Aligning Optical and Radiometric Reference Frames:

Using Gaia and VLBI Data

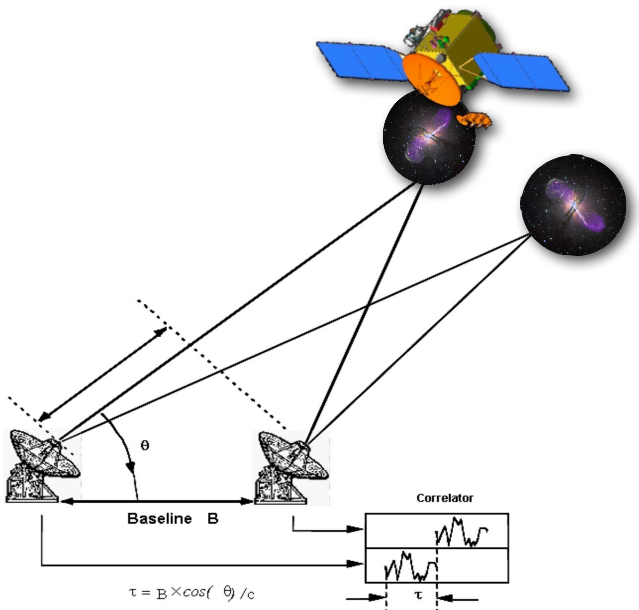


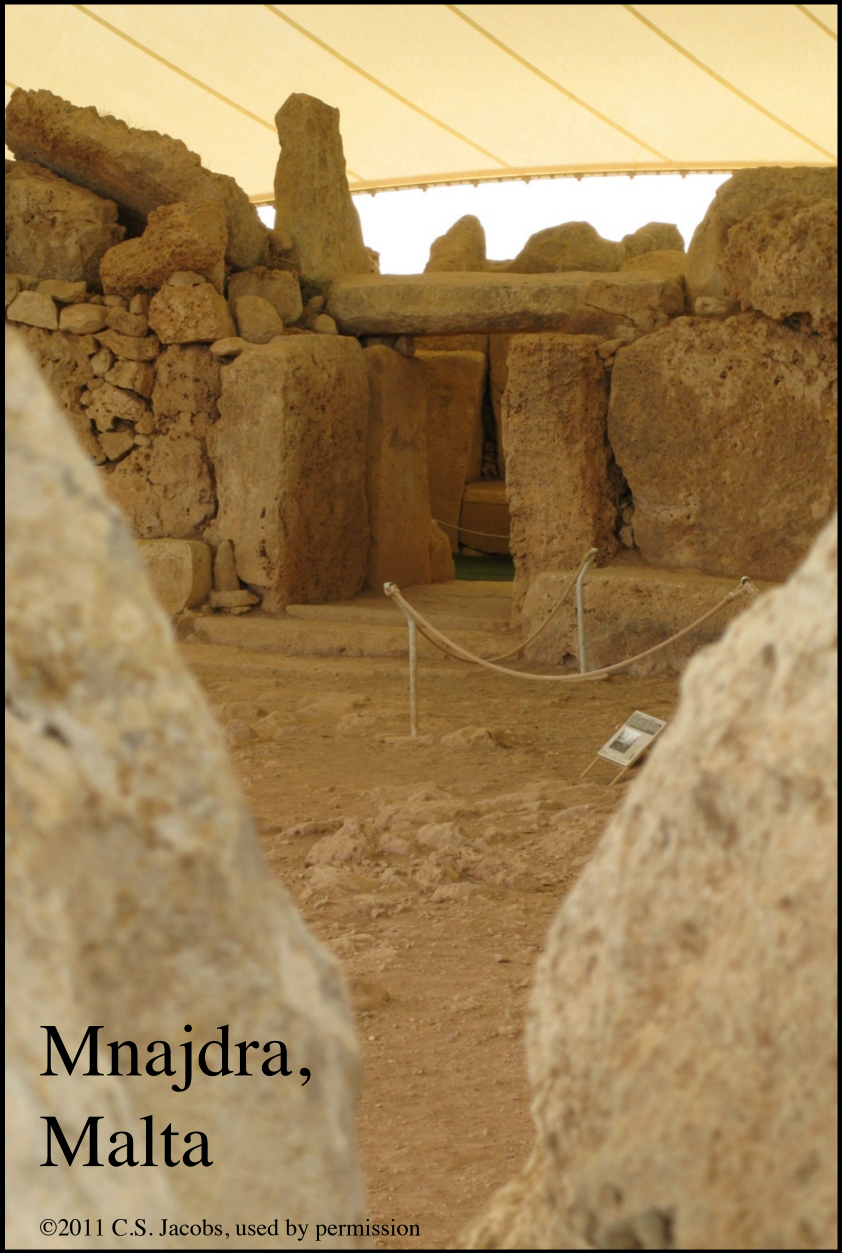
Photo Credit: Dimitry Bobroff, www.ludmillaalexander.com

Christopher S. Jacobs, Jet Propulsion Laboratory, California Institute of Technology

C. Garcia-Miro. S. Horiuchi, J.E. Clark, L. Snedeker, G. Bourda, P. Charlot, A. De Witt, J. Quick, J. Lovell, J. McCallum

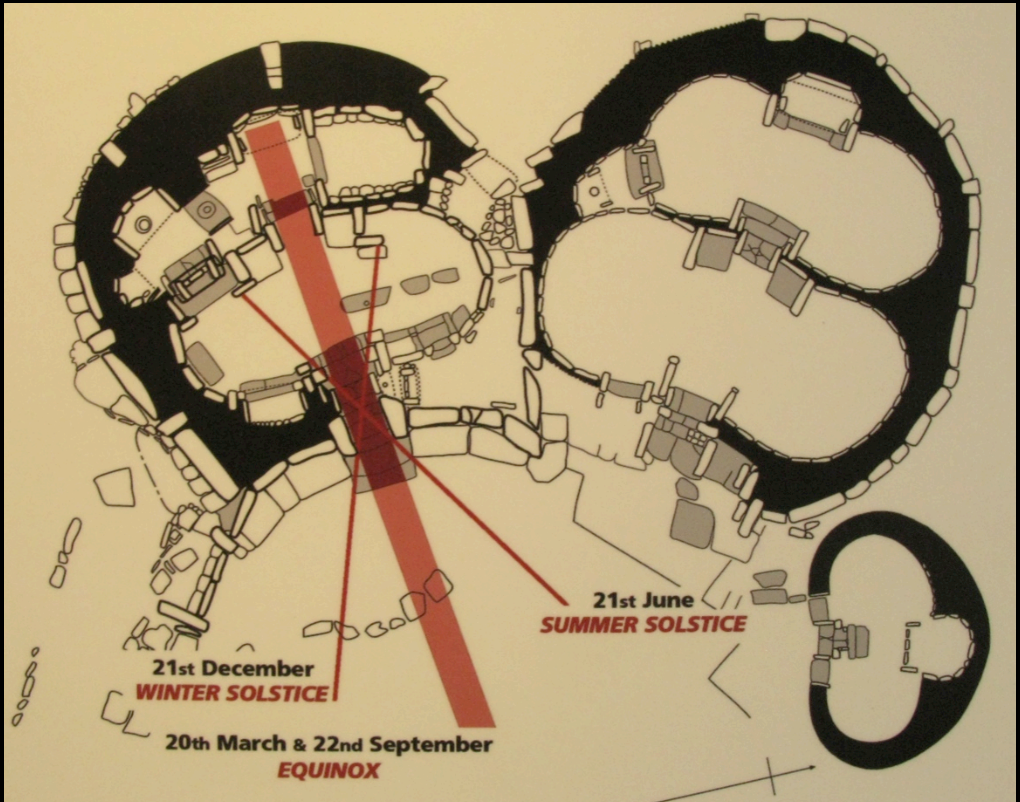
Astrometry: measures positions in the sky, 5000+ years history!

Credit: Heritage Malta



Island of Malta
Ggantija ~3500 B.C.
Mnajdra ~3200 B.C.

Mnajdra solar alignments



Credit: Heritage Malta

Introduction: Tying Optical and Radio Celestial Frames

- **Motivation:** *Deep Space Navigation in Optical Era*
  Optical communications is driven by potential for order of magnitude increase in data rates to deep space missions e.g. Hi-Def video from Mars.

  Optically based missions will want optical navigation which calls for an optical celestial reference frame ("star" catalog, "star" map).

- **Good news:** ESA funded $1B Gaia optical frame of over 1 billion sources
  Bonus: positions/velocities of > 200K solar system objects!

- However, Deep Space navigation, planetary ephemeris, Earth orientation, even definition of coordinates on the sky (ICRF) all currently use Radio-based system.

- Need to **seamlessly connect** existing radio-based products to the new optical frame.
  Accuracy needed: better than 1 part-per-billion.

Introduction: What objects can we use?

Methods for Tying Optical and Radio Celestial Frames

- Need common objects well measured in both optical and radio

- **Radio stars:** Previous generation used galactic stars that emit in radio,

  Crude by today's standards: difficult to achieve desired accuracy level.

  e.g. Lestrade et al. (1995).

- **Thermal emission from regular stars:**

  350 GHz astrometry using Atacama Large Millimeter Array (ALMA)

  Fomalont et al. (pilot observations)

  Verifies bright end of optical, but likely limited to 500 – 1000 μas (2.5 to 5 ppb).

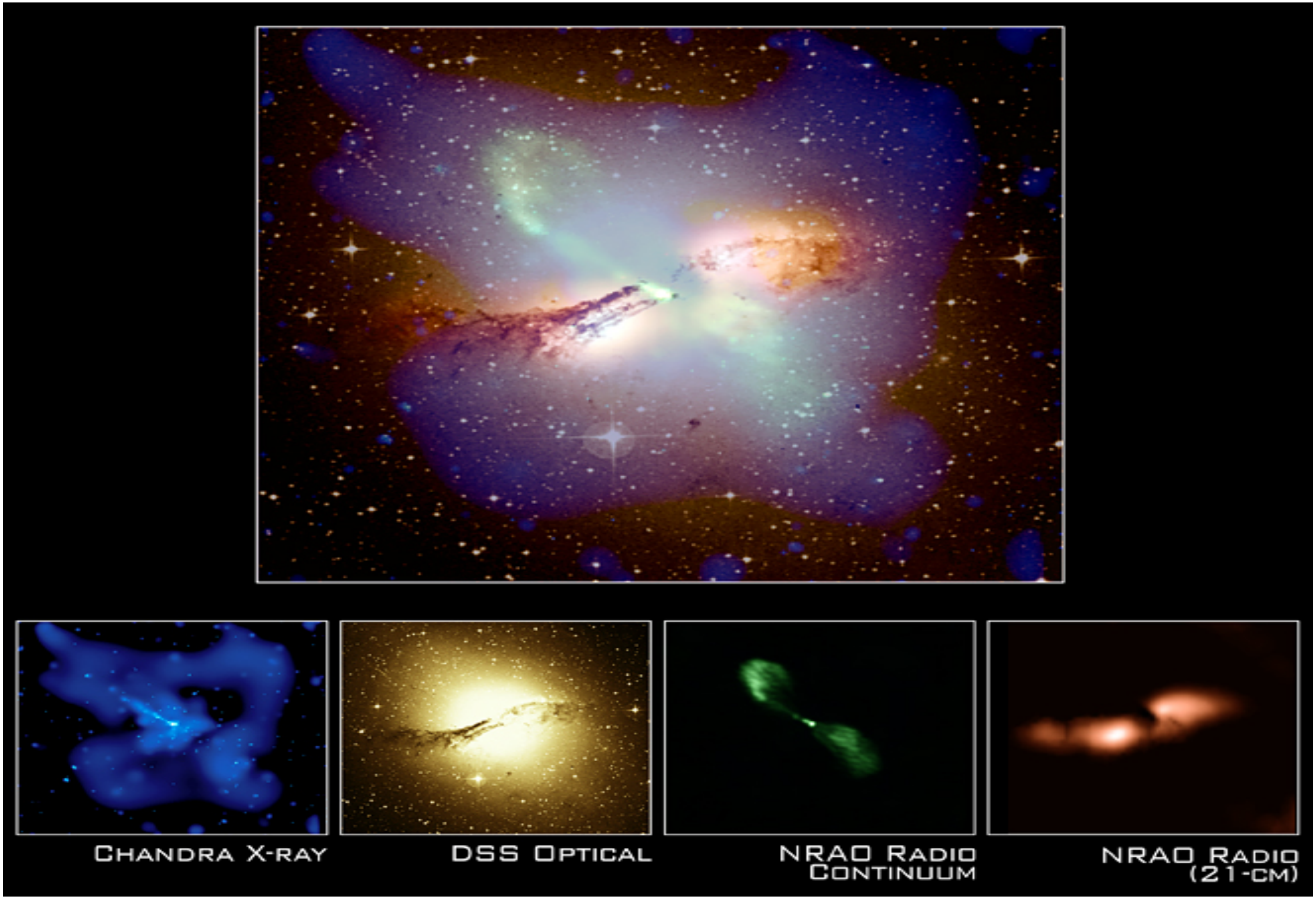
- **Extra-galactic Quasars:** detectable in both radio and optical

  potential for better than 100 μas to 20 μas (0.5 to 0.1 ppb).

  Strengths: extreme distances (> 1 billion light years) means no parallax or proper motion

The Source Objects

Example Extragalactic Source: Centaurus-A in X-ray, Optical, Radio



Credits: X-ray (NASA/CXC/M. Karovska et al.); Radio 21-cm image (NRAO/VLA/Schiminovich, et al.),
Radio continuum image (NRAO/VLA/J.Condon et al.); Optical (Digitized Sky Survey U.K. Schmidt Image/STScI)

Optical vs. Radio positions

Positions differences from:

- Astrophysics of emission centroids

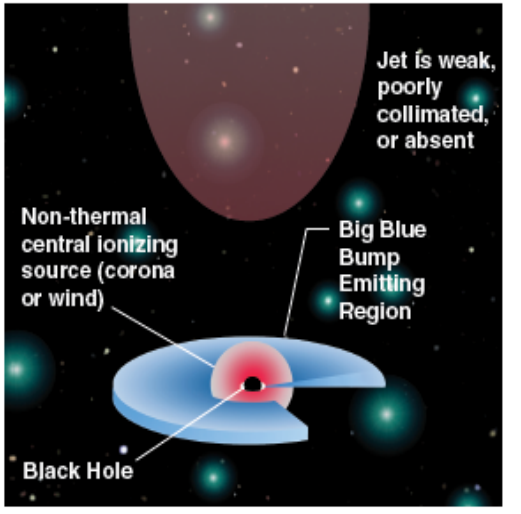
  - radio: synchrotron from jet

  - optical: synchrotron from jet?
    non-thermal ionization from corona?
    big blue bump from accretion disk?

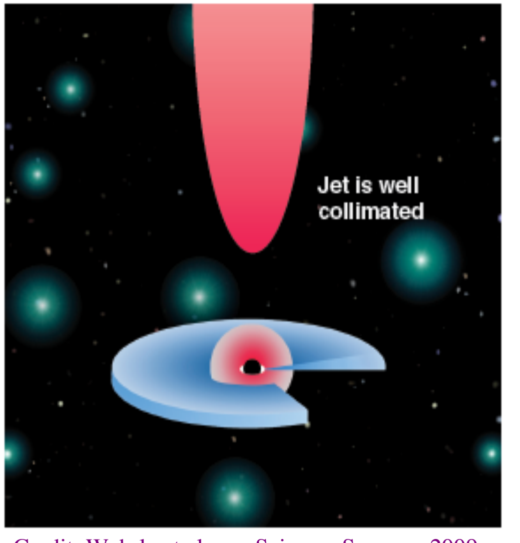
- Instrumental errors both radio & optical

- Analysis errors

Radio-quiet Quasar

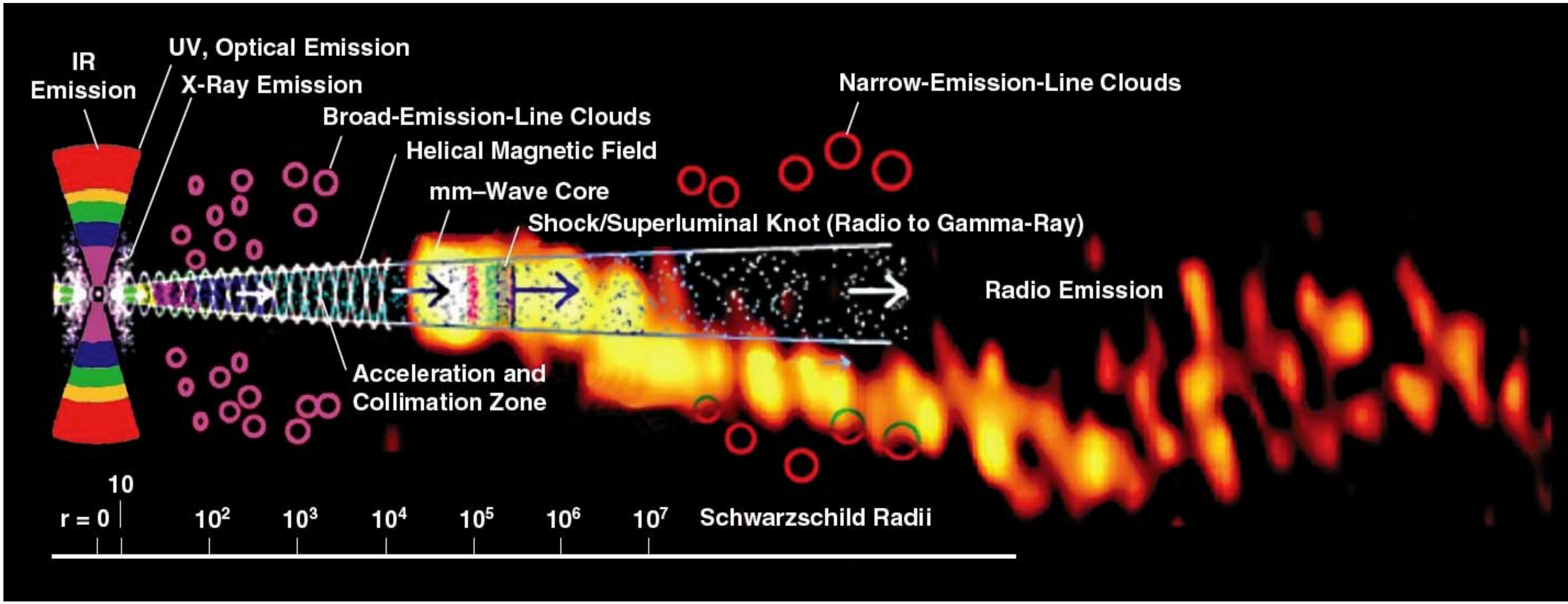


Radio-loud Quasar



Credit: Wehrle et al, μas Science, Socorro, 2009
http://adsabs.harvard.edu/abs/2009astro2010S.310W

Active Galactic Nuclei (*Marscher*)

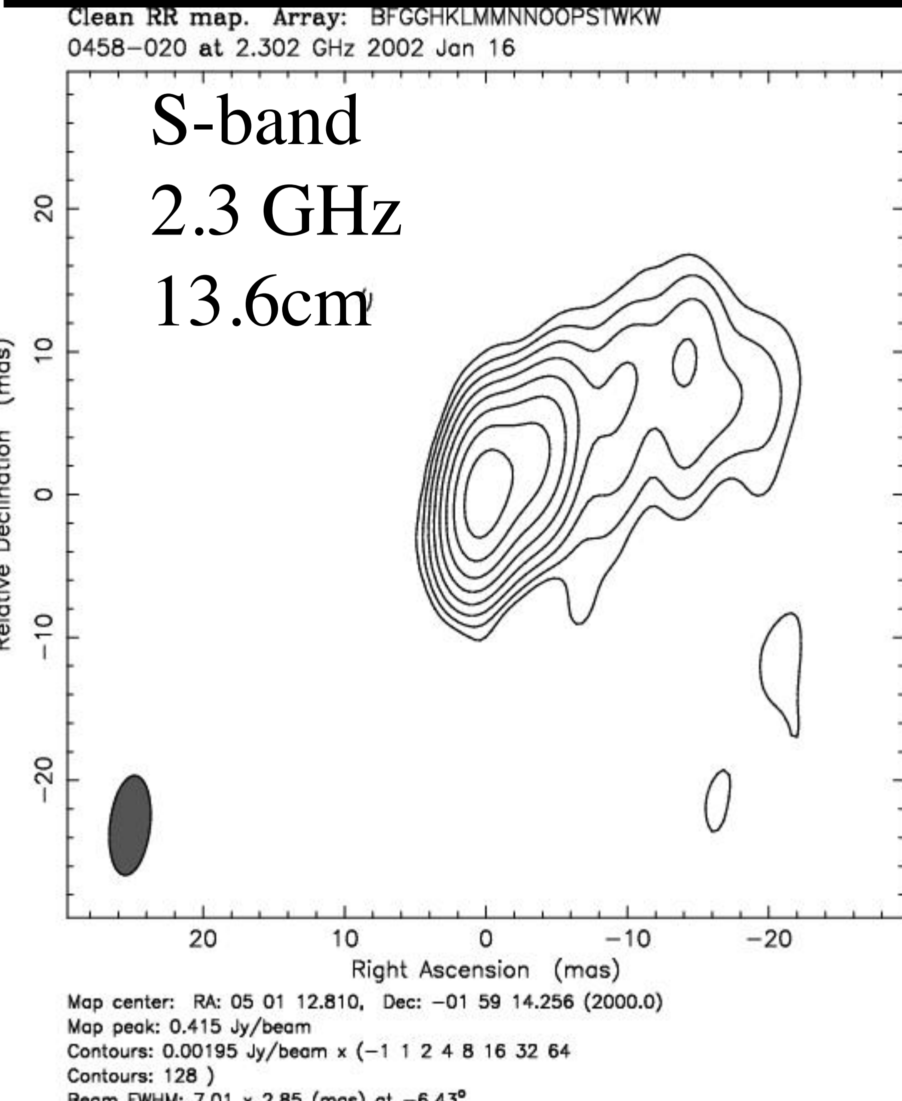


R~0.1-1 μas 1mas

Features of AGN: *Note the Logarithmic length scale.*
"Shock waves are frequency stratified, with highest synchrotron frequencies emitted only close to the shock front where electrons are energized. The part of the jet interior to the mm-wave core is opaque at cm wavelengths. At this point, it is not clear whether substantial emission occurs between the base of the jet and the mm-wave core."

Credits: Alan Marscher, `Relativistic Jets in Active Galactic Nuclei and their relationship to the Central Engine,' Proc. of Science,VI Microquasar Workshop: Microquasars & Beyond, Societa del Casino, Como, Italy, 18-22 Sep 2006. Overlay (not to scale): 3 mm radio image of the blazar 3C454.3 (Krichbaum et al. 1999)

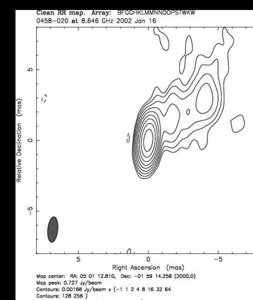
Radio Source Structure vs. Frequency

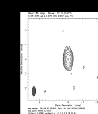


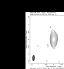
X-band
8.6 GHz
3.6cm

K-band
24 GHz
1.2cm

Q-band
43 GHz
0.7cm







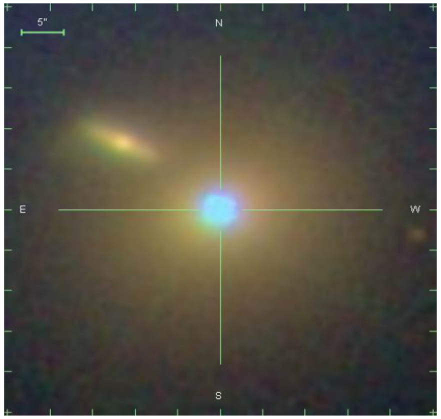
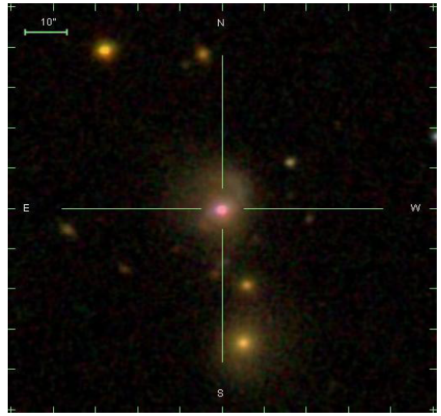
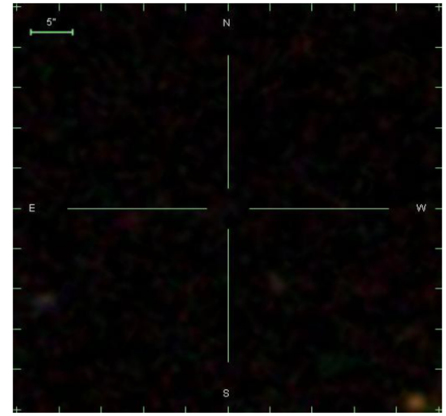
The sources become better →
smaller structure indexes
(Fey & Charlot 1997)

Ka-band
32 GHz
0.9cm

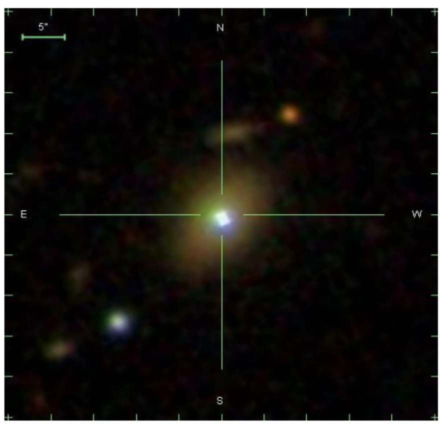
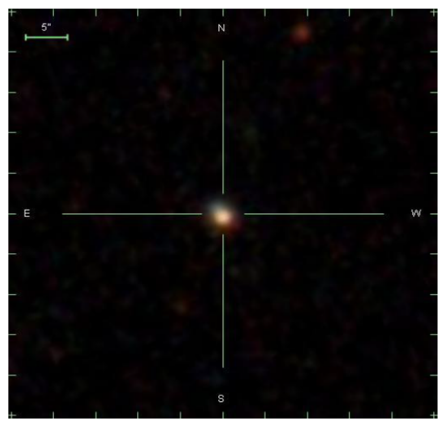
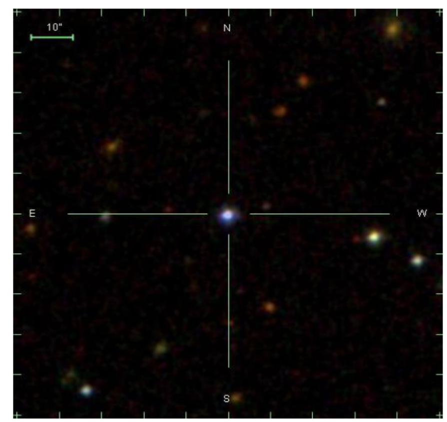
Images credit: P. Charlot et al, AJ, 139, 2010

Optical vs. Radio systematics offsets

SDSS Optical images of quasars

1101+384 0007+106 0920+390

1418+546 1514+192 1546+027

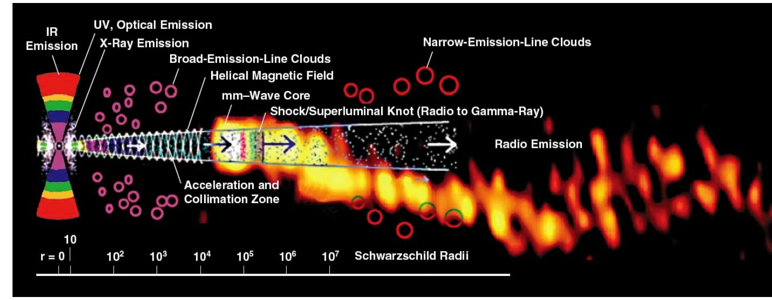
Credit: SDSS

- Optical structure: The host galaxy may not be centered on the AGN or may be asymmetric.
- Optical systematics unknown, fraction of millarcsecond optical centroid offset?

The goal:

Alignment into Common Frame

Optical-Radio Frame Tie Geometry

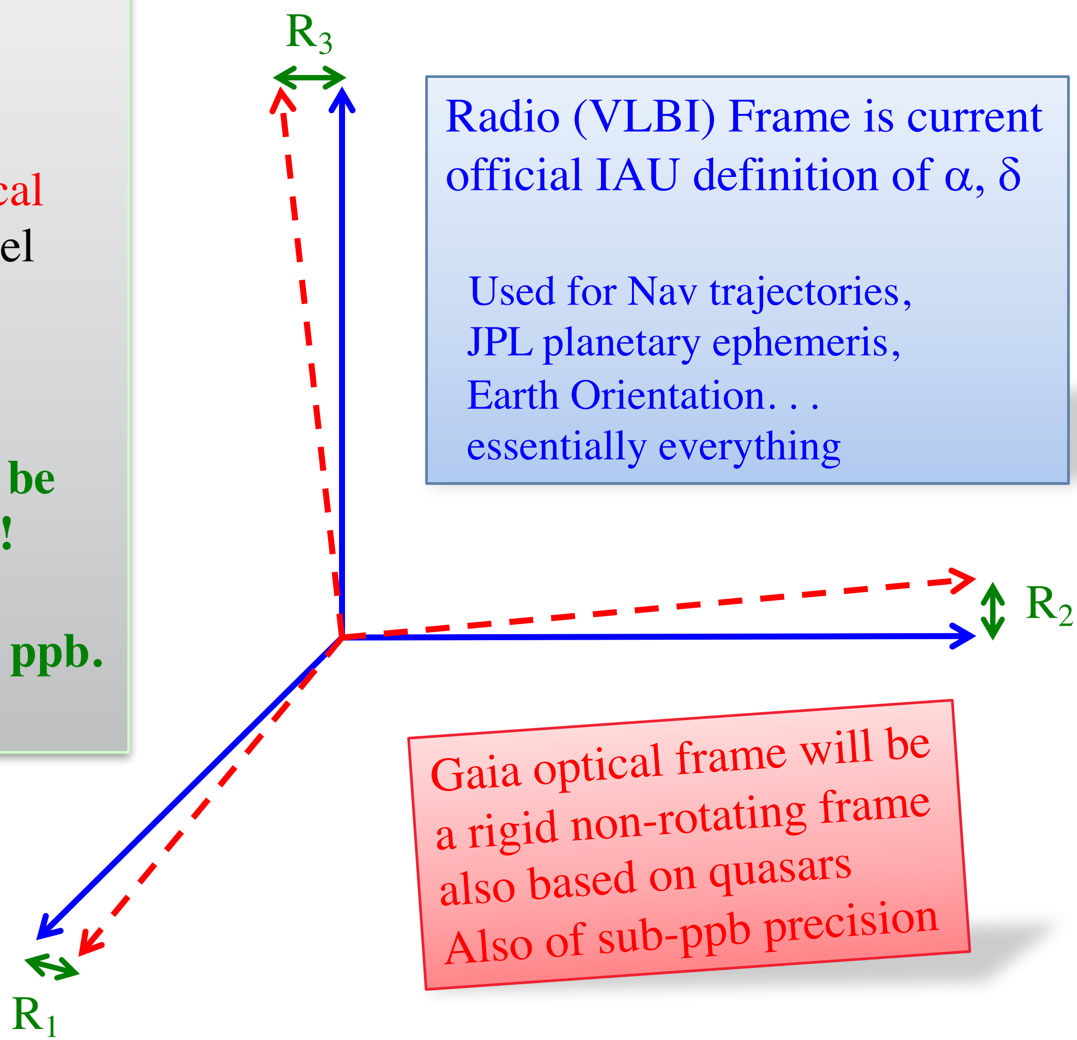


Frame tie task will determine 3 small rotations ($R_{1,2,3}$) between the individually rigid, non-rotating radio and optical frames to sub-part per billion level

Allows seamless integration into united frame.

More than 1 billion objects will be integrated into common frame!!

Frames objects to < 100 μas 0.5 ppb. want tie errors 10X smaller.



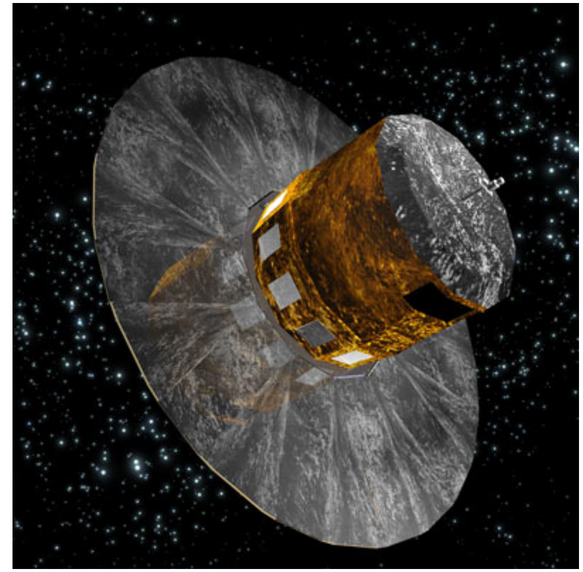
Radio (VLBI) Frame is current official IAU definition of α, δ

Used for Nav trajectories,
JPL planetary ephemeris,
Earth Orientation. . .
essentially everything

Gaia optical frame will be a rigid non-rotating frame also based on quasars
Also of sub-ppb precision

The Optical Frame

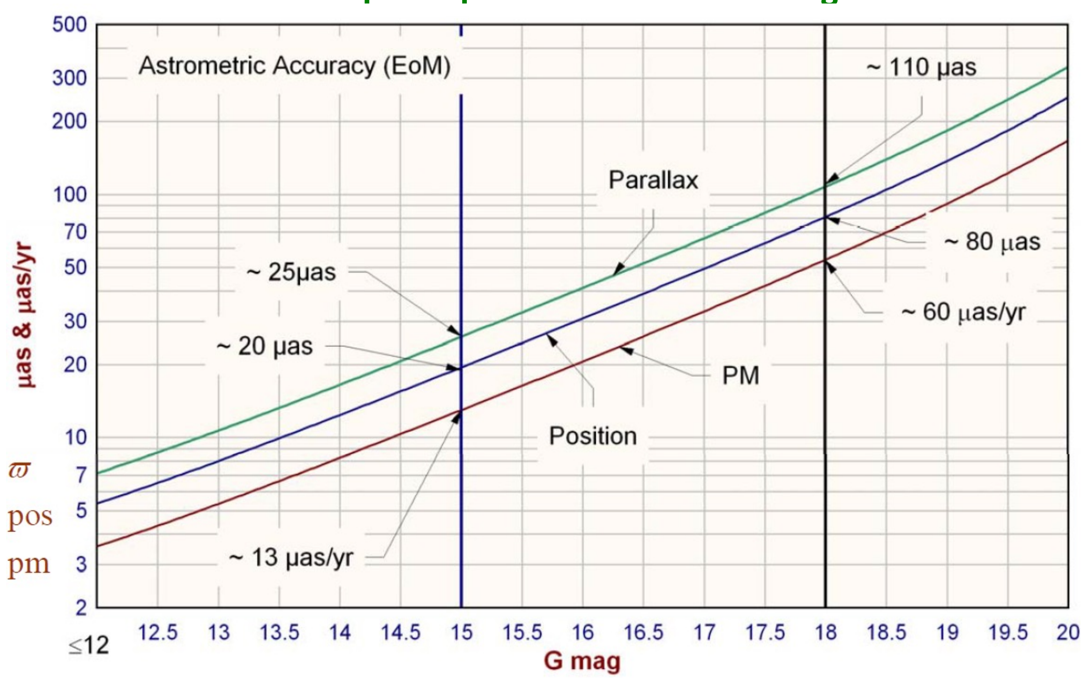
ESA's Gaia optical Astrometry



- Method: extremely accurate centroid of CCD pixels
- **Astrometry & photometric survey to V = 20.7^{mag}**
  - ~10^9 objects: stars, QSOs, solar system, galaxies.
  - Need to tie to existing radio frame so that this wealth of objects can be of use to JPL
- **Gaia Celestial Reference Frame (GCRF):**
  - Optically bright objects (V< 18mag) give best precision
  - 1st release Gaia astrometric catalog DR1 Sep 2016, 2nd Apr 2018.

Credit: F. Mignard (2013)

Anticipated precision of Gaia catalogue



Gaia release-1:

~0.3 mas in positions and parallaxes for 2 million brightest stars

~10 mas for rest of the stars

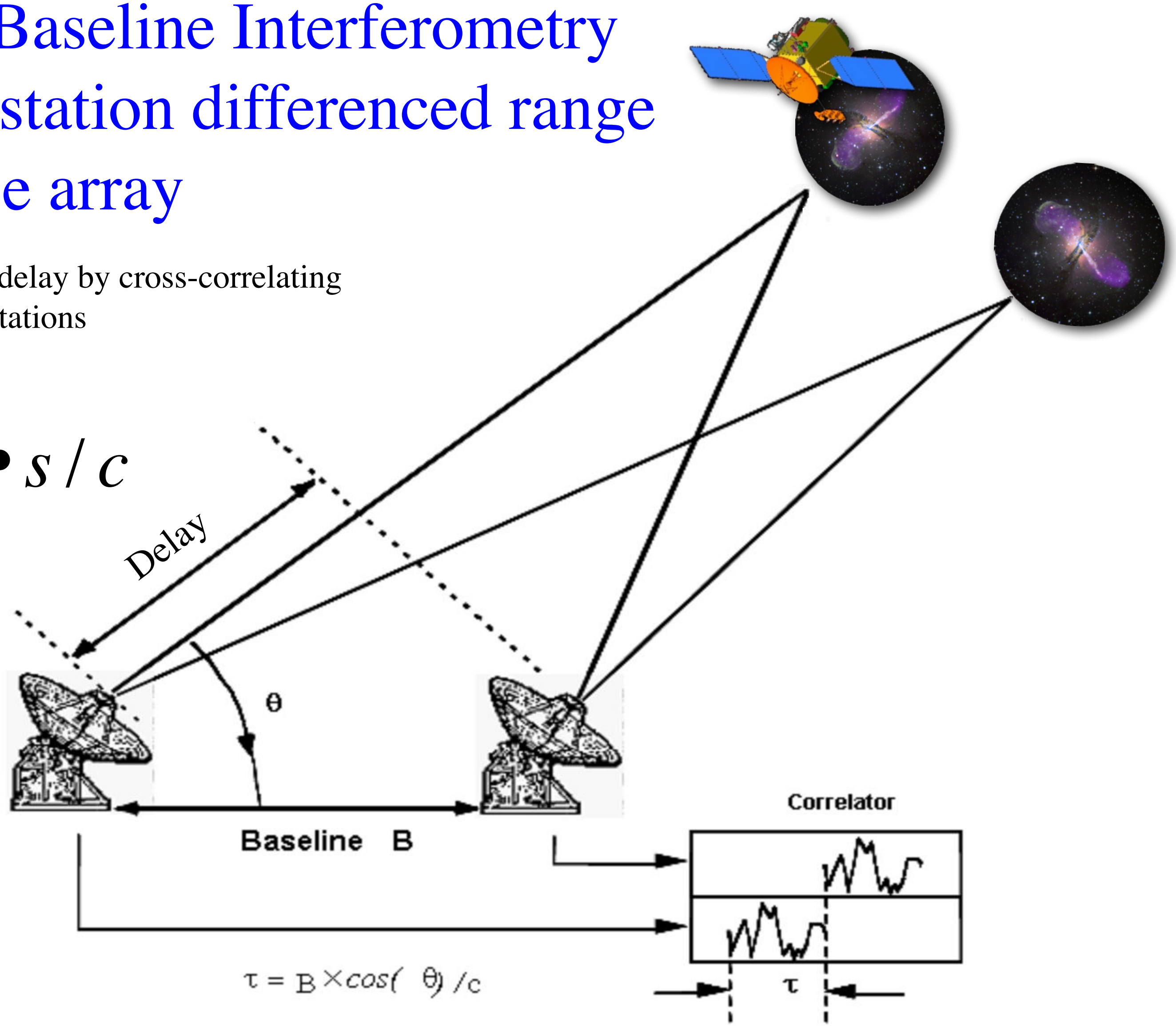
The Radio Frame using Radio Interferometry (VLBI)

Radio Interferometry: Long distance phased arrays

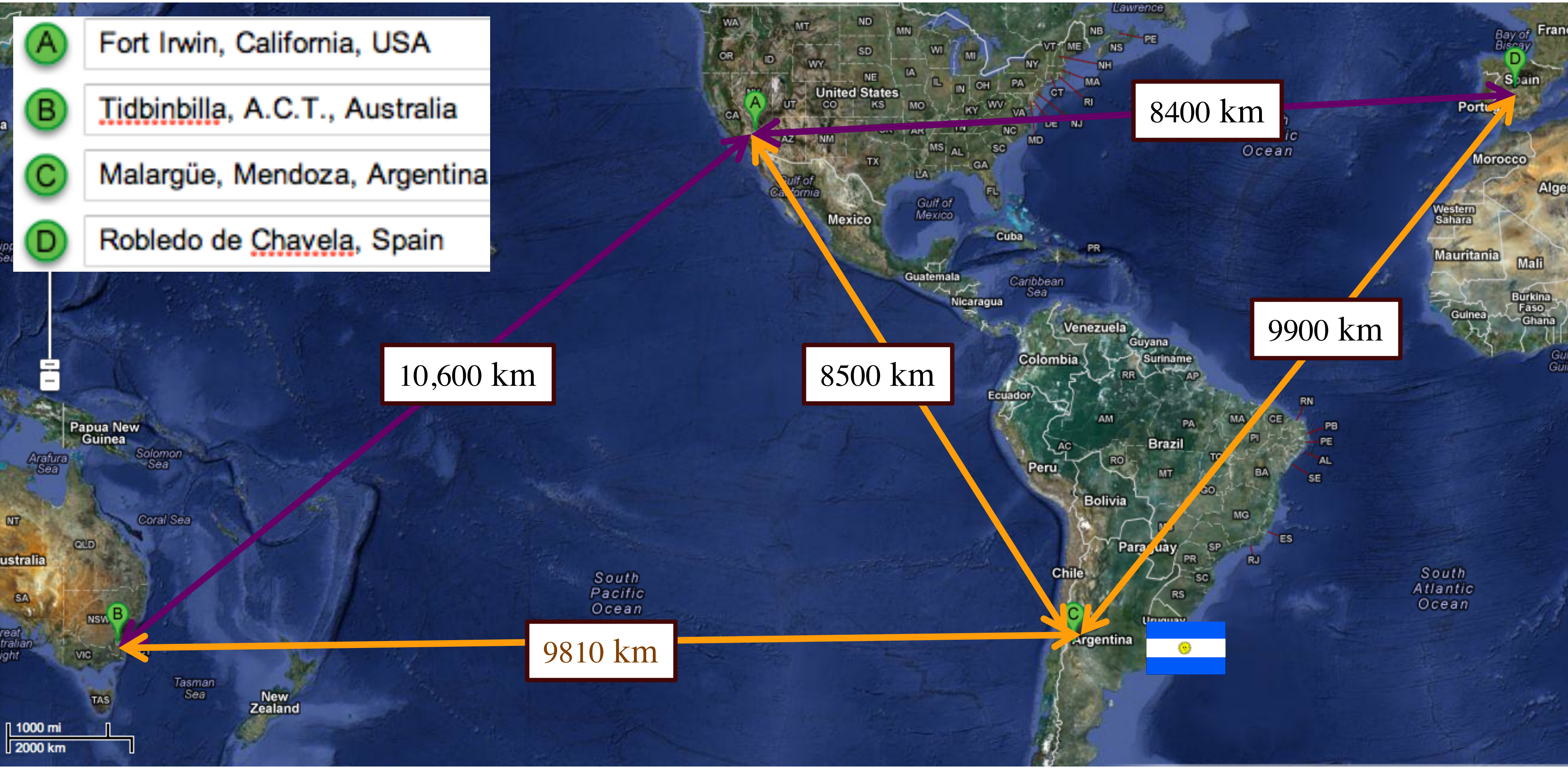
Very Long Baseline Interferometry is a type of station differenced range from a phase array

- Measures geometric delay by cross-correlating signal from two (2) stations

$$\tau = B \bullet s / c$$



32 GHz radio stations for VLBI



Maps credit: Google maps

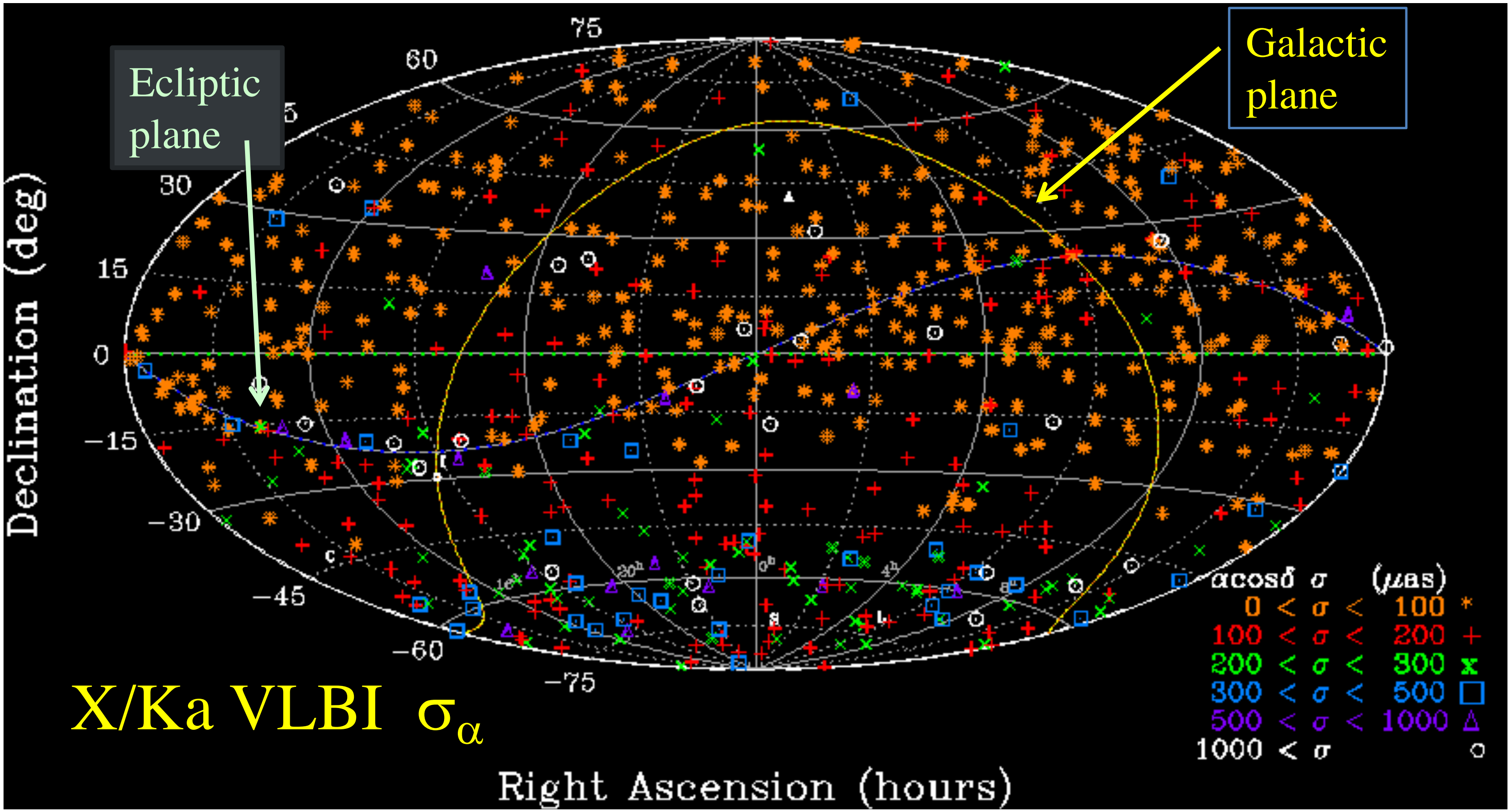
ESA's Argentina 35-meter antenna **adds 3 baselines** to DSN's 2 baselines

- Full sky coverage by accessing south polar cap
- near perpendicular mid-latitude baselines: CA to Aust./Argentina

Jacobs et al, EVGA, 2013 http://adsabs.harvard.edu/abs/2013evga.confE...1J

Results

VLBI 32 GHz Radio Results

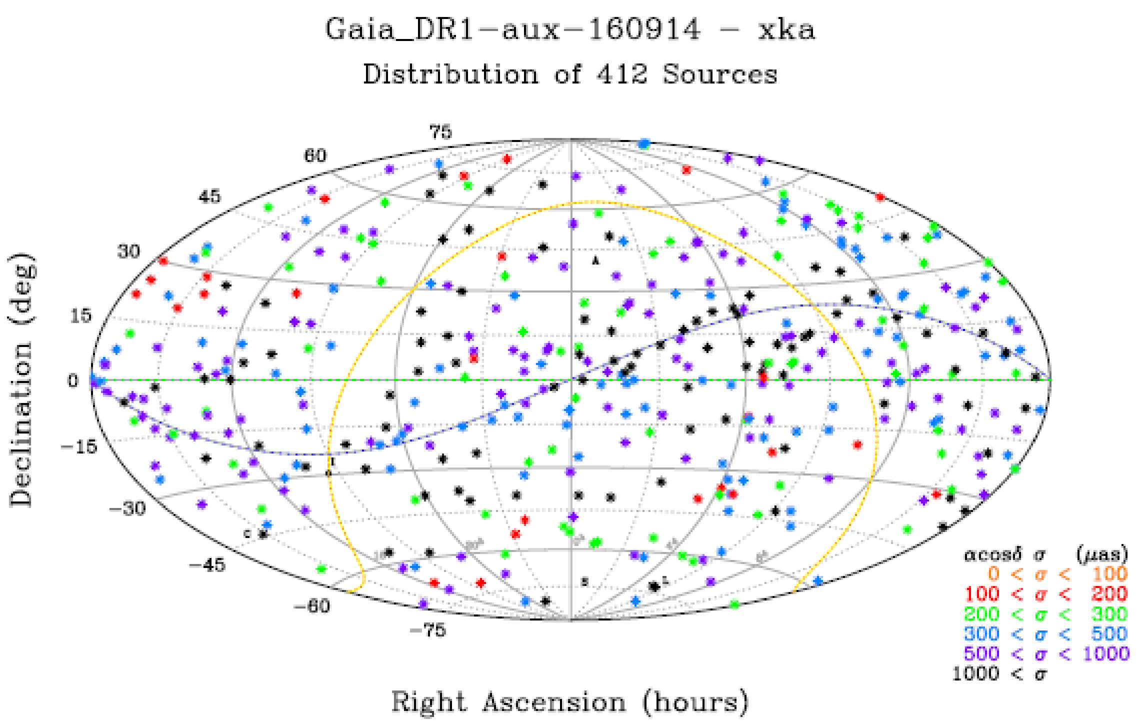


- **Collaboration with Argentina and ESA to extend DSN reach to SPC**
- **Detected 674 sources. 100+ sessions, 50K group delay/phase rate obs**
  Approximately 100 μas precision, 400 μas systematics

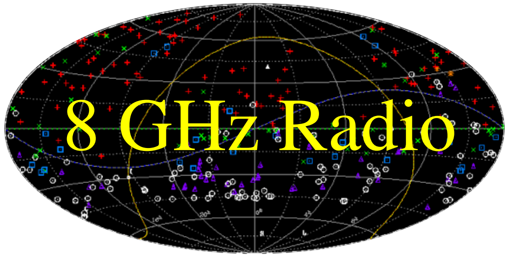
Tying optical and Radio Celestial Frames

Gaia optical (DR1-aux) vs. 32 GHz VLBI

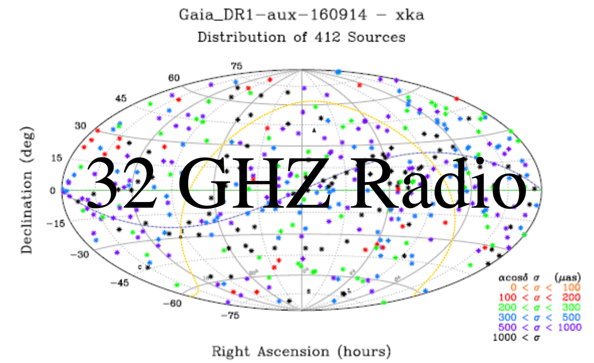
- **Tying to Gaia's optical frame using Gaia preliminary release (DR1-aux)**
- **Approx. 500 *μ*as optical precision per object, ~100 *μ*as precision in radio**
- **Gaia archive** http://gea.esac.esa.int/archive/)
  - **412 common sources (-7 outliers), including 184 ICRF2 "defining" sources**
  - **25 *μ*as (0.1 ppb) precision in 3-D rotation angles,**
  - **Systematics ~ 500 *μ*as(2.5 ppb)**



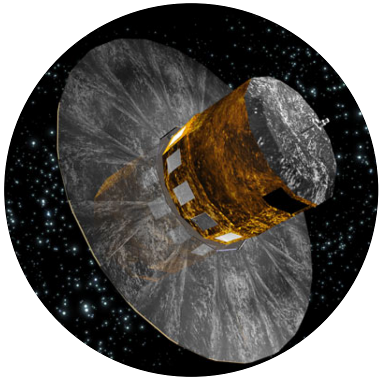
Summary: Tying Optical & Radio



- **Goal:** Tie of optical and radio celestial frames for deep space navigation and astronomical applications.



- **Roadmap:**
  - Preliminary optical & radio data are in-hand.
  - Increase number of sources in common between optical and radio
  - Expect to be limited by systematic calibration errors
  - Quantify and reducing systematics by
    - getting data in three radio bands (8, 24, 32 GHz)
    - Compare independent analysis chains
    - Image sources in radio to quantify non-pointlike structure



Gaia Optical

- **Preliminary results: Gaia_DR1-aux alignment vs. VLBI**
  - Excellent 3-D tie precision of ~ 20 μas.
  - Systematic errors 200 – 500 μas.
  - 32 GHz radio work very efficient, ppb synthesized beam, more compact objects
  - Control of systematics will require increased southern hemisphere observations.