... to enhance VLBI performance with Next Generation Space and Ground instruments

Review of Next Generation Methods for Ultra-precise astrometry

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In collaboration with
Richard Dodson (ICRAR-UWA) ➔ "Astrometry with Space VLBI"

CSIRO

Curtin University

The Government of Western Australia

The University of Western Australia

Next Generation Space VLBI workshop , ASTRON/JIVE, 17-19th October 2022

Outline

- Motivation & Context
- Identify origins of current astrometric limits
- Status and future prospects in the field of astrometry
- Pathways to boosting VLBI performance
  1. Methods
  2. Technological solutions to meet Method's performance
- Conclusions

MOTIVATION & CONTEXT

Unique science with extreme baseline lengths with GRT-space VLBI…
But it is challenging

Limited Sensitivity and ASTROMETRY (with PR):

Limited antenna size

Receiver system temperatures

Limited instrumental coherence

Uncertainties in orbit determination ➔ $\Delta\phi = 2\pi(\Delta B/\lambda)\theta$

Source switching complicated

Atmospheric propagation effects

➔ Short atmospheric coherence time τ_{coh}

Sources intrinsically weaker, in general

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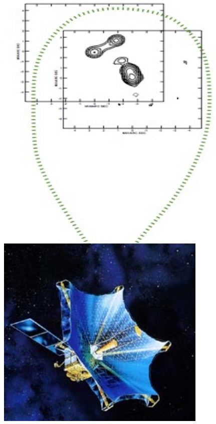
- Receiver system temperatures
- Limited instrumental coherence
- Uncertainties in orbit determination → $\Delta\phi=2\pi(\Delta B/\lambda)\theta$
- Source switching complicated
- **Atmospheric propagation effects**

Astrometry with VSOP/HALCA

1997: 1038+528A/B@1.6 GHz (33" apart); 1998: 1308+326/8@5 GHz (14.3' apart)



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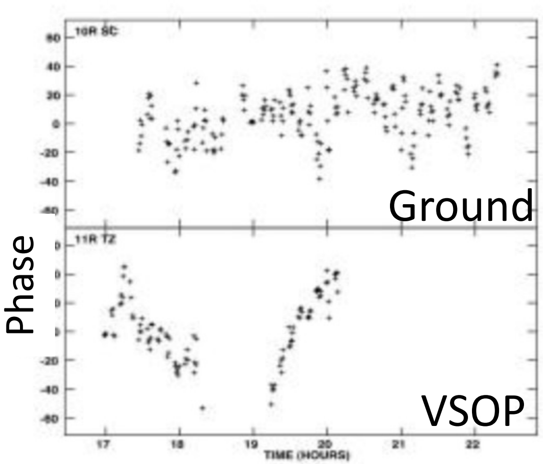
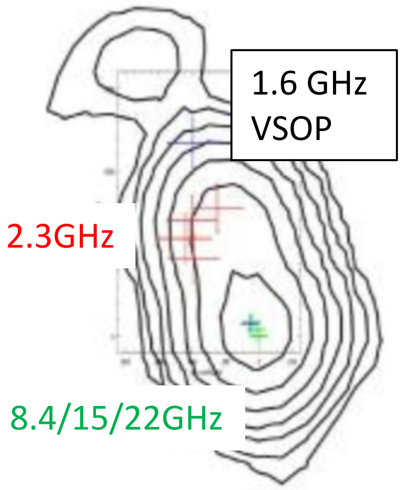




Porcas&Rioja 2000
Rioja,Porcas,Dodson+ 2009

- Demonstration with VSOP/HALCA
  Porcas and Rioja 2000 @ 1.6 and 5 GHz;
  Guirado+ 2001; Rioja+ 2009
- VSOP-2 specifications included PR
  - not launched
- Current Space Missions specifications to include astrometry capability

The Many Faces of the Propagation Medium

COLLECTING AREA

$\tau_{ION} \propto \lambda^2$
(λ^2 signature)

IONOSPHERE
(dispersive)

+ PAF

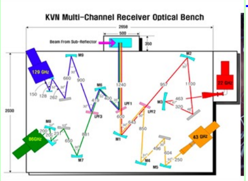
TECHNOLOGY

METHODS

MultiView (MV)
(Rioja+,2009,2017)

TROPOSPHERE
(non dispersive)

τ_{TRO} = C



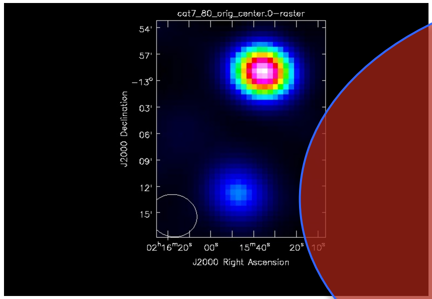
PR Alef 1988
PR+ Reid + 2009
Honma+2008

SFPR (Rioja&Dodson 2011,'15)
MFPR (Dodson,Rioja+ 2017)

cm-dm-m waves

Sweet cm-spot

mm-submm waves



$\Phi_{ION} \propto \nu^{-1}$

MultiView
< 8 GHz

Advanced
Phase
Referencing
> 8 GHz
< 22,43 GHz

Frequency Phase Transfer "family"

Source Frequency Phase Referencing
&
Multi Frequency Phase Referencing
> 22 GHz

...rors:
...(trop)
...TECU (ion...

Log ν

~ 8 GHz

METHODS

TECHNOLOGY

Micro-Jy ...
Micro-as ...
Wide applicability
A history of success!

Where we ... ys):

Wish list:

- Widely applicable:
  - to many sources and
  - at wider range of frequencies (100s MHz to 100s GHz),
- Ground&Space
- Robust against weather conditions

➔ ASTROMETRIC SCIENCE SURVEYS ACROSS RADIO SPECTRUM

100 µas | 10 µas

thermal | In-beam systematic | MV

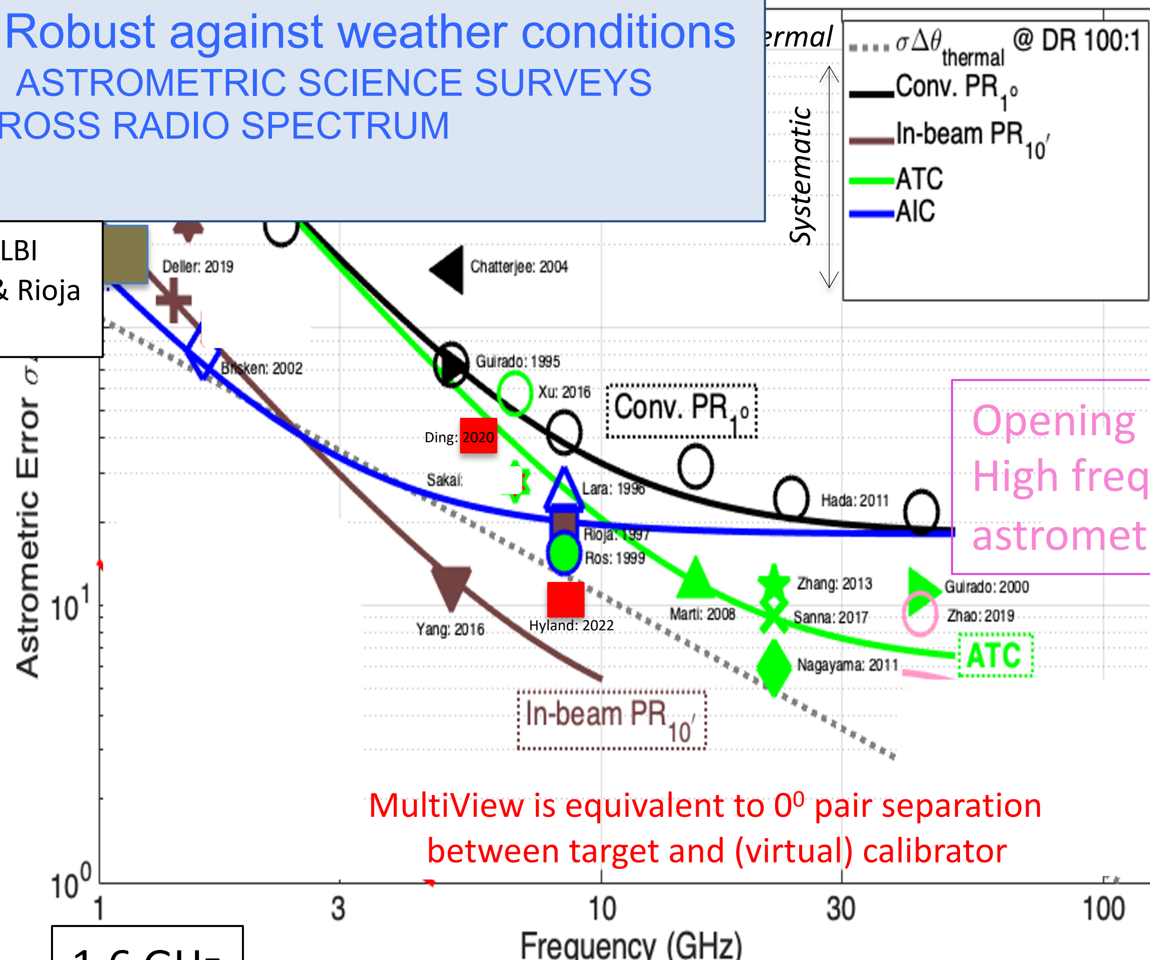
Systematics:

Conventional PR (scaled to 1^0 separation)

Advance Tropospheric Calibrated PR (mainly from GeoBlocks)

in-beam PR (close calibrators ∴ <5GHz)

Space-VLBI Porcas & Rioja 2000



Opening up High frequency astrometry

MultiView is equivalent to 0^0 pair separation between target and (virtual) calibrator

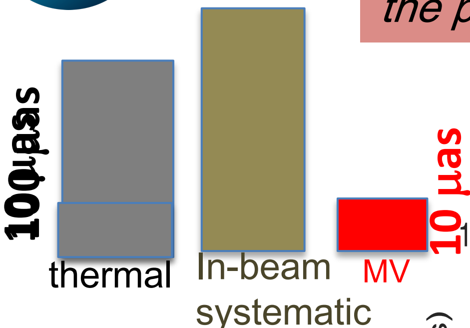
1.6 GHz

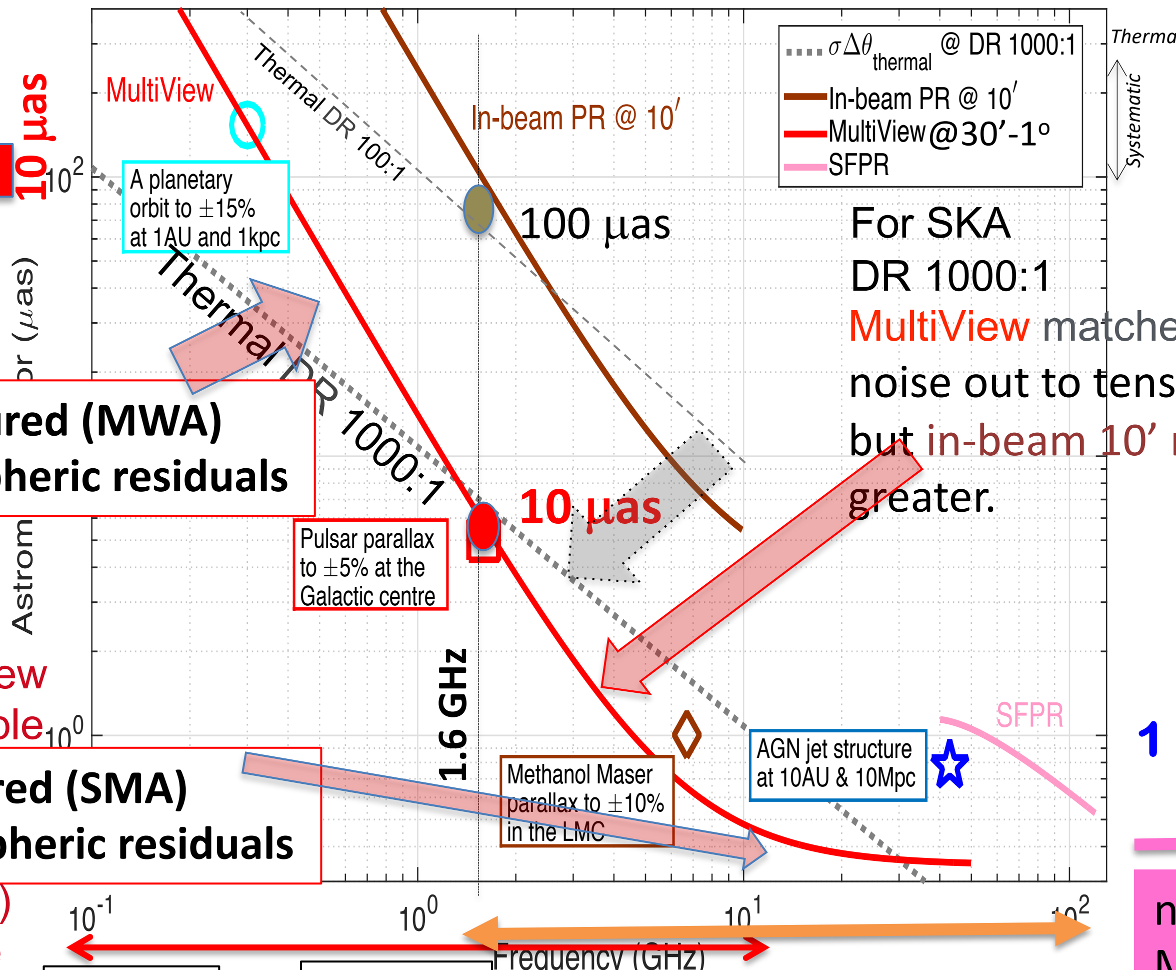
Details in: Precise radio astrometry .. Rioja & Dodson, 2020, AARv; SFPR details: Rioja & Dodson 2011; MV Details: Rioja,Dodson+2017

In NextGen telescope Era

MultiView calibration will out-perform in-beam at 10' by a factor ~ 10, reaching the potential of huge collecting areas.

SFPR enables ultra precise astrometry at 100's GHz





For SKA
DR 1000:1
MultiView matches thermal noise out to tens of GHz, but in-beam 10' noise is far greater.

Measured (MWA) ionospheric residuals

Measured (SMA) tropospheric residuals

~1µas (per epoch) astrometry above a few GHz should be feasible

~100µas (per epoch) astrometry should be feasible at 300MHz

1 µas

ngEHT, EHT Millimetron…

100 MHz

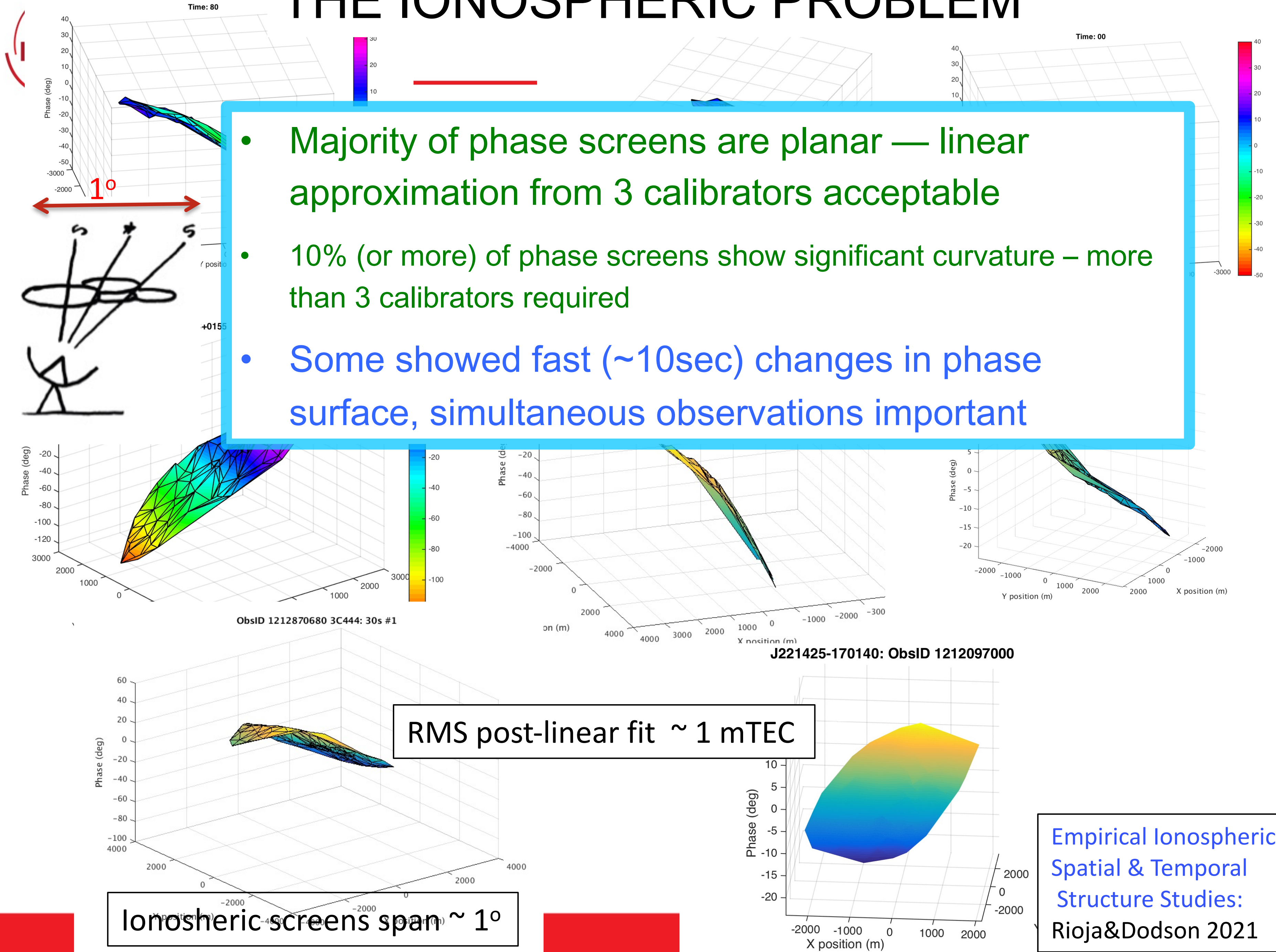
1.6 GHz

SKA-Low

SKA-Mid

ngVLA

THE IONOSPHERIC PROBLEM



- Majority of phase screens are planar — linear approximation from 3 calibrators acceptable
- 10% (or more) of phase screens show significant curvature – more than 3 calibrators required
- Some showed fast (~10sec) changes in phase surface, simultaneous observations important

RMS post-linear fit ~ 1 mTEC

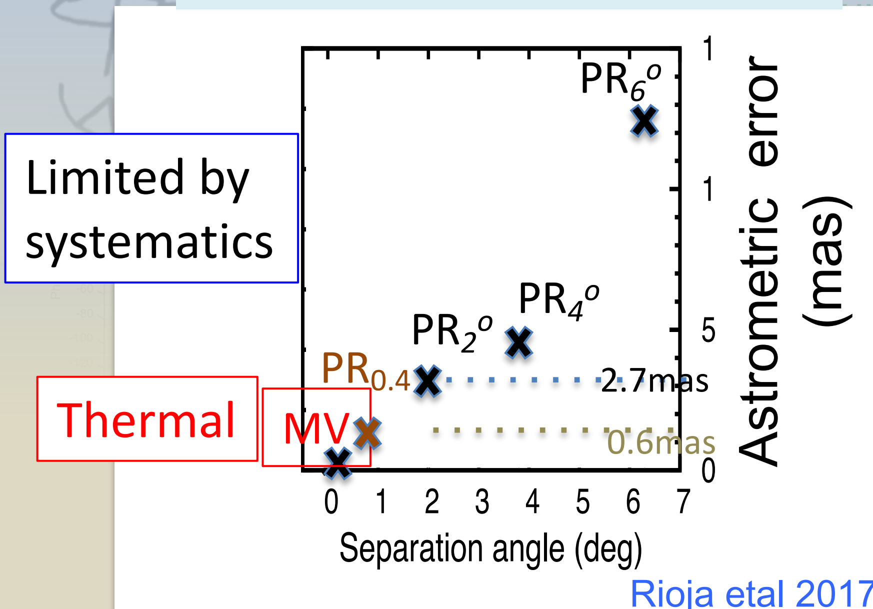
Ionosheric screens span ~ 1°

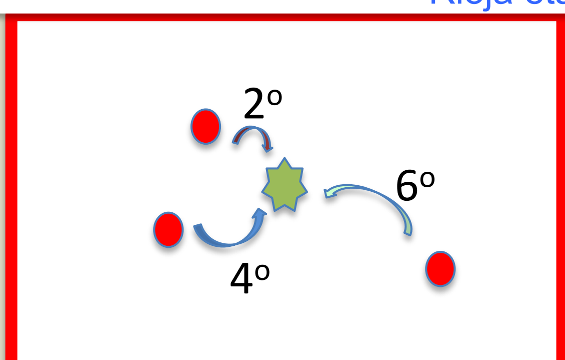
Empirical Ionospheric Spatial & Temporal Structure Studies: Rioja&Dodson 2021

THE IONOSPHERIC PROBLEM

Empirical Demonstration:

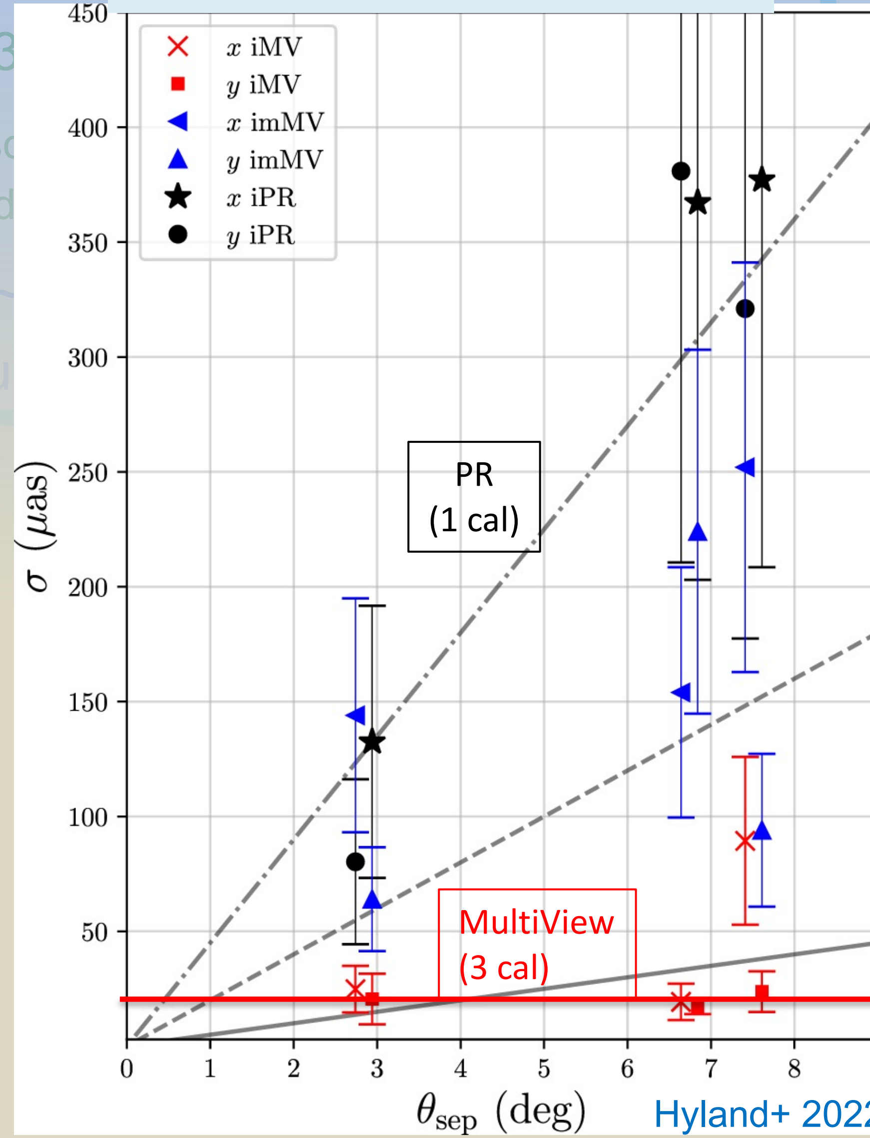
MultiView @ 1.6 GHz





Empirical Demonstration:

iMultiView @ 8 GHz

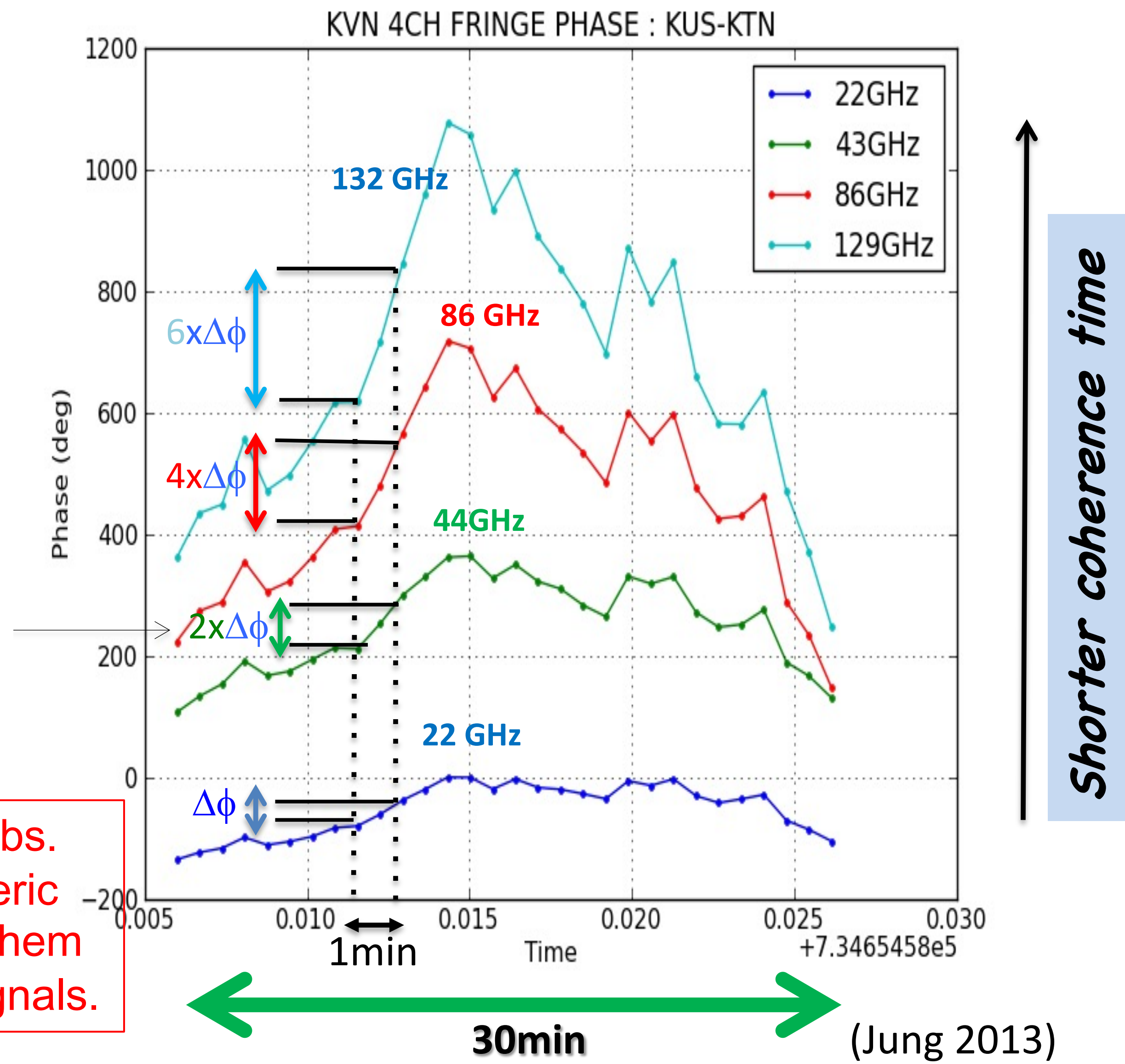


Troposphere "in action"

Fluctuations in water vapor component (=turbulences) ➔phase fluctuations

TROPOSPHERE
(non dispersive)

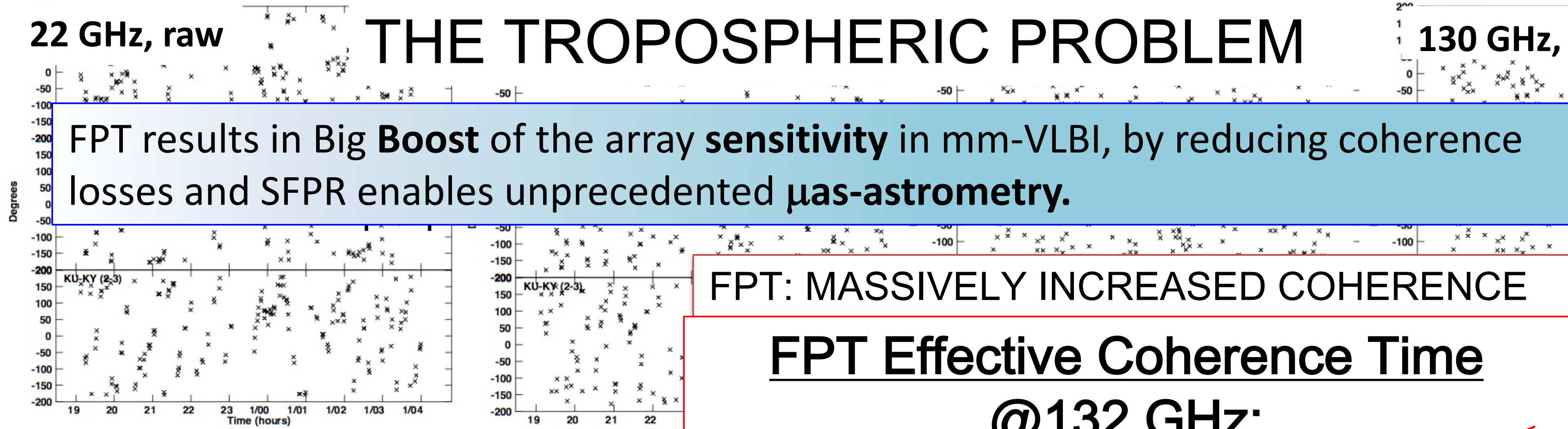
$$\tau_{TRO} = C$$
$$\Phi_{TRO} \propto \nu$$



Leverage multi-freq obs. to measure tropospheric errors and eliminate them from the observed signals.

(Jung 2013)

THE TROPOSPHERIC PROBLEM



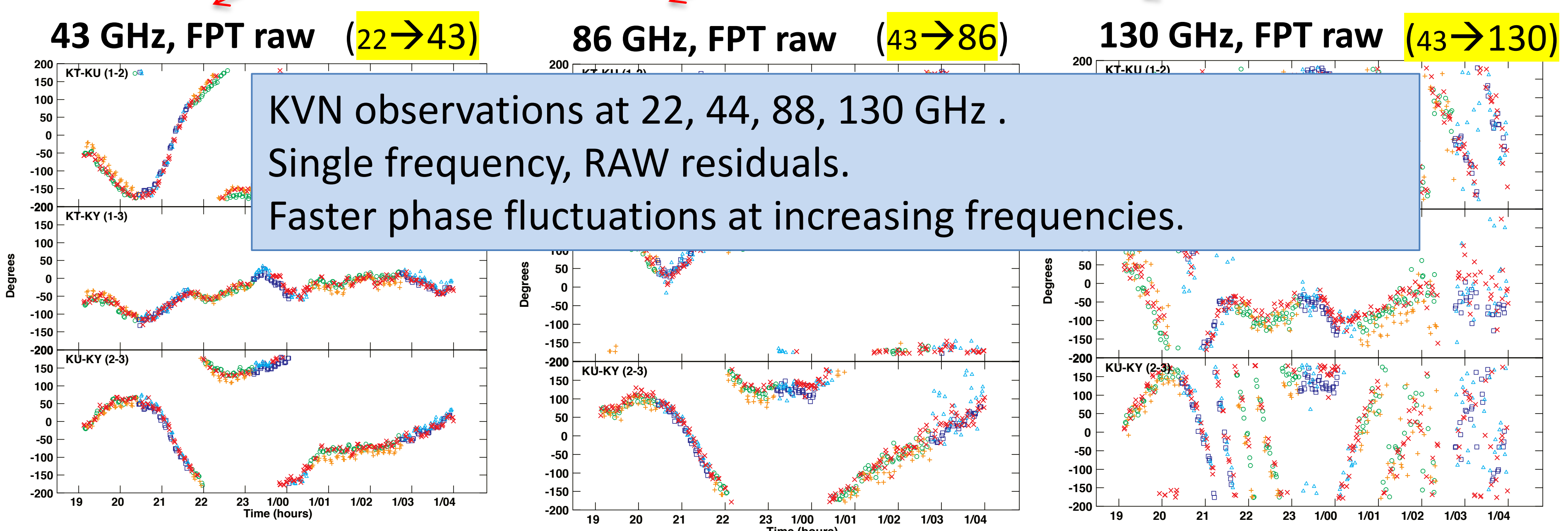
FPT results in Big **Boost** of the array **sensitivity** in mm-VLBI, by reducing coherence losses and SFPR enables unprecedented **μas-astrometry.**

Excellent Tropospheric Co

FPT: MASSIVELY INCREASED COHERENCE

FPT Effective Coherence Time @132 GHz:

20 minutes (hundred fold increase!)



KVN observations at 22, 44, 88, 130 GHz .
Single frequency, RAW residuals.
Faster phase fluctuations at increasing frequencies.

Rioja&Dodson 2015

"SFPR" Fact Sheet:

Basis:

- SFPR uses lower frequency phase solution to correct higher frequency data
- Offers a solution when non-dispersive troposphere dominates error contribution; all non-dispersive errors corrected
- Dispersive errors corrected.

Outcomes: astrometric registration between frequencies (**λ**-

Domain of Application:

- Frequencies 22GHz and above; ground and space VLBI; continuum and spectral line

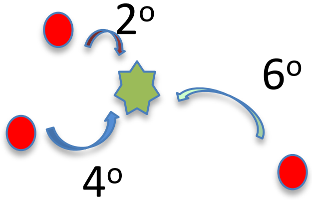
Optimum Performance: Simultaneous observations of multiple frequencies, integer ratio

Key Technology: Multi-frequency Receivers, or Very Wide Band Receivers (Han+2008,2013,2017 CTR) or BRAND (Flygare+2019))

Empirical Demonstrations: Rioja+(2011a (VLBA), 2015 (KVN@130GHz), *KSP KVN ES(Se-Hyung Cho, Youngjoo Yun+):* Kim+2018, Yoon+2018, Cho+2018, Yang+(2020); Algaba+2015 & Zhao+2018 FPT^2 (iMogaba); Dodson+2018 (MFPR); Zhao+2019 (KaVA); Abellan+2018,Wu+2018

Feasibility Studies for ngVLA/space VLBI/submm VLBI: Rioja+ 2011b,Rioja+Dodson 2020, Dodson+Rioja ngVLA Community Study, Rioja,Dodson,Asaki 2022

“MultiView” Fact Sheet:



Basis:

- Use observations of >~ 3 calibrators surrounding the target and a 2D interpolation in the visibility domain to provide corrections at the position of the target.
- Three calibrators allows for a planar fit to errors; more, higher order terms.
- **Precisely** eliminates most systematic residual error contributions: atmospheric propagation and antenna position (i.e. relevant for space VLBI)

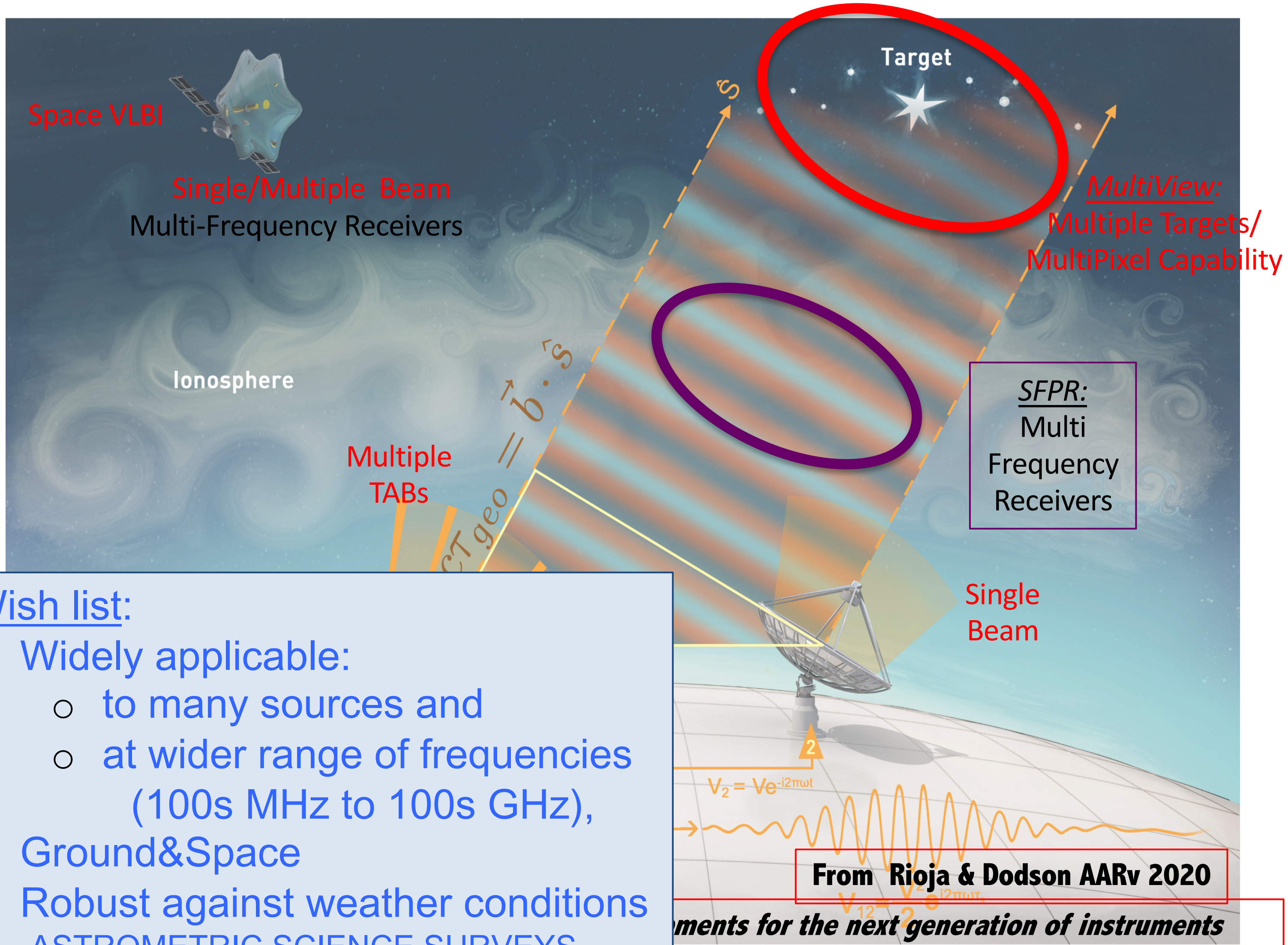
Outcome: Astrometry ‘a la’ PR & increased sensitivity

Domain of Application: All regimes:
high and especially low frequencies, ground and space VLBI

Optimum Performance: **Simultaneous** obs. of target and nearby calibrators

Key Technology: Multiple TABs (for arrays) & Multi Beam or PAFs (for large dishes)

Technological Solutions for ultra precise astrometry
In the Era of High Angular Resolution Radio Astronomy



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Summary & Conclusions

- Bona fide Precise Astrometry adds a new dimension to your research, with positions, proper motion, distances, and direct registration of temporal and frequency monitoring.
- Reviewed atmospheric origins and resulting astrometric limits For current and future VLBI arrays
- Three pillars are required to achieve ultra-precise astrometry: greater Collecting Area, new Methods and enabling Technology
- Introduced two solutions to the limits: Source/Frequency Phase Referencing combined with Multi-Band receivers and MultiView combined with PAFs technology
- Applicable to all regimes, ground VLBI & Space VLBI, across the spectrum
- Developments of new calibration methods and new instruments are providing a leap in the astrometric performance .

Summary & Conclusions

Next generation *Instruments, Methods and Technologies* are a game changer

- ...etry adds a new dimension to your research, ...positions, proper motion, distances, and

A pathway to BOOSTING PERFORMANCE for space VLBI with next gen atmospheric/orbit errors calibration methods and enabling technology

→ ultra high angular resolution,
ultra high sensitivity,
ultra high bona fide astrometric precision,
across electromagnetic spectrum.

- ...ectrum
- ...providing

Will enable the addressing of a host of innovative open scientific questions in the “Physics of Relativistic Jets on All Scales” and much more.

THANK YOU FOR YOUR ATTENTION!