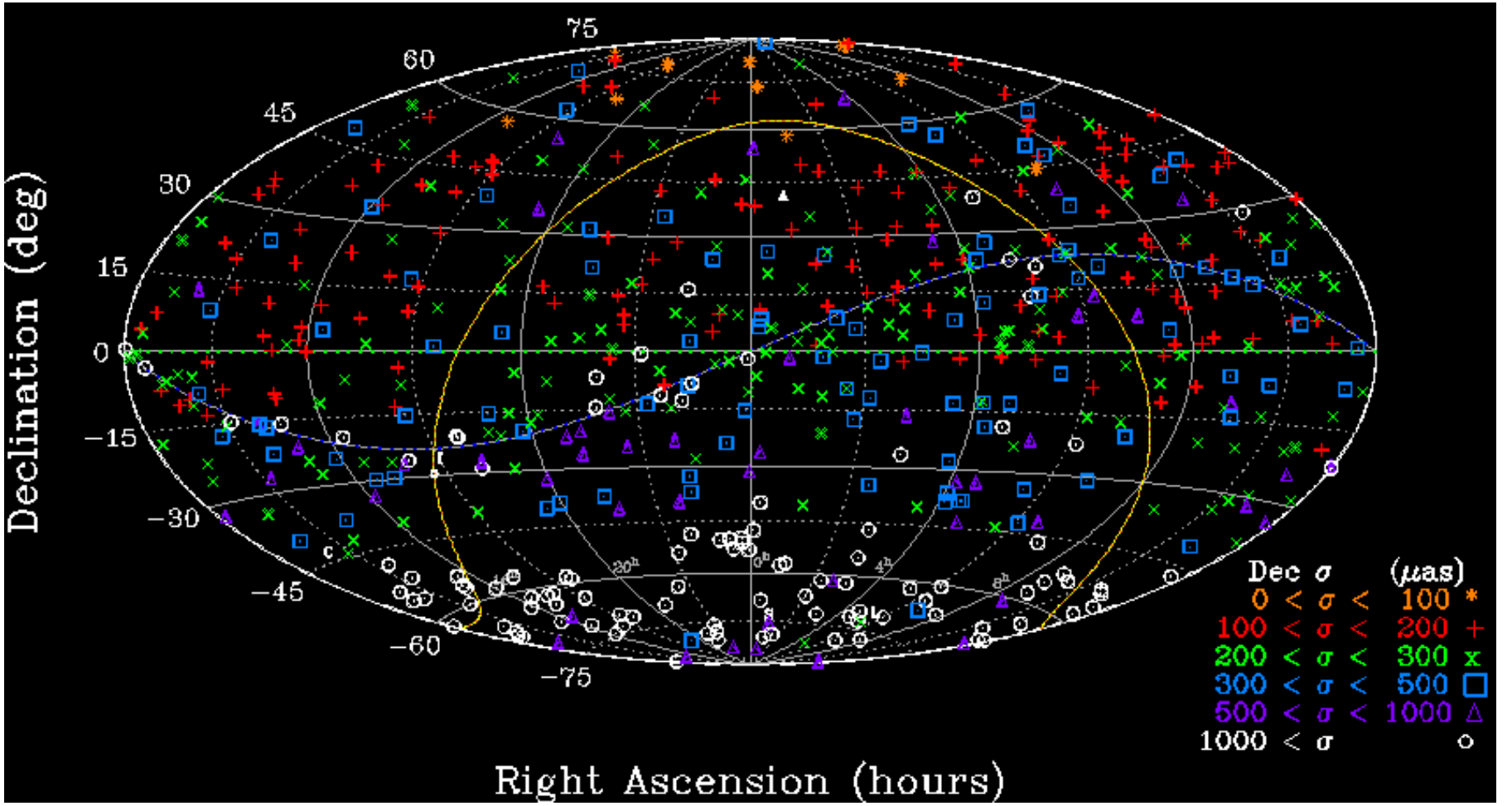
NASA-only 32GHz Dec results: 482 sources



Goldstone, CA to Madrid, Australia. Weakens southward, no south Cap

Credit: Jacobs et al, ISSFD, Pasadena, 2012

NASA-ESA 32GHz Dec results: 577 sources



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

Gaia/VLBI frame tie & Accuracy test

Gaia: 10^9 stars

- 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, IAU, Beijing, 2012*)

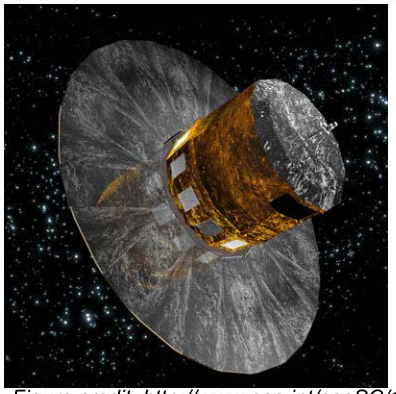
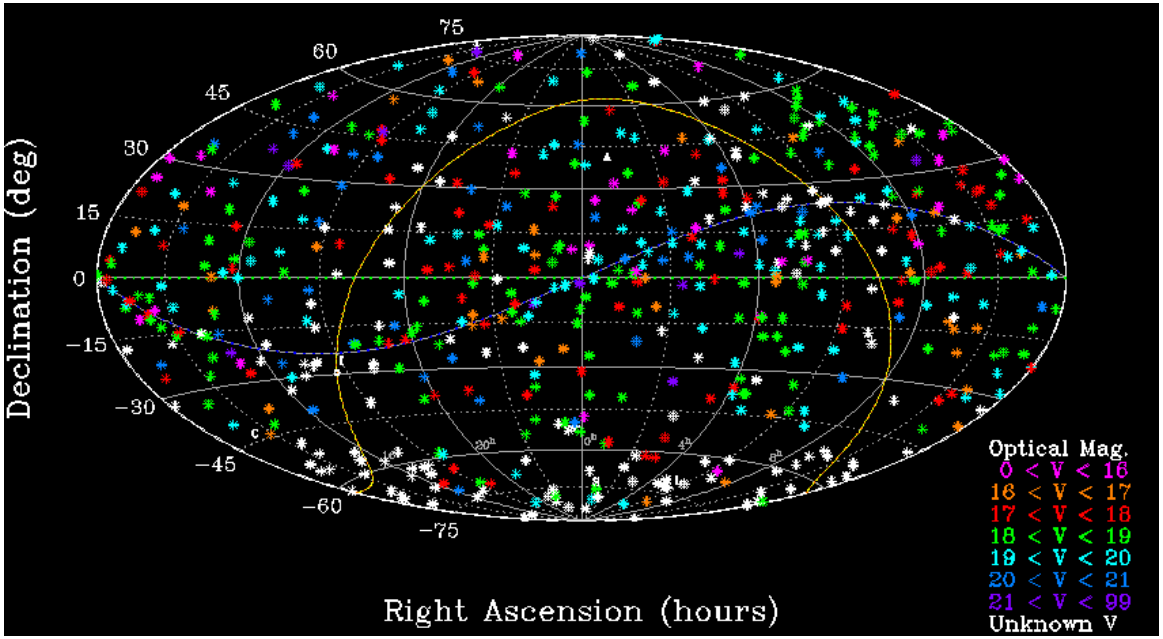


Figure credit: http://www.esa.int/esaSC/120377_index_1_m.html#subhead7

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

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

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



XKa: 146 optically bright counterparts: V< 18mag

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

Conclusions

- **Increasing frequency -> lower sensitivity, but more compact**
- **Celestial Frame Overview:**

  S/X ICRF-2 ~70 µas 3414 sources

  K-band ~100 µas 268 sources

  X/Ka-band ~250 µas 577 sources
- **Future Improvements:**

  SNR (2Gbps), Instrumentation: DBEs, PCGs, Trop.: WVRs

- **ESA-NASA collaboration: add Malargüe, Argentina 35-meter**

  Improves net from 2 to 5 baselines, orthogonal mid-lat baselines

  Full sky coverage by accessing south polar cap!

  95 in south polar cap (dec<-45). Cap sources 2/3 non-ICRF2

  19 ICRF2 Defining in south polar cap
- **Frame tie:** XKa VLBI/Gaia optical tie precision ~10 µas.

Research described herein partially done under contract with NASA. U.S. Government sponsorship acknowledged. Copyright ©2013. All Rights Reserved

BACKUP SLIDES

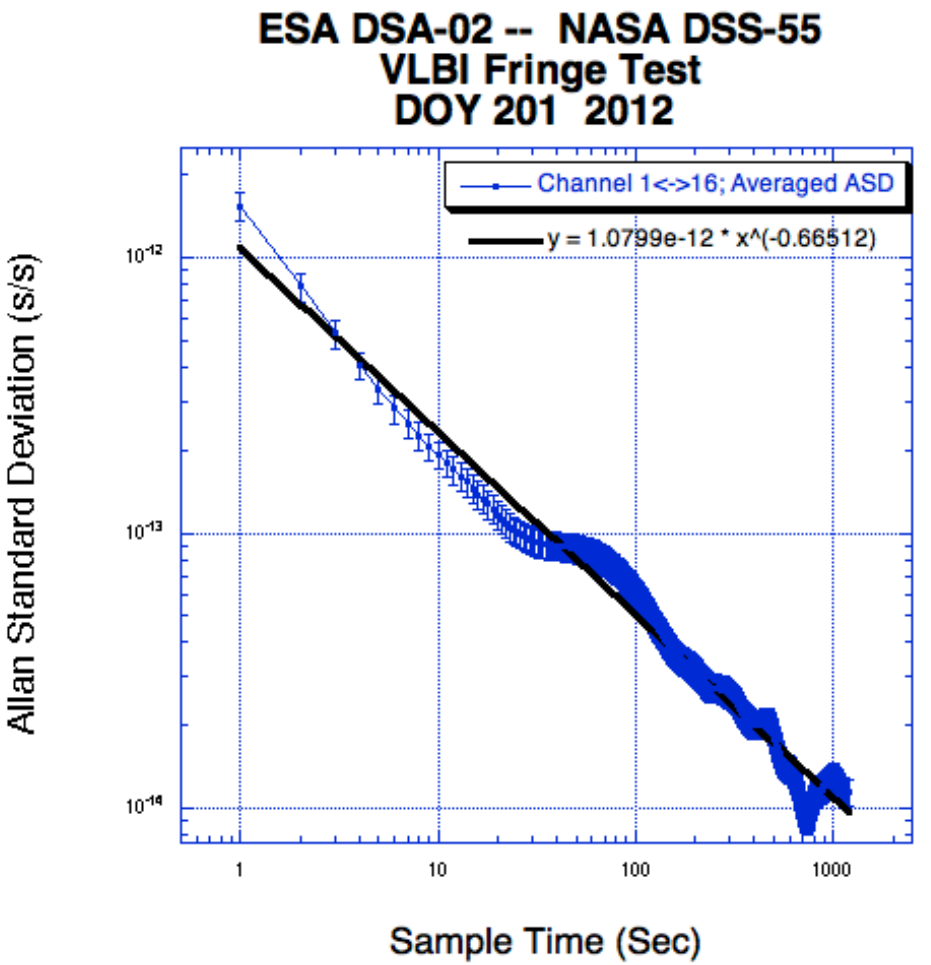
Instrumental Stability: Allan St. Dev.

- Spain: Cebreros-DSS 55
  Ka-band, 10km baseline,
  2000 sec of data

- Time Scale 60 - 1200 sec
  Slope = -0.69
  consistent with 2-D
  Kolmogorov frozen flow
  trop noise (slope = -2/3)
  (*Treuhaft & Lanyi, R.Sci,1987*)

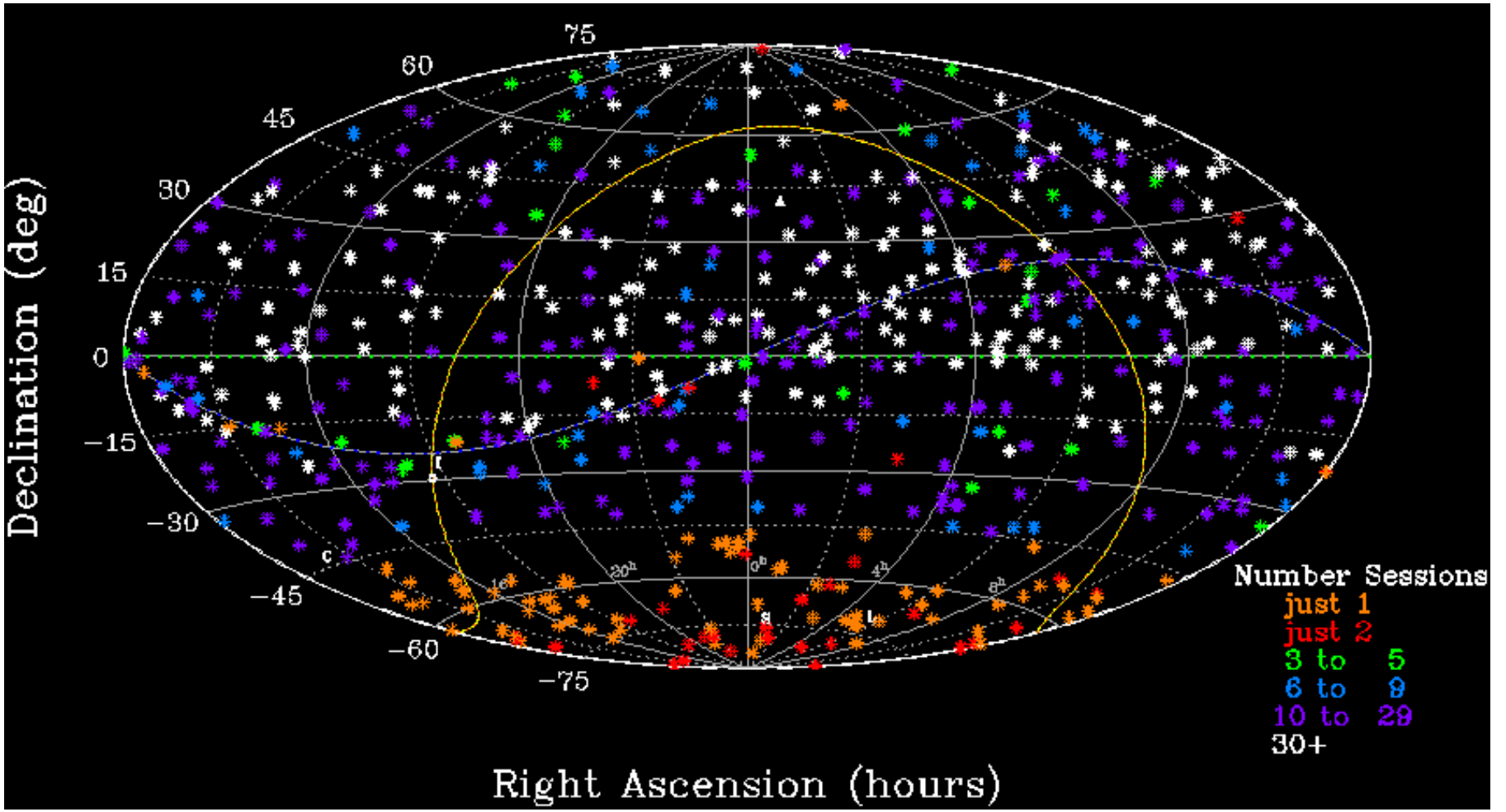
- Time scale 1-20 sec: Slope = -0.84
  shows some sign of white noise
  limitation (slope ~ -1)

- Time scale 20-60 sec: Slope = -0.18
  3-D trop turbulence noise (-1/6)
  from small scale fluctuations?
  thermal drift of instrument?



Validated ESA-DSN baseline & interfaces **(Jacobs et al, EVN, Bordeaux, 2012)**

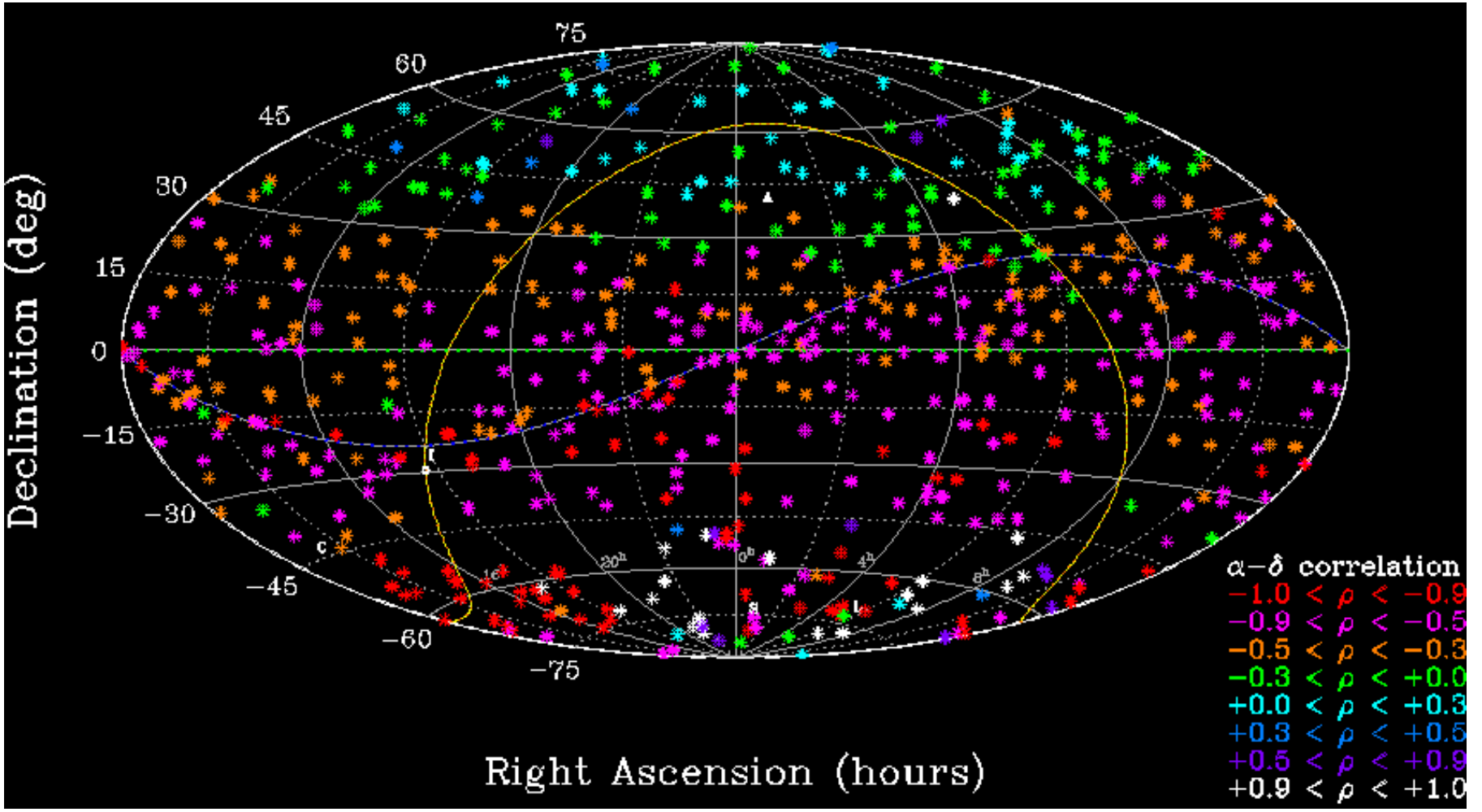
Number of sessions for 577 XKa sources



South polar cap: two sessions (3 hr + 8 hr)

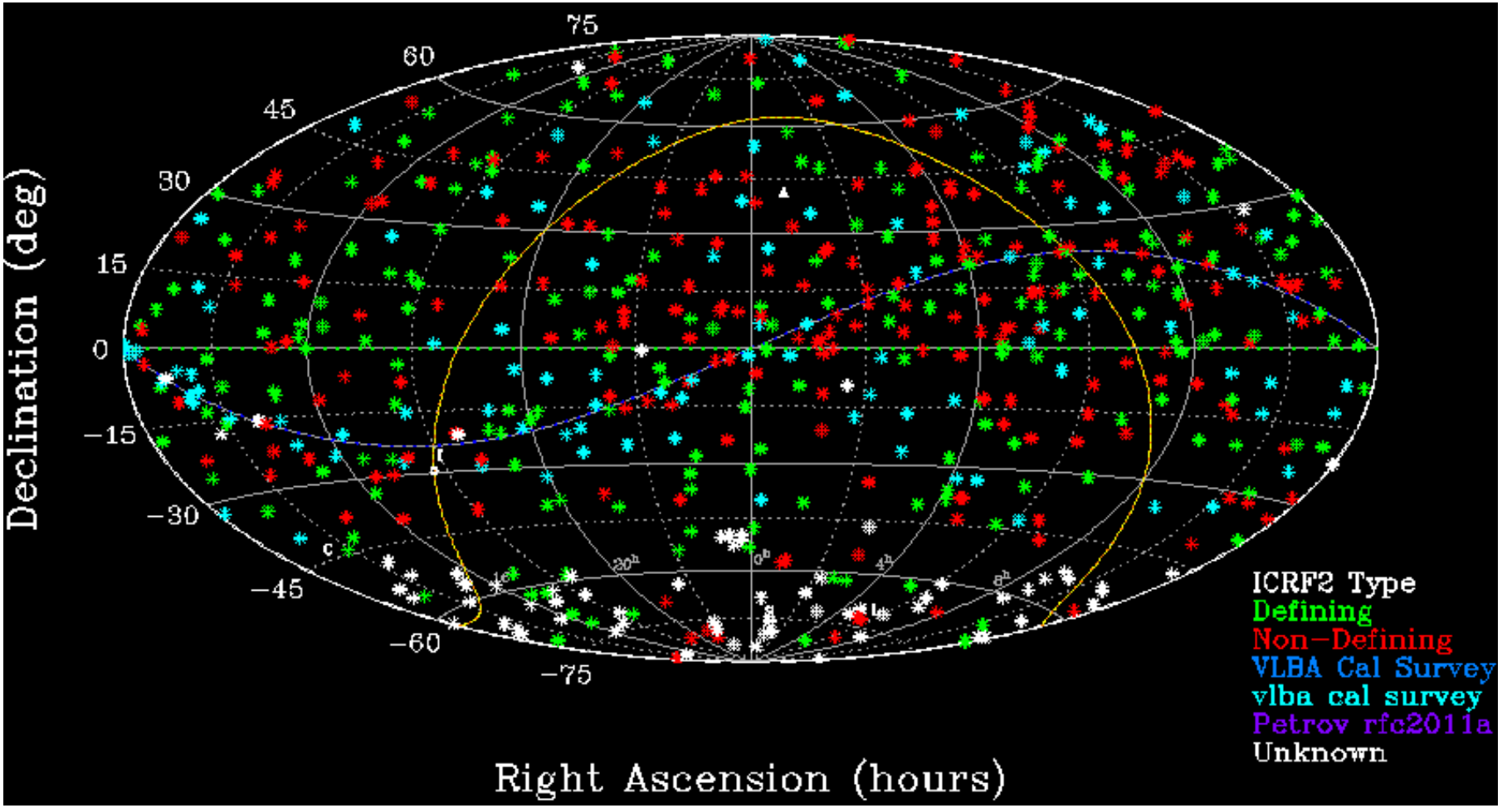
Some parts of Declination -45 to -60 not yet observed

RA-Dec correlation for 577 XKa sources



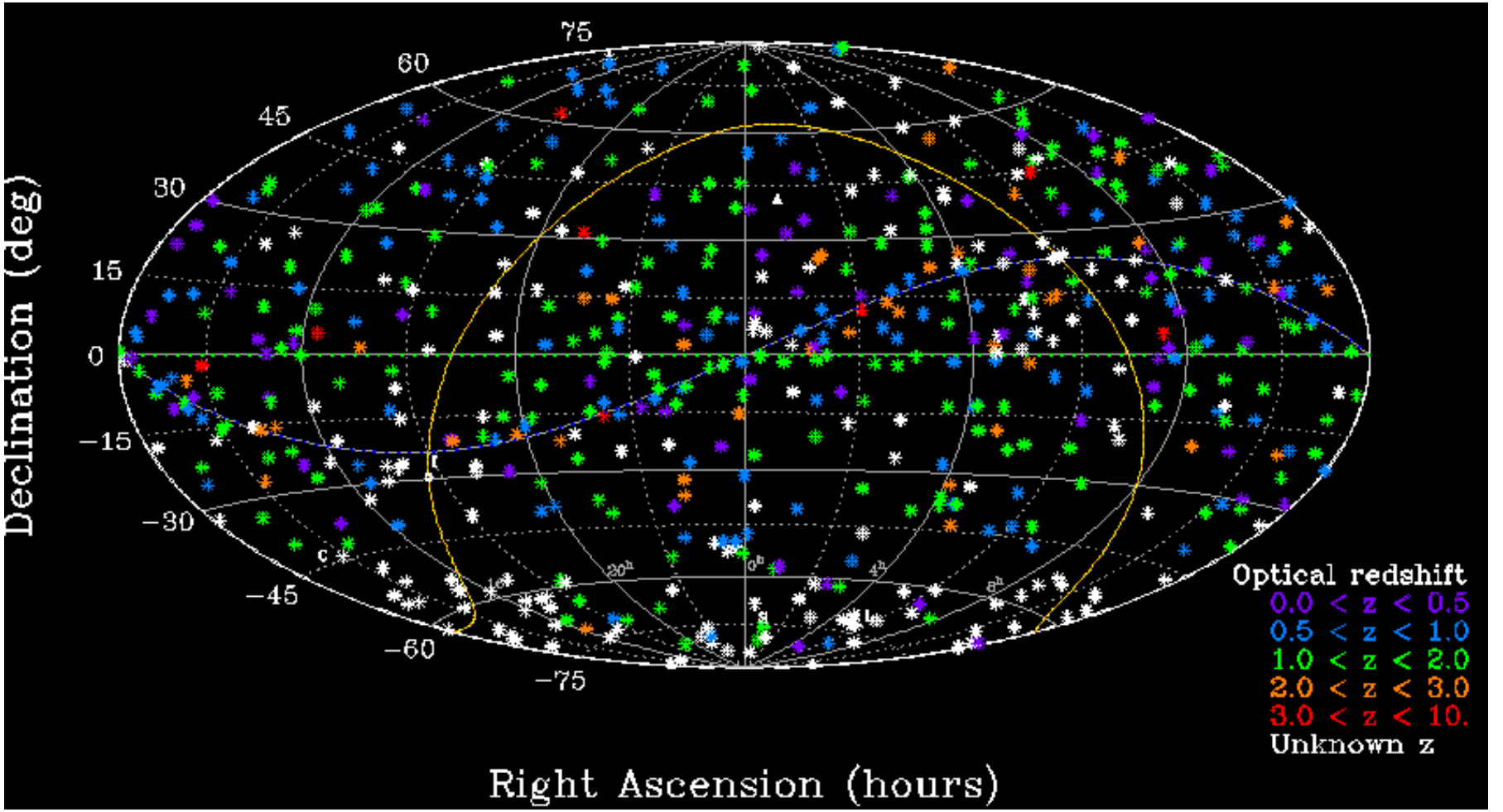
Note systematic trend in correlation vs. declination

ICRF2 type for 577 XKa sources



Note 19 ICRF2-Defining sources in
South polar cap: Declination -45 to -90 deg

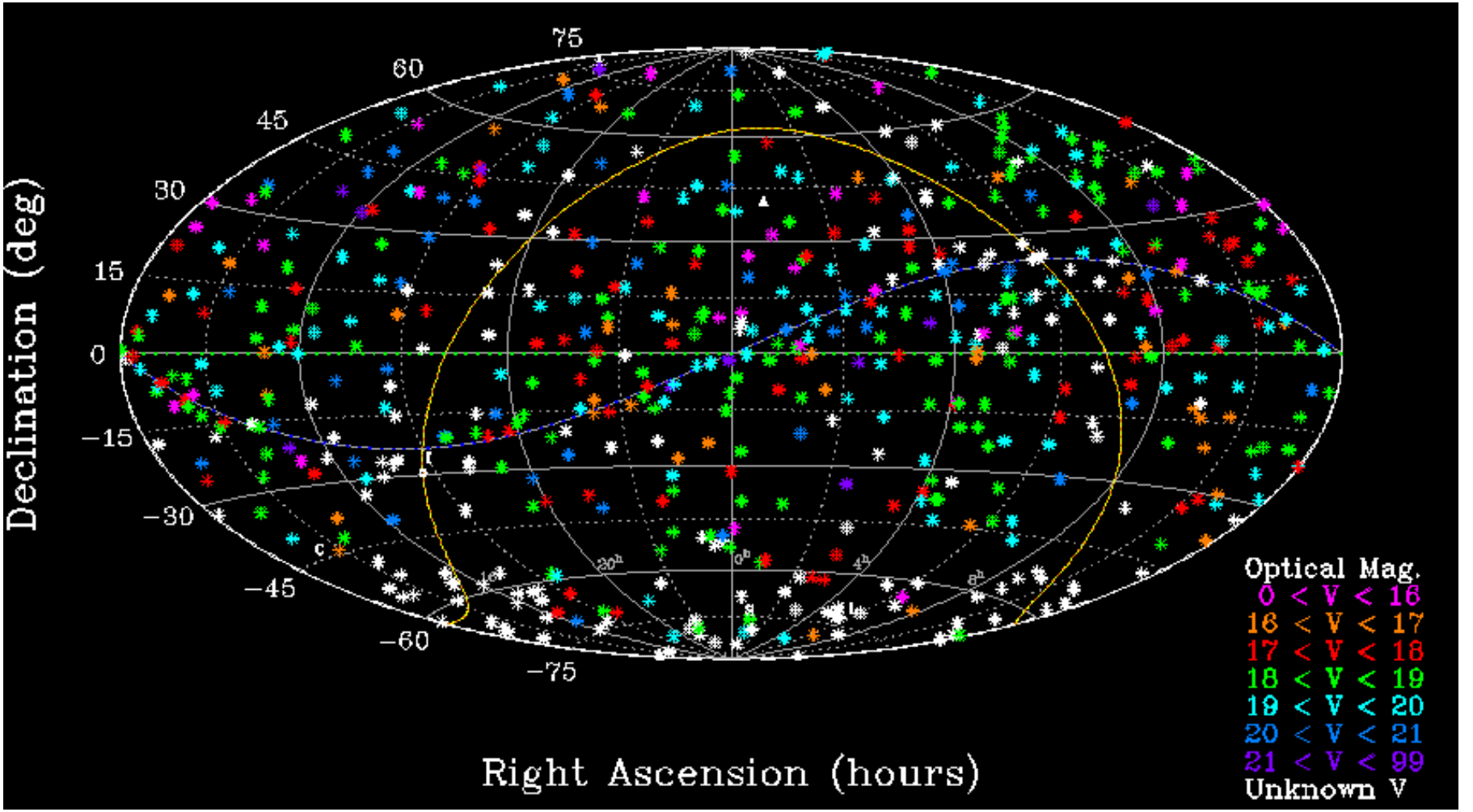
Redshift for 577 XKa sources



Optical redshift, z.

Very distant (z > 2) sources may be of value in cosmological studies

Optical magnitude for 577 XKa sources



Optical Visual magnitude, V.

Gaia satellite will detect V< 20 and V< 18 is “bright” for Gaia.

The Potential for a

Ka-band Worldwide VLBI Network

Journees, Vienna, 2011.

C. S. Jacobs[1],
U. Bach[6], F. Colomer[7], C. Garcia-Miro[2], J. Gomez-Gonzalez[7], S. Gulyaev[9], S. Horiuchi[3], R. Ichikawa[12], A. Kraus[6], G. Kronschnabl[5], J.A. Lopez-Fernandez[7], J. Lovell[8], W. Majid[1], T. Natusch[9], A. Neidhardt[4], C. Phillips[13], R. Porcas[6], A. Romero-Wolf[1], L. Saldana[14], U. Schreiber[5], I. Sotuela[2], H. Takeuchi[11], J. Trinh[1], A. Tzioumis[13], P. de Vicente[7], V. Zharov[10]

(1) Jet Propulsion Laboratory, California Institute of Technology/NASA (2) Madrid Deep Space Communications Complex/NASA, INSA,, Spain, (3) Canberra Deep Space Communications Complex/NASA, C.S.I.R.O., Australia (4) Technische Universitaet Muenchen, Germany (5) Bundesamt fuer Kartographie und Geodaesie, Bad Koetzting, Germany (6) Max-Planck-Institut fuer Radioastronomie, Bonn, Germany (7) Instituto Geografico Nacional, Madrid, Spain (8) University of Tasmania, Hobart, Australia (9) Institute for Radio Astronomy and Space Research, Auckland University of Technology, New Zealand (10) Sternberg State Astronomical Institute, Moscow, Russia (11) ISAS/JAXA, Sagamihara, Japan (12) Kashima Space Research Center, NICT, Kashima, Japan, (13) CSIRO Astronomy and Space Science, Australia, (14) ITT Mission Systems, Monrovia, CA