



The International Celestial Reference Frame and Earth Orientation Parameters



Why geodesy starts billions of light-years away

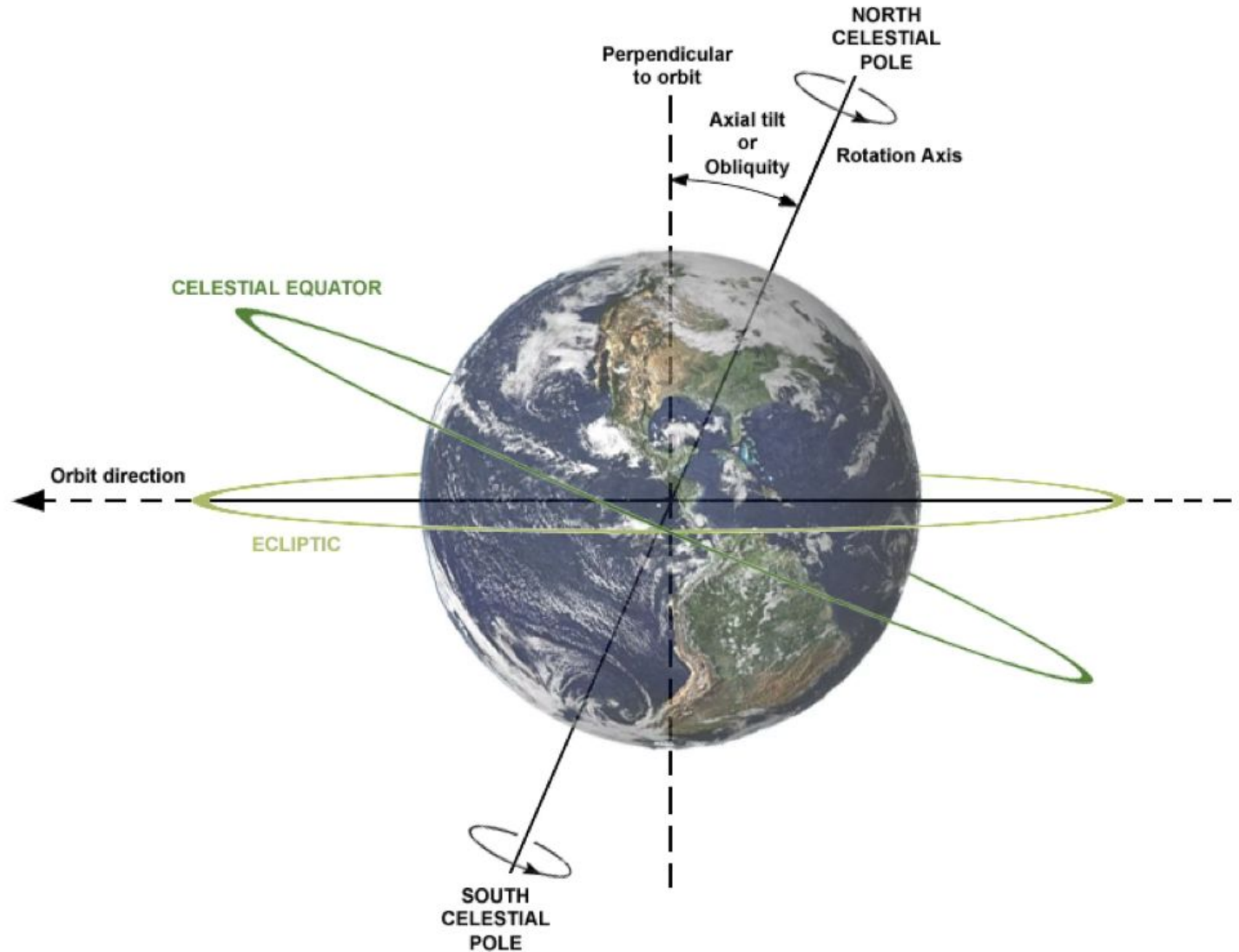
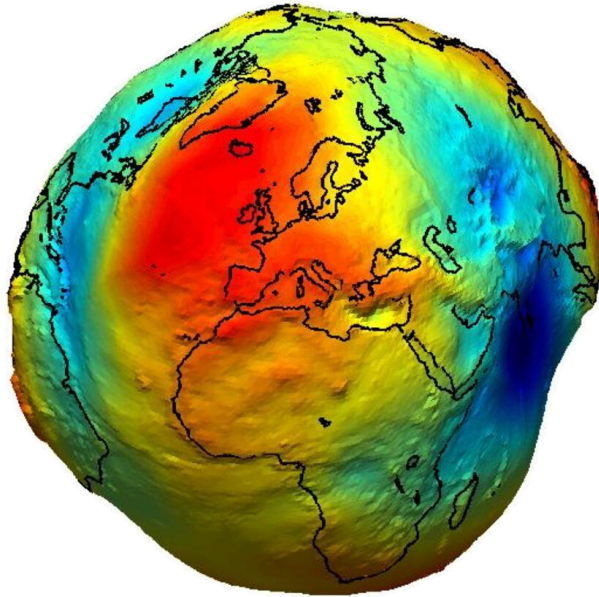
Aletha de Witt

South African National Geodesy Workshop 2026 | 30 September – 02 October 2026 | DLRRD, Pretoria



What is Geodesy?

Geodesy is the science of measuring the Earth's dynamic shape, its gravity field, and its orientation and motion in space



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(Space) geodesy



VLBI

Very Long Baseline Interferometry

Earth rotation, station coordinates, quasar positions

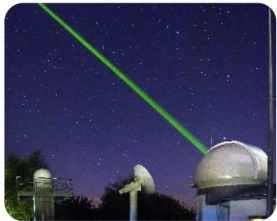


GNSS

Global Navigation Satellite Systems

(GPS, GLONASS, Galileo, Beidou)

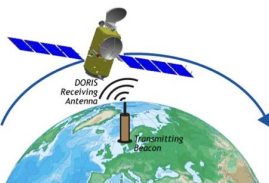
Station coordinates, Earth rotation, Geodynamics



SLR

Satellite Laser Ranging

Satellite orbits, station coordinates, Earth rotation, centre of mass of the Earth



DORIS

Doppler Orbitography and Radiopositioning Integrated by Satellite

Satellite orbits, Station coordinates, Earth rotation, gravity field

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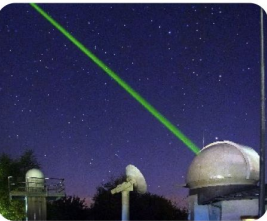


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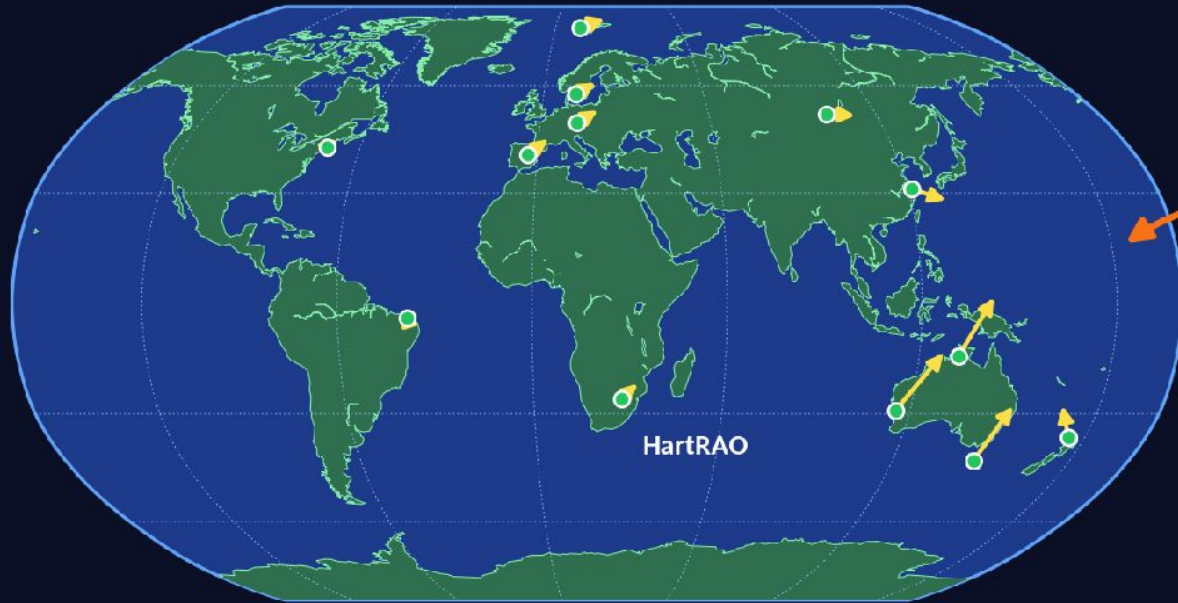
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(Space) geodesy

Parameter	VLBI	GNSS	DORIS	SLR
ICRF				
Nutation				
Polar motion				
UT1				
Length-of-day				
Subdaily ERPs				
ERP oceantide amplitudes				
Coordinates/velocities (ITRF)				
Geocentre				
Gravitational field				
Satellite orbits				
LEO satellite orbits				
Ionosphere				
Troposphere				
Time synchronisation				

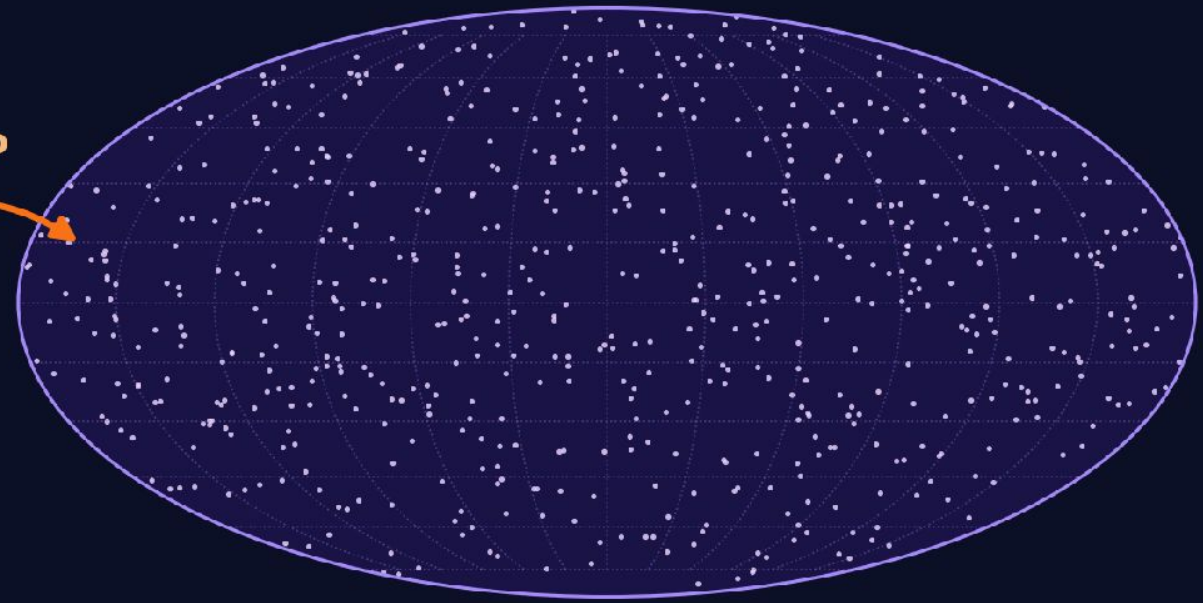
Two maps

Map of the Earth
ITRF



Where our stations are, and how they move
as the continents drift

Map of the sky
ICRF



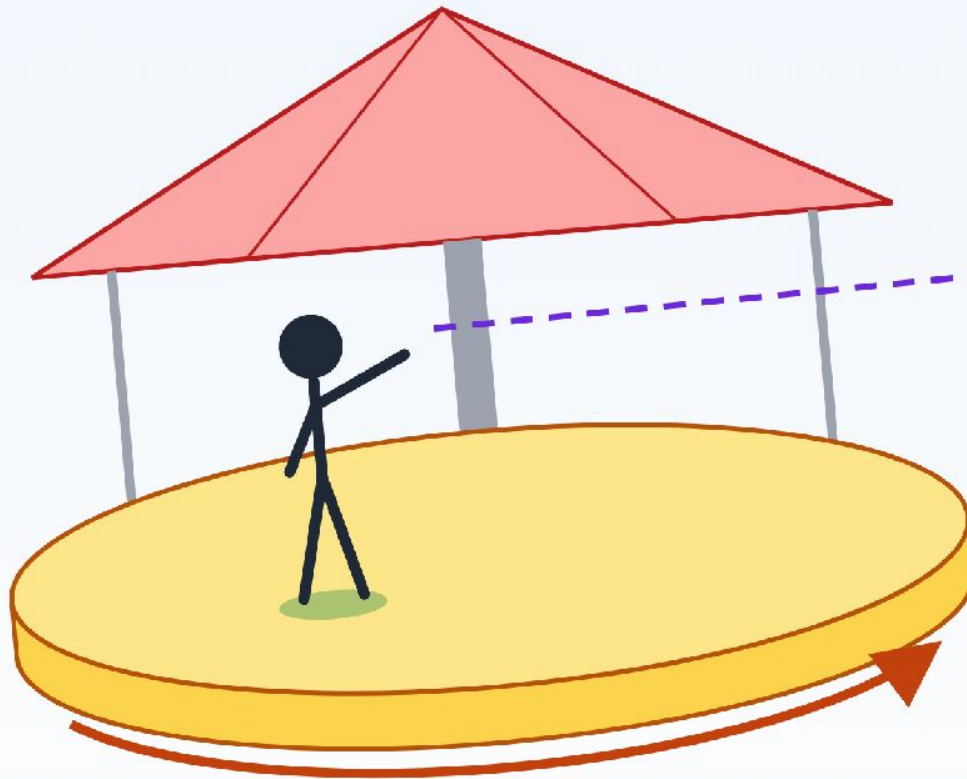
Positions of distant quasars,
fixed in space

EOP



The Earth Orientation Parameters tell us how one map is turned relative to the other at any moment.

Pointing from a spinning merry-go-round



1 Where the lighthouse is
a distant, fixed reference

2 Where you stand on the platform
your position on the moving surface

3 How the platform is turned and tilted right now
it speeds up, slows down and wobbles

Get any one of these wrong and you point in the wrong direction.

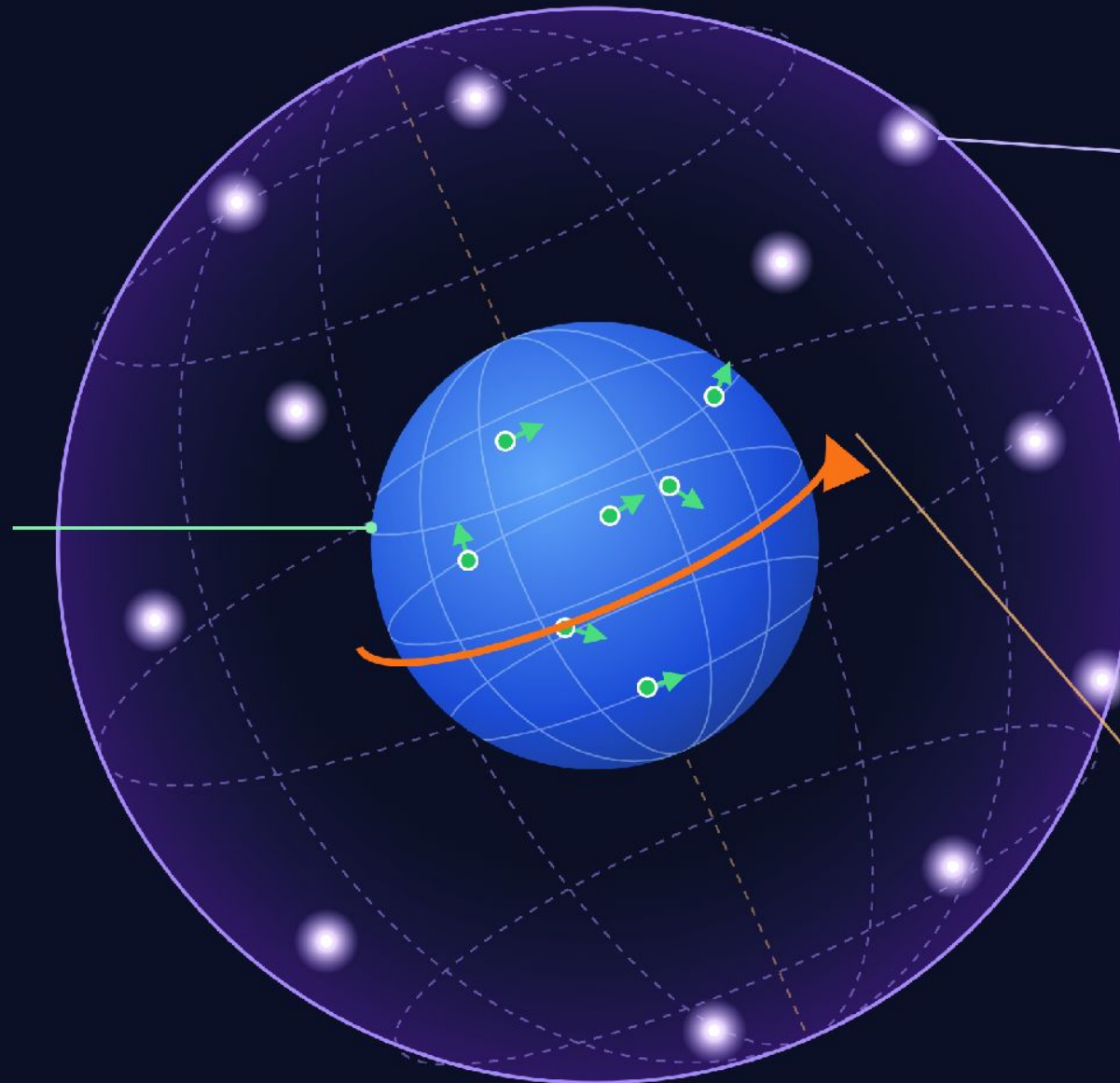
Two maps

Map of the Earth ITRF

Where our stations are,
and how they move as
the continents drift

Map of the sky ICRF

Positions of distant quasars,
fixed in space



The Earth turns
underneath the sky

The Earth Orientation Parameters tell us how one map is turned relative to the other at any moment.

Two maps, and how we connect them

Radio telescopes

VLBI

The only technique that observes the quasars, linking the Earth to the sky

Map of the Earth

ITRF

Where our stations are, and how they move as the continents drift

Satellites

GNSS, SLR, DORIS

Orbit in space, tracked from stations on the ground

Map of the sky

ICRF

Positions of distant quasars, fixed in space

The Earth turns underneath the sky, but not perfectly:

- the length of day changes by fractions of a millisecond
- the pole wanders over a few metres
- the spin axis wobbles slowly in space

Four space geodetic techniques

- VLBI radio telescopes observe quasars
- SLR lasers range to satellites
- ~ GNSS receivers track satellites
- DORIS ground beacons signal satellites

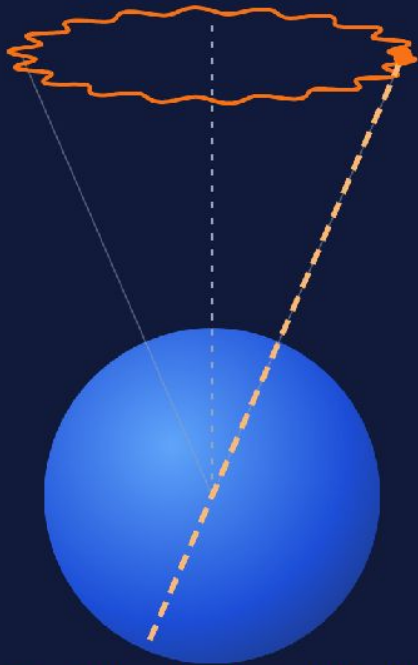
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Earth Orientation Parameters

The five numbers we must measure to know how the Earth is oriented in space

The axis wobbles in space

Precession-nutation



Celestial pole offsets (dX, dY)

Small corrections to the precession-nutation model

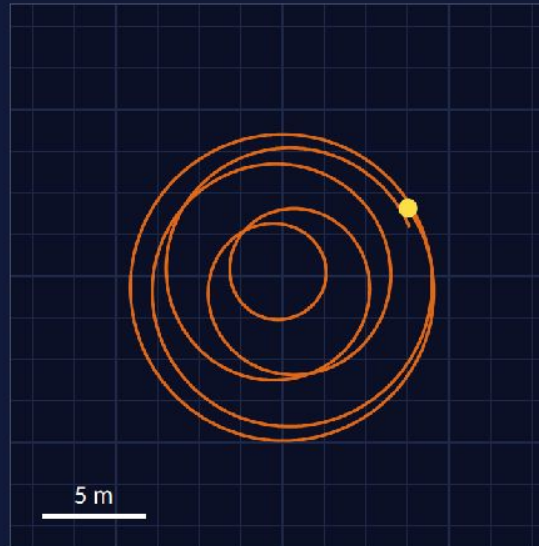
Precession: one slow circuit in ~26 000 years

Nutation: small nods, the largest every 18.6 years

If ignored: nutation alone tilts the axis by up to ~9",
about 300 m at the Earth's surface.
dX, dY: up to ~1 cm

The rotation pole wanders

relative to the Earth's crust



Illustrative model of the pole path over six years,
seen from above the North Pole

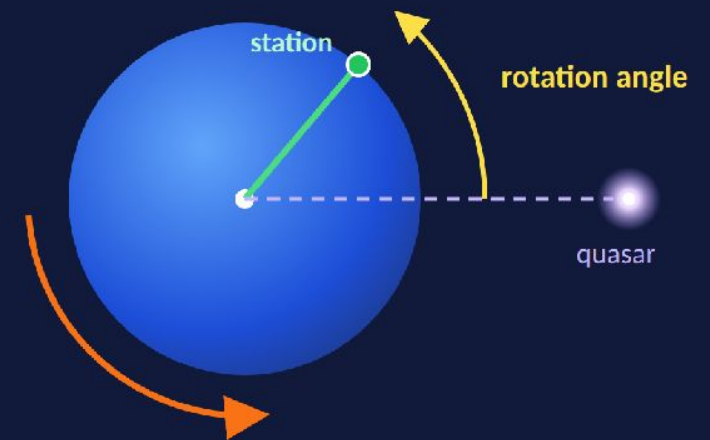
Polar motion (x, y)

The pole circles every ~14 months (a natural wobble)
and every year (seasons), and drifts ~10 cm per year

If ignored: station coordinates appear to shift
by metres, changing through the year.
1 mas ≈ 3 cm at the Earth's surface

The spin rate varies

Earth rotation



UT1-UTC

How far the Earth has turned, against atomic time.

The day varies by up to a few milliseconds

Long term: mainly because of tides from the Moon,
the day lengthens by about 1.8 ms per century

If ignored: 1 ms of UT1 ≈ 46 cm at the equator
and up to ~2 m at GNSS satellite orbits;
a day 1 ms too long: ~170 m at the equator after a year

VLBI is the only technique that measures UT1-UTC and the celestial pole offsets directly.

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Very Long Baseline Interferometry

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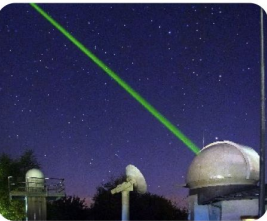


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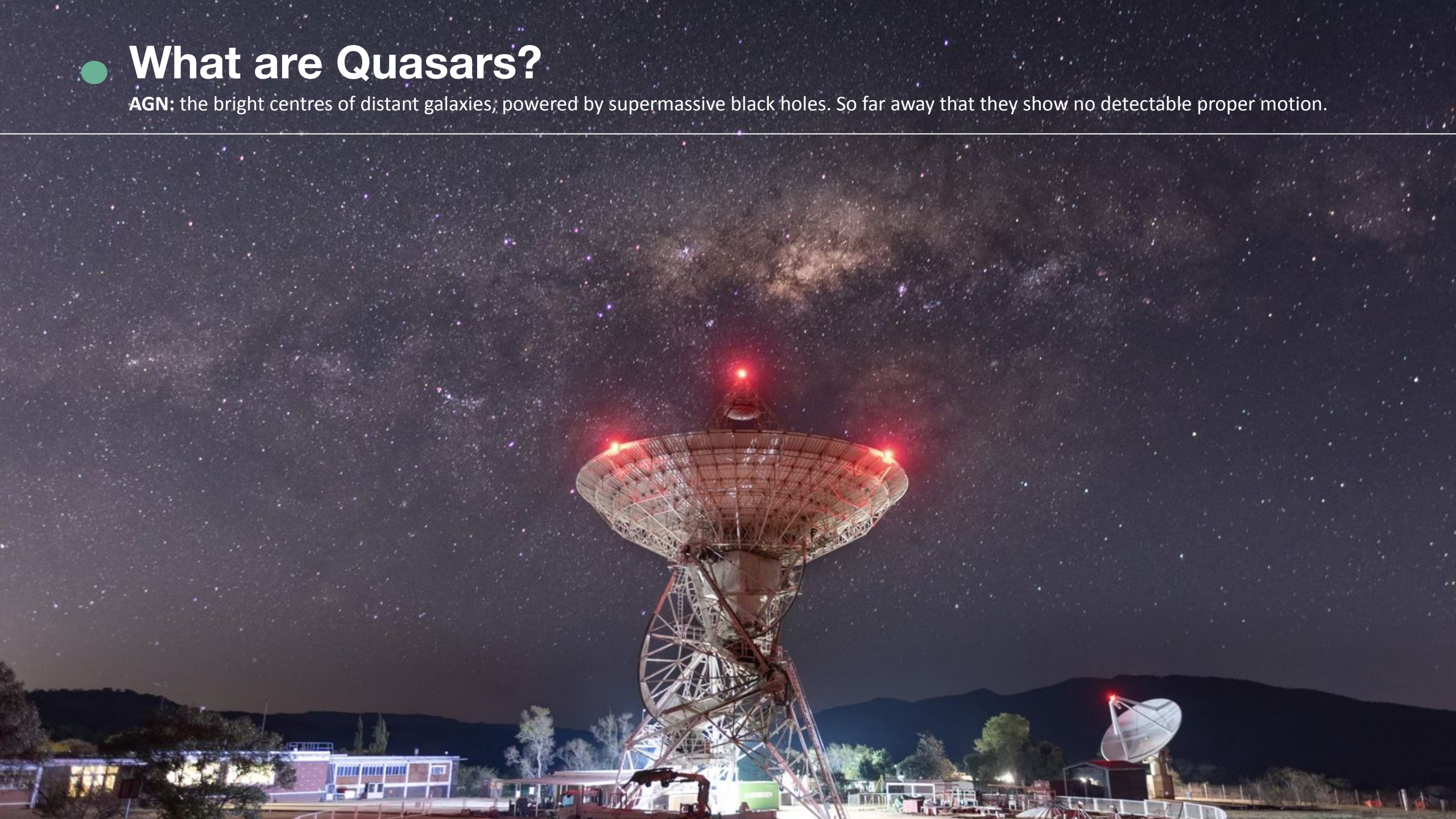
● How does VLBI work?

VLBI: Very Long Baseline Interferometry using radio telescopes across the to observe quasars



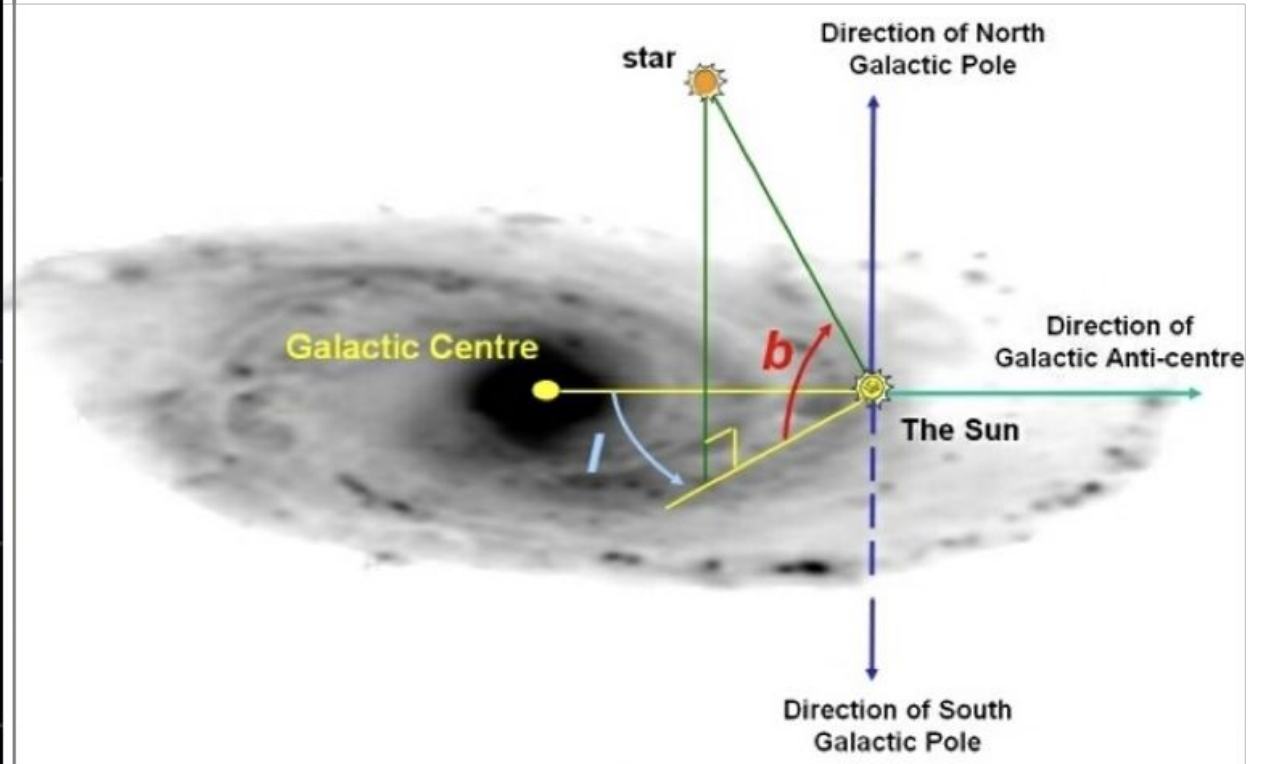
● What are Quasars?

AGN: the bright centres of distant galaxies, powered by supermassive black holes. So far away that they show no detectable proper motion.



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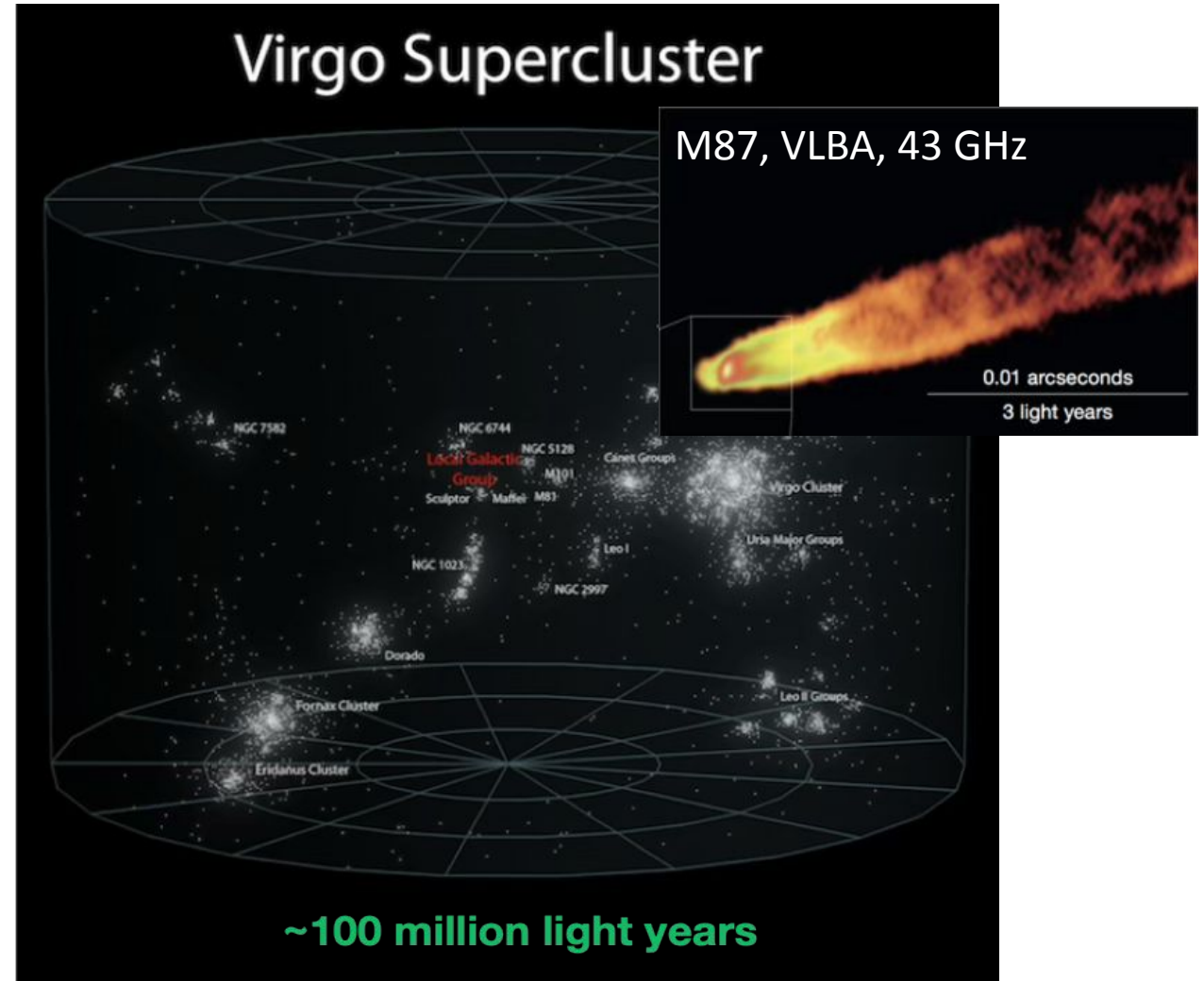
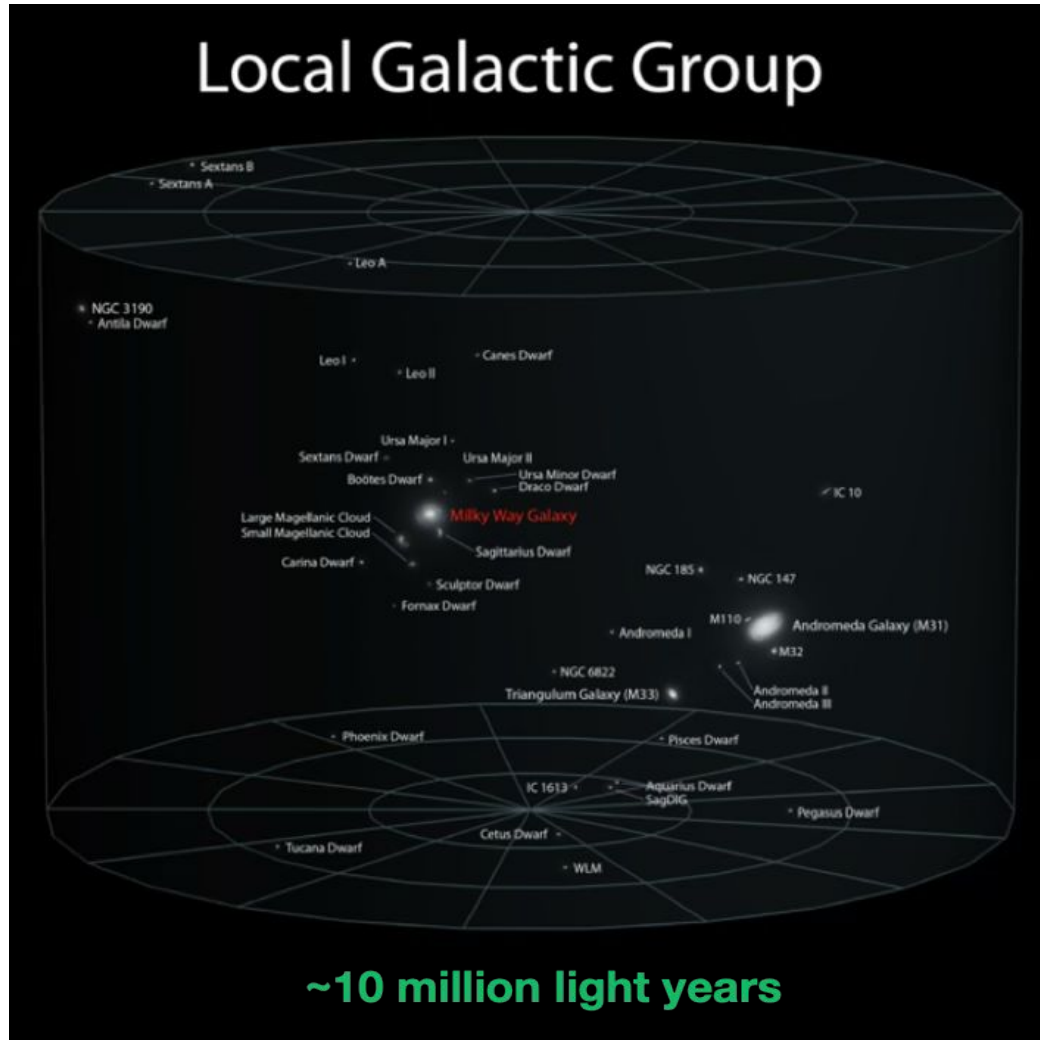


<http://astronomy.swin.edu.au/cosmos/N/North+Galactic+Pole>

<http://tracingknowledge.wordpress.com/tag/milky-way/>

● How far before we get to the quasars?

Even larger structures: local group of galaxies, Virgo cluster, Virgo super cluster....



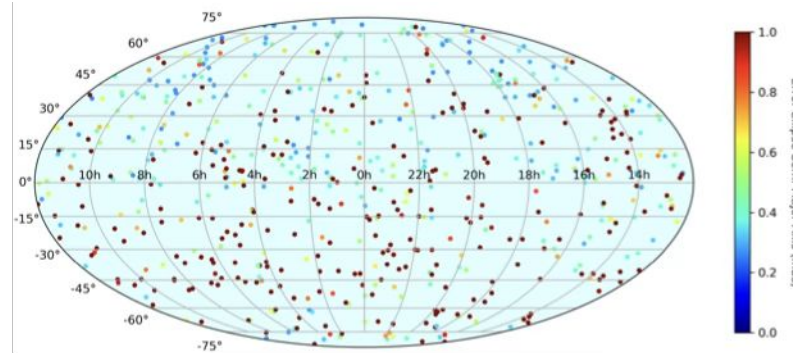
Credit: Andrew Z. Colvin [http://commons.wikimedia.org/wiki/File%3AEarth's_Location_in_the_Universe_\(JPEG\).jpg](http://commons.wikimedia.org/wiki/File%3AEarth's_Location_in_the_Universe_(JPEG).jpg)

$$1 \text{ ly} = 9.5 \times 10^{12} \text{ (9 trillion) km} = 63\,241 \text{ AU} \quad 1 \text{ pc} = 3.26 \text{ ly} = 206\,265 \text{ AU}$$

● The International Celestial Reference Frame

ICRF1-SX (2.3/8.4 GHz, 3.6cm)

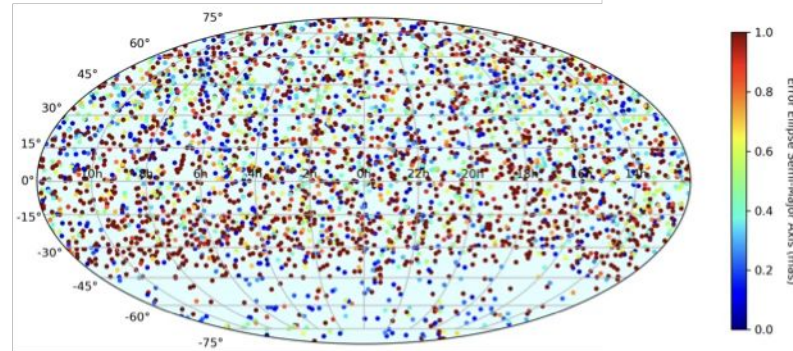
(Ma et al., 1998)



ICRF1 **1998 Jan 01**
Nsources 608
Ndefining 212
Noise floor: 250 μ as in RA/Dec

ICRF2-SX (2.3/8.4 GHz, 3.6cm)

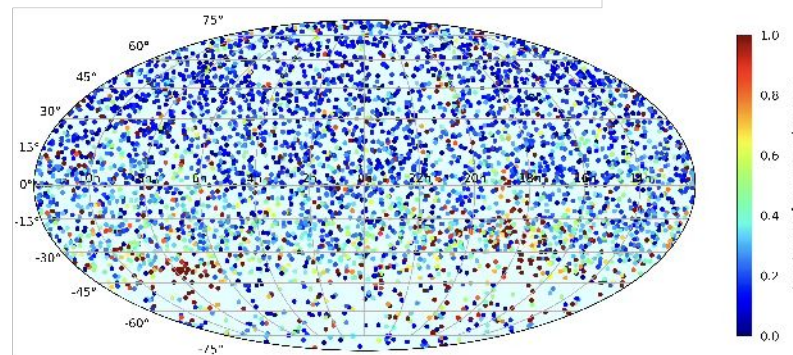
(Fey et al., 2015)



ICRF2 **2010 Jan 01**
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Ndefining 295
Noise floor: 40 μ as in RA/Dec

ICRF3-SX (2.3/8.4 GHz, 3.6cm)

(Charlot et al. 2020)



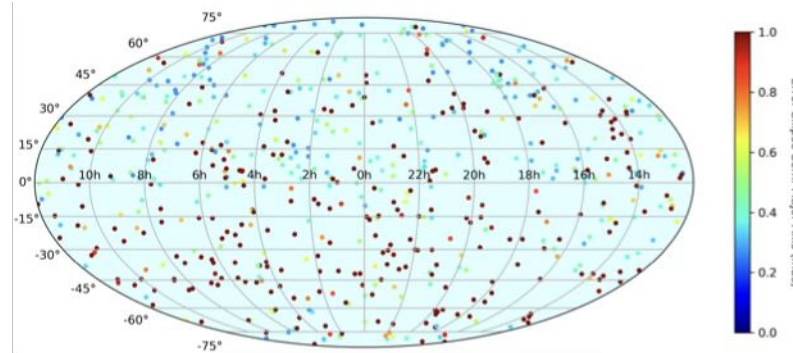
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Nsources 4536
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(Overview paper, de Witt et al., 2022)

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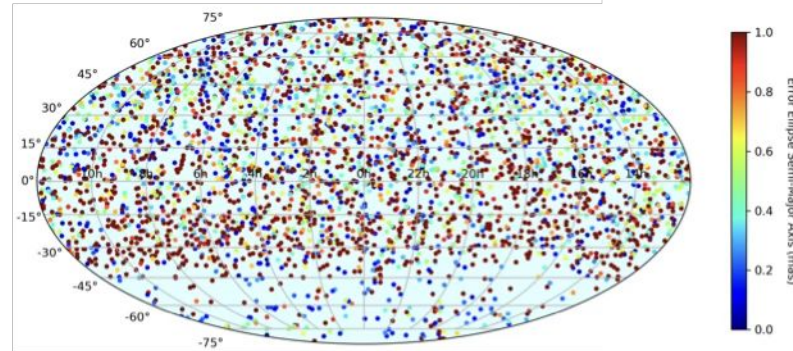
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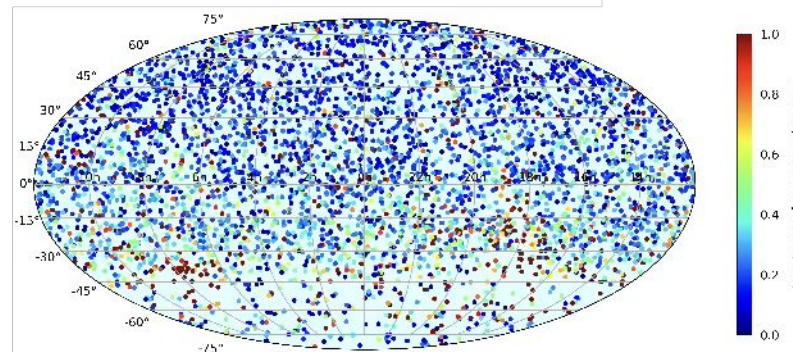
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200 μ as... about the size of a Euro coin from Korea to South Africa

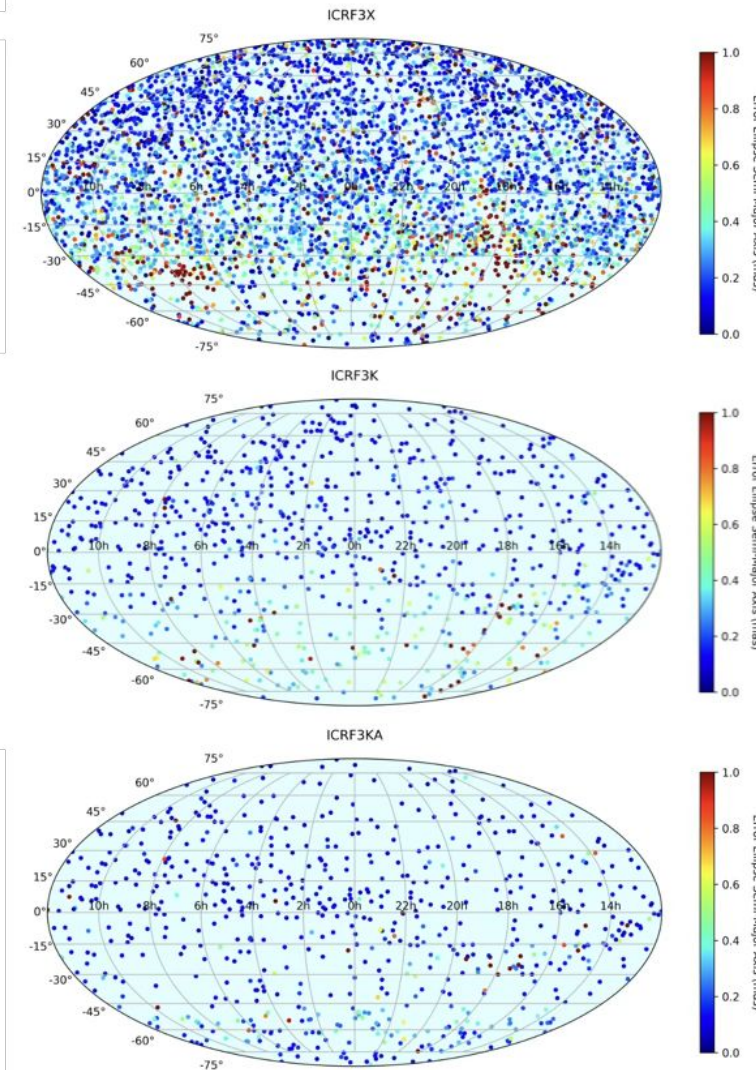
● The International Celestial Reference Frame

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ICRF3-SX (2.3/8.4 GHz, 3.6cm)

ICRF3-K (24 GHz, 1.2cm)

ICRF3-X/Ka (8.4/32 GHz, 9mm)



Time span: 1979-2018
Obs: 13 million (167 stations)
Sessions: 6206
Sources: 4536 (127/218 μ as in RA/Dec)
Sources: 600 (48/64 μ as in RA/Dec)
Noise floor: 30 μ as in RA

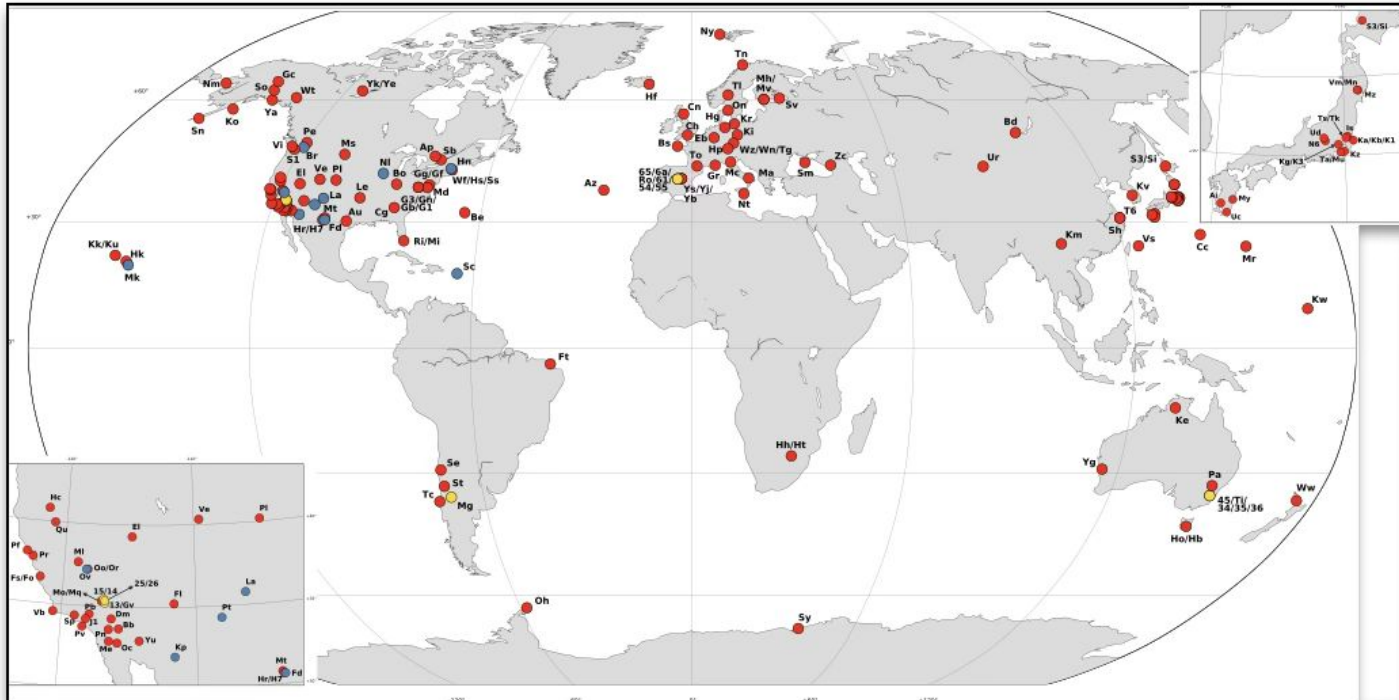
Time span: 2002-2018
Obs: 0.5 million (12 stations)
Sessions: 40 VLBA & 16 Hart-Hobart
Sources: 824 (74/136 μ as in RA/Dec)
Sources: 600 (68/132 μ as in RA/Dec)
Noise floor: 30/50 μ as in RA/Dec

Time span: 2005-2018
Obs: 0.07 million (7 DSN stations)
Sessions: 168 single-baseline
Sources: 678 (76/104 μ as in RA/Dec)
Sources: 600 (69/100 μ as in RA/Dec)
Noise floor: 30 μ as

● The International Celestial Reference Frame - 3



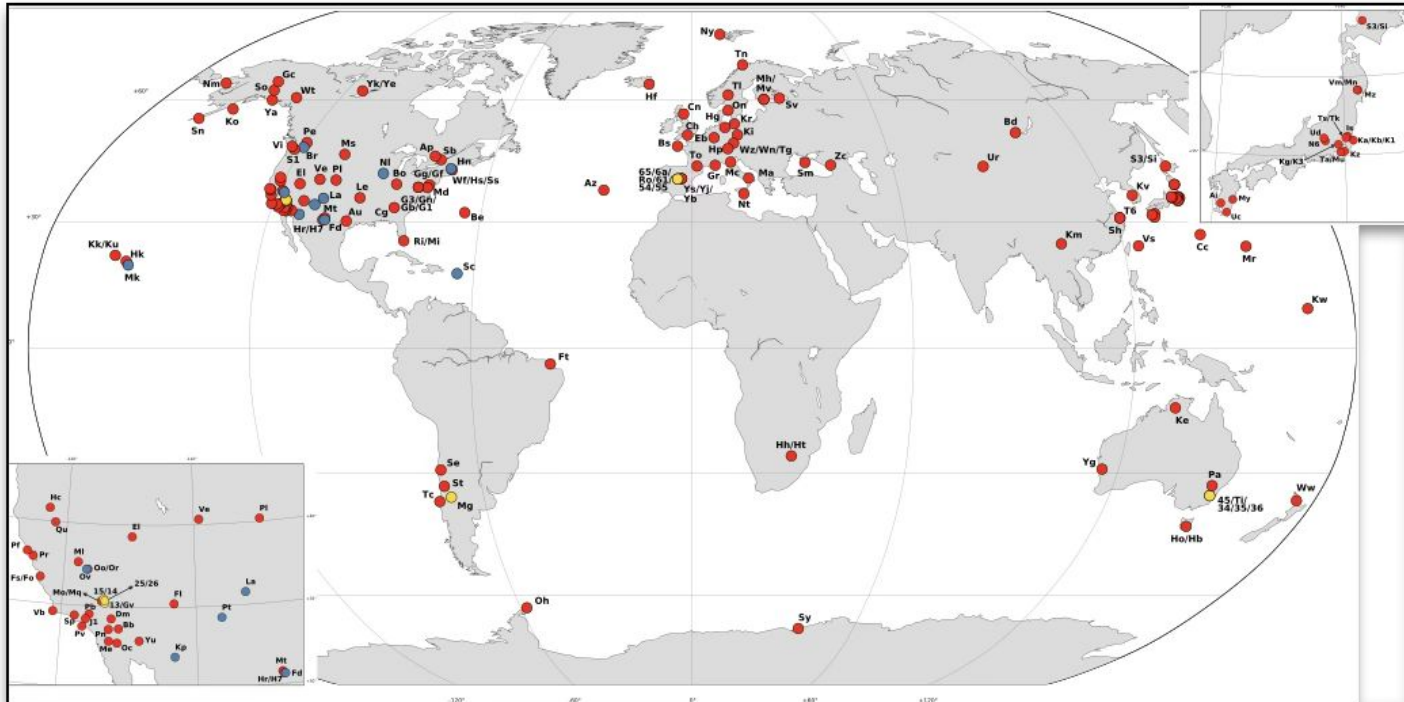
Frame	Date	N_{sources}	Noise Floor (μas)
ICRF-1	1 January 1998	608	250
ICRF-2	1 January 2010	3414	40
ICRF-3	1 January 2019	4536	30



(Charlot et al. 2020)

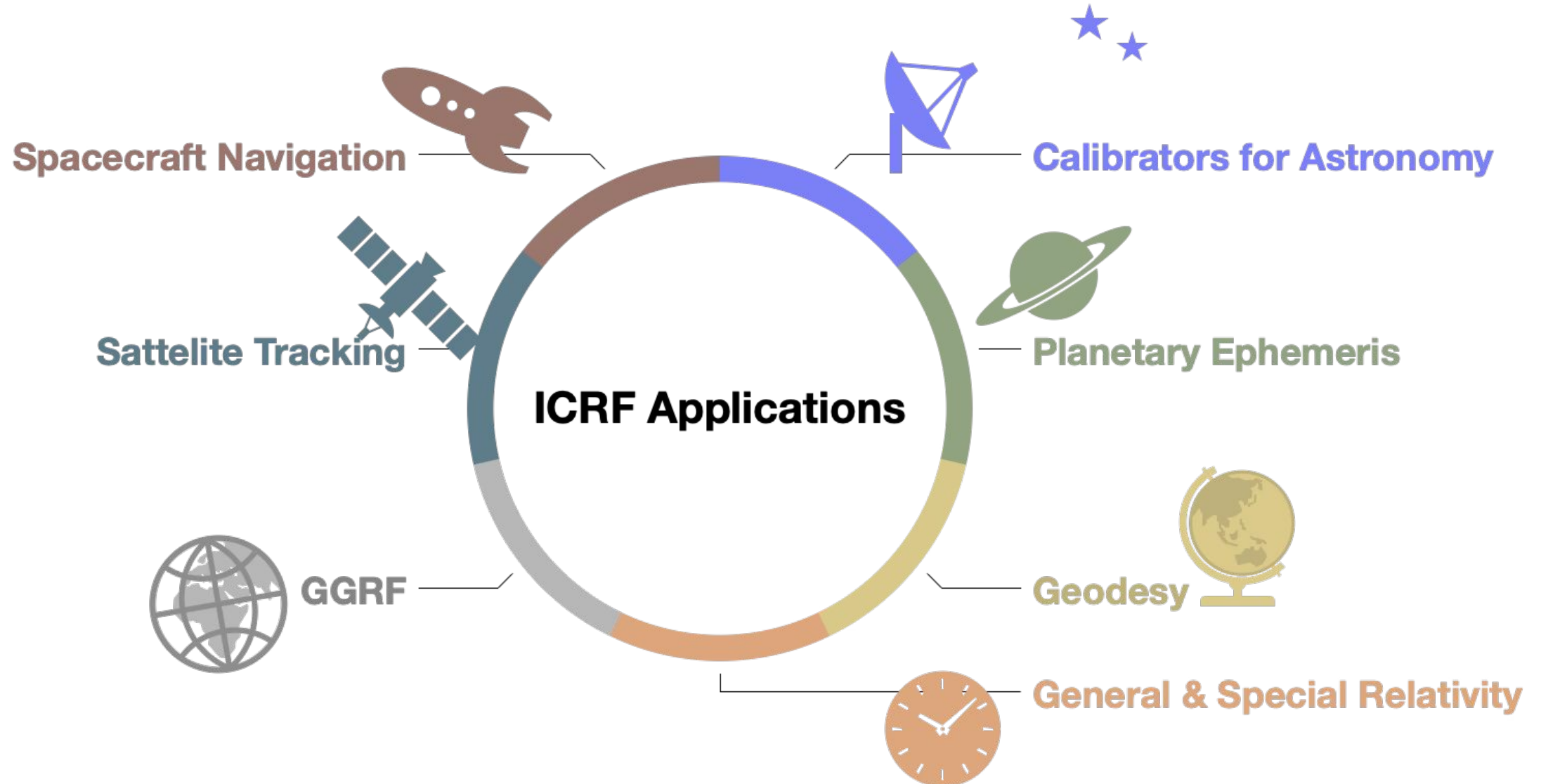
- Based on nearly **40 years of VLBI** data (1979–2018) at the standard S/X frequencies
- **Noise floor ~30 μas** , with median position error of ~0.1 and 0.2 mas in RA and Dec (factor of 3 improvement over ICRF2)
- **First multi-frequency frame** realised with observations at K-band and X/Ka-band that were initiated in the early/mid 2000s
- The data come from a total of **167 radio telescopes** organised under the umbrella of the IVS, VLBA, and DSN, or through ad hoc VLBI networks in the early years.
- **4588 sources in total** with 4536 sources at S/X-band, (~1/3 more than ICRF2), supplemented with independently estimated positions for 824 sources at K-band and 678 at X/Ka
- Another new feature is the incorporation of a **Galacto-centric acceleration correction** of 5.8 $\mu\text{as}/\text{year}$, estimated directly from the S/X-data
- 303 fairly compact and uniformly distributed **defining sources** selected from S/X-band, median uncertainties ~36 and 41 μas in RA and Dec

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● Applications of the ICRF





Maintenance and continuous improvement of the ICRF requires a substantial investment from many individuals and institutions across the globe. No single person or entity can implement and monitor these programs on their own.

Thank you



Aletha de Witt

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