15th European VLBI Network Symposium
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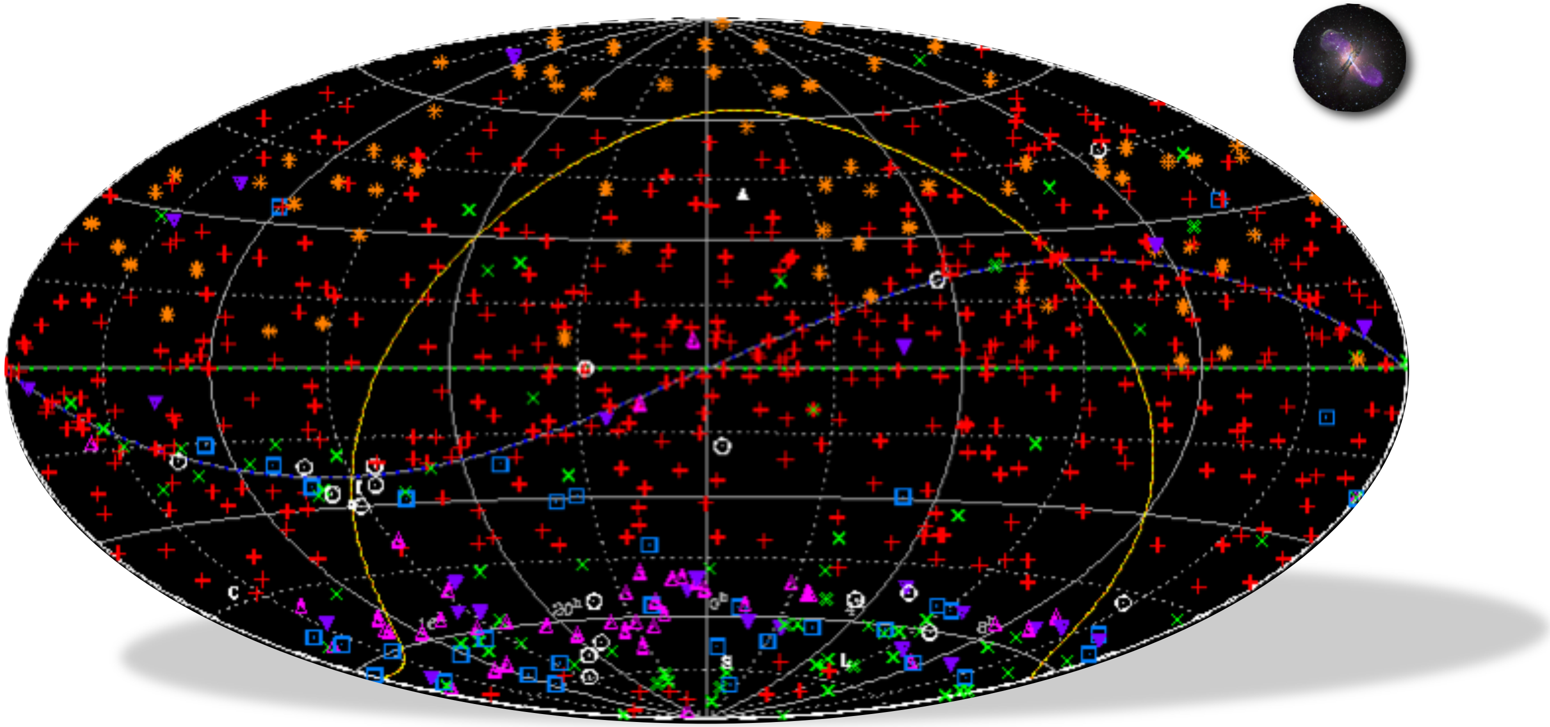
The Accuracy of the JPL 2022c X/Ka Celestial Reference Frame



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Outline

- Why Build a Celestial Frame at X/Ka-band. (8.4/32 GHz) ?
- X/Ka Frame has been a part of ICRF-3 since 2019 Jan 01.
- X/Ka ground station network geometry has limited accuracy especially in Declination
  - In 2014 we added Malargüe, Argentina 34-meter.
    - This was a big step forward as it enabled full sky coverage.
  - In 2020 we added JAXA's new 54-meter at Misasa, Japan.
- X/Ka results
- Comparison to ICRF3-S/X and recent S/X celestial frame
  - The importance of accounting for full RA-Dec correlations
- Next steps to improve data and analysis.

Why build a Celestial Reference Frame at X/Ka?

- Spacecraft are allocated three frequencies: S (2.3 GHz), X (8,4 GHz), Ka (32 GHz)

- S-band usefulness is decreasing rapidly
  Very few new missions at S-band
  RFI at S-band is degrading the band (Wi-Fi etc.)
  Source structure worse at low frequencies (*cf. Hunt et al, de Witt et al, IVS-GM, 2022*)

- X-band is now the "workhorse" frequency,
  but nearing structure floor at ~30 μas? (*LeBail, EVGA, 2019*).
- Ka-band advantages:
  More bandwidth: 500 MHz allocation, spacecraft tones can spread up to 200 MHz
  Higher telemetry rates
  Solar plasmas effect reduced as 1/ frequency squared
  This allows tracking much closer to the Sun e.g. Parker Solar Probe
  Core shift reduced as 1/ frequency
  X/Ka dual-band calibrates ionosphere (solves K-band ion calibration issue)
  More compact structure than S/X (*Hunt et al IVS-GM 2022; de Witt et al, IVS-GM, 2022 and this meeting*)

Current Status of X/Ka Celestial Frame

Current Status of X/Ka Celestial Frame

- 680 sources
  Ka-band 32 GHz, 500 MHz spanned bandwidth
  X-band 8.4 GHz, 400 MHz spanned bandwidth

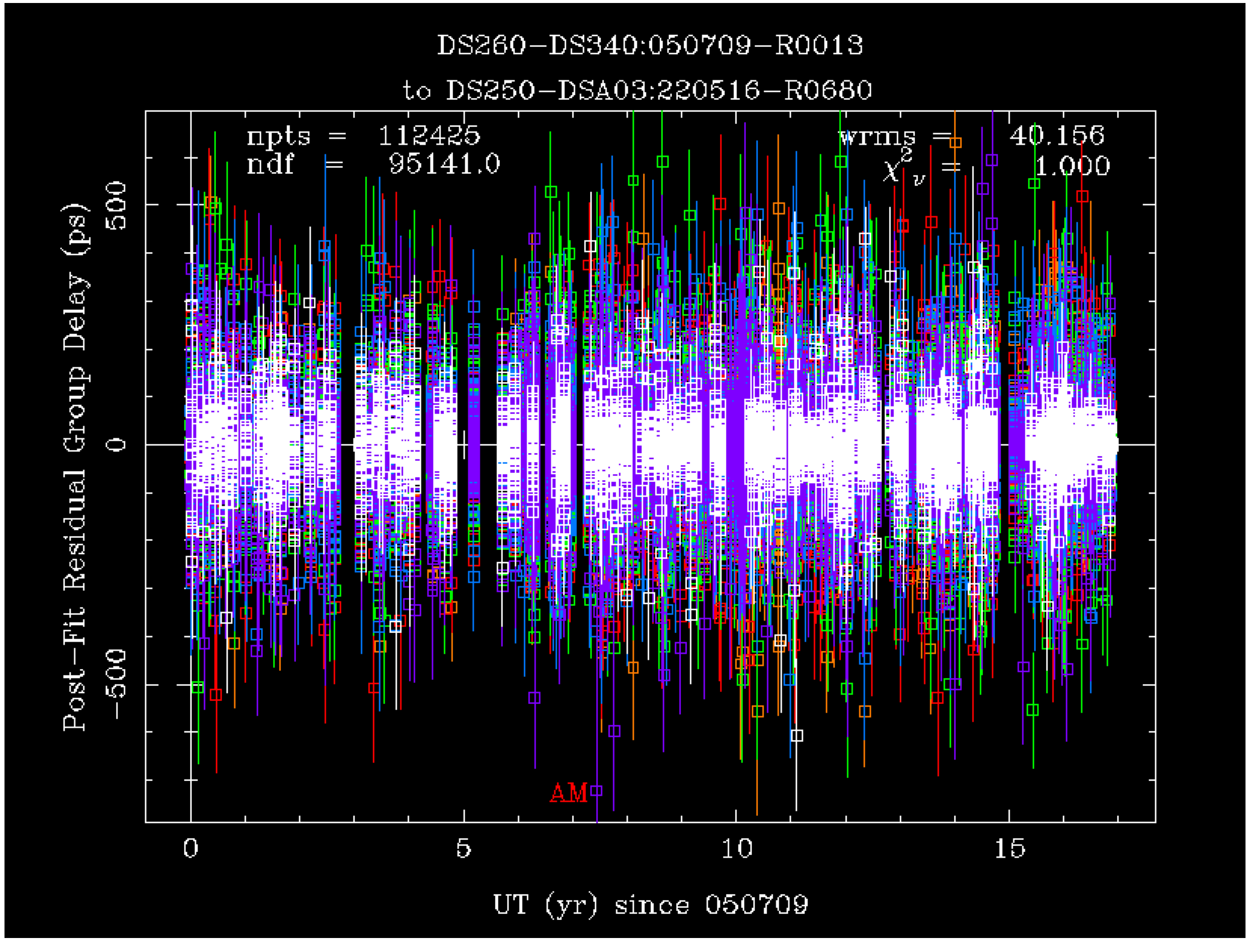
- Observed 2005 July until 2022 May
  Started at 56 Mbps in 2005
  at 2048 Mbps since 2014

- 249 single baseline sessions
  7 baselines, mostly 3 baselines
  using pairs of 34-meters
  all baselines > earth radius

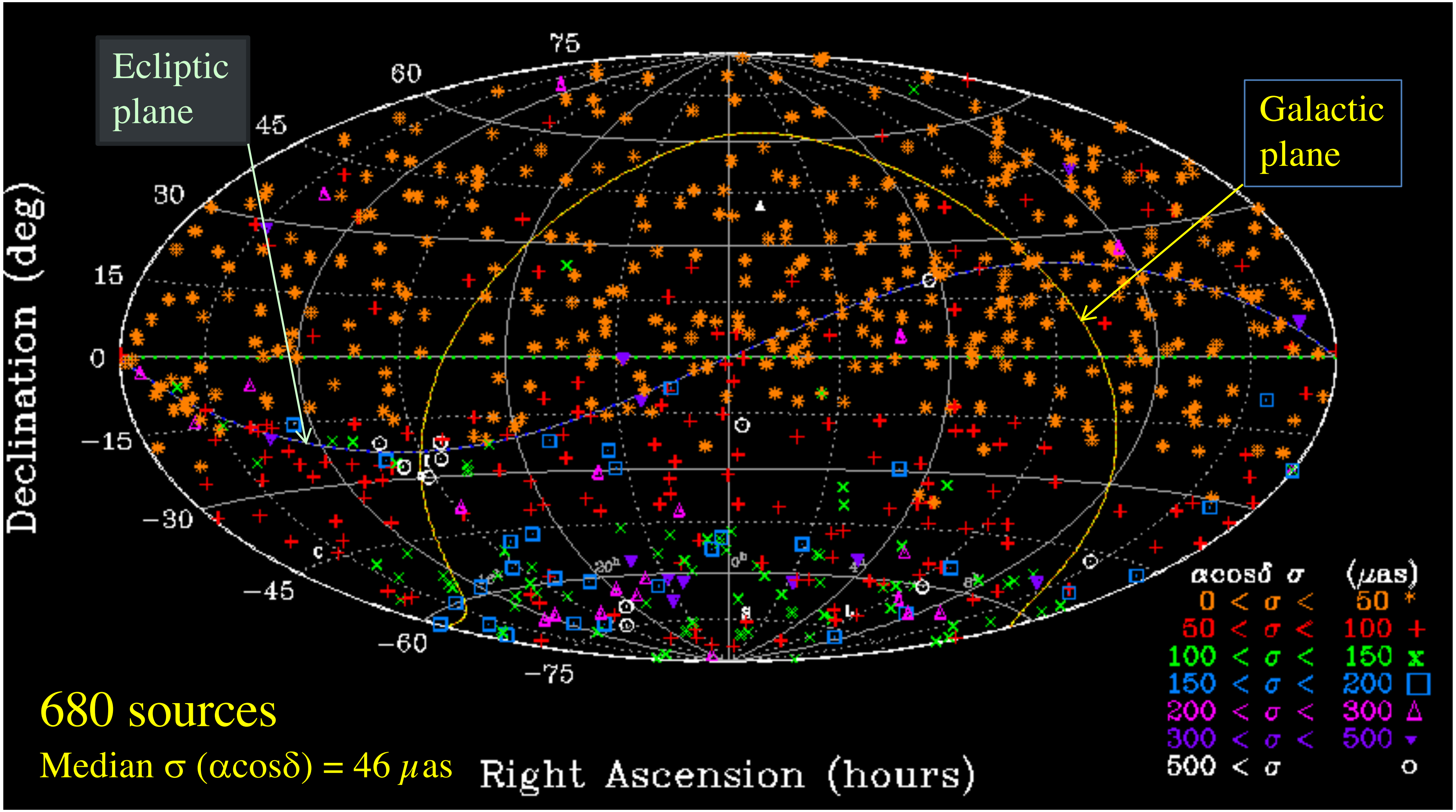
- 112, 425 observations,
  40 psec wRMS scatter

- **XKa-2022c**
  Median σ (αcosδ) = 46 μas
  Median σ (δ) = 65 μas

  ICRF3-SX
  Median σ (αcosδ) = 56 μas
  Median σ (δ) = 78 μas



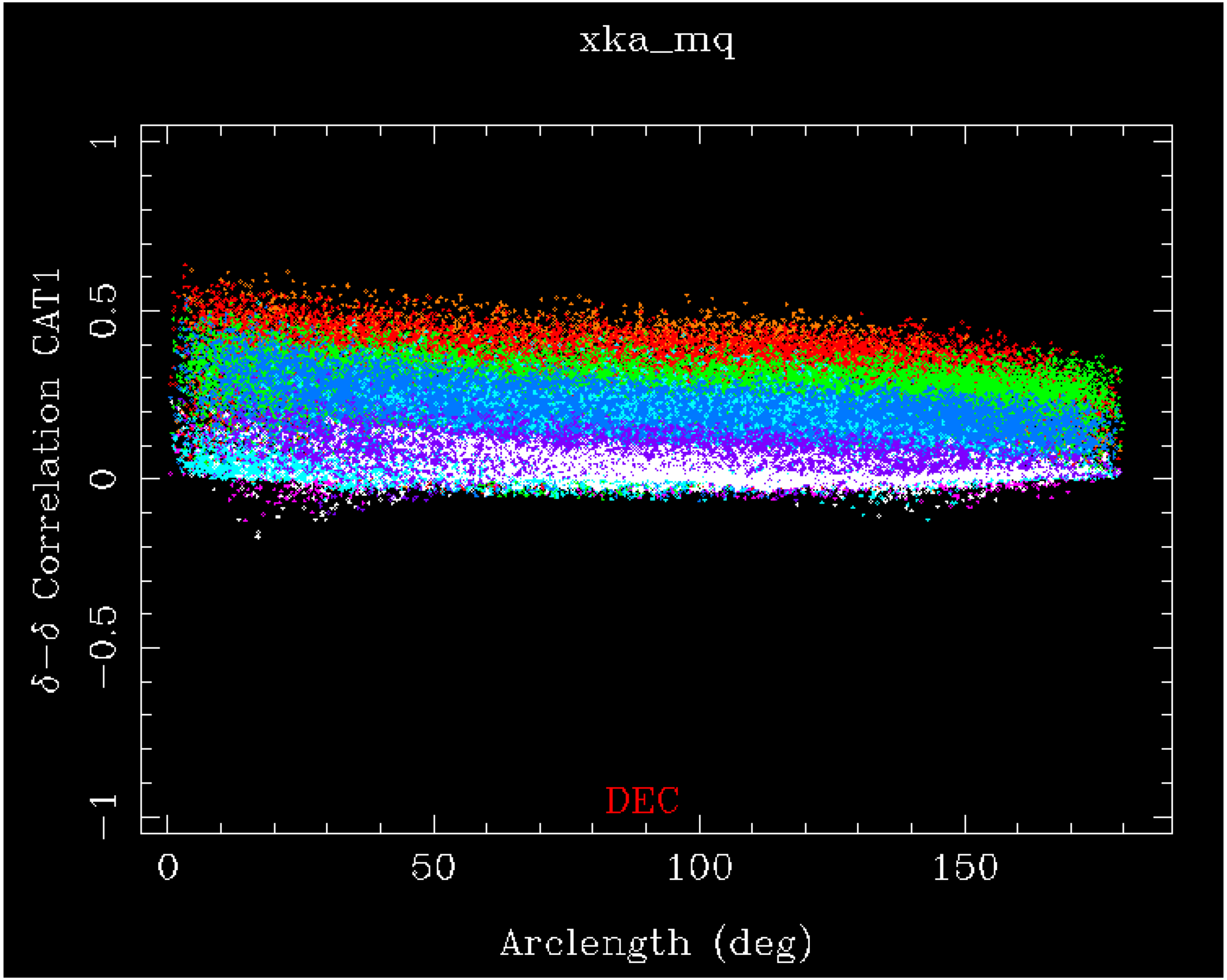
Ka (32 GHz, 9mm) Right Ascension sigmas (precision)



• Strengths:
- Uniform spatial density
- less structure than S/X (3.6cm)
- needed only 0.12 million observations
  vs. K-band 1.8 million
  vs. SX's 16.5 million!

• Weaknesses:
- Poor near Galactic center due to inter-stellar media scattering
- South weak due to limited time on ESA's Argentina station
- Limited Argentina-California data makes vulnerable to δ zonals
- Limited Argentina-Australia weakens δ from -45 to -60 deg
- Misasa, Japan just started

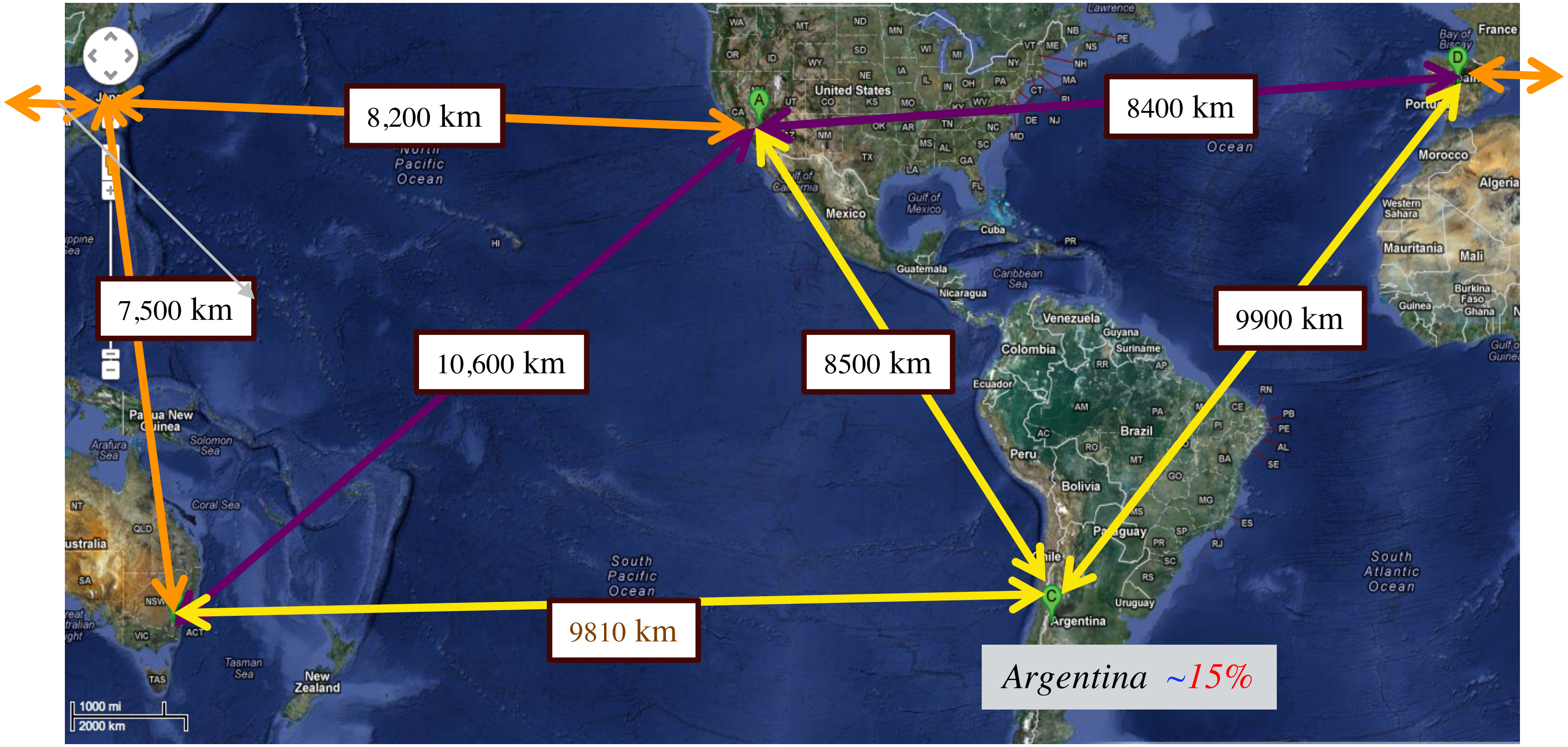
XKa: δ_i - δ_j correlations vs. arclength



Inter-source correlations almost all in range of 0 to 0.5
while any individual correlation is small, there is a cumulative effect.

Ka-band combined NASA/ESA/JAXA Deep Space

ESA Argentina to NASA-California under-observed by order of magnitude!
JAXA Misasa. Japan just started in Nov 2020



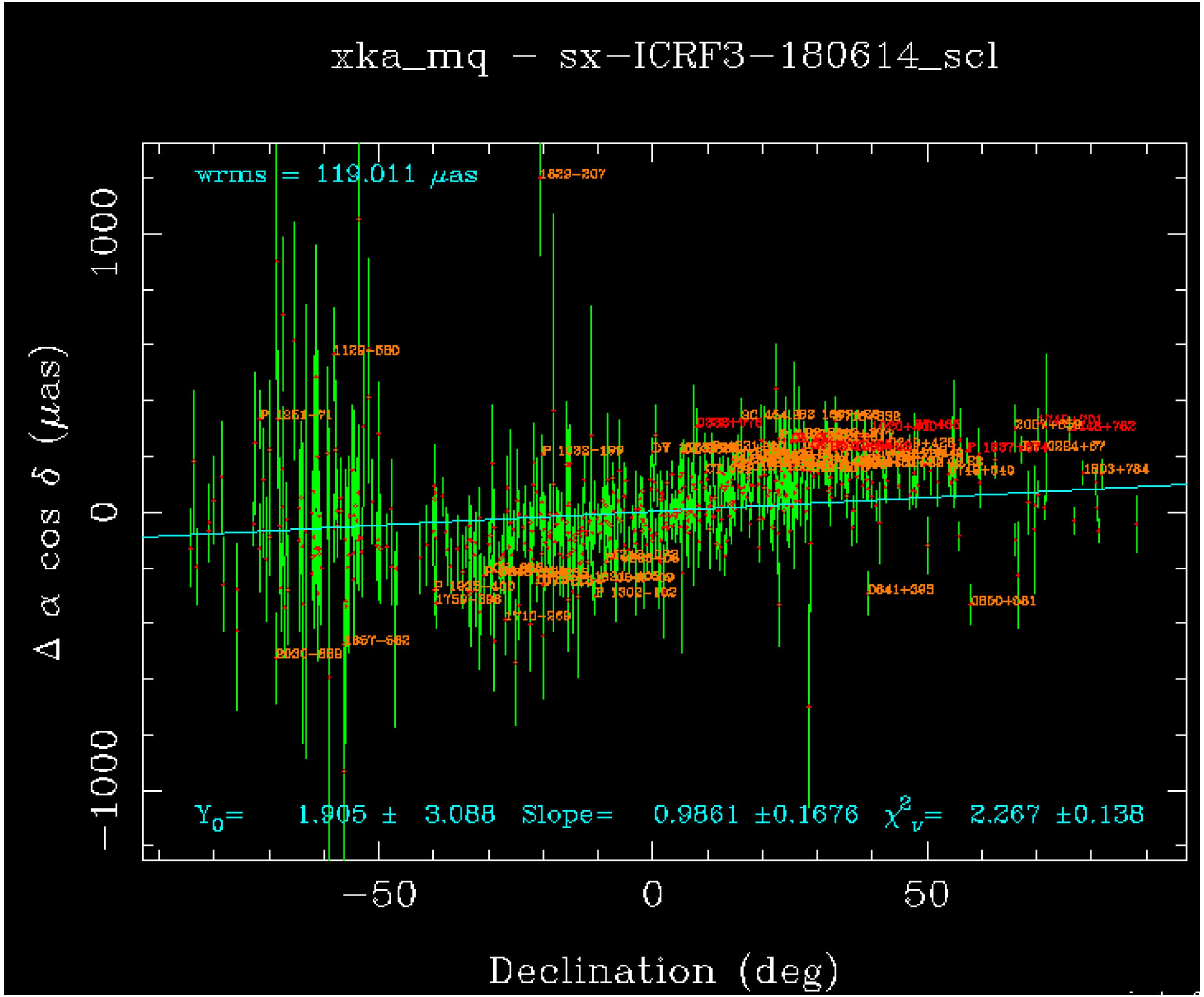
Maps credit: Google maps

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

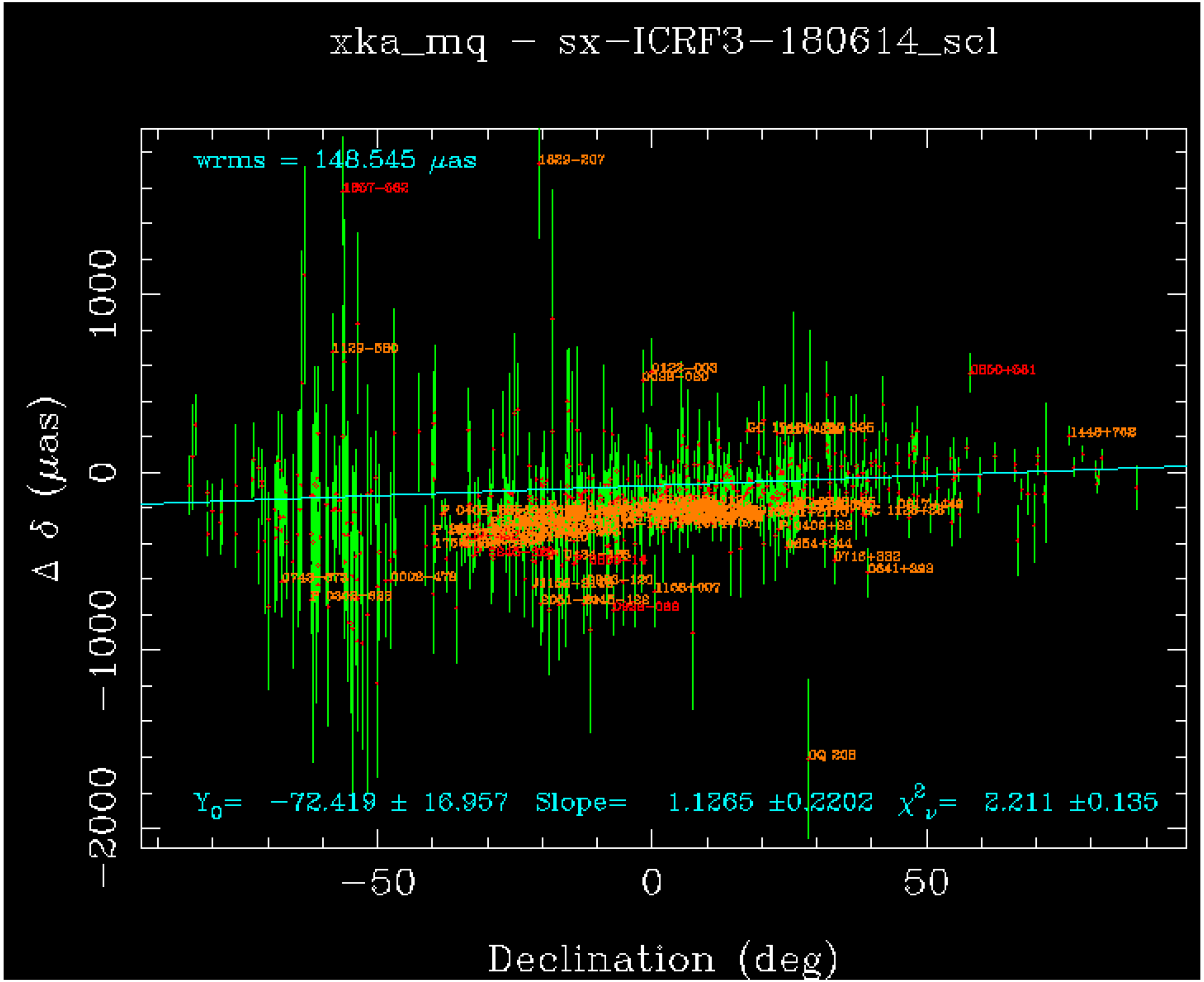
JAXA's Misasa, 54-meter antenna adds another 3 baselines

XKa vs. SX-ICRF3: RA Zonal errors



Zonal Errors Δαcosδ ~ sin (2δ):   Quadrupole 2,0 = 142 +- 1 μas
Suspect North-South tradeoffs of troposphere and Celestial Frame

XKa vs. SX-ICRF3: Dec Zonal



Zonal Errors $\Delta\delta \sim \cos\delta$: Dipole Z = -74 +- 45 μas

Dipole Z precision is 3 times weaker than X or Y dipole terms. Need stronger geometry

ICRF3-X/Ka vs. ICRF3-S/X *(Charlot et al, 2020)*

Spherical Harmonic Differences for 546 common sources (~10% outliers removed)

Diagonal covariance for XKa RA, Dec

Parameter_name		value		sigma		scaled_σ	norm	norm+scale
R1 rotation_X	=	32.9	+-	7.1	μas	8.6		
R2 rotation_Y	=	-0.3	+-	7.1	μas	8.6		
R3 rotation_Z	=	-6.5	+-	4.6	μas	5.5		
Dipole-1	=	2.8	+-	6.6	μas	8.1		
Dipole-2	=	36.9	+-	6.6	μas	8.0		
Dipole-3	=	-331.4	+-	6.6	μas	8.0	-50.2σ,	-41.4σ
Quad 20 Mag (Δα ~sin2δ)	=	196.0	+-	6.4	μas	7.8	30.6σ,	25.1σ
Quad 20 Elc (Δδ ~sin2δ)	=	78.1	+-	8.8	μas	10.7		

Full covariance (include inter-source correlations)

Parameter_name		value		sigma		scaled_σ	norm	norm+scale
R1 rotation_X	=	12.0	+-	6.4	μas	9.2		
R2 rotation_Y	=	1.3	+-	6.6	μas	9.5		
R3 rotation_Z	=	-6.6	+-	4.4	μas	6.3		
Dipole-1	=	9.8	+-	12.3	μas	17.7		
Dipole-2	=	39.0	+-	11.9	μas	17.1		
Dipole-3	=	-87.8	+-	43.5	μas	62.5	-2.0σ,	-1.4σ
Quad 20 Mag (Δα ~sin2δ)	**=**	**196.5**	**+-**	**15.5**	**μas**	**22.3**	**12.7σ,**	**8.8σ**
Quad 20 Elc (Δδ ~sin2δ)	=	-9.4	+-	21.8	μas	31.4		

Comparisons of zonal differences vs. Time.

Spherical Harmonic Differences for common sources (~10% outliers removed)

Z-Dipole: $\Delta\delta$ ~ cos δ

	Diagonal covariance		Full α–δ covariance	
XKa-ICRF3 vs. SX-ICRF3	-331 μas	(−41.4σ)	-88 μas	(−1.4σ)
XKa 2022c vs. SX-ICRF3	-156 μas	(−22.2σ)	-74 μas	(−1.6σ)
XKa 2022c vs. SX-220703 scale. σ	-151 μas	(−22.4σ)	-58 μas	(−1.3σ)
XKa 2022c vs. SX-220703 formal σ	-152 μas	(−22.0σ)	-15 μas	(−0.3σ)

→ **Proper accounting of geometric correlations accounts for weakly determined but insignificant Z-Dipole**

Quadrupole 2,0 magnetic term: $\Delta\alpha\cos\delta$ ~ sin 2δ

	Diagonal covariance		Full α–δ covariance	
XKa-ICRF3 vs. SX-ICRF3	196 μas	(25.1σ)	197 μas	(8.8σ)
XKa 2022c vs. SX-ICRF3	177 μas	(38.4σ)	142 μas	(7.7σ)
XKa 2022c vs. SX-220703_scale σ	169 μas	(25.6σ)	127 μas	(7.0σ)
XKa 2022c vs. SX-220703 formal σ	174 μas	(27.6σ)	94 μas	(4.2σ)

Next Steps for X/Ka Frame: Better Data

- More JAXA Misasa 54-meter North-South baseline data

- ESA Malargüe upgrading front end:
  300 MHz → 500 MHz 1st use 2022 May 16: 30 psec wRMS
  Data rate increased from 1.792 Gbps to 2.048 Gbps.

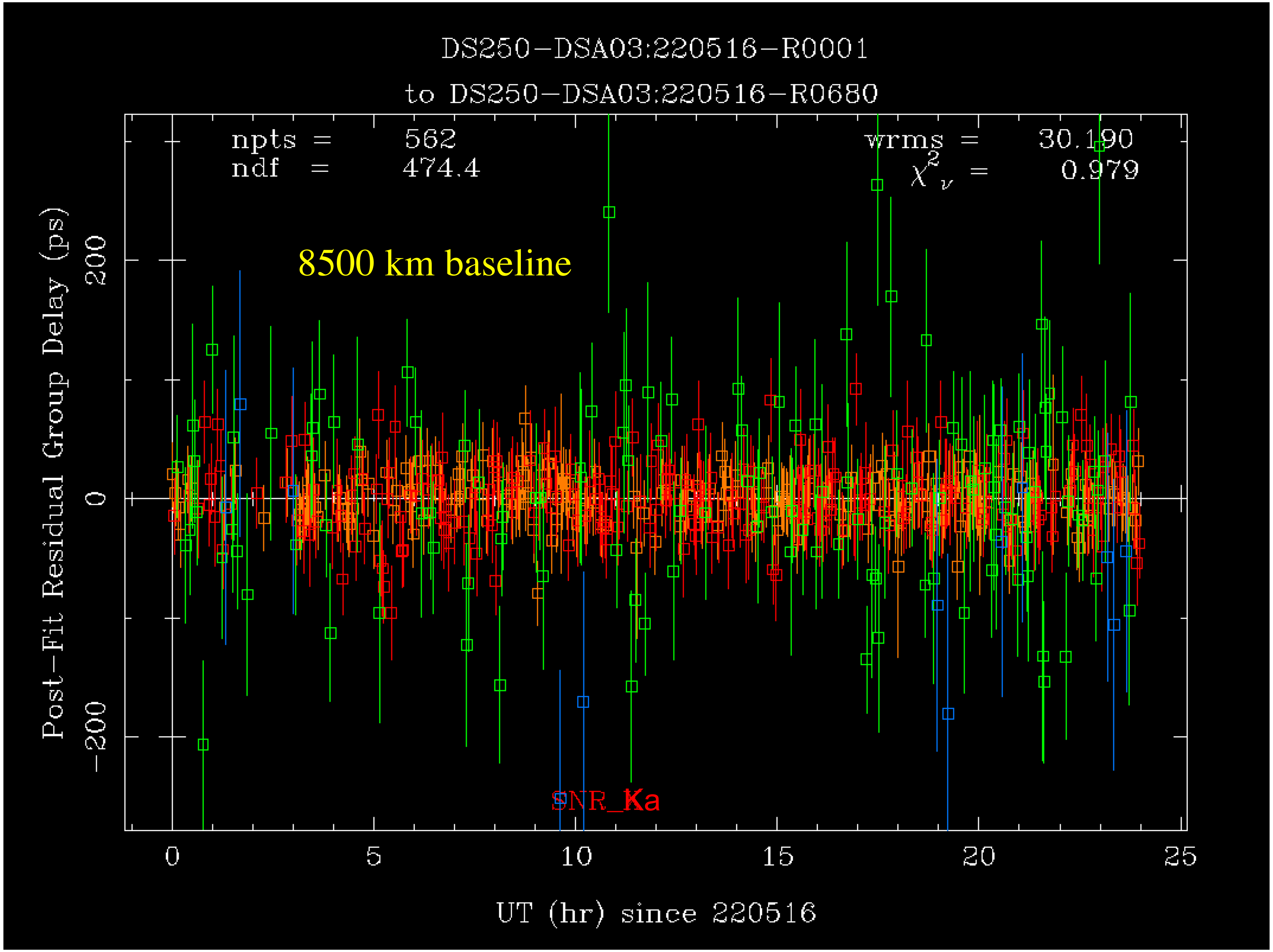
  Fully cooled: zenith Tsys 80K → 40K in about a year

- DSN Ka-band pointing thermal deformations calibrated in realtime?
- DSN has potential for 4 Gbps: 2 Gbps RCP + 2 Gbps LCP
  (*not funded at this time*)

- VLBA: Potential for 8-36 GHz broadband System (*Kooi et al, 2022*)
  This would add 45 baselines and solve the sparse Ka network issue.
  Increase analog bandwidth from 0.5 GHz to 4 GHz
  → almost factor of three in sensitivity,
  → potential for order of magnitude improvement in delay precision

Malargüe front end upgrade 300 -> 500 MHz

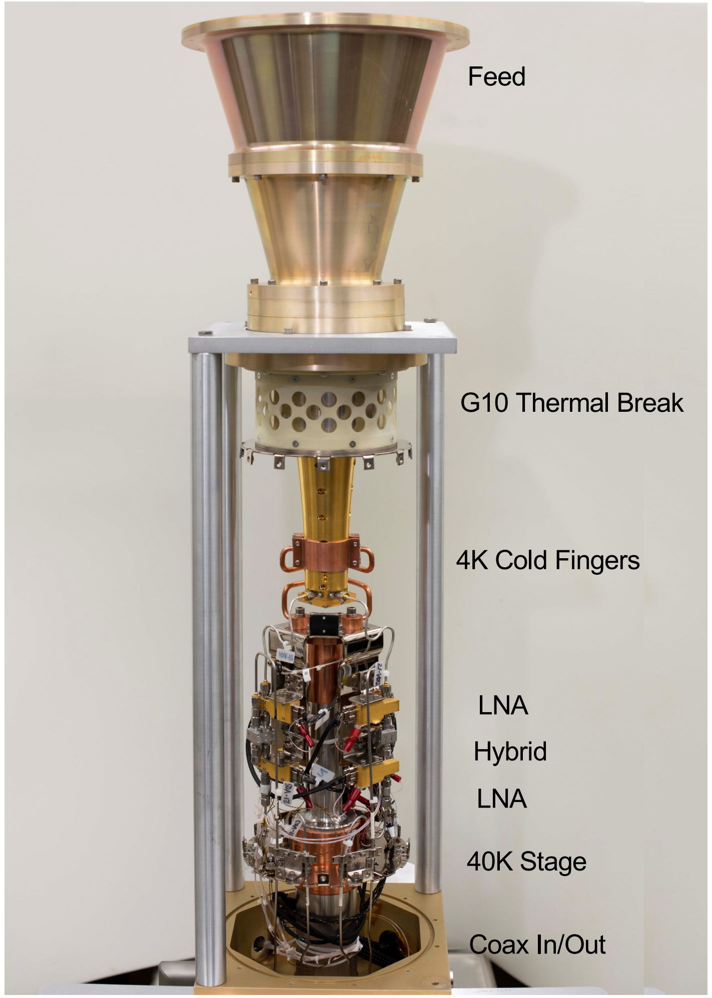
trops 30min
clock ~24h



First light: 2022 May 16, Argentina to California 8500 km baseline

JPL broadband 8-36 GHz for VLBA *(Kooi et al, 2022)*

Receiver System On-Sky Testing



Receiver unit on roof of JPL Telecommunications building

Supports X, Ku, K, Ka-bands each band starts at 1 GHz, later 4 GHz

VLBA Installation preparations
for 8-36 GHz broadband at OVRO

View from above

View from below

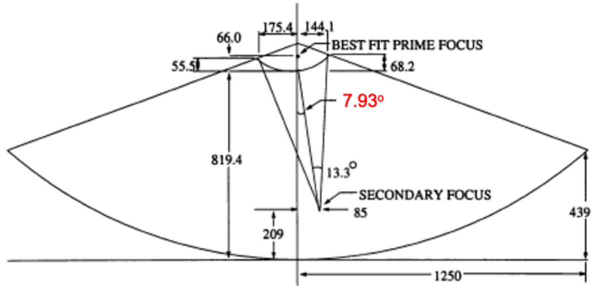
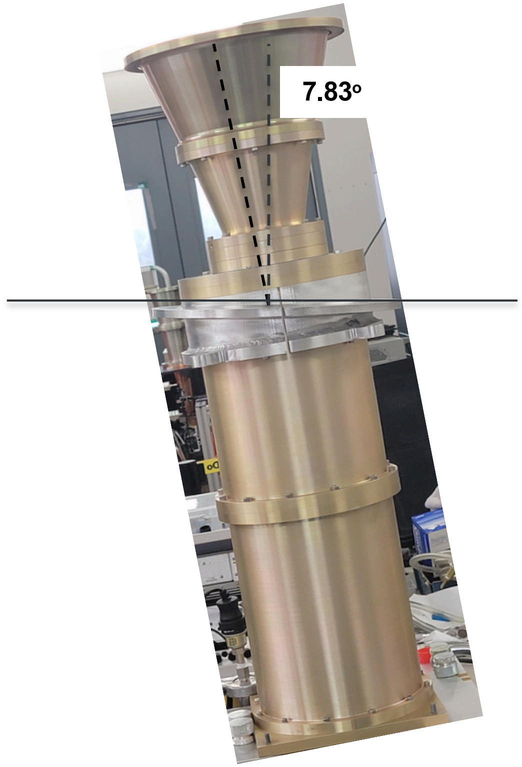


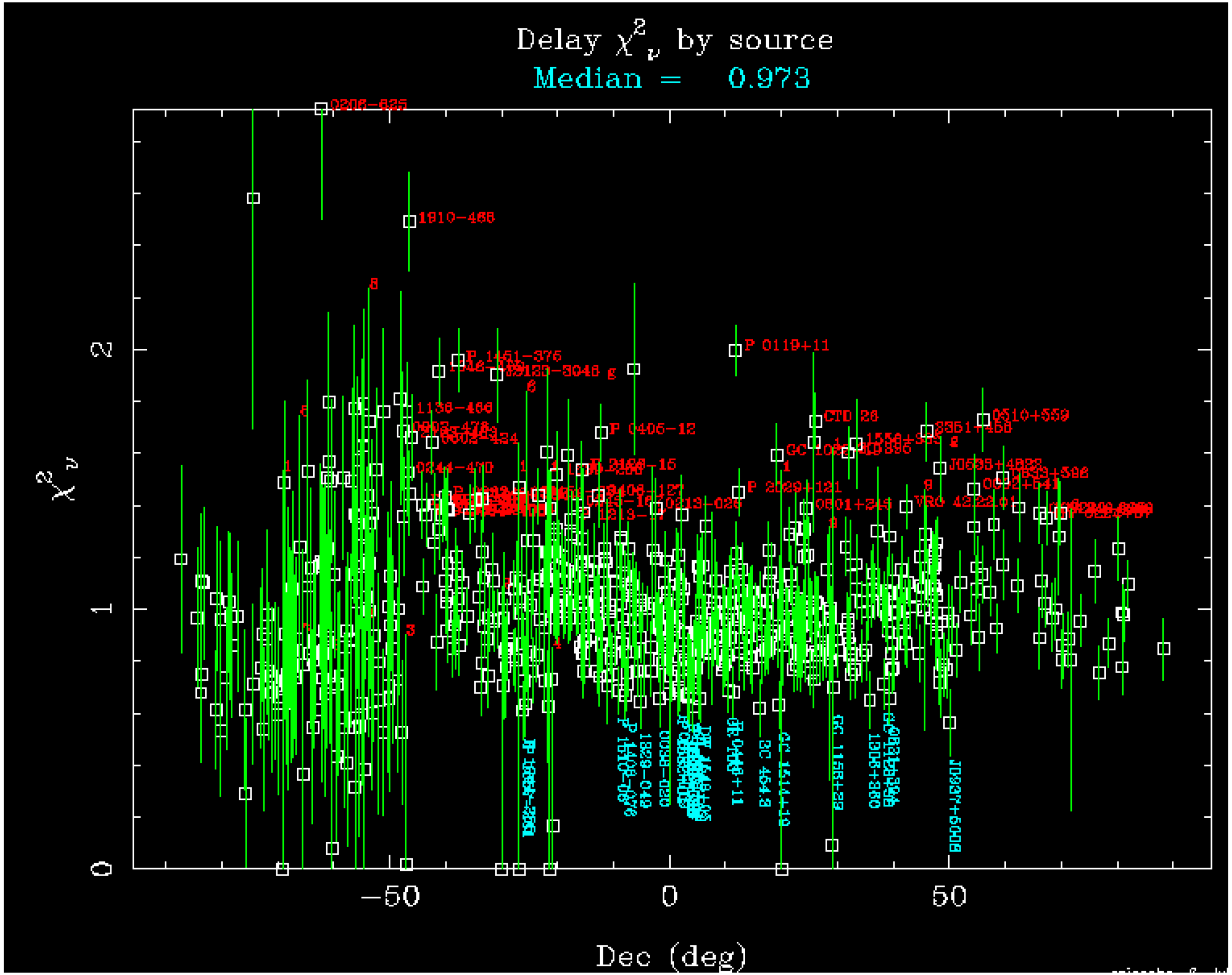
Figure 4.4: VLBA offset Cassegrain geometry, dimensions in cm.



(Kooi et al, 2022)

Delay χ^2 by source:

evidence of some small structure for ~10% of sources



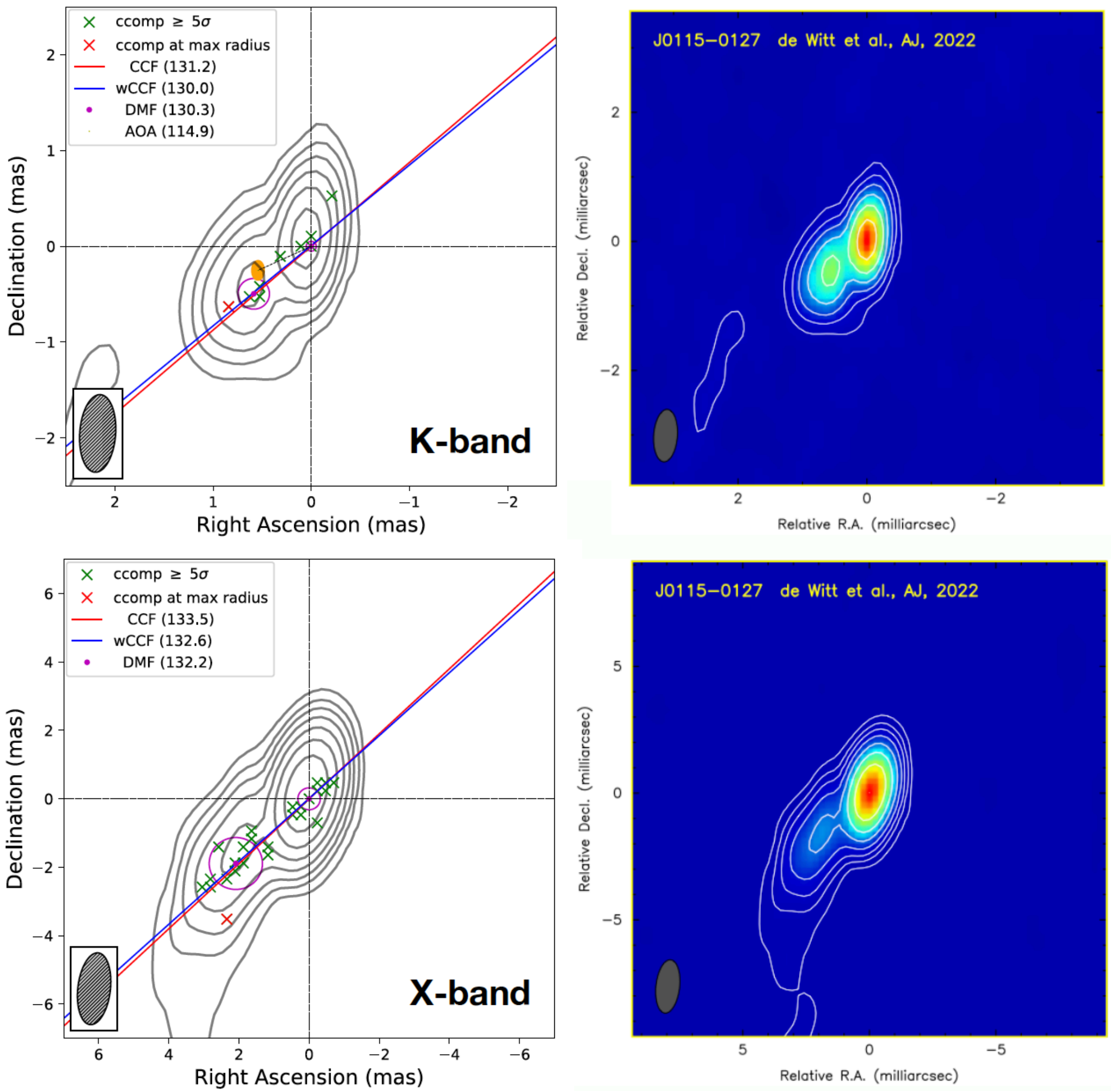
Frequency Dependent positions

0112-017 *(de Witt et al, 2022)*

Source structure can bias position along jet direction.

This explains most outliers > 5σ for X vs. K-bands.

No Ka imaging yet, but working on Ka-band system for VLBA.



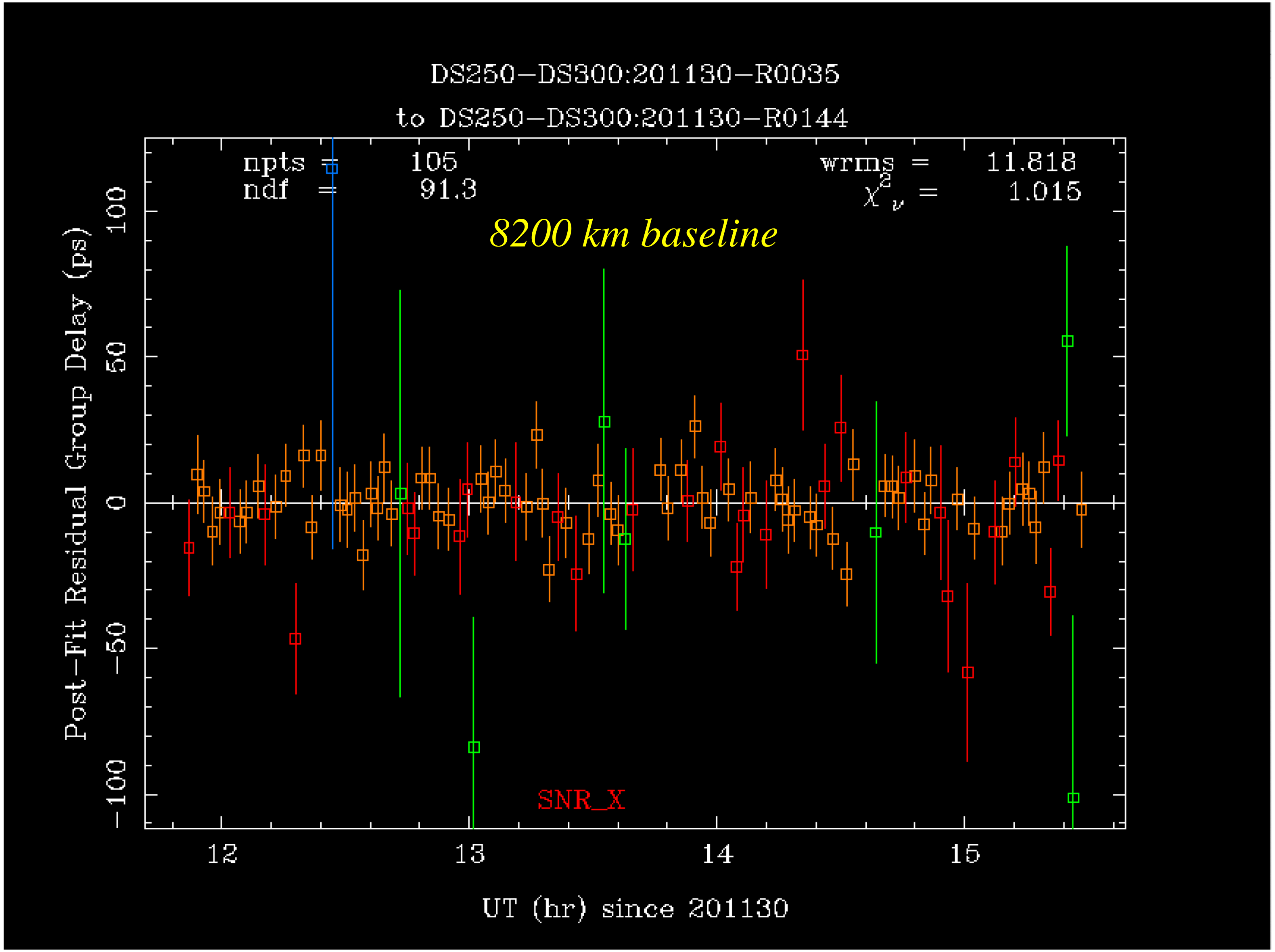
JAXA's Misasa 54m: online November, 2020

8200 km baseline, cold winter session, wet trop. frozen out

Misasa, Japan to Goldstone, CA: *2020 Nov 30*

12 psec wRMS !! Thus, source structure < 12 psec

(Jacobs et al, EVGA, 2021)



Next Steps for X/Ka Frame: Better Analysis

- Character of errors is undergoing change
  from uncorrelated white noise
  to noise that has both spatial and temporal correlations.

  In 2005 at start of X/Ka, SNR was major issue:
    low data rate: 56 Mbps now 2048 Mbps
    poor Ka-band pointing (half of scans lost, now 5-10% loss)

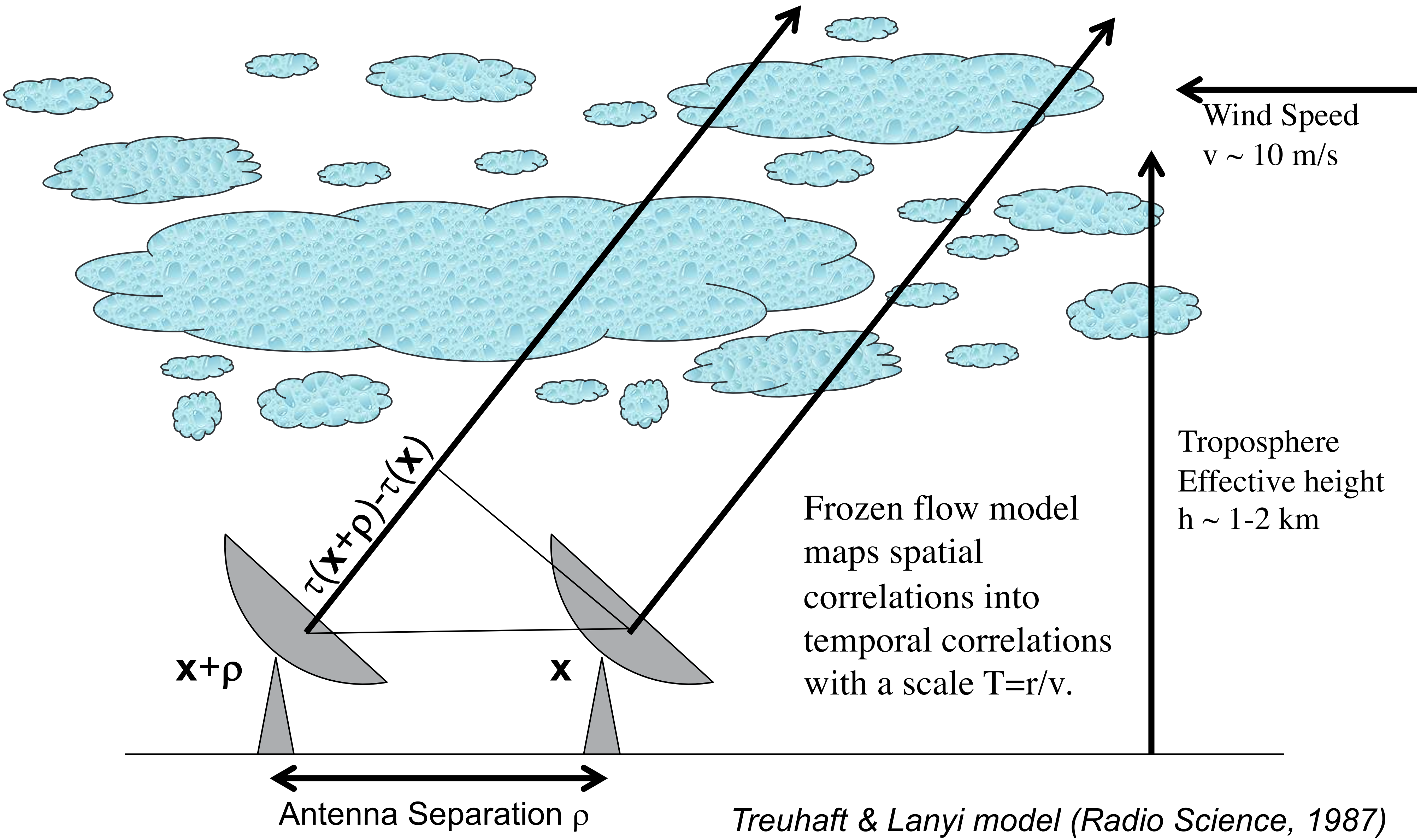
  As uncorrelated noise shrinks, correlated noise becomes more dominant.

- Revive Kolmogorov Spectrum correlated troposphere noise
  (*Treuhaft & Lanyi, Radio Sci, 1987*)

  Demonstrated to help Celestial frame at 10-20% level
  (*Romero-Wolf & Jacobs Journees 2011, IVS-GM 2012*)

- Implement correlated clock noise:
  Work underway. . .

Temporal Correlations on Delay



Frozen flow model maps spatial correlations into temporal correlations with a scale T=r/v.

Treuhaft & Lanyi model (Radio Science, 1987)

Romero-Wolf & Jacobs, Journees 2011

Summary: JPL 2022c X/Ka Celestial Frame

- **X/Ka part of ICRF-3 since 2019 Jan 01** (*Charlot, Jacobs et al, A&A, 2020*)

- **X/Ka 2022c:** 680 sources, 0.12 million observations,
- **Precision:** **Median $\sigma(\alpha \cos\delta)$ = 46, $\sigma(\delta)$ 65 μas.** **Comparable to SX and K-band CRFs.**
  Precision has been limited by lack of data on North-South baselines
  2013 added Goldstone, CA to Malargüe, Argentina
  2020 added Misasa, Japan to Tidbinbilla, Australia
  2022 upgraded Malargüe front end 300-> 500 MHz, 2023 fully cooled 80K-> 40K

- **Accuracy:** limited by systematic zonal errors vs. Declination due to network and troposphere

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→ **Proper accounting of geometry helps, but still leaves significant quadrupole 2,0**

- **Source structure:** issue for about 10% of sources
  Broadband X→Ka (8-36 GHz) for VLBA to allow Ka-band astrometry & imaging
  Prototyped tested. Fringe test at VLBA-OVRO 2^{nd} half 2022.