National Aeronautics and Space Administration

Advancing Celestial Frame Construction at Multiple Wavelengths

Principal Investigator: Christopher Jacobs (335); Co-Investigators: Christopher Volk (335)

Program: FY21 R&TD Strategic Initiative **Strategic Focus Area: Advanced Celestial Reference Frames**

Objectives

- Establish celestial frames at X/Ka and K-bands as part of the international standard reference frame, the ICRF-3, including aligning the optical, S/X, K-band, and X/Ka-band radio frames in 3-D orientation to ±0.1 nanoradians (20 μas) or better.
- Increase the number of objects common to radio and optical frames with better than 1 nanoradian (200 μas) weighted RMS agreement.
- Reduce optical-radio vector spherical harmonic differences to 1 nanoradian or less.
- Increase the sensitivity of our measurement systems to improve precision and speed the addition of new sources.
- Image sources at K-band to quantify source structure effects at K-band and by proxy at Ka-band.
- Improve the network geometry for radio observations by adding new stations in geometrically favorable locations.
- Understand the limiting errors for celestial frame accuracy.

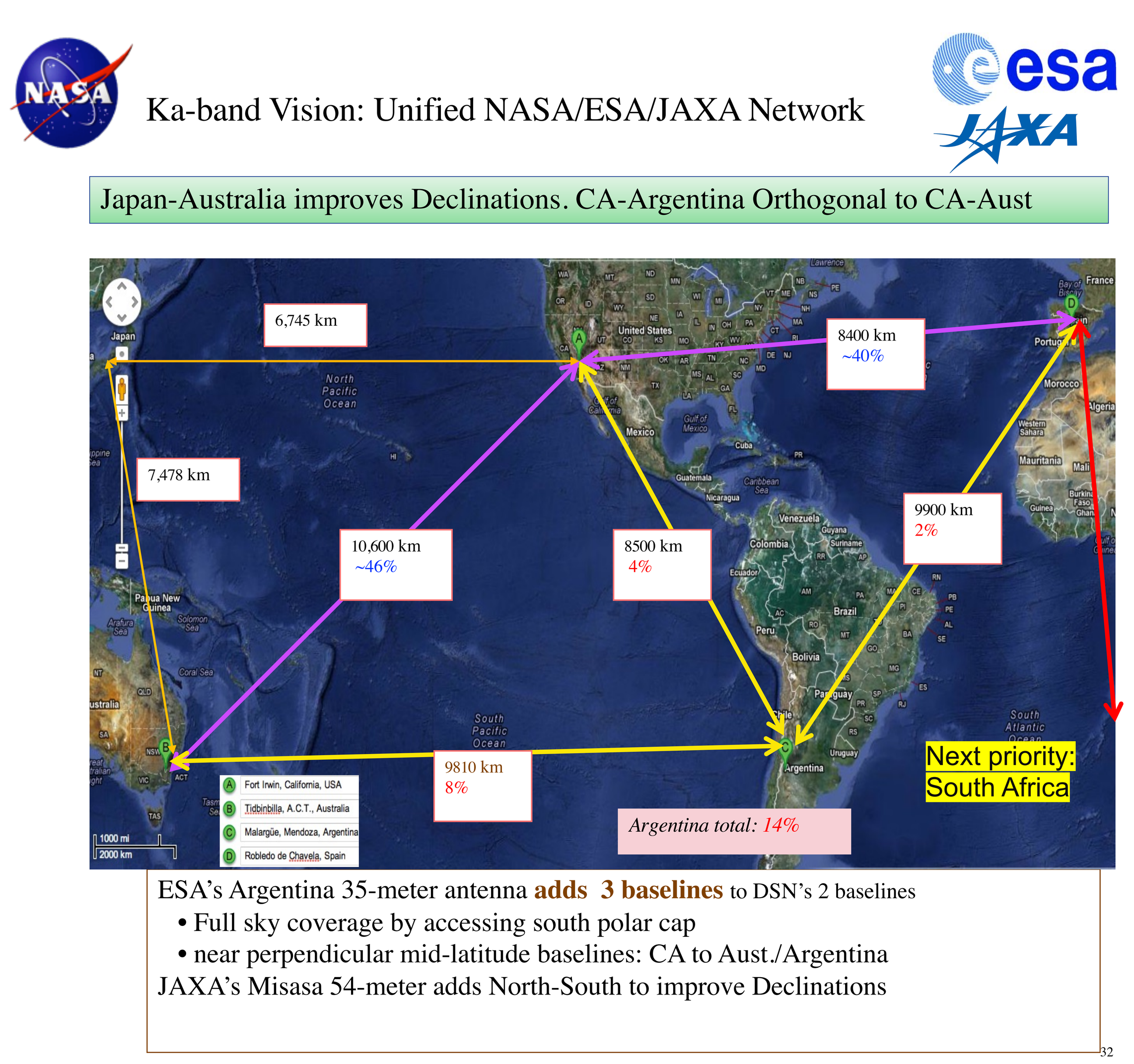

Figure 1. Combined NASA, ESA, JAXA network.
The combined network provides a stronger and more diverse geometry producing more accurate results and allowing increased contingencies in the event of an outage at any one site e.g. fires, earthquakes, mechanical failures

Figure 2. JAXA's 54-meter at Misasa, Japan
We succeeded in integrating the 54-meter into our network during the last year.

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Background

We seek to ensure JPL's leadership in defining next-generation celestial reference frames. As a world leader in deep space telecommunications, JPL has moved to a higher radio frequency (Ka-band, 32 GHz). The traditional means of navigating deep space spacecraft relies on the use of their radio telecommunications equipment—measuring the relative separations between the spacecraft and reference sources on the sky. JPL has developed a reference frame at Ka band, the X/Ka reference frame. The IAU will likely adopt a new International Celestial Reference Frame in the next few years in order to integrate the new Gaia optical frame with multi-wavelength radio frames at the S/X, K, and X/Ka radio bands. We will continue JPL leadership in this area that was established by having a JPL chair of the ICRF3 working group thus ensuring that the next generation international standards meet JPL's navigation needs. Specifically, we propose (1) to improve the X/Ka frame, especially in declination, (2) quantify source compactness using images at K-band (24 GHz) as proxies for Ka-band, (3) assess and reduce systematic errors by comparing the 24 and 32 GHz radio frames to the Gaia optical frame which provides a totally independent wavelength and technique for verification.

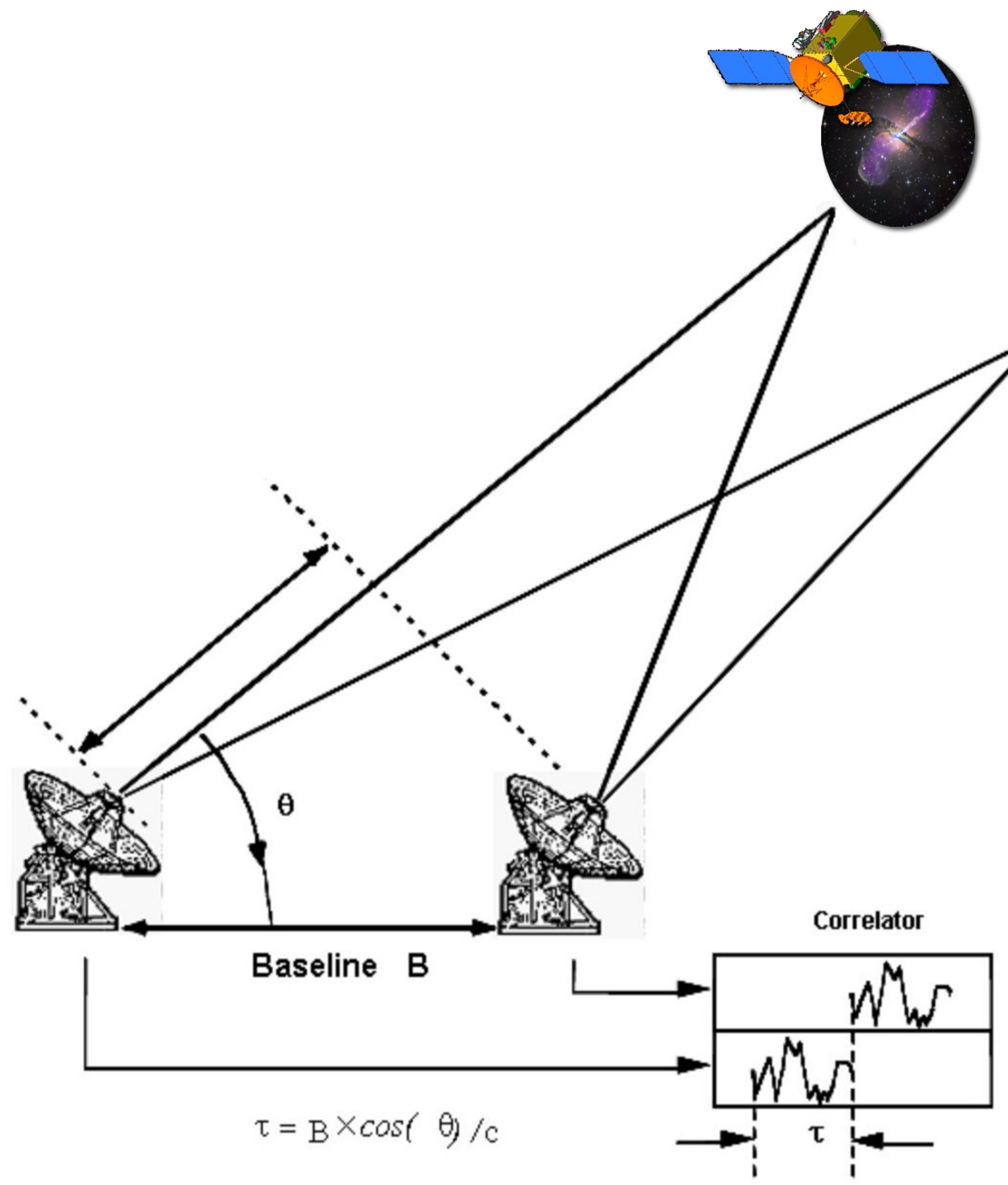

Figure 3: Schematic of a Very Long Baseline Interferometry (VLBI) measurement. The observed delay, tau, contains information about the geometry of the baseline, B, and the source directions.

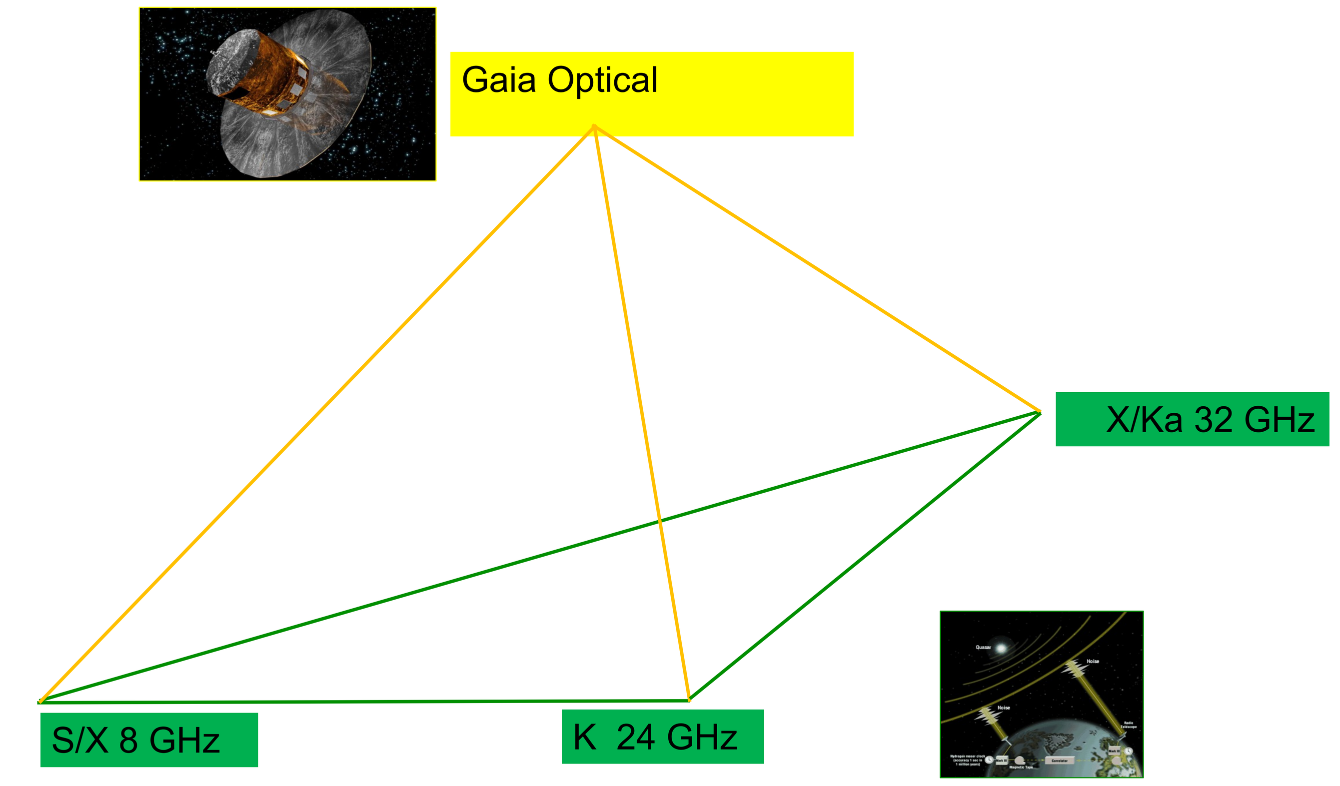

Figure 4: The lines represent intercomparison of frames. Comparing ground based radio interferometry results at 8, 24, and 32 GHz (green) with Gaia mission space based optical (yellow) allows one to assess accuracy because the techniques and their systematic errors are very different.

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Approach and Results

Approach: We will increase sensitivity and diversify geometry. We will infuse our results into the operational Delta-DOR system.

Results: Published 11 papers including the ICRF3 paper (61 citations). Three other referred journal papers are nearing submission.

Sensitivity: On the baselines to ESA Malargüe we increased data rates to 1.8 Gbps, a factor of two increase.

Geometry: We successfully executed VLBI passes to JAXA's 54-meter antenna at Misasa. The initial pass achieved better than 12 psec group delay scatter--a new record for any X/Ka baseline! Later we demonstrated a full 24-hour pass through the end-to-end pipeline.

Imaging: We imaged 731 sources at K-band (24 GHz) using the VLBA--most at multiple epochs. These images were delivered to the Delta-DOR team for use as proxies for Ka-band images given the lack of a Ka-band imaging array. The results are documented in a paper which is about to be submitted to a refereed journal. See sample in Fig 5. below.

Alignment and VSH: We aligned our K and X/Ka frames to the ICRF3-SX to approximately 0.1 nrad thus meeting out goal. K-band vector spherical harmonic (VSH) differences were reduced to less than 0.5 nrad. X/Ka-band to 0.7 ±0.1 nrad and 0.4 ± 0.15 nrad in the quadrupole 2,0 magnetic and electric terms respectively. The z-dipole term was reduced to the statistically insignificance at -0.2 ± 0.25 nrad. These levels met our goal of reducing systematics below 1.0 nrad.

Gaia comparison: We compared our VLBI results to the space-based optical results from ESA's Gaia mission as an independent check on our technique. Right ascensions agreed to 1.1 nrad and declinations to 1.2 nrad slightly above our goal level.

X/Ka source strengths: We improved our models of antenna gain and system temperatures vs. elevation. We delivered the results to the Delta-DOR team using a new improved interface.

X/Ka source catalog: was delivered to Delta-DOR operations: DSN 810-005 module 108.

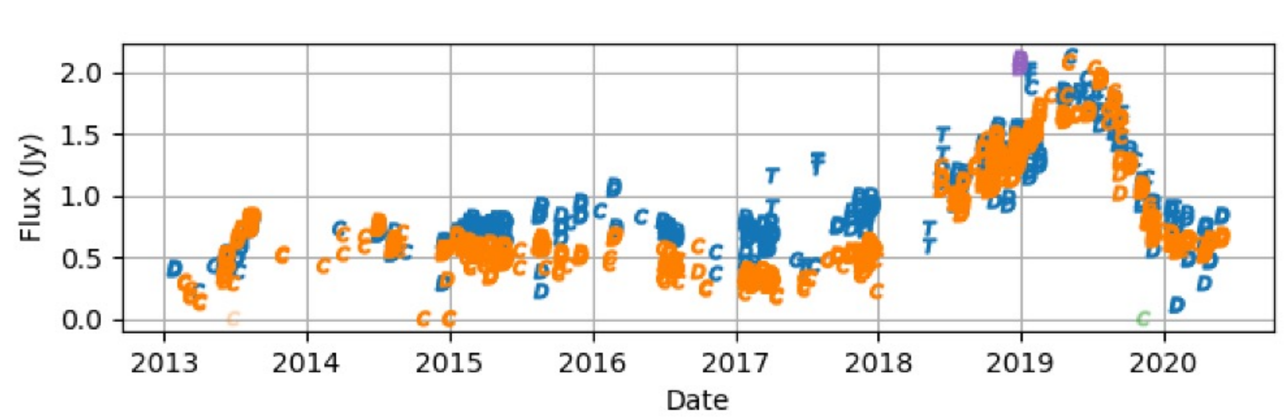
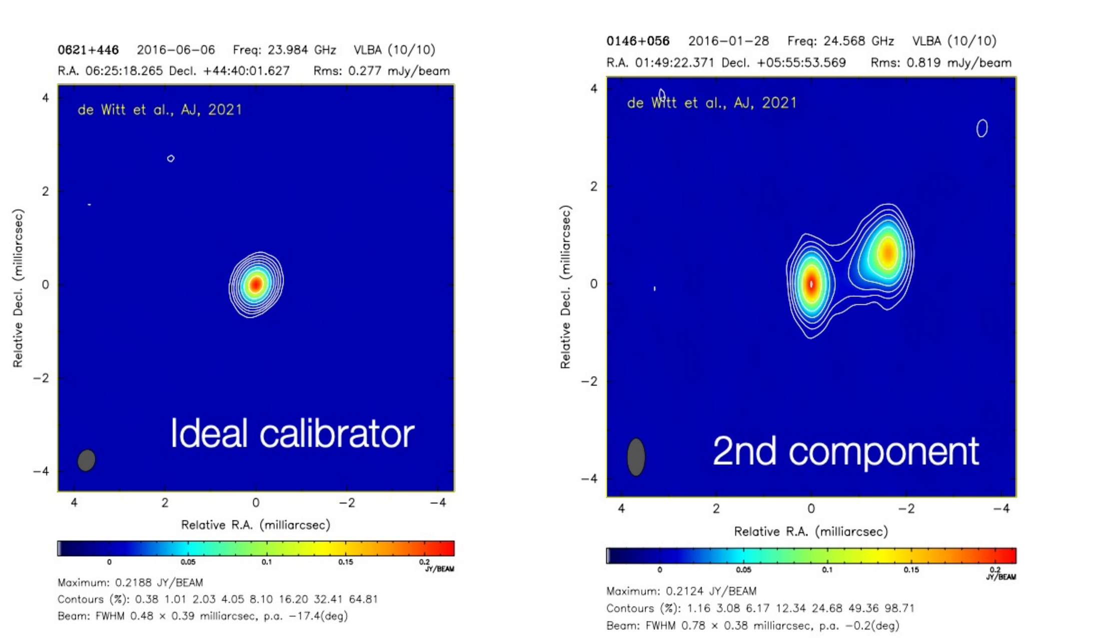


Figure 5: Source Strength history from correlated flux density measurements of extra-galactic source OV-213 at X-band on two DSN baselines:
Goldstone - Canberra (orange) and
Goldstone - Madrid (blue).
The variations with time drive the need to monitor source strength vs. time.



credit: de Witt, et al, AJ, 2021, in prep.

Figure 6: Images of two sources at K-band (24 GHz) using the Very Long Baseline Array of ten antennas. These images allow the DeltaDOR team to select the most point-like (ideal) sources (left panel) and avoid problems from extended sources such as the double (right panel)

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Significance/Benefits to JPL and NASA

(1) The ICRF-3 publication (Charlot, Jacobs et al, 2020) documents the official international standard that unifies the alignment of S/X, K, X/Ka radio frames and the Gaia optical frame to ±0.1 nrad thereby enabling seamless navigation across all these wavelengths.

(2) The increased sensitivity at both the VLBA (4 Gbps) and ESA's Malargüe station (1.8 Gbps) the time to a given precision improving responsiveness to Delta-DOR navigation needs with reduced resources.

(3) Reducing radio-radio optical-radio vector spherical harmonic differences to 0.7 nrad or less verifies the accuracy of our celestial frames to a level that meets the needs of many missions. All four celestial frames (S/X, K, X/Ka, Gaia optical) can now be used seamlessly and interchangeably at the nanoradian level without requiring the use of inter-frame transformation parameters.

(5) Imaging 731 sources at K-band quantifies source structure effects at K-band and by proxy at Ka-band enabling more reliable selection of Ka-band Delta-DOR sources.

(6) Collaborations with ESA and JAXA are enabling a unified multi-agency terrestrial reference frame. This enables seamless inter-agency Delta-DOR, Doppler and Range measurements. It also provides robustness to the DSN in the event of disruptive events such as the July 2019 Ridgecrest earthquake.

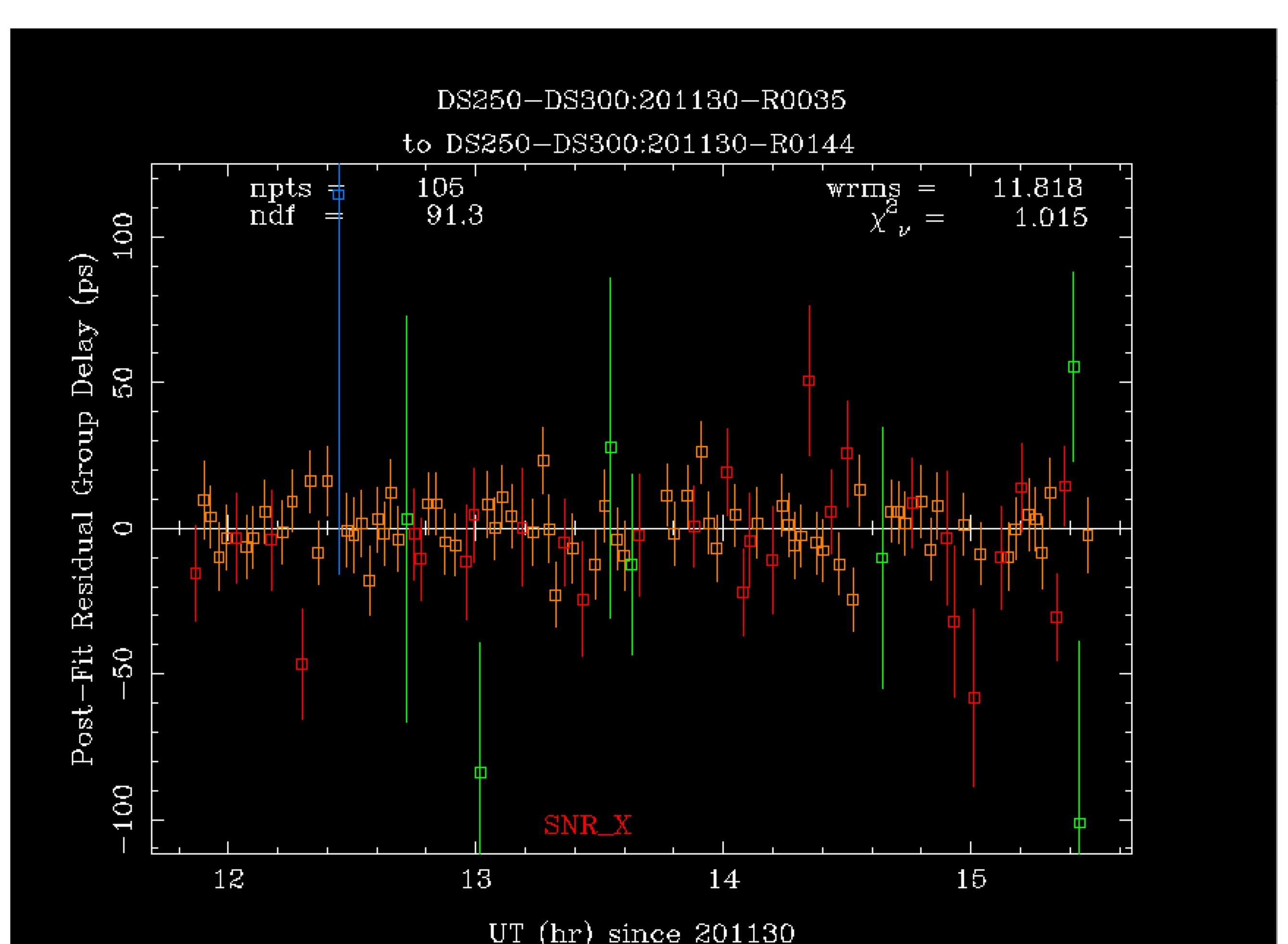

Figure 7. Misasa, Japan 54-m to Goldstone, CA 34-m VLBI results.
The 11.8 psec residual wRMS scatter is the best ever
in the 16 year history of the X/Ka VLBI program.
This result proves that we can produce state-of-the-art data
in our collaborations with JAXA

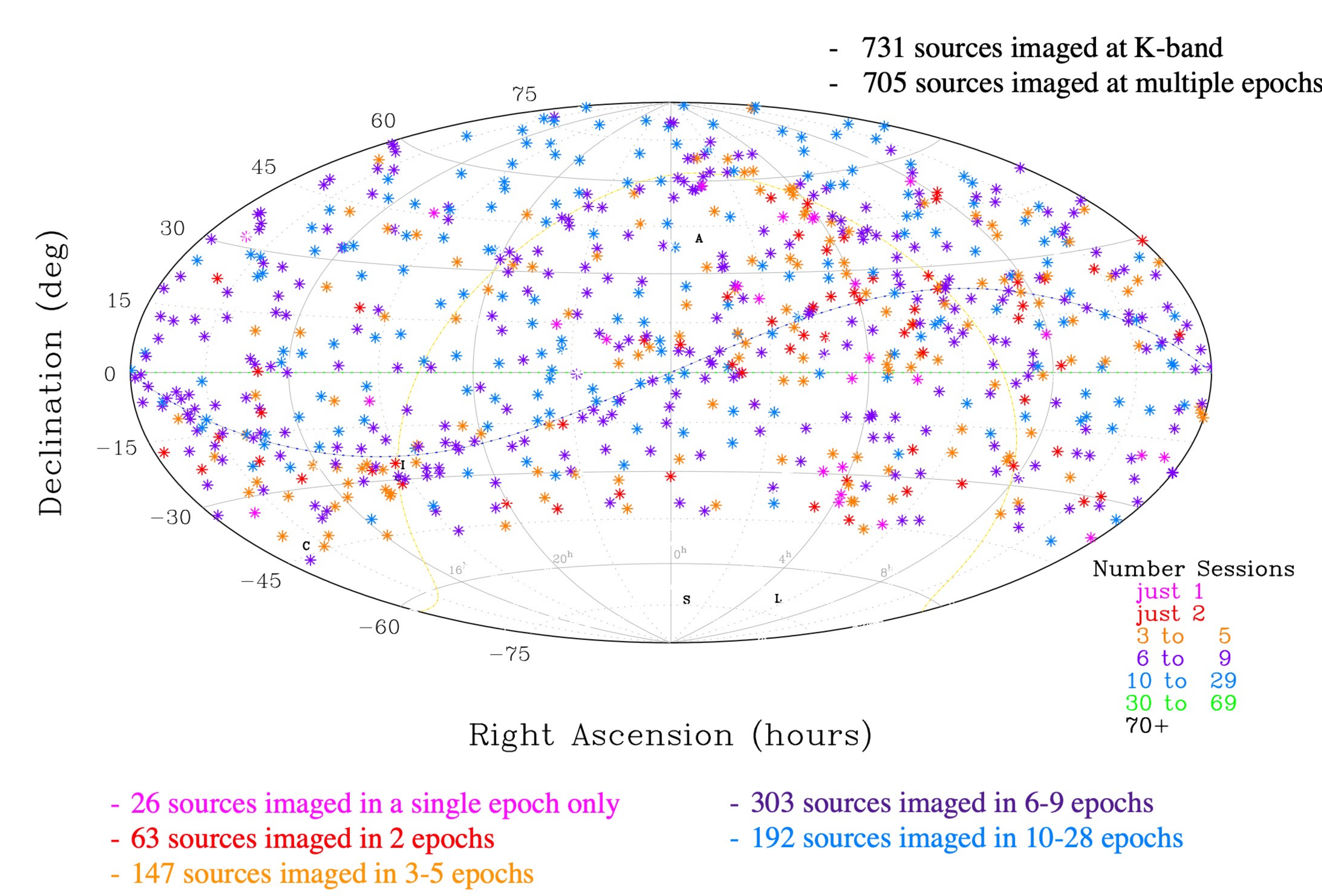

Figure 8. Sky distribution of 731 sources imaged at K-band (24 GHz).
These K-band results serve as proxies for images at Ka-band where no imaging network exists.

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Publications

[A] P. Charlot, C.S. Jacobs, et al, 'The Third Realization of the International Celestial Reference Frame by Very Long Baseline,' A&A, Dec. 2020.

[B] C.S. Jacobs, A. de Witt, D. Gordon, J. Quick, J. McCallum, M. Nickola,S. Horiuchi, L. Neira, D. Firre, J. DeVicente, Y. Murata, H. Takeuchi, `K and X/Ka Celestial Frames,' U.S. VLBA Navigation and Reference Frame Virtual Workshop, 9 Nov 2020.

[C] Kurtz, Stanley E.; Stander, Tinus; de Villiers, Dirk I. L.; Cerfonteyn, William; de Witt, Aletha; Ferrusca Rodriguez, Daniel; Hiriart, David; Hughes, David H.; Jacobs, Christopher; Loinard, Laurent; van den Heever, Fanie; Velaquez de la Rosa Becerra, Miguel, 'The potential for a K-band receiver on the Large Millimeter Telescope,' Proc. SPIE 11453: Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy X, 1145340, 13-19 June 2020, Yokohama, Japan published online 13 Dec 2020. https://ui.adsabs.harvard.edu/abs/2020SPIE11453E..40K/abstract. https://doi.org/10.1117/12.2563132

[D] C.S. Jacobs, Y. Murata, H. Takeuchi, S. Horiuchi, D. Firre, S. Asmar, T. Uchimura, K. Numata, `X/Ka Network Enhanced by Misasa, Japan's 54-meter antenna,' 25th Working Meeting of the EVGA, Virtual location, 14-18 Mar 2021. https://www.chalmers.se/en/conference/EVGA2021/Documents/EVGA2021_abstractbook.pdf

[E] A. de Witt, C.S. Jacobs, D. Gordon, M. Nickola, A. Bertarini, `K-band Imaging of 731 ICRF-3 sources,' 25th Working Meeting of the EVGA, Virtual location, 14-18 Mar 2021. . https://www.chalmers.se/en/conference/EVGA2021/Documents/EVGA2021_abstractbook.pdf

[F] A. de Witt, S. Basu, P. Charlot, D. Gordon, C. Jacobs, M. Johnson, H. Krasna, K. Le Bail, F. Shu, O. Titov, M. Schartner, `Improving the S/X Celestial Reference Frame in the South: A Status Update,' 25th Working Meeting of the EVGA, Virtual location, 14-18 Mar 2021. . https://www.chalmers.se/en/conference/EVGA2021/Documents/EVGA2021_abstractbook.pdf

[G] Soriano, J. Kooi, J. Bowen, A Fung, D. Hoppe, R. Mathena, Z. Abdulla, L. Samoska, C. Jacobs, `Simultaneous X- and Ka-Band Receiver for Astrometry and Navigation,' URSI GASS 2021, Rome, Italy, 28 Aug - 4 Sep 2021. https://www.ursi2021.org

[H] C. Jacobs, P. Kroger, C. Volk, Ka-band Radio Source Catalog, DSN 810-005 module 108 rev A, JPL, 12 Nov 2020. https://deepspace.jpl.nasa.gov/dsndocs/810-005/108/108.pdf

[I] D. Gordon, A. de Witt, C. Jacobs, 'The Position and Proper Motion of SgrA* in the ICRF3 Frame from VLBI Absolute Astrometry,' AJ, in prep. 2021.

[J] A. de Witt, C. Jacobs, D. Gordon, et al, 'The Celestial Frame at K-band: Imaging,' AJ, in prep. 2021.

[K] D. Gordon, A. de Witt, C. Jacobs, et al, 'The Celestial Frame at K-band: Astrometry,' AJ, in prep. 2021.

The ICRF3 paper above (Charlot, Jacobs et al, A&A, 2020) re-defined the official International Astronomical System (IAU) system of angular coordinates on the sky (RA, Dec). It has already been cited 61 times in less than a year.

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