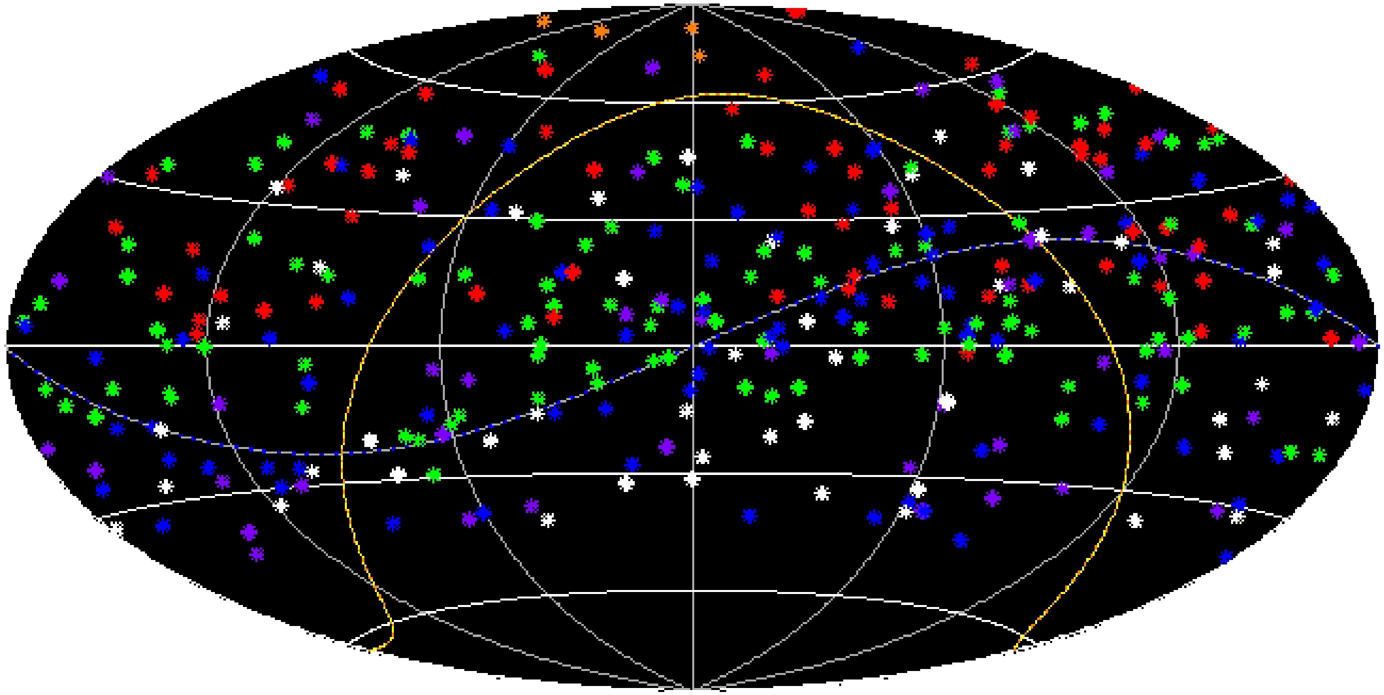
X/Ka Frame Improvements: Vision to Reality



Christopher S. Jacobs

D. Bagri, M. Britcliffe, E. Clark, M. Franco, C. Garcia-Miro, C. Goodhart, S. Horiuchi, S. Lowe, E. Moll, R. Navarro, S. Rogstad, R. Proctor, E. Sigman, L. Skjerve, M. Soriano, O. Sovers, B. Tucker, D. Wang, and L. White

JPL/Caltech/NASA

10 Feb 2010 - Session 04-T03

Outline

- **Motivation for a Celestial Frame above 8 GHz**

- **X/Ka-band frame as it exist today**
  - Accuracy: X/Ka vs. S/X based ICRF-2
  - Spatial Coverage

- **Reducing the X/Ka error budget:**
  - SNR: improved data rate 4X now, 40X within few years
  - Instrumentation:

    Ka-band phase calibrator

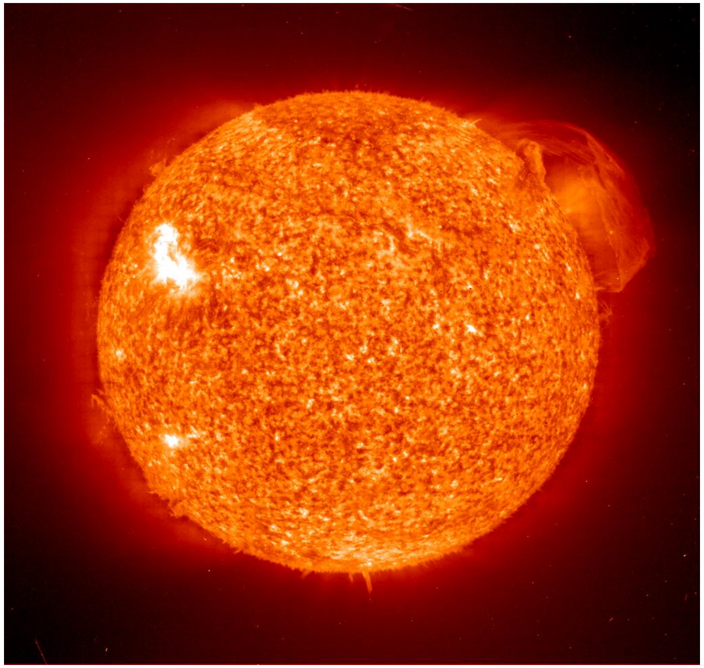
    Digital Back End
  - Troposphere calibration: (cheaper?) WVRs

Motivation

- **Astrometry, Geodesy and Deep Space navigation, now at 8.4 GHz (X-band) with 2.3 GHz (S-band) plasma calibrations**

Going to Higher radio frequencies allows

- **More *compact* sources which should lead to more *stable* positions**
- **Higher Telemetry Rates to Spacecraft**
- **Smaller, lighter RF spacecraft systems**
- **Avoid S-band *RFI* issues**
- **Ionosphere & solar plasma down 15X !! at 32 GHz (Ka-band) compared to 8 GHz thus observe closer to Sun & Galactic center**



Picture credit: SOHO/ESA/NASA

Drawbacks of Higher radio frequencies:

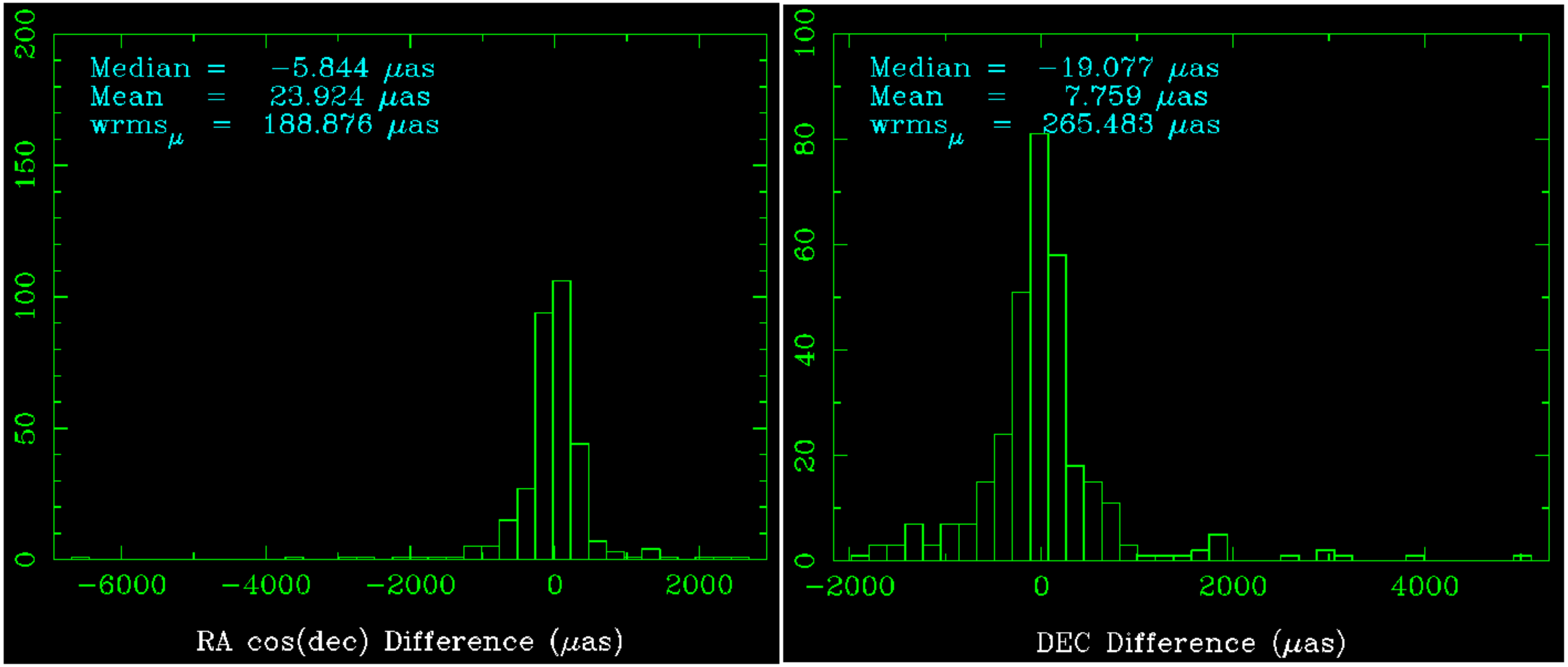
- **More weather sensitive, higher system temp.**
- **Shorter coherence times**
- **Weaker sources, Many sources resolved**
- **Antenna Pointing more difficult**

Results from Deep Space Network 8.4/ 32 GHz observations

The X/Ka Frame
current status

ΔRA, Δ Dec: X/Ka vs. S/X ICRF2

Accuracy tested vs. S/X ICRF2 the current IAU standard

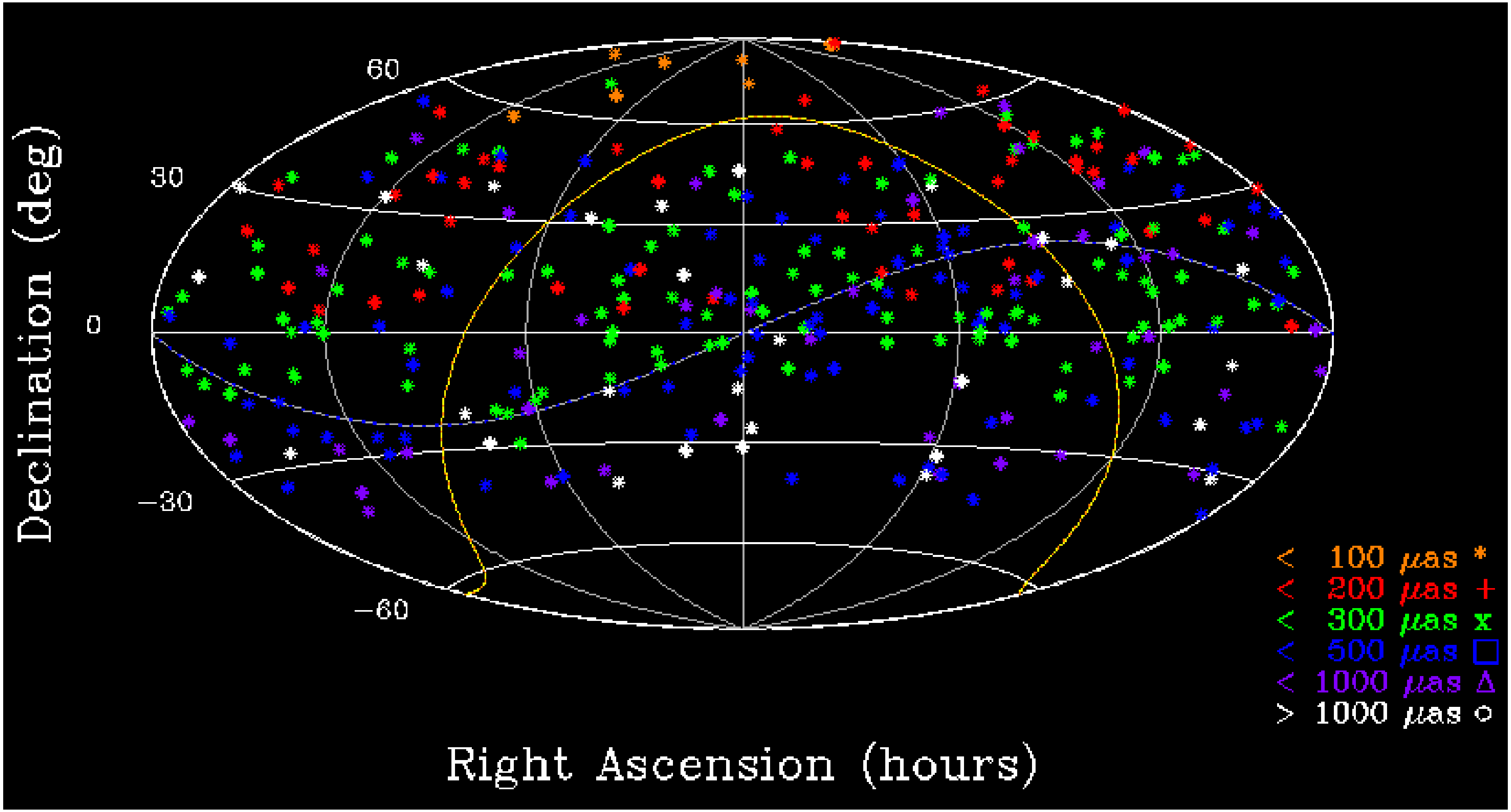


RA: 190 μas = 0.9 nrad

Dec: 265 μas = 1.3 nrad

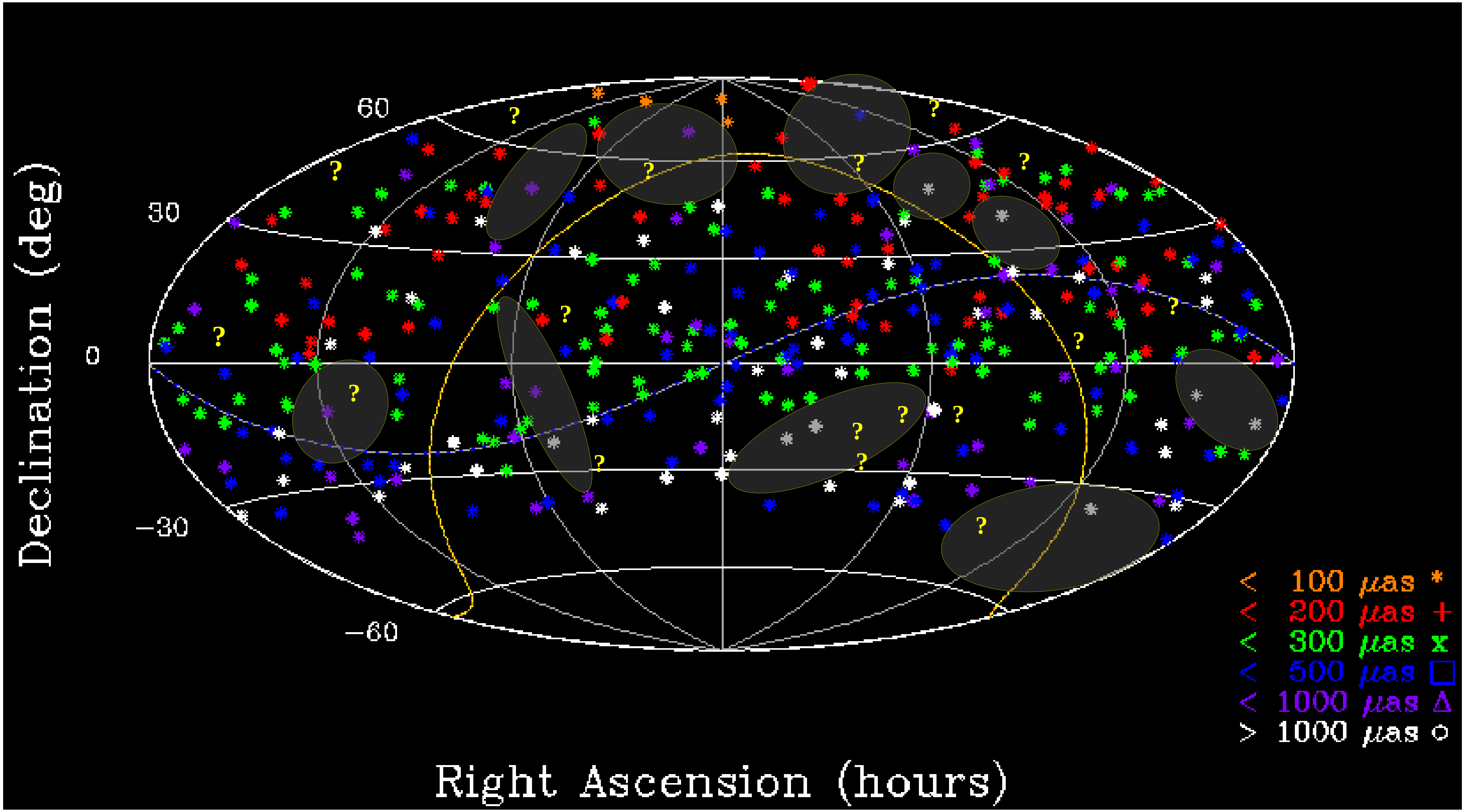
Credit: Jacobs & Sovers, EVGA, Bordeaux, 2009

X/Ka *vs.* S/X-based ICRF-2



323 common sources--at least 2 group delays, < 5mas sigma

X/Ka results: 351 Sources detected



Recent work fills holes: near Galactic plane & in south

17 candidates (marked '?') await correlation

Attacking the X/Ka Error budget:

- **SNR can be improved +8 dB!**

- Instrumentation:
  Phase calibrators
  Digital Back End

- Troposphere cals: WVR

Results have been limited by Ka-band SNR

Solution:

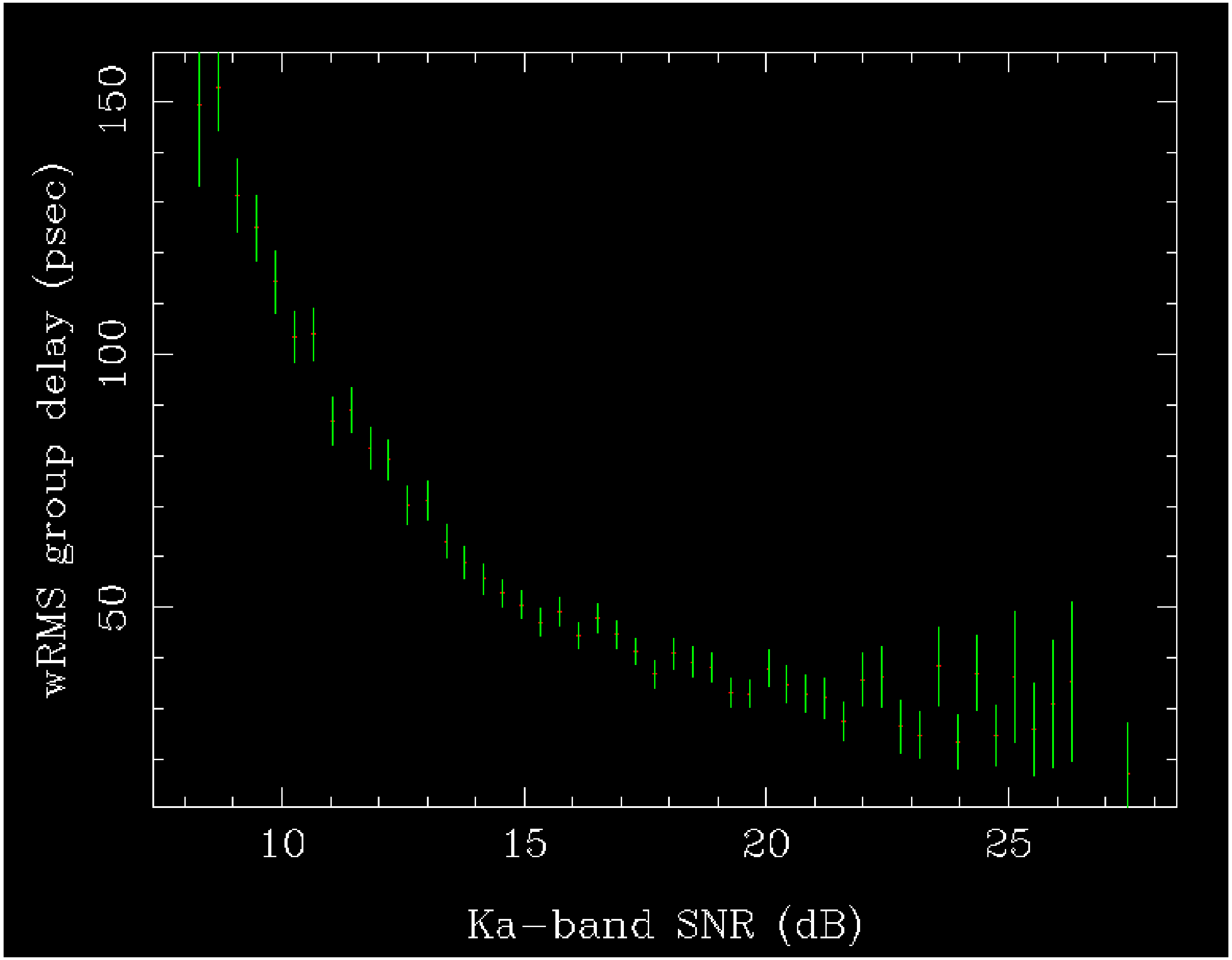
1) More bits:

4X operational
8X R&D
in ~6 months
Will yield +5 dB SNR increase

2) Ka pointing

Now with improved Pointing calibrations ~3 dB more SNR

Total vs. early passes +8 dB SNR increase!



Results have been SNR limited for SNR < 15 dB

X/Ka delay precision

Deep Space Network 34m Beam-waveguide antennas

• 47 sessions, 10K delays/rates, median delay sigma 45 psec

very small data set by S/X standards of 6 x 10e+6 delays

• **Data rate: 43 passes @ 112 Mbps (X/Ka 56/ 56 Mbps)**

3 passes @ 224 Mbps (X/Ka 80/144) ~ 3X

1 recent @ 448 Mbps (X/Ka 160/288) ~ 5X

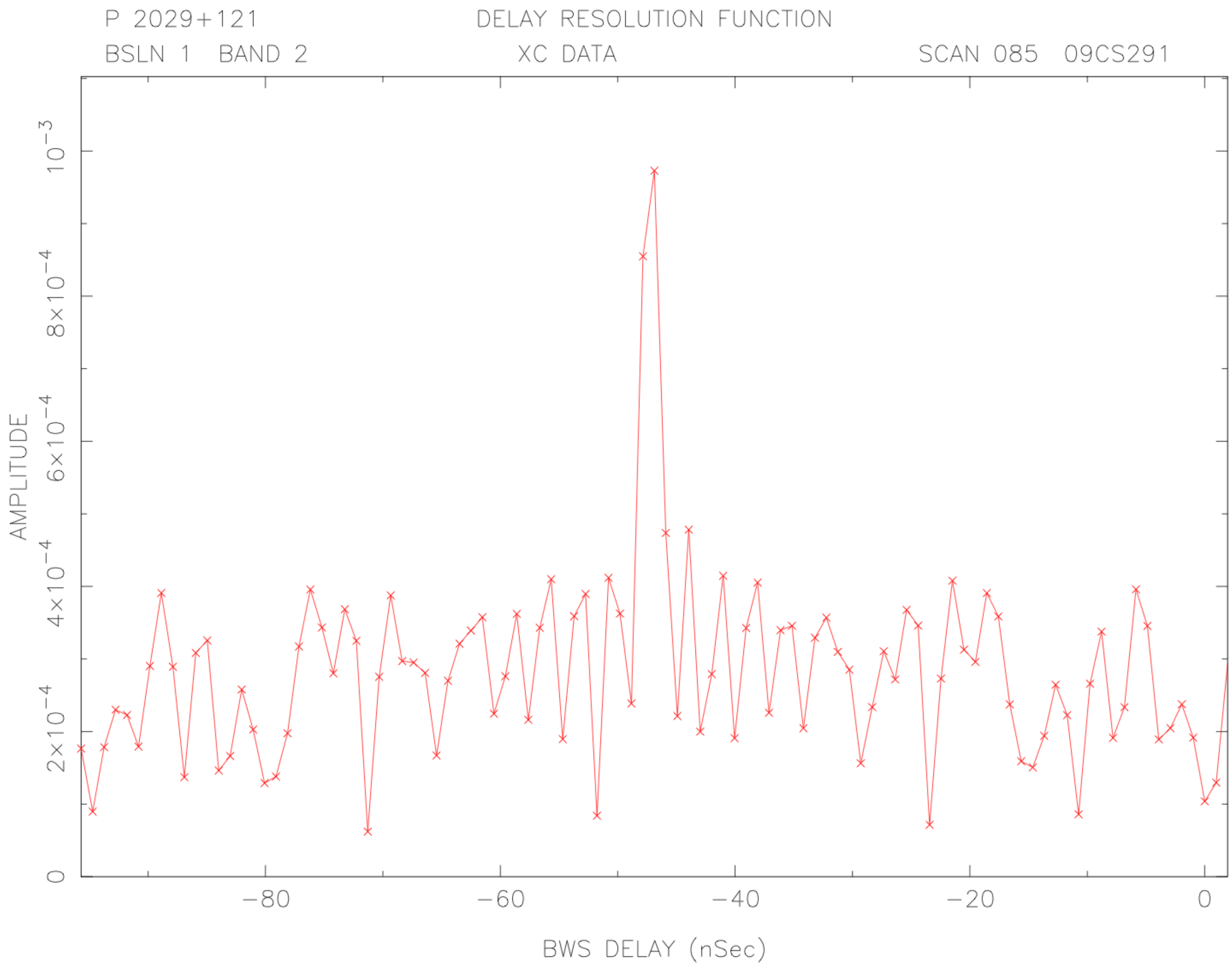
in 6 mo. @ 896 Mbps (X/Ka 320/576) ~10X

Total Ka improvement 56 to 576 Mbps => 15 psec delay precision

Reduces SNR below troposphere with +5.1dB Ka sensitivity!

Credit: C. Jacobs, D. Bagri, E. Clark, C. Garcia-Miro, C. Goodhart, S. Horiuchi, S. Lowe, E. Moll, L. Skjerve, L White

First Ka-band fringe @ 448 Mbps on Software Correlator



Credit: C. Jacobs, D. Bagri, E. Clark, C. Garcia-Miro, C. Goodhart, S. Lowe, E. Moll, L. Skjerve

Improving the X/Ka frame for the future

Attacking the X/Ka Error budget:

- SNR can be improved +8 dB!

- *Instrumentation:*
  Phase calibrators
  Digital Back End

- Troposphere cals: WVR

Results limited by No Ka-band Phase cal

Problem:

180 psec ~diurnal effect

Solution:

Ka-band Phasecal Prototype Demo'd

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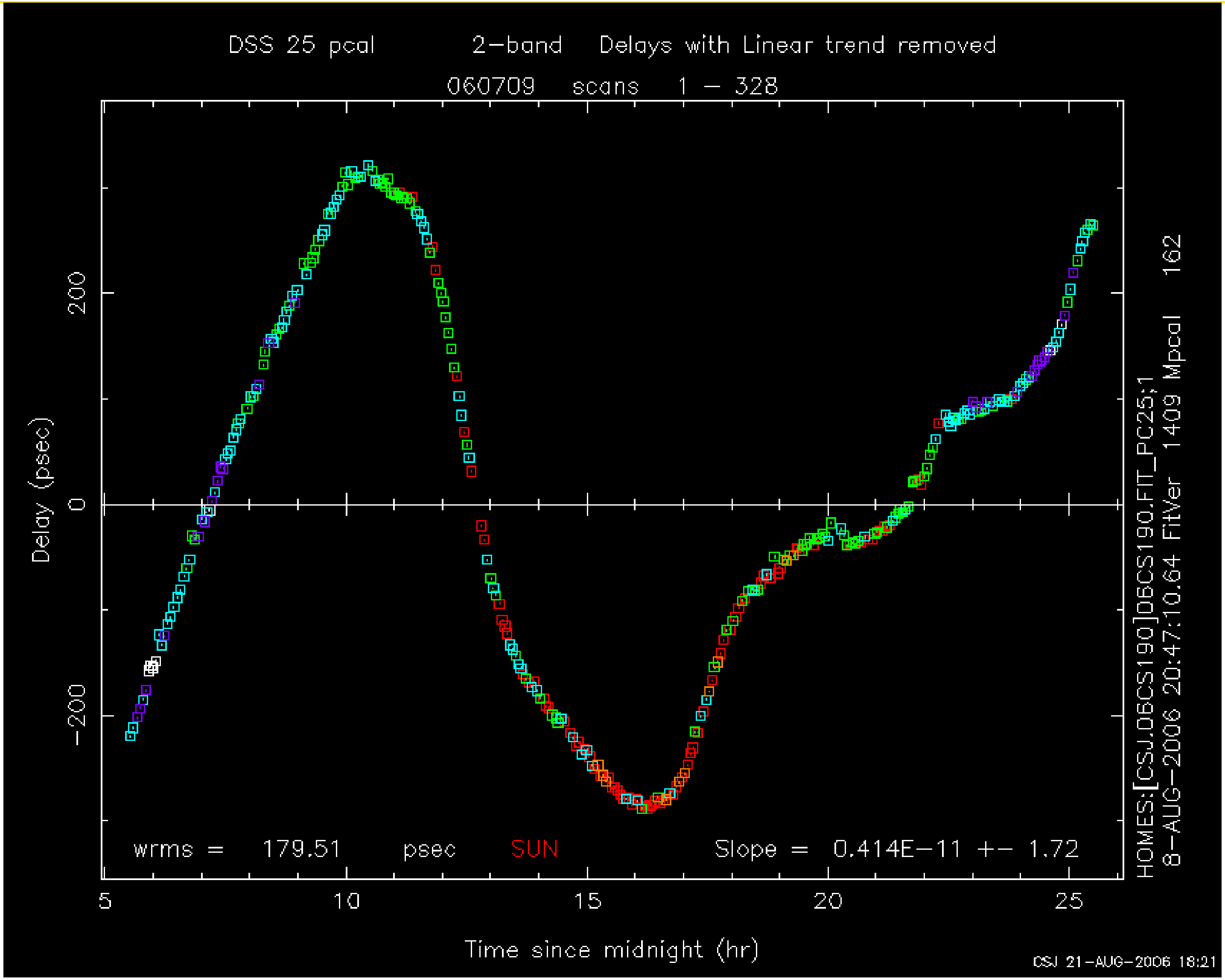
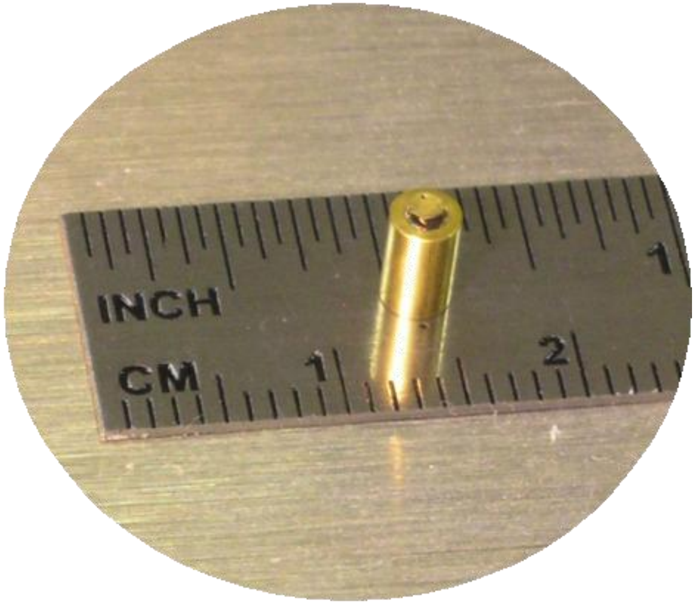
Units being Built. Operations in ~1 year



Credit: C. Jacobs, B. Tucker, L. Skjerve

Ka-band Phase Calibrator

- Concept: Tunnel diode
  Alan Rogers et al (Haystack)



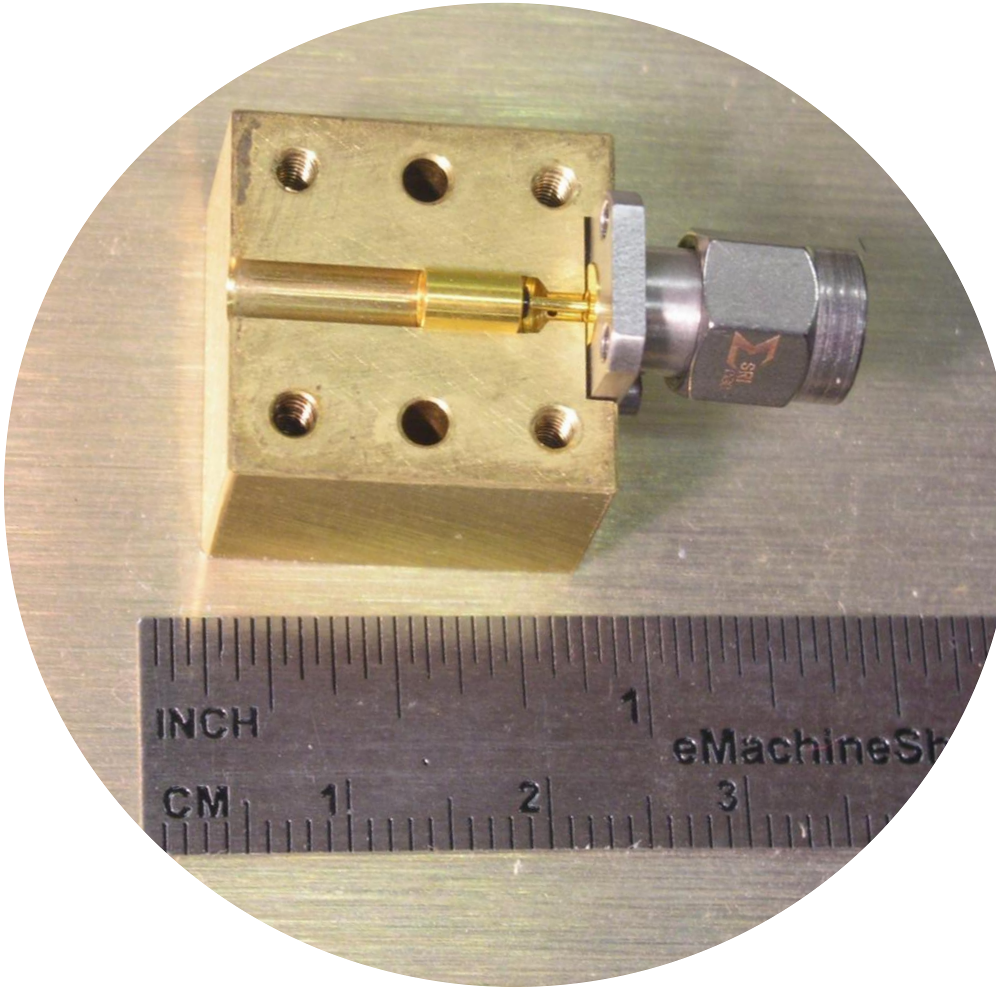
Tunnel Diode Chip
0.055" diameter by
0.020" thick
Mounted on
0.119" diameter carrier
for solid grounding

- JPL prototype Ka-band phase cal:
  Hammel, Tucker, & Calhoun,
  JPL Progress Report, 2003

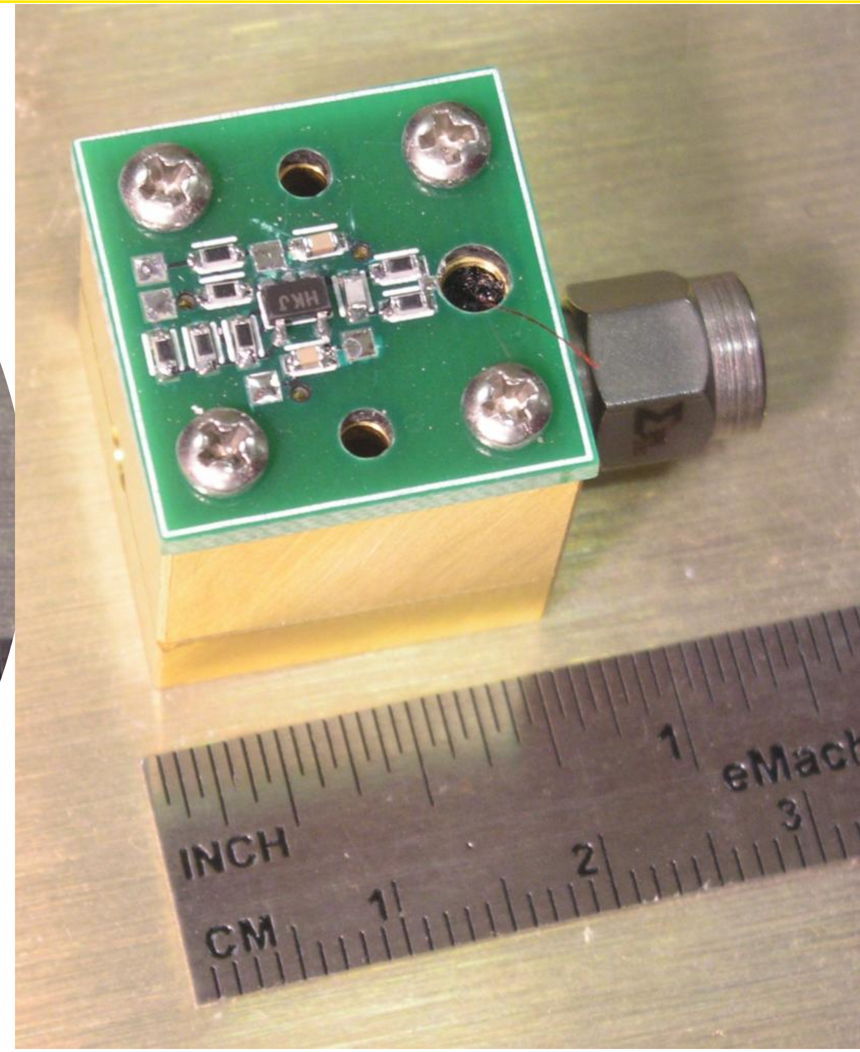
  tmo.jpl.nasa.gov/progress_report/42-154/154H.pdf

- Production units: Blake Tucker

Ka-band phase calibrator



Direct interface to K connector inside coaxial structure.

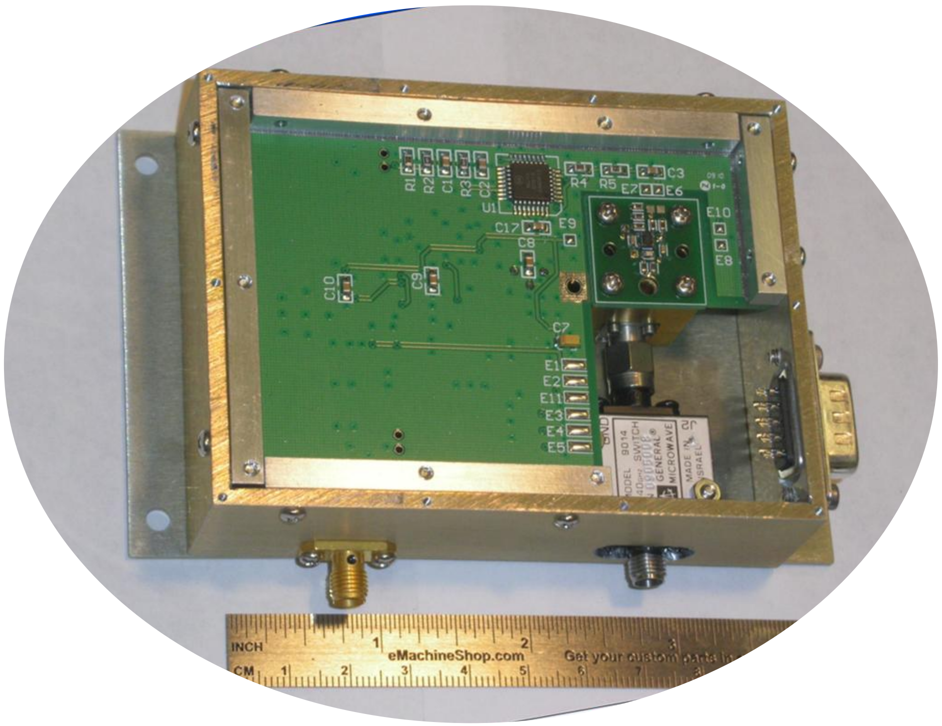


Pulse driver mounted as close as possible and fed through coaxial structure to minimize rise time and ringing

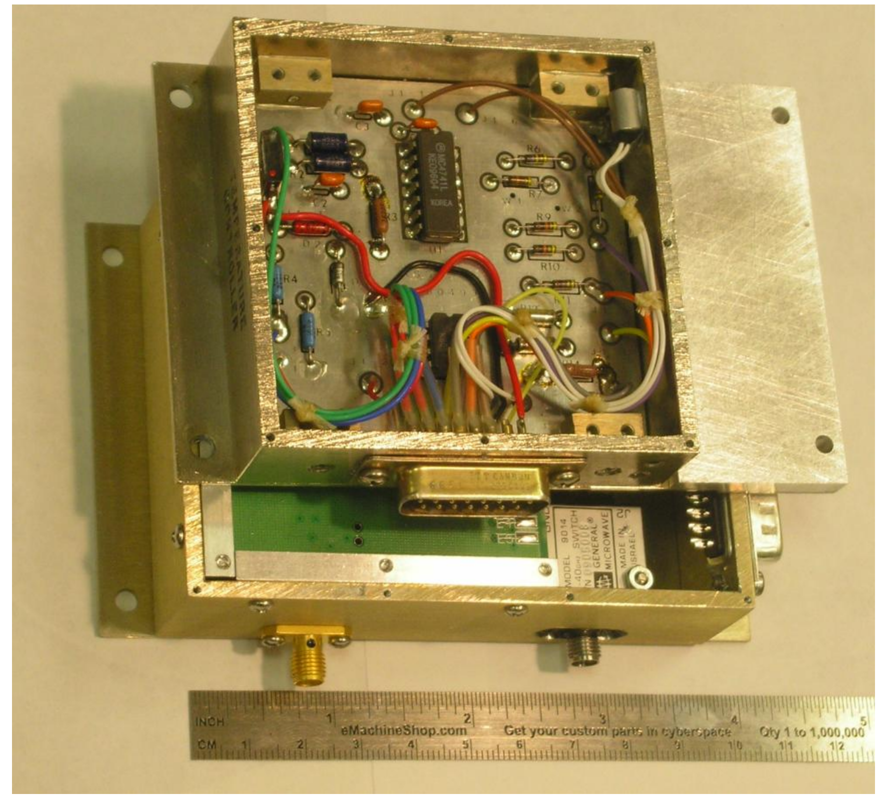
Credit: Blake Tucker

X/Ka Frame Improvements: Vision to Reality

Ka-band phase calibrator



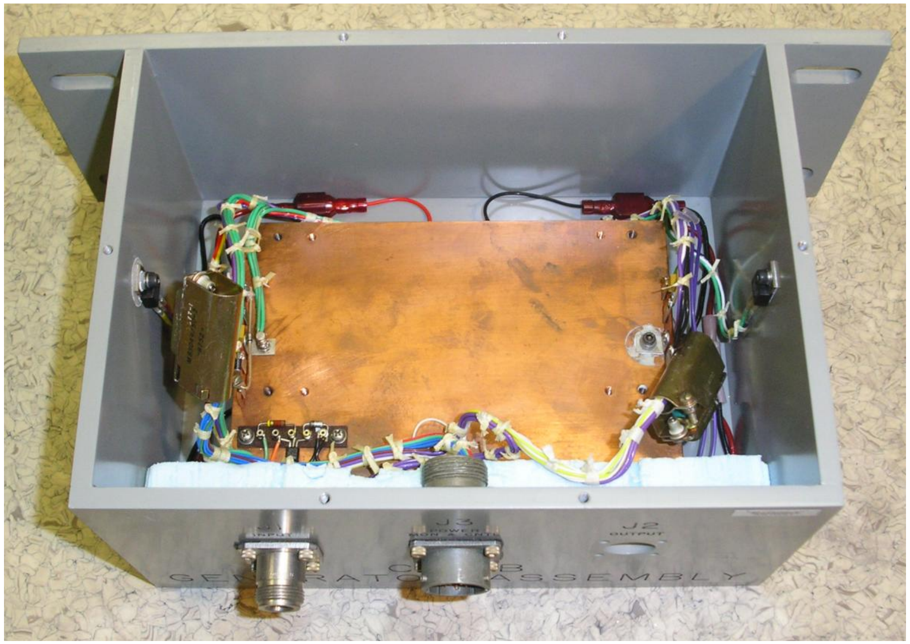
Tunnel diode module and
pulse gating switch
mount inside reference divider
housing to form the
comb generator module.

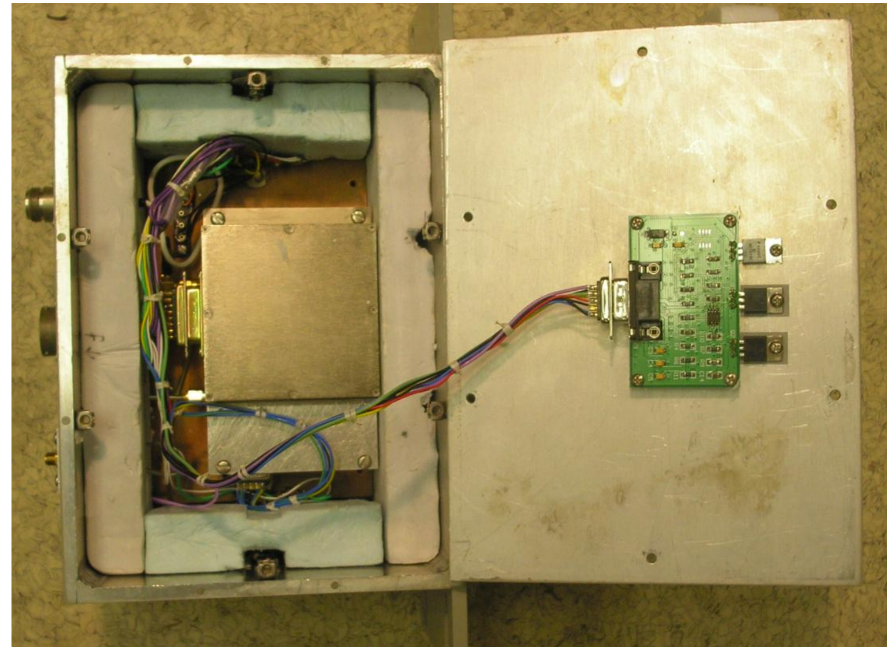


Oven control electronics stacks on
top of the comb generator module.

Credit: Blake Tucker

Ka-band phase calibrator





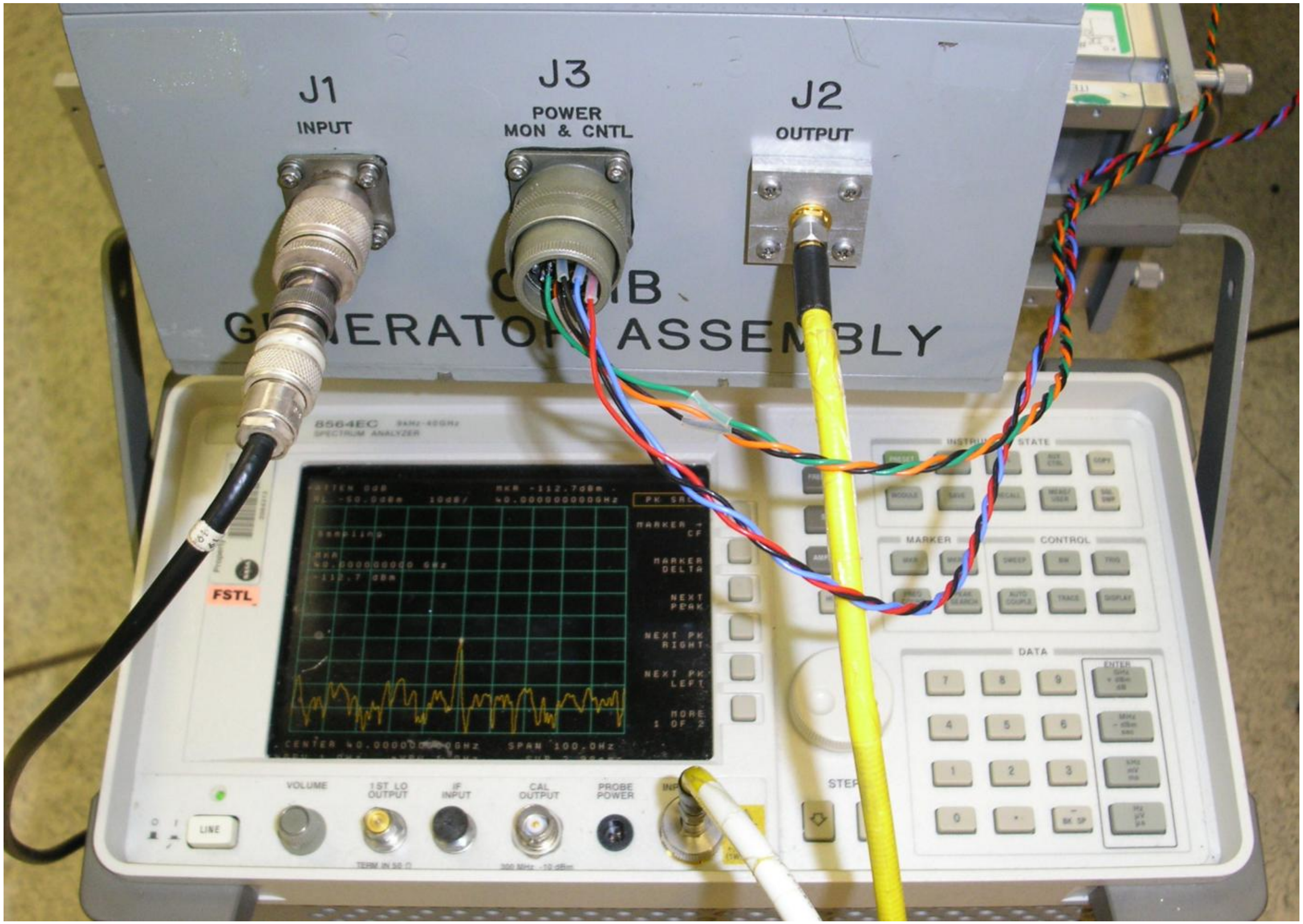
Thermally controlled baseplate and housing salvaged from de-commissioned X-band comb generators.

Comb generator module and oven control electronics mounted inside oven.

Power conditioning mounted on outer cover to dissipate heat.

Credit: Blake Tucker

Ka-band phase calibrator



Completed Ka-band phase calibrator with 32 GHz output signal. *Credit: Blake Tucker*

Attacking the X/Ka Error budget:

- SNR can be improved +8 dB!
- Instrumentation:
  Phase calibrators
  Digital Back End
- Troposphere cals: WVR

Instrumentation: Digital Back End

- **Digital Back End:**

  Replace 30 yr old analog Mk3/4 Data Acquisition Terminal with
  - Digital phase linear FIR filters
  - Programmable gate array design: powerful & flexible

  > Spanned bandwidth increases from 360 to 500 MHz

  > Data rates increase from 1024 to 4096 Mbps max

- **Digital Back End team:**

  Robert Navarro - *lead (see poster paper)*

  Charles Goodhart

  Robert Proctor

  Steve Rogstad

  Elliott Sigman

  Melissa Soriano

  Duo Wang

  Les White

Digital Back End: hardware in the lab

IF select switch:
12 inputs allows
multiple bands,
multiple antennas

Command & Control

Mark-5C recorder

Sampler: 1280 MHz, 8-bit/sample

Copper to fiber, **Digital filter**, Format

Design: Navarro et al. Photo credit: Les White

Summary of Instrumental Improvements

Instrument	MkIV	DBE/Mk5-C	Comment
Filters	Analog 7-pole Butterworth	Digital FIR phase linear	removes phase ripple in channel
Spanned bandwidth	360 MHz	500 MHz	Mk4 baseband limit 1.4X improvement
Data rate @ start	112 Mbps	2048 Mbps	DSN SNR limited
@ max.	896 Mbps	4096 Mbps	trop/inst. limited 6X sensitivity
Phase Cal: S/X	Yes	Yes	
X/Ka	No	Yes	removes 100s of psec

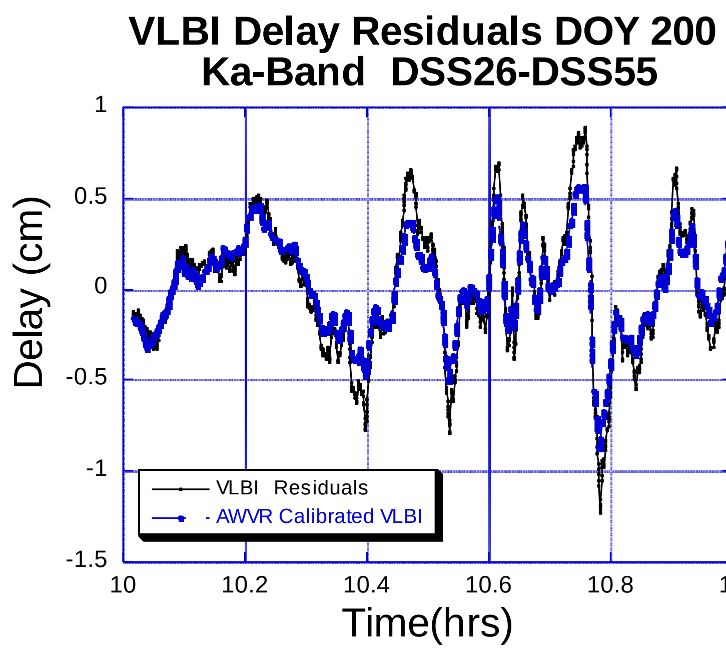
Attacking the X/Ka Error budget:

- SNR can be improved +8 dB!
- Instrumentation:
  Phase calibrators
  Digital Back End
- **Troposphere cals: WVR**

Troposphere Solution 2: Better Calibration

- **JPL Advanced Water Vapor Radiometer**
  ~ 1 deg beam better matches VLBI
  improved gain stability
  improved conversion of brightness temperature to path delay

- **Demos show 1mm accuracy!**
  Goldstone-Madrid 8000 km baseline using X/Ka phase delays
  (Jacobs *et al*, AAS Winter 2005).
  (Bar-Sever et al, IEEE, 2007).



- **A-WVRs deployed at Goldstone & Madrid**
  Seeking funding for Tidbinbilla, Australia

- **A-WVR will not be used operationally for X/Ka catalog until SNR and phase cal errors are peeled back.**

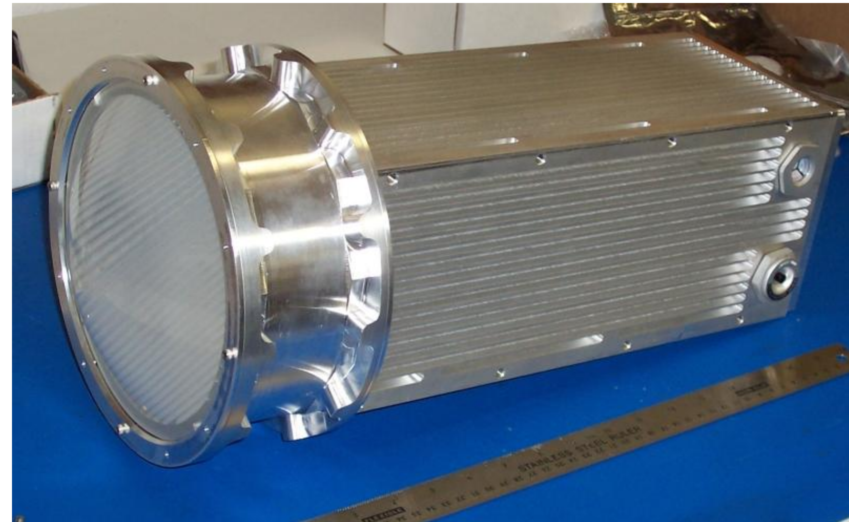
Troposphere Solution 3: Cheaper WVR?

- Advanced R&D WVR is very accurate but expensive on order ~$500K
  Mounted 50-100m from VLBI antenna

- Investigating "Radiometrics" WVR
  - 21 channels cover 20-30 GHz
  - "Inexpensive" at $120K (U.S.)
  - Light weight: ~7 kg

- Subreflector mounting
  - enabled by low weight
  - ideal co-pointing, no offset
  - better match with VLBI beam volume
  - enables calibration of doppler/rate
  - improves performance at high freq.

- Gain stability needs investigation



Credit: M. Britcliffe, M. Franco

Summary

- ***X/Ka Celestial Frame: 351 sources detected***

Observations: **10K observations from 47 sessions**
Deep Space Net 34m beam waveguide antennas
8,400 and 10,500 km baselines

Accuracy: X/Ka vs. S/X ICRF2 common 323 sources
ΔRA ~ 190 μas wRMS (0.9 nrad)
ΔDec ~ 265 μas wRMS (1.3 nrad)

- ***Near term potential 100 μas accuracy***

Attacking three main error sources:
SNR: +8 dB of SNR improvements almost done!
Increased bit rate: ~5dB increase in SNR (~6 month)
Pointing cals: ~3dB increase in SNR (done)
Instrumentation: Ka-band phase calibrators & Dig. Back End being built
Troposphere: Estimation using spatial/temporal correlations
Calibration using (cheaper?) Water Vapor Radiometers