"*MultiView*" Calibration For Precise Astrometry at Low Frequencies

Maria J. Rioja

(ICRAR -UWA/ CSIRO, Australia

OAN, Spain)

in collaboration with:

Richard Dodson (ICRAR,Au)

Gabor Orosz & Hiroshi Imai (U.Kagoshima, Jp)

ICRAR International Centre for Radio Astronomy Research

CSIRO

Curtin University

The Government of Western Australia

The University of Western Australia

OUTLINE

- Impact of Accurate Astrometry
- Challenges of Low Frequencies
- MultiView (MV): A method using multiple calibrators
- Demonstration at low frequencies
- MV in SKA-era
- Work-in-progress and Future Studies

The quest for accurate astrometry…

$\sigma_{POS} \sim \theta_B / SNR$ **(Thermal Noise Limit)**

VLBI ➔ micro-as (μas) astrometry

IF you can remove SYSTEMATICS

Just for fun.... *(rep. EVN symp. 2014)*

"Microarcsecond Radio Astrometry" by Reid & Honma, ARA&A, 2014

Time Interval	# Pub.	# Pub./year
-- 1990	few	
1991 – 2000	24	2 / year
2001 --2005	26	5 / year
2006 - 2010	73	15 / year
2011 – 2013	63	21 / year

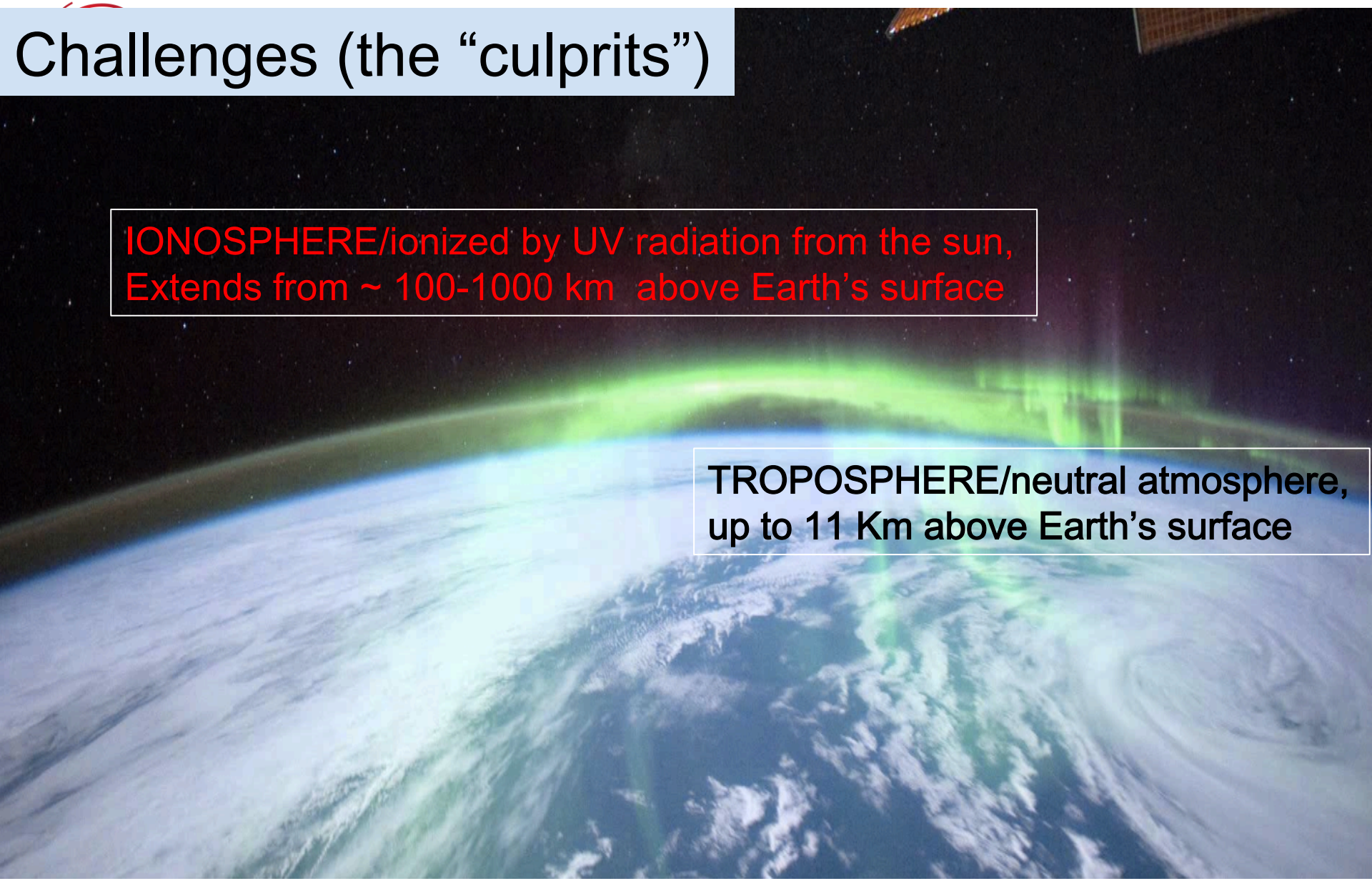
OH maser:
at best sub-mas
van Langevelde+2000
Vlemmings+2003
Vlemmings+2007

10s micro-arcsecond accuracy, ΔΘ~1-2°

Predominantly high (22 GHz) frequency

Methods for Advanced Tropospheric Calibration:
Reid & Brunthaler 2004
Honma et al. 2008

Challenges (the “culprits”)



(Image credit: NASA/ESA)

Challenges at Low Freqs: Ionospheric systematics

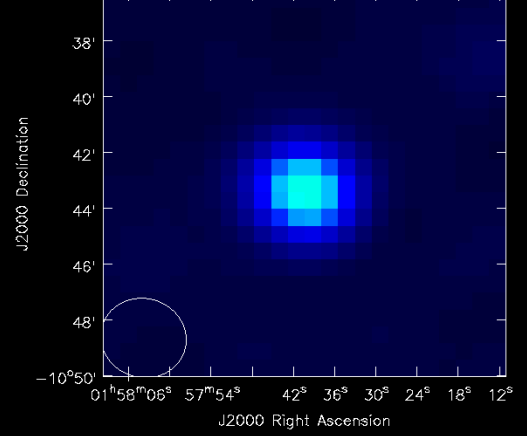
Dir 1

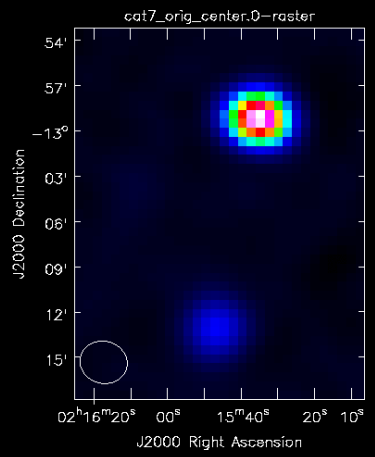
150 MHz

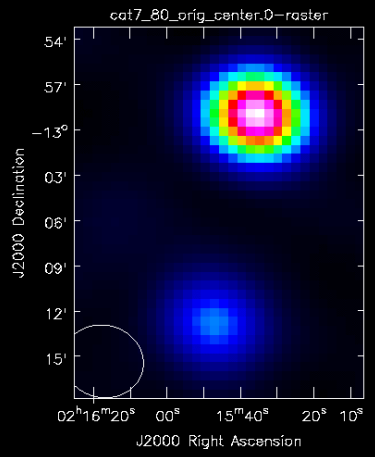
Dir 2

80 MHz

Dir 2







Multi Snapshots

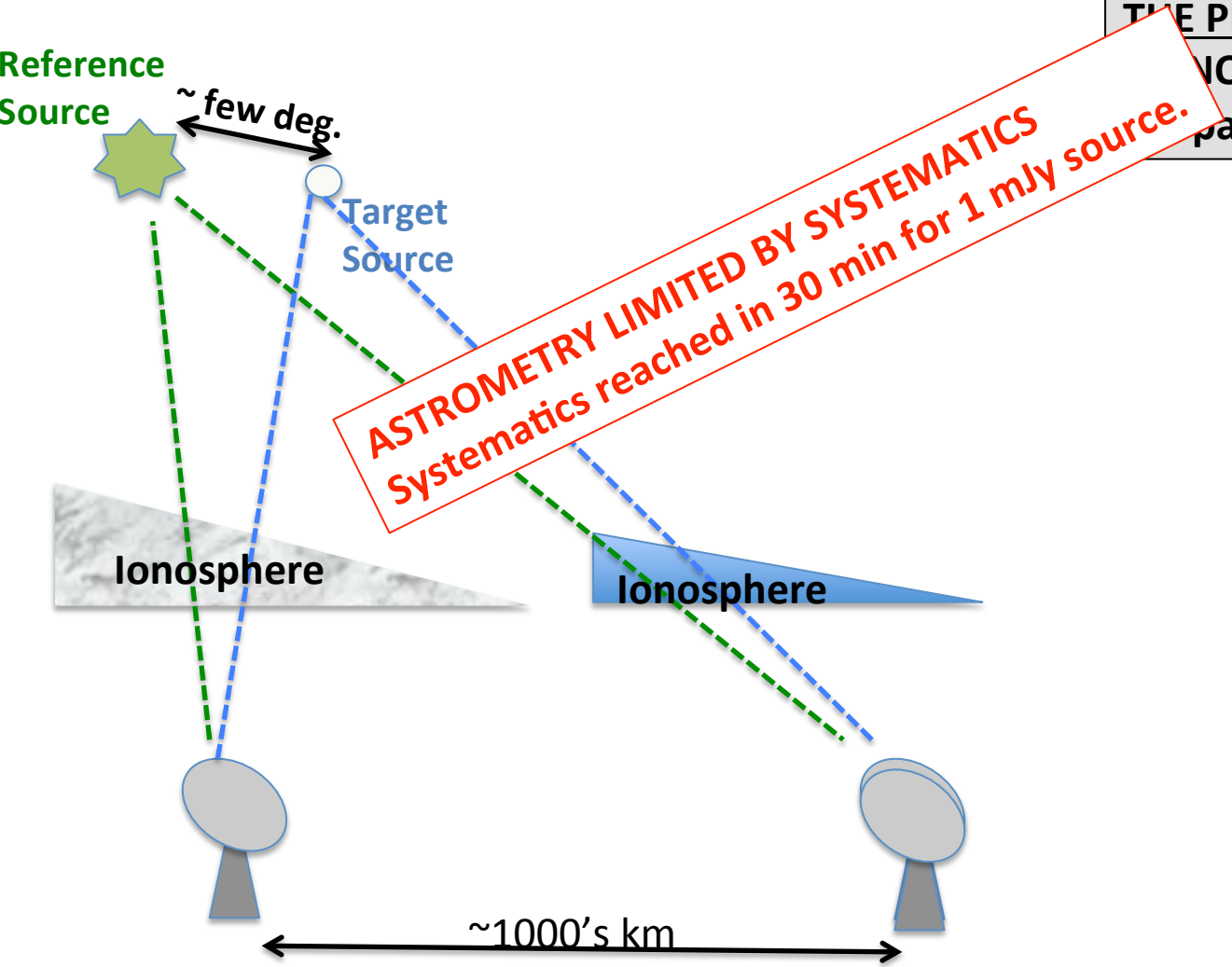
The IONOSPHERIC residuals INDUCE POSITION SHIFTS:
Direction Dependent
(spatial structure)
Time Dependent
(temporal structure)

PLUS Defocusing in severe cases

Larger at lower frequencies

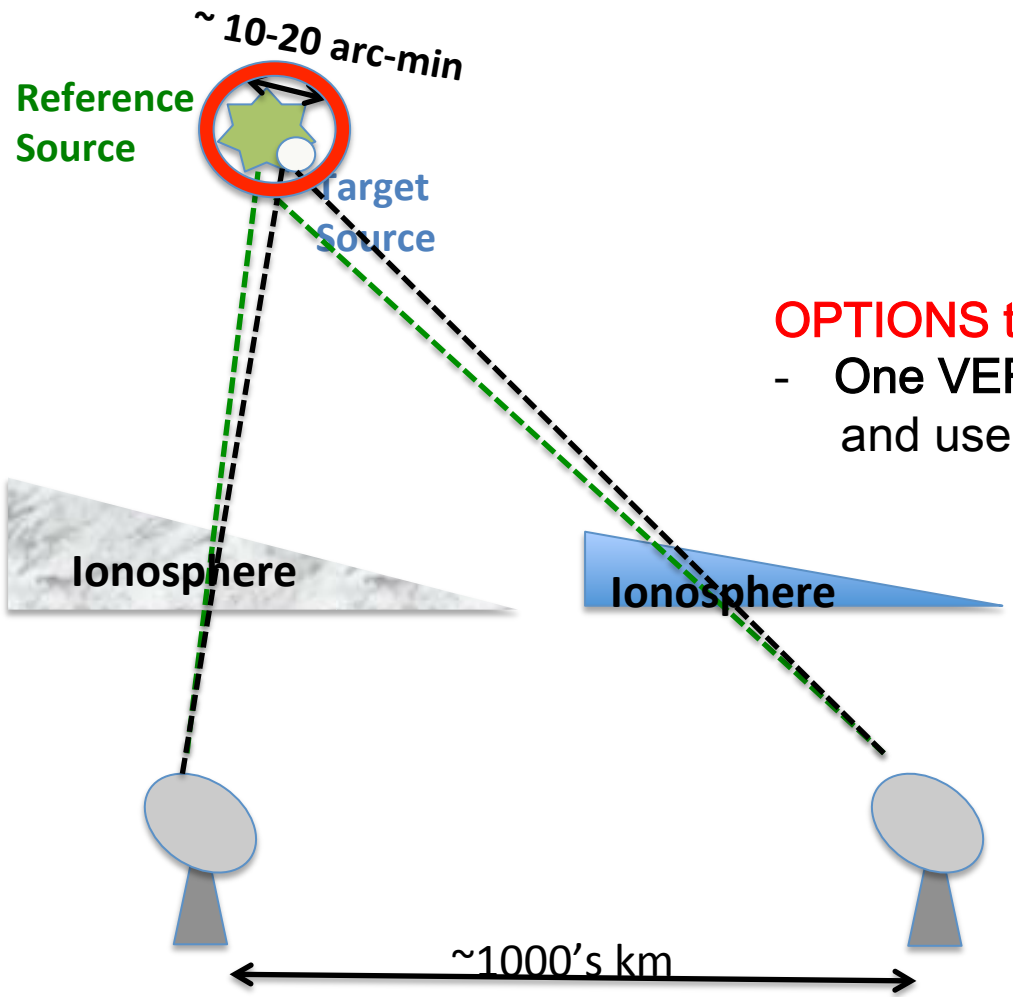
Low Frequencies & Ionosphere

THE PROBLEM:
IONOSPHERIC WEDGE"
Spatial structure



Sketch showing the limitations of general PR at low frequencies

Low Frequencies & Ionosphere



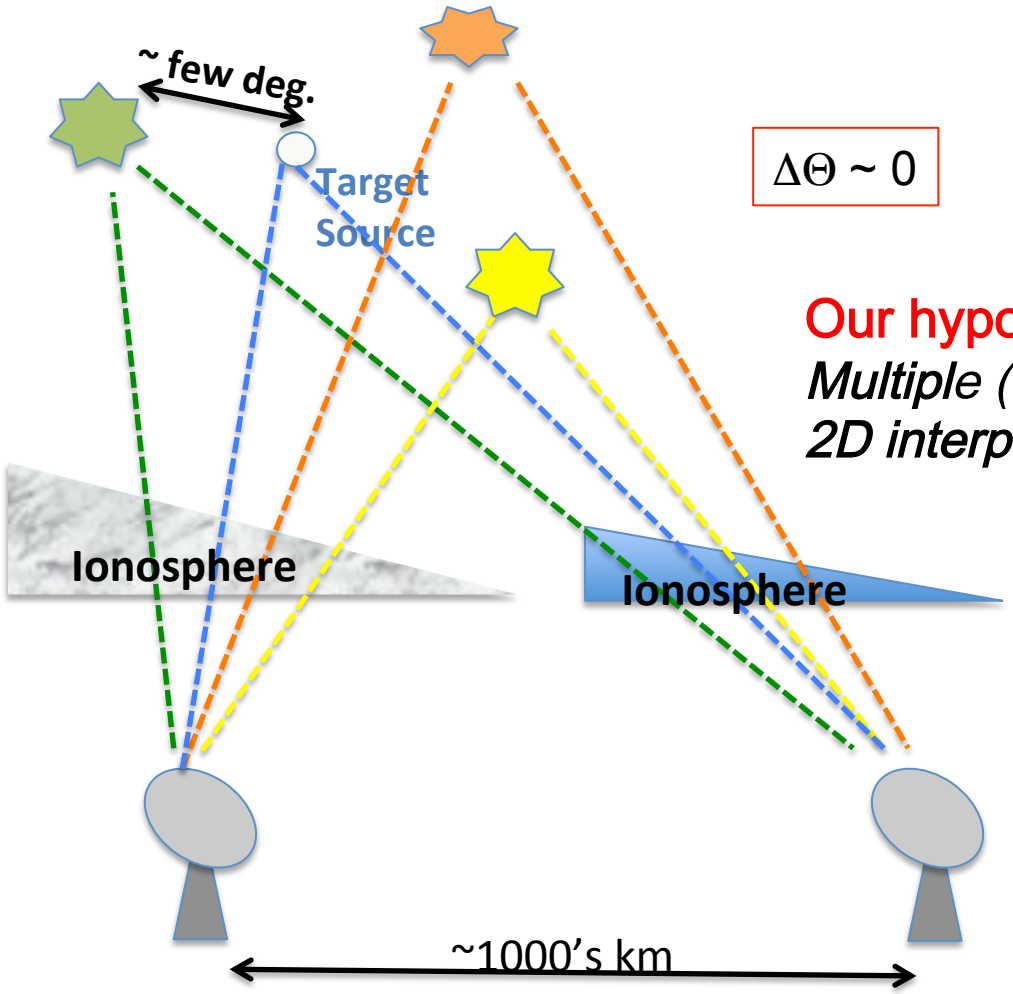
THE PROBLEM:
"IONOSPHERIC WEDGE"
➔Spatial structure

OPTIONS to overcome DDEs:
- One VERY close reference source and use conventional PR *(in-beam)*

Issue: Calibrator availability

Sketch representing ionospheric direction dependent effects

Low Frequencies & Ionosphere



$\Delta\Theta \sim 0$

THE PROBLEM:
"IONOSPHERIC WEDGE"
➔Spatial structure

Our hypothesis: to overcome DDEs with
Multiple (3) reference sources, further away,
2D interpolation in visibility domain: MultiView

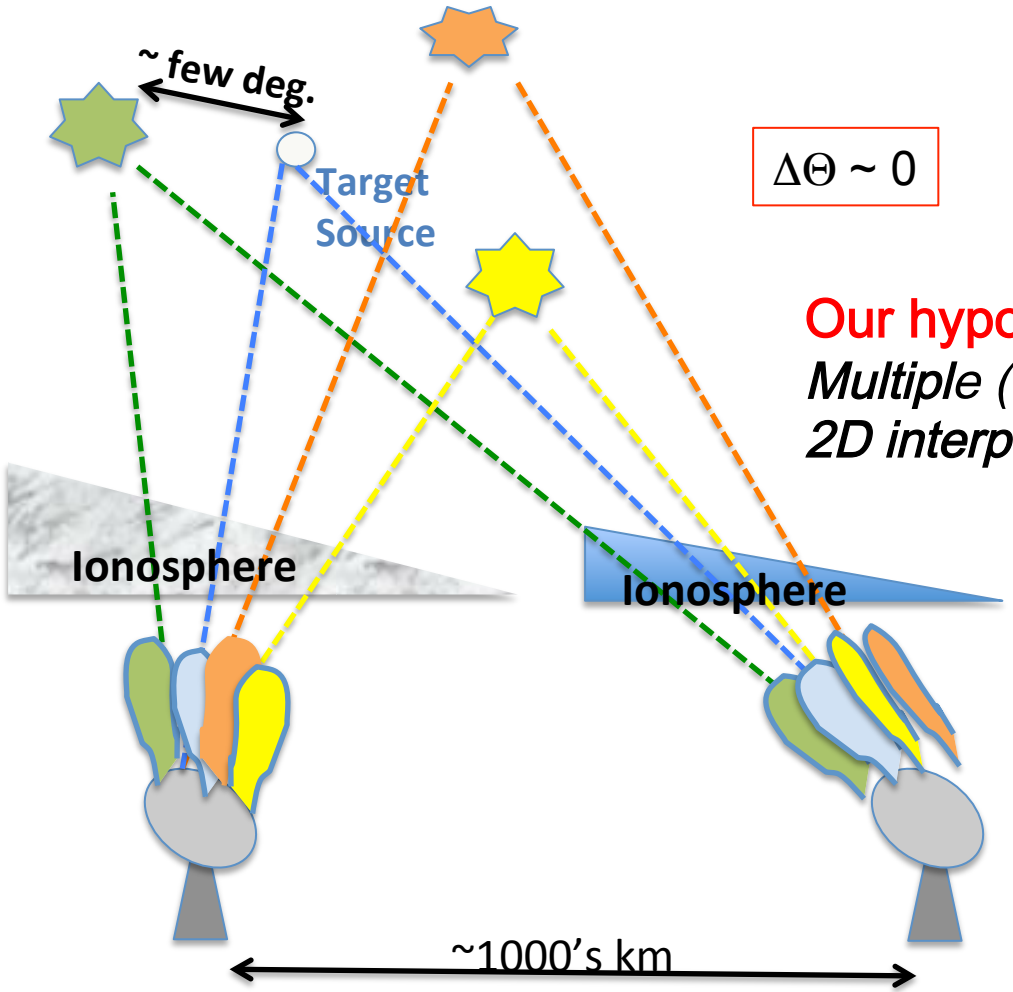
obs. strategy: switching
fast slewing

Rioja, Dodson + 2009;
Rioja+ 2017

Sketch representing ionospheric direction dependent effects

Low Frequencies & Ionosphere

THE PROBLEM:
"IONOSPHERIC WEDGE"
➔Spatial structure



$\Delta\Theta \sim 0$

Our hypothesis: to overcome DDEs with
Multiple** (3) reference sources, **further away,
2D interpolation in visibiity domain: MultiView

obs. strategy: **switching**
fast slewing - - much less efficient

*obs. strategy: **simultaneous***
minimum 4 beams

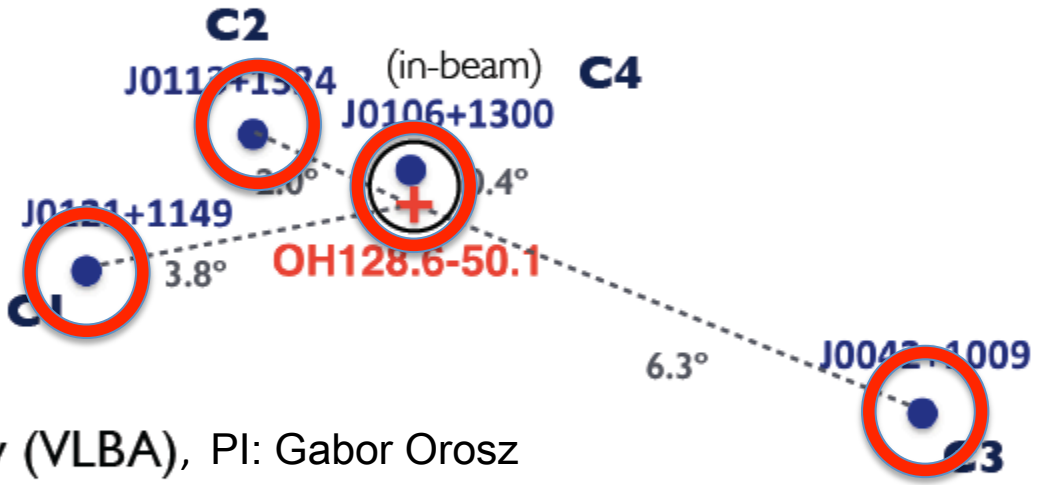
Rioja, Dodson + 2009;
Rioja+ 2017

Sketch representing ionospheric direction dependent effects

Demonstration of MultiView: Observations



(Rioja+ 2017; Orosz+ 2017)



Very Long Baseline Array (VLBA), PI: Gabor Orosz

Frequencies: 1.4 – 1.7 GHz (L-band AGN and OH masers)

Switching cycle: 5 min

2 epochs, 4 hours/epoch **(time on source: 30%)** 1 month apart

RA (deg)

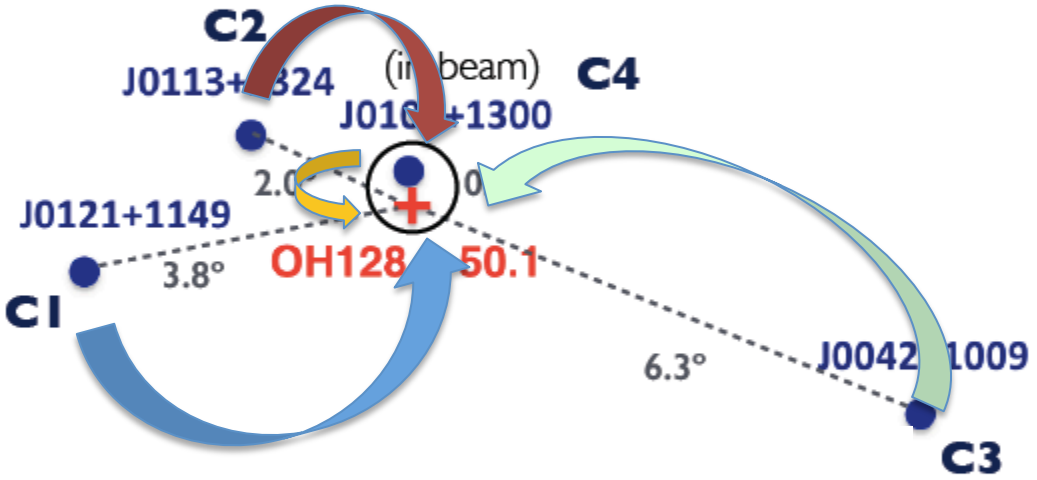
Dec (deg)



Demonstration of MultiView: Comparative Astrometric Analysis

(use repeatability as empirical estimate of systematics)

(Rioja+ 2017; Orosz+ 2017)



ANALYSIS:

➔Phase Referencing (PR) : Single Calibrator (no spatial interpolation), range of angular separations ($\Delta\Theta = 2^o, 4^o, 6^o, 0.4^o$)

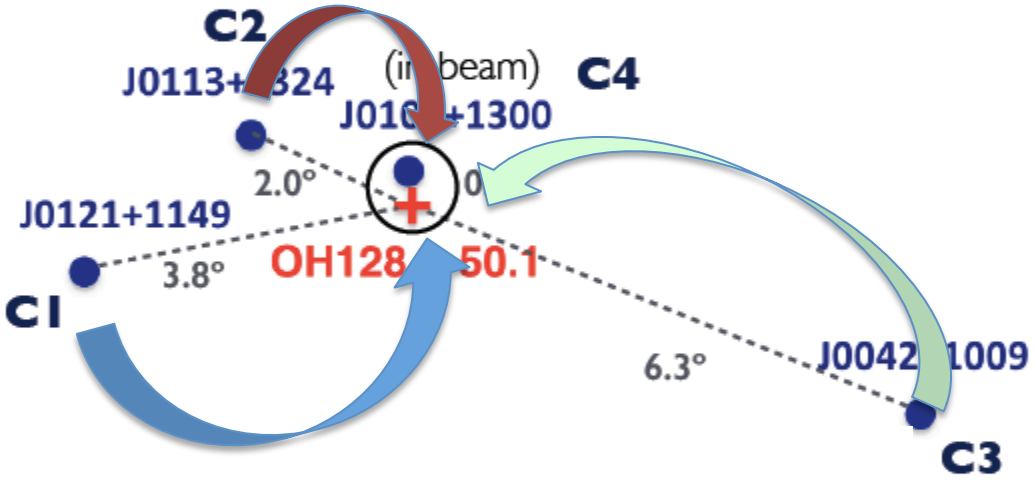
RA (deg)

Dec (deg)



Demonstration of MultiView: Comparative Astrometric Analysis

(Rioja+ 2017; Orosz+ 2017)



ANALYSIS:

➔Phase Referencing (PR) : Single Calibrator (no spatial interpolation), range of angular separations ($\Delta\Theta = 2^o, 4^o, 6^o, 0.4^o$)

➔MultiView (MV) : Three Calibrators together + 2 D interpolation to position of target.

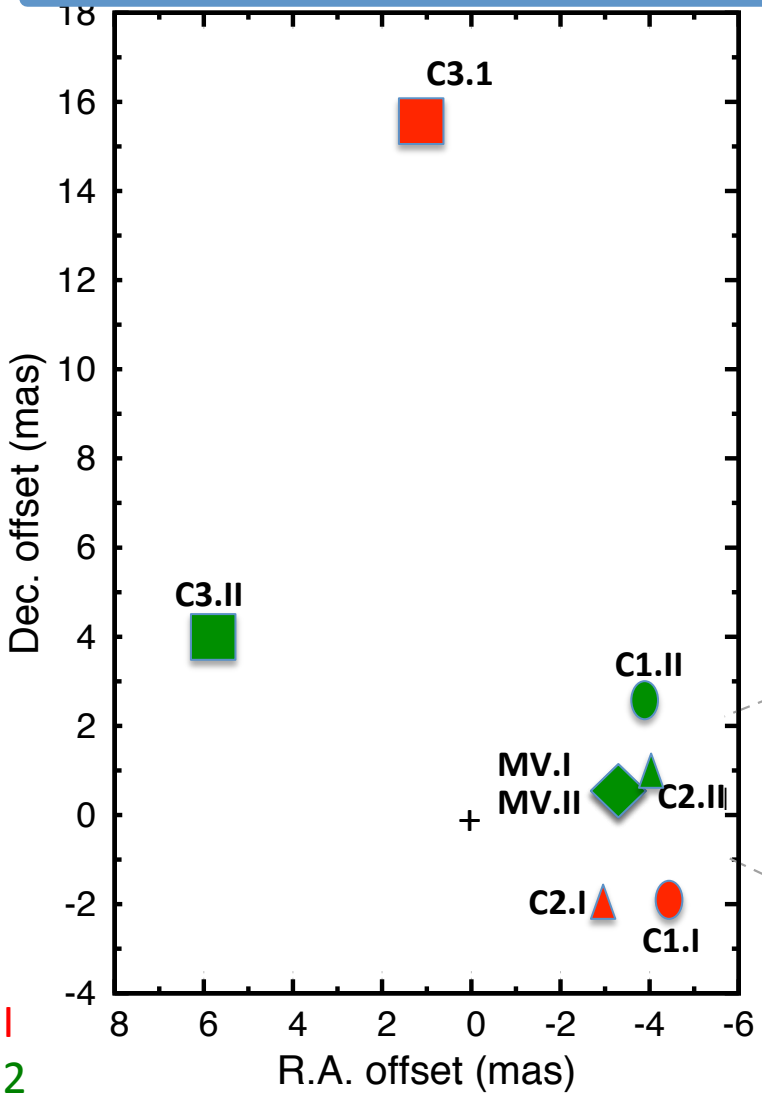
MultiView: $\varphi_{calib} = [\varphi_{c3}\, w_1 + \varphi_{c2}\,(1-w_1)]\, w_2 + \varphi_{c1}\,(1-w_2)$

Figure of Merit: "Spread" of the measured positions between the two epochs

Astrometric Results: Systematics (qso-only)

Comparative Study (MV 2º+4º+6º vs. PR 2º;4º;6º): Position Accuracy

Spread between Epochs ➔ Systematics

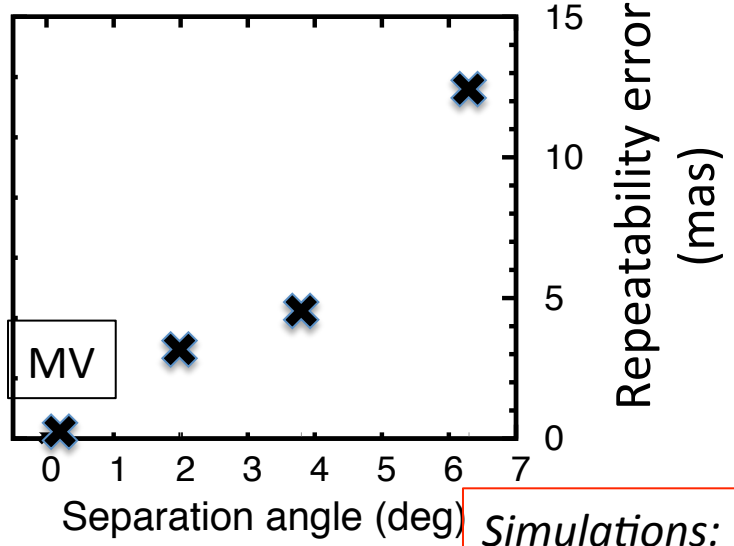


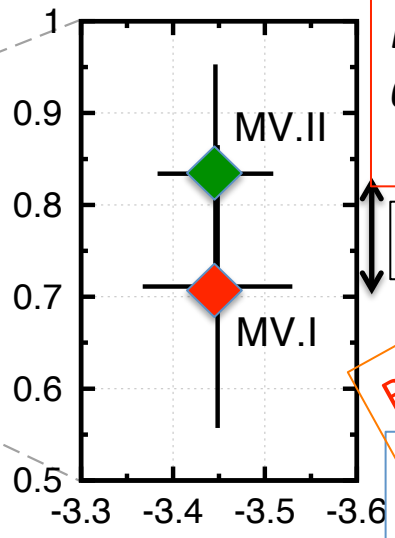
Epoch I

Epoch 2

[Rioja et al. 2017]

$\sigma_{pos} \propto \Delta$I-II





Simulations:

Equiv. Sep ~ 2º/10

0.2 deg = 12arcmin

[Jimenez, Rioja+2010]

~130 μas

Reach theoretical Thermal noise limit!

Astrometric Error per measurement ~ 100 μas

Comparative Astrometric Errors

(per measurement)

	QSO-QSO *(High SNR regime)*		QSO-OH *(Low SNR regime)*
Conventional PR Sep. = 2 deg	~2700 μas	In-beam PR Sep = 0.4 deg	~620 μas
MultiView Equiv. Sep = 0.2 deg	~100 μas	MultiView Equiv. Sep = 0.2 deg	~290 μas

MV is equivalent to that of a single source 10 times closer, and has reached the thermal noise limit

Comparing the two MV results, which have the same ionospheric calibration, the astrometric errors are larger for fainter source, which highlights that high SNR is desirable.

Astrometry with SKA-VLBI

Huge increase in sensitivity (very small thermal noise errors)
Potential for 10 micro-arcsecond astrometric accuracy at L-band
Requires matching calibration of ionospheric systematic effects

HOW?

Calibration	Target-Cal Separation	Probability
PR (1 cal.)	$\Delta\Theta \sim 1'$	Unlikely
MV (3 cals.)	$\Delta\Theta \sim 10'$	OK

MultiView drives the requirement for a minimum of 4 SKA1-MID VLBI beams.

SUMMARY & Future work

Astrometry rapidly reaches systematic limits; increased sensitivity does not improve accuracy

MultiView calibration results in superior ionospheric calibration with angular separations of a few degrees. Simultaneous observations will improve results.

General calibration method, for all frequencies.
Demonstration shown VLBA obs. @ 1.6 GHz; also successful 6.7 GHz; trying at 0.3 GHz

MV is widely applicable right now, with:

- Simultaneous observations with PAFs /multi-beam
- Fast-source switching

For SKA-VLBI, with multiple in-beam calibrators, will deliver 10 micro-as astrometric accuracy.