Precise Astrometry today and tomorrow with Next-Generation Observatories

Maria J. Rioja
ICRAR –CSIRO (Australia) & OAN (Spain)
Overview

Sample of Astrophysical Applications in a variety of fields
Bona fide astrometric measurements with VLBI 2016-2018

① SKA and methods for high precision (~ μas) astrometry
   MultiView and Pathfinder demonstration
② VLBI in Gaia era
   Comparisons and comments
③ Galactic Structure
   Updates on BeSSeL /VERA project
④ Evolved Stars and chromatic-Astrometry
   Results from the KVN
⑤ AGN core-shifts & alternative Calibration Methods
   UVPAP, MFPR
⑥ Technological Developments relevant to astrometry
   BRAND, PAFs, Global multi-freq. mm-VLBI array
The quest for accurate astrometry...

\[ \sigma_{\text{POS}} \sim \frac{\theta_B}{\text{SNR}} \quad \text{(Thermal Noise Limit)} \]

VLBI \( \Rightarrow \) micro-as (\( \mu \)as) astrometry

IF you can remove SYSTEMATICS

1) Long baselines, large collecting areas to reduce \textit{thermal errors}

2) Requires a matching improvement in \textit{methods} to calibrate out \textit{systematic errors}.

VLBI with

Propagation Medium

(independent atmospheres)
The Many Faces of the Propagation Medium

Low Frequency

\[ \tau_{\text{ION}} \propto \lambda^2 \]

(\lambda^2\text{ signature})

IONOSPHERE (dispersive)

TROPOSPHERE (non dispersive)

 Typical errors:

\[ ZPD=3 \text{cm (trop)} \]

\[ \Delta = 5 \text{TECU (ion)} \]

SKA-Low

MultiView (MV)

(Rioja+, 2009, 2017)

cm-dm-m waves

MultiView

< 8 GHz

Advanced Phase Referencing & Multi Frequency Phase Referencing

> 8 GHz

< 22,43 GHz

Source Frequency Phase Referencing

> 22 GHz

mm-submm waves

mm-VLBI

ALMA

Micro-Jy sensitivity

Micro-as astrometry

Wide applicability

A history of success!

SKA-Mid

+ MB

TECH. DEV.

METHODS

PR+ Reid + 2009

Honma+2008

MFPR (Dodson,Rioja+ 2017)

SFPR (Rioja&Dodson 2011)

Source Frequency Phase Referencing

~ 8 GHz

MV (Rioja+, 2009, 2017)

+ MB

Micro-View (MV)

< 8 GHz

Advanced Phase Referencing & Multi Frequency Phase Referencing

> 22 GHz

mm- VLBI

ALMA
High Frequencies & Troposphere

ΔΘ ~ few deg

Target Source

Reference Source

Ionosphere

Troposphere

~1000’s km

Widely applicable

ΔΘ

few deg

Thermal Errors
Systematic Errors
Total Errors

Thermal Errors
Systematic Errors
Total Errors
THE PROBLEM: "IONOSPHERIC WEDGE" Direction Dependent (DD) effects

Sketch showing the limitations of general PR at low frequencies

ASTROMETRY LIMITED BY SYSTEMATICS
Systematics reached in 30 min for 1 mJy source.

Target Source

Reference Source

\( \Delta \Theta \sim \text{few deg} \)

\( \sim 1000 \text{'s km} \)
Low Frequencies & Ionosphere

THE PROBLEM: “IONOSPHERIC WEDGE” Direction Dependent (DD) effects

OPTIONS to overcome DDEs:
One VERY close reference source and use conventional PR \((in-beam)\)
Low Frequencies & Ionosphere

THE PROBLEM:
“IONOSPHERIC WEDGE”
Direction Dependent (DD) effects

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

(Rioja, Dodson+, 09,17)
Low Frequencies & Ionosphere

THE PROBLEM: "IONOSPHERIC WEDGE"

\[ \Delta \Theta_{\text{eff}} \approx 0 \]

Spatial structure

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

obs. strategy: **simultaneous**
minimum 4 (tied array) beams

Multi-Beam capability:

Thermal noise limited regime

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

(Rioja, Dodson+, 09,17)
Low Frequencies & Ionosphere

Target

Source

Low Frequencies & Ionosphere

~1000's km

Sketch representing ionospheric directional effects

Ionosphere

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

obs. strategy: simultaneous

THE PROBLEM:
“IONOSPHERIC WEDGE”
⇒ Spatial structure

Widely applicable

Thermal noise limited regime

ΔΘ ~ few deg

ΔΘ_{eff} ~ 0

Wide FoVs with PAFs:

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

(Rioja, Dodson+, 09,17)
Demonstration of MultiView: Comparative Astrometric Analysis

VLBA observations at L-band, AGNs / OH maser.
2 epochs, 1 month apart

(Rioja+ 2017; Orosz+ 2017)

ANALYSIS METHODS:

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

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

FoM: Use astrometric repeatability at both epochs as empirical estimate of systematics.
Comparative Astrometry (PR $2^\circ$; $4^\circ$; $6^\circ$ vs. MV $2^\circ+4^\circ+6^\circ$): Position Accuracy

Astrometric Results

Repeatability between Epochs → Systematics

- **Epoch I**
- **Epoch II**

Limited by systematics

MV

PR$_{6^\circ}$

PR$_{4^\circ}$

PR$_{2^\circ}$

Simulations:
Equiv. Sep $\sim 2^\circ/10$
0.2 deg = 12arcmin

[$\text{Jimenez, Rioja+2010}$]

Thermal noise limit

Reach theoretical

~130 µas

Astrometric Error per measurement

~ 100 µas

- MV.I
- MV.II

The higher repeatability of MV illustrates the gain using MV.
Ultra Precise 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

Current Instruments: (per measurement)
100 μas
thermal systematic

<table>
<thead>
<tr>
<th>Calibration</th>
<th>Target-Cal Separation</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>PR (1 cal.)</td>
<td>ΔΘ ~ 1’</td>
<td>Unlikely</td>
</tr>
<tr>
<td>MV (3 cals.)</td>
<td>ΔΘ ~ 10’ - 30’</td>
<td>OK</td>
</tr>
</tbody>
</table>

MultiView drives the requirement for a minimum of 10 SKA tied array beams.
Beams for MultiView Observations

FAST: 300m

2'
FAST19-beams array receiver for MultiView

- FAST MB: 300m
- Single-pixel 30m matches FAST FoV
- Multibeam receiver 1050-1450 MHz
FAST19-beams array receiver for MultiView

Proof of concept of MultiView with MB already demonstrated using Parkes

Non-overlapping beams on the sky

FAST MB: 300m

Single-pixel 30m matches FAST FoV

MeerKAT/SKA: Tied-array beams for 6km baseline (for future)

Multi Beam capabilities at other frequencies (i.e. 1.6 GHz) would enable other science (OH-maser ultra precise astrometry)
FAST MB: 300m

Multi Beam capabilities at other frequencies (i.e. 1.6 GHz) would enable other science (OH-maser ultra precise astrometry)
Wide FoV Technologies in large European telescopes

Effelsberg & Lovell – CSIRO MKII PAF

0.7-1.7 GHz

~9 beams for VLBI with MV to match the 20' FOV of FAST MB (~4 beams for Lovell)

1.1-1.7 GHz

Multiple independent steerable tied-array beams across the central 25-m disk equivalent beam for VLBI with MV

18-26 GHz

~4 beams for VLBI with MV to match the 20' FOV of FAST MB

3-4.5 GHz 7-feed under development

WSRT - Apertif

UL2m Fit SKA FoV – 15m diameter

PAF FoV = 25 x single pixel FoV

PAF FoV = 36 x single pixel FoV

Fast, GB, Arecibo, Parkes, Askap…
Early Science Case for FAST – VLBI:
Ultra Precise Pulsar Astrometry

*Improve parallax/proper motion to enhance timing results*

“Now”: Large dishes provide 10-fold increase in sensitivity
10 μas-astrometry

“Future”: Goal 1% error in distance for GC pulsar target, with FAST+SKA

- Many suitable targets.
- Proof of concept of MultiView with MB already demonstrated using Parkes
Astrometry rapidly reaches systematic limits; increased sensitivity does not improve accuracy.

Ultra Precise Astrometry with SKA-VLBI requires new experimental methods: MultiView addresses these requirements.

FAST, like SKA, provides increased sensitivity. FAST has a MultiBeam receiver, so can perform MultiView-VLBI.

FAST can provide an early science demonstrator for ultra precise astrometry in SKA-era.
Review of Recent Advances

Constrained by Selection Effects and Biases

Astrometry continues to demonstrate wide applicability

⇒ Many many results to cover!

Limited to:
`bona-fide’ astrometric measurements with VLBI 2016-2018

Attempt to break down by technique (e.g. in-beam, SFPR, MV)

Link to new technological developments that facilitate techniques
(e.g. increased sensitivity, simultaneous freq., multiple beams)
Parallax uncertainties: 0.04 mas (G<15); 0.1 mas (G=17); 0.7 mas (G=20)
All sources treated as single stars.
Systematics < 0.1 mas depend on position, magnitude, colour
Bias ~ 30 μas  (Lindegren+ 2018)

Comparison between Gaia and Accurate VLBI astrometry to verify Gaia results.
Very active field!

VLBI
Phase referencing
Accuracy ~ 10 μas
Comparable to, or better than Gaia’s target accuracy
1. Radio Astrometry in the Gaia Era

VLBA Pleiades LP: 4 new parallaxes (total 8)

Mellis + 2018
https://osf.io/byrclf/

Gaia results agree with all VLBI Pleiades astrometry

Remember…
Hipparcos Pleiades
Distance controversy
1. Radio Astrometry in the Gaia Era

Comparison of astrometric Solutions btw Gaia and VLBA

Orion Star Forming Complex

Kounkel + 2018

Gaia struggles with binaries and dusty stars

<table>
<thead>
<tr>
<th>Source Astrometric Parameter</th>
<th>VLBI Value</th>
<th>Gaia Value</th>
<th>Gaussian Astrometric Excess Noise (mas)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pleiades Triple System HII 3197</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parallax (mas)</td>
<td>7.27±0.08</td>
<td>2.22±0.71</td>
<td>2.56</td>
</tr>
<tr>
<td>pmRA (mas yr⁻¹)</td>
<td>+18.0±0.8</td>
<td>+31.1±0.9</td>
<td></td>
</tr>
<tr>
<td>pmDE (mas yr⁻¹)</td>
<td>-42.5±1.8</td>
<td>-41.4±0.9</td>
<td></td>
</tr>
<tr>
<td><strong>Bright Young Binary System V1046 Ori</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parallax (mas)</td>
<td>2.64±0.075</td>
<td>0.44±0.17</td>
<td>0.62</td>
</tr>
<tr>
<td>pmRA (mas yr⁻¹)</td>
<td>+1.88±0.09</td>
<td>+0.45±0.39</td>
<td></td>
</tr>
<tr>
<td>pmDE (mas yr⁻¹)</td>
<td>+1.2±0.14</td>
<td>+2.5±0.38</td>
<td></td>
</tr>
<tr>
<td><strong>Dusty Red Supergiant Star VY CMa</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parallax (mas)</td>
<td>0.855±0.057</td>
<td>5.92±0.82</td>
<td>4.48</td>
</tr>
<tr>
<td>pmRA (mas yr⁻¹)</td>
<td>-2.80±0.58</td>
<td>+0.93±1.77</td>
<td></td>
</tr>
<tr>
<td>pmDE (mas yr⁻¹)</td>
<td>+2.60±0.58</td>
<td>-6.47±1.75</td>
<td></td>
</tr>
</tbody>
</table>

All outliers within $3\sigma$ agreement with VLBI when astrometric excess noise is added in quadrature to Gaia quoted uncertainties (whenever $\sigma > 2!$).
The (unresolved) optical jets are a dominant contribution to Gaia/VLBI offsets.

Anticipate that a study of VLBI/Gaia position offsets will become a power tool for probing properties of the accretion disk and the relativistic jet in the AGNs ➔ Talk by L. Petrov
Mapping Spiral Structure with VLBI

Major “Key Science” Projects for VERA and VLBA (BeSSeL survey), PR+

- Parallaxes: ~170 parallaxes for massive young stars
- Arms assigned by CO l-v plot
- Tracing most spiral arms, eg... Outer arm traced
  Perseus arm “gap”
  Local arm significant
  Sagittarius arm
- Inner, bar-region is complicated

Plan view of the Milky Way with locations of HMSFR with trigonometric parallaxes.

Reid et al. 2014, 2016
Honma et al. 2012
Most distant parallax to date on the far side of the MW (H$_2$Omasers)

\[ \pi = 49 \pm 6 \mu \text{as} \quad (D=20.4 \pm 2.8 \ -2.2 \text{ kpc}) \]

**A** Sky view

**B** Decomposed offset position along the east and north directions vs. time

**C** Only parallax

Sanna+ 2017 (Science)
The Milky Way’s Rotation Curve

Gunn, Knapp & Tremaine (1979) for a flat rotation curve…

\[ \Theta_0 = \sim 240 \text{ km/s} \]

Slope, \[ \theta_0 = 220 \text{ km/s} \]

Based on 3-D motions and “gold standard” distances.

Revised IAU recommendation:

The increase in speed increases the Milky Way’s mass by 50 percent, bringing it even with the Andromeda Galaxy.

Widespread impact on astrophysics:

Map the spiral structure of our Galaxy and to determine fundamental Parameters, such as the rotation velocity and distance to the GC.

Gunn, Knapp & Tremaine (1979) for a flat rotation curve…

Slope, \[ \theta_0 = 220 \text{ km/s} \]
Includes high precision astrometry at 6.7 GHz (Methanol Masers)

**2. Maser astrometry And Galactic Structure**

Additions

Xu + 2016, Science

Sakai et al. 2018 in preparation

+4 more In Sgr spiral arm (Kazi Rygl talk)

Different Astrometric calibration than for H$_2$O masers

Reid + 2017 (similar to MultiView in Image Domain) “artificial quasar method”

FUTURE

“Bessel-South” @ 6.7 GHz AuScope-Ceduna Interferometer (ASCI)

In commissioning…

Plan to use MultiView

Rioja, Dodson + 2017
EVOLVED STARS STUDIES with the KOREAN VLBI NETWORK (KVN, SFPR)

H$_2$O and 43.1/42.8/86.2/129.3 GHz SiO masers of a late stellar processes, mass loss and pumping mechanisms

Bona fide astrometrically registered images of the emission at all transitions, ring sizes and temporal evolution to discriminate btw proposed maser pumping mechanisms (radiative / collisional)

Game Changer: Robust data set to advance understanding and theoretical models.
**Temporal Evolution**

VY CMa (Cho + in prep)

22 GHz (H$_2$O maser) to 42.8, 43.1, 42.9, 86.2 & 129.3 GHz (SiO masers) with full astrometric imaging, every few months.

Talk by Youngjoo Yun

- Asymmetric spatial distribution of H$_2$O maser
- Typical spoke-like or snail trail features of SiO
- Gaps in emission for different transitions

See also posters by Cho + for an overview of the ES KSP Yoon+ VX Sgr dynamical development from the SiO to the H$_2$O maser regions.

Work in progress ... KVN SFPR astrometry testing the pumping models & astro-chemistry
Enabled by the innovative KVN receiver system

Single Frequency Receiver

Simultaneous Multi-Frequency Receiver

Reference Source

Target Source

PR

SFPR
High-Precision wide-angle astrometry at 43 GHz
(VLBA, UV PAP)

Do we have to have close calibrators?

Astrometry between pairs of sources up to ~ 15° separations is feasible using a parametric approach.

Precisely solve for every contribution to the delays: Geometric, Instrumental, Tropospheric, Ionospheric along with source positions.

RECORD FREQUENCY 43 GHz

Abellan + 2018

“Core-shift” values agree with predictions from SSA effects (Kovalev+ 2008, Lobanov 1998)

- Study of core-shifts in a complete radio sample (13 radio loud AGNs around the N. Celestial Pole)
- Frequencies: 15 & 43 GHz
- First Global differential phase delay astrometry analysis at 43 GHz over such wide angles.
- Uses dedicated software (UVPAP) (highest frequency so far – probably the limit)
- Measured core-shift between U (15 GHz) and Q (43 GHz) bands & compared to SFPR
Revealing a recollimation Shocks in AGNs
(VLBA, MFPR)

Going beyond the B&K core-shift to unveil the standing shock, for BL-Lac

There are many reasons (particularly the association of gamma ray & radio flares (Marscher, Nature ‘12) to believe that in Blazars there are standing shocks at which the B&K model breaks-down. These should be revealed at the higher frequencies.
Revealing a recollimation Shocks in AGNs (VLBA, MFPR)

Going beyond the B&K core-shift to unveil the standing shock, for BL-Lac

**SIMULATIONS**

MHD Simulations

Predict deviation from B&K optical depth core-shift model

Perfect match to observations

*Left:* Sync. emission from RMHD models (JLGomez; J. Marti)

*Right:* Expected core-shifts for this class of AGN (black) vs BK (red)

Looks to fall short of BK expectation ➔ standing shock?

(Dodson + 2017, Molina + 2017)
Revealing a recollimation Shocks in AGNs  
*(VLBA, MFPR)*

To uncover the transition from B&K core-shift to unveil the standing shock, for BL-Lac

**SIMULATIONS**

MHD Simulations

Predict deviation from B&K optical depth core-shift

Perfect match to observations

Fit $r \propto \nu$

$\alpha_{43} - \alpha_{43BK} \approx 120\mu$as

**Relevance:**
Jet formation physics

**MFPR:**
Single Source!
Alternate “ion blocks” (L/C/K) &
fast frequency switching (K/Q)

Jet Physics of AGNs

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>MFPR</th>
<th>Predict deviation from B&amp;K optical depth core-shift</th>
<th>Perfect match to observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>22/43</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>22/6/1.4 GHz</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Revealing a recollimation Shocks in AGNs (VLBA, MFPR)

To uncover the transition from B&K core-shift to unveil the standing shock, for BL-Lac

**SIMULATIONS**

MHD Simulations

Predict deviation from B&K optical depth core-shift model

- $r \propto \nu^{-0.9}$

Perfect match to observations

MFPR: Single Source!

Alternate "ion blocks" (L/C/K)

fast frequency switching (K/Q)

Jet Physics of AGNs

Revealing a recollimation Shocks in AGNs (VLBA, MFPR)

**SIMULATIONS**

MFPR: Single Source!

Alternate "ion blocks" (L/C/K)

fast frequency switching (K/Q)

K band 21.8-22 GHz

Wide C band 3.9 - 7.9 GHz

L band 1.4 - 1.7 GHz
 Revealing a recollimation Shocks in AGNs
(VLBA, MFPR)

Posters on AGN “core-shift” measurements:
Ilje Cho + SgrA* (KVN, 22/43/86 GHz)
Voitsik + 24 AGNs (EVN, 1.7/2.3/5/8 GHz)

Errors in $\Delta TEC \sim 0.1 TECU$

Made possible by VLBA frequency agility:
Fast switching between 22/43/86 GHz
Slower switching between 22/6/1.4 GHz

Perfect match to observations

$\tau(\nu) \propto \Delta TEC \cdot \nu^{-2}$

K band 21.8-22 GHz
Wide C band 3.9 - 7.9 GHz
L band 1.4 - 1.7 GHz
PSR-π is the large VLBA campaign to measure the parallax and proper motion of pulsars using VLBI.

PSR-π paper II (“Data paper”) has been submitted (arXiv:1808.09046, Deller + 2018) listing results for all 60 (of the 70 pulsars searched) with in-beam calibrators.

Median error 40 μas
Precise (10%) distance to 2.5kpc

Distances provide improvements to galactic models of free electron density

VLBI precise proper motions can improve pulsar GW timing arrays.

SKA1 x10 more sensitive:
Provide precise distances/pm to 10kpc

VLBI pm can have smaller errors than those from pulsar timing...

... timing noise?
Understand formation mechanism of high mass stars

Revise PMS evolutionary models to underpredict masses by 10-40%

Dynamical Mass determination

Accurate calibration of the first step of the cosmic distance ladder

Proto Planetary Nebulae Calabash with KVN&SFPR

Outflows and evolution of pPNs

Confirm the pPN paradigm

Cosmological implications, H

TDE's
TECHNOLOGICAL DEVELOPMENTS RELEVANT TO ASTROMETRY
1. BRAND EVN

- BRoad bAND EVN, a project to build a prototype primary focus receiver for the EVN (and other telescopes) with a very wide frequency range from 1.5 GHz to 15.5 GHz.

- Innovative, very wide bandwidth.

- To use full bandwidth requires coherent fringe-fitting over the very wide frequency range, including $\nu^{-2}$ term for ionosphere plus linear ($\nu$) slope, carried out inside CASA with RINGS.

RELEVANT FOR ASTROMETRY AT CM-wavelengths:
With coherent fringe-fitting chromatic astrometry information between simultaneous images at different frequencies.

The BRAND EVN partners include Germany (MPIfR), Italy (INAF), Sweden (OSO), Spain (IGN), The Netherlands (ASTRON), and Latvia (VIRAC).

Project Engineer Gino Tuccari; Project Manager: Walter Alef
2. PAFs for SKA astrometry

Effelsberg & Lovell – CSIRO MKII PAF

0.7-1.7 GHz

~9 beams for VLBI with MV to match the 20' FOV of FAST MB (~ 4 beams for Lovell)

Multiple independent steerable tied-ray beams across the central 25-m disk equivalent beam for VLBI with MV

1.1-1.7 GHz

~4 beams for VLBI with MV to match the 20' FOV of FAST MB

18-26 GHz

3- 4.5 GHz 7-feed under development
The quest for largest angular resolution (=highest astrometric accuracy):

3. A Global “Multi-Frequency” mm-VLBI array

Techniques relevant for ALMA (long baselines)

Dodson + 2017
“The science case for simultaneous mm-wavelength receivers in radio astronomy”
Outcome of ERATEC meeting held in Florence Oct. 2015
Bona fide Precise Astrometry adds a new dimension to your research, with positions, proper motion, distances, and direct registration of temporal and frequency monitoring.

Fundamental contribution to many research fields in astrophysics: widely applicable to many targets and at a wide range of frequencies (m to (sub)mm waves) in conjunction with appropriate methods.

All regimes, ground VLBI & Space VLBI

Developments of new calibration methods and new instruments are providing a leap in the astrometric performance.

Acknowledgements: This presentation has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 730562 [RadioNet]
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.