Conceptual Foundations of the Standard Celestial Reference System and Frame

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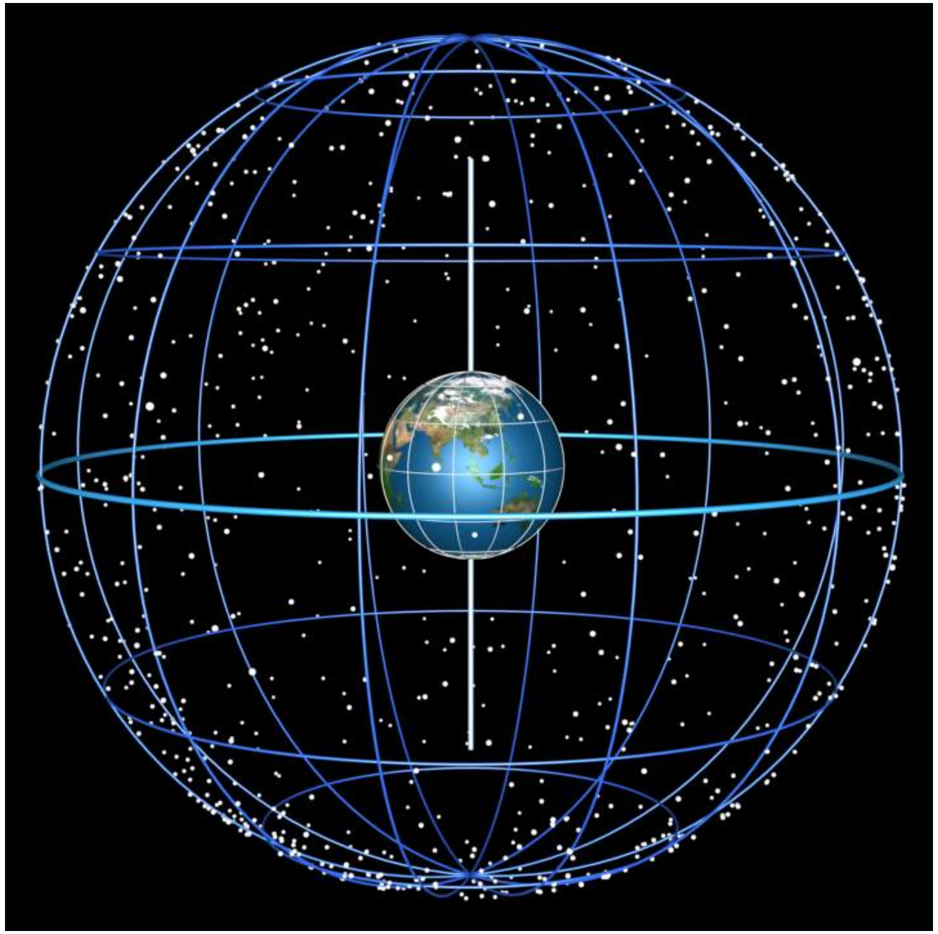
Conceptual/Historical Background

The International Celestial Reference Frame (ICRF)



The extragalactic reference frame

The Evolution of the ICRF

Very Long Baseline Interferometry

QSO astrometric stability

Impact of QSO variability on the optical reference frame

Conceptual and Historical Background

- The purpose of a ***reference frame*** is to provide the ***materialization*** of a ***reference system***, so that it can be used for the *quantitative description* of positions and motions of celestial bodies
- The above constructs are based on the concept of an ideal ***reference system***:
  - a ***reference* (or *coordinate*) *system*** consists of the **theoretical framework** that allows the specification of a *direction* and *position* of a point (*event*) in a particular ***coordinate frame;***
  - the latter can be equivalently represented by a triad of *rectangular coordinate axes* or by a *reference plane* plus an *origin* on it (*spherical coordinates*)
- The ***actual realization*** of such a system implies the choice of a *physical structure* (a *dynamical system*) whose time evolution in the ideal reference system can be described by **physical theories**; this means that the environment acting upon the physical structure must be modelled by a set of **parameters** whose choice is not unique (physical constants, practical models, algorithms…):
  - this procedural set-up is referred to as ***conventional reference system***
- Once the conventional reference system is in place, one is able to <u>*determine the coordinates of space-time events from observations*</u>; such coordinates, which can be time dependent, constitute the so called ***conventional reference frame***, i.e., a set of *reference points* with respect to which the axes of the coordinate frame are defined
  - the coordinates of the reference points form a set of ***intermediaries*** to which new points may be referred by relative measures *(**differential astrometry**)*

Dynamical Reference System

- Conceptually, the simplest reference system is ***inertial***, i.e., one in which the differential equations of motion do not contain any rotational or acceleration terms. Such a system is said to be ***dynamically defined***, and it can be materialized by analysing the motions of an ensemble of celestial bodies, assuming that a correct dynamical model describing it exists

Kinematic Reference System

- If, on the other hand, one can materialize the reference system by using objects sufficiently far away that they do not show measurable intrinsic motion, such celestial system is said to be ***kinematically defined***

Reference Frame Accuracy

- The ***accuracy*** of a celestial frame is the evaluation of the (systematic) errors in the *dynamical* or *kinematic* definition of the frame due to errors in the **dynamical modeling** or in the determination of the **kinematic conditions**

Reference Frame Precision

- The ***precision*** of a celestial frame describes the errors, superimposed on the systematic part , due to inaccuracies of positions and motions of the **reference points** materializing the system

The dawn of relativistic celestial reference systems

- Originally, the assumption underlying the concept of reference system was that space was **Euclidean** and **time absolute** → the system was defined by a set of coordinate axes which did not change by a translation of the *origin*; only geometric (*parallactic*) and optical (*aberrations*) corrections were needed.
- In such an ideal space, a coordinate system non-rotating with respect to distant objects in the Universe would also be *dynamically* inertial, i.e., no **Coriolis** or **centrifugal forces** appear in the equation of motion.

- In terms of *General Relativity* (GR), an ***inertial reference frame*** is a coordinate frame in which the square of the line element is given by the **Minkowsky** metric ($ds^2 \equiv c^2 d\tau^2 = c^2 dt^2 - dx^2 - dy^2 - dz^2$ → $g_{ij} = \eta_{ij}$) at *infinite distance* from the origin and in a region *far removed* from any masses.
- Because of the distribution of matter in the Universe, we cannot expect the existence of a unique global inertial frame, but only ***quasi-inertial*** frames for ***finite regions*** of space. *(This can be deduced from Einstein's Equivalence Principle, which implies that **local inertial frames** can be constructed at any point in a gravitational field)*
- The **effects of GR** on particles moving about the Sun are of the order of $(V_{orb}/c)^2$, i.e. **10^{-8} for typical velocities**; with the increasing accuracy of measurements, these effects **can no longer be disregarded**. It is also evident that the **validation** of **dynamically defined** reference systems becomes more and more theoretically **challenging.**

⬇️

- **In 1991 the International Astronomical Union (IAU), in one of its recommendations, explicitely introduces General Relativity as the theoretical background for the defnition of the celestial space-time reference frame**

Establishment of a Quasi-Inertial (non-rotating) Reference System and Frame

- To comply with GR and in order to provide an optimal approximation to a **non-rotating** celestial reference frame, the IAU as early as 1992 urged the establishment of a ***quasi-inertial*** **system**.
- This decision marks a **huge gap** with the long series of ***fundamental star catalogues*** (FK catalogs compiled by the *Astronomishes-Rechen Institut* of Heidelberg, Germany) defined by the dynamics of Solar System bodies.
  The last catalog of this series was the Fifth Fundamental Catalogue (**FK5**) consisting of **1535** bright stars plus a fainter extension of **3117** stars, referred to as ***Equator and Equinox J2000.***
- In **2000**, the IAU defined two coordinate systems for use in astronomy, one with its origin in the *Solar System Barycenter* (**BCRS**) and one at the *geocenter* (**GCRS**).
- The **metric tensor** of the BCRS specified in **IAU resolution B1.3** reads

$$g_{00} = -1 + \frac{2w}{c^2} - \frac{2w^2}{c^4} \ , \ \ g_{0i} = -\frac{4}{c^3} w^i \ , \ \ g_{ij} = \delta_{ij}\left(1 + \frac{2}{c^2} w\right)$$

  where *w* and w^i are the scalar and vectorial *gravitational potential* of the Solar System.
  It is a ***post-Newtonian*** reference system with higher-order terms neglected; it is constructed for an isolated solar system (no tidal forces due to the Galaxy nor effects of the cosmological background). The BCRS is used for **Solar System ephemerides**, **spacecraft navigation**, **high-precision astrometry**, and it is accurate to the *micro-arcsecond* for observations up to 1° from the Sun
- Formally, the BCRS metric tensor does not fix the coordinates completely, leaving the spatial orientation of the axes undefined (it is assumed to be oriented according to the ***Extragalactic Reference Frame)***

The Extragalactic Reference Frame

- **High-precision coordinates** of **extragalactic objects** are to materialize the new *conventional celestial reference system.* This system is *kinematically* defined - in contrast with the essentially dynamical definition of the FK5 system - and shall be materialized by a frame fixed with respect to the non-rotating Universe
- On the hypothesis of an *isotropic Universe* model, as inferred from the *3K microwave background radiation*, the ***global rotation** of the Universe* is **less than 10^{-9} mas/year**, therefore negligible
- Extragalactic radiosources at distances exceeding 10 Mega parsecs are regarded as suitable objects for realizing such frame

Quasars

- In **1953** it was shown that the radio source Cygnus A was associated with a remote galaxy; in **1963 optical counterparts of radio sources** were discovered, leading to the recognition of a **new class of objects** that looked like ordinary stars on photographic plates. Their spectra displayed ***large redshifts***, indicative of their extragalactic origin: they were named QUASARS (**QSO**) for '**quasi-stellar radio source**'.
- While **radial velocities increase systematically** with distance, **transverse velocities are randomly distributed** and do not depende on distance.
- Typical transverse velocities are $V_{pec} \cong$ 600 Km/s, but in rich galaxy clusters it may reach 1500 Km/s. The proper motion is then $\mu_{pec} \sim V_{pec}/d(z)$ where *d(z)* is the *comoving distance* (objects' separation with the effect of the Hubble expansion taken out). For low redshifts this becomes $\mu_{pec} \sim \frac{V_{pec} H_0}{cz}$, where H_0 is the Hubble constant, giving a ***peculiar motion*** of QSOs in the range of **3-7 muas/year** at z=0.01

Concepts of Astrometric Radio Interferometry

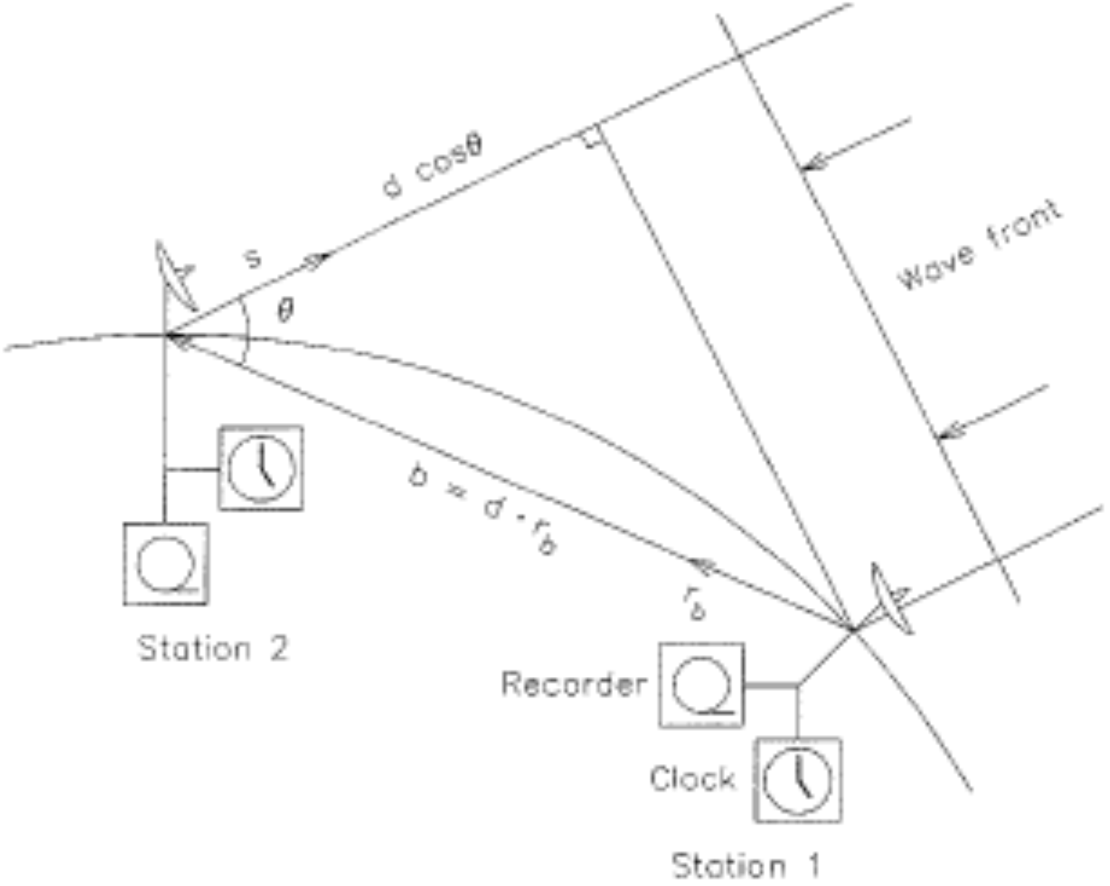
- Observations by *radio interferometry* are based on the analysis of **interference patterns of radio waves** in a window extending from λ=20 m (15 MHz) to λ=1 mm (300 GHz)
- The *astrometric* potential of ***Very Long Baseline Interferometry*** (**VLBI**) derives from the ability of detecting a change in the geometric ***time delay*** with the direction of the source.
- The *time delay* τ_g is given by $c\tau_g = d\cos\theta$
- The *variation* of *time delay* with ***source direction*** is therefore

$$\Delta\tau_g = -\frac{d}{c}\sin\theta\,\Delta\theta$$

- For example, a change by 10% of a wavelength (easily detectable by the cross-correlators) produces a variation in the time delay $\Delta\tau_g$= 0.1 λ/c ; then the corresponding variation of the source direction will be

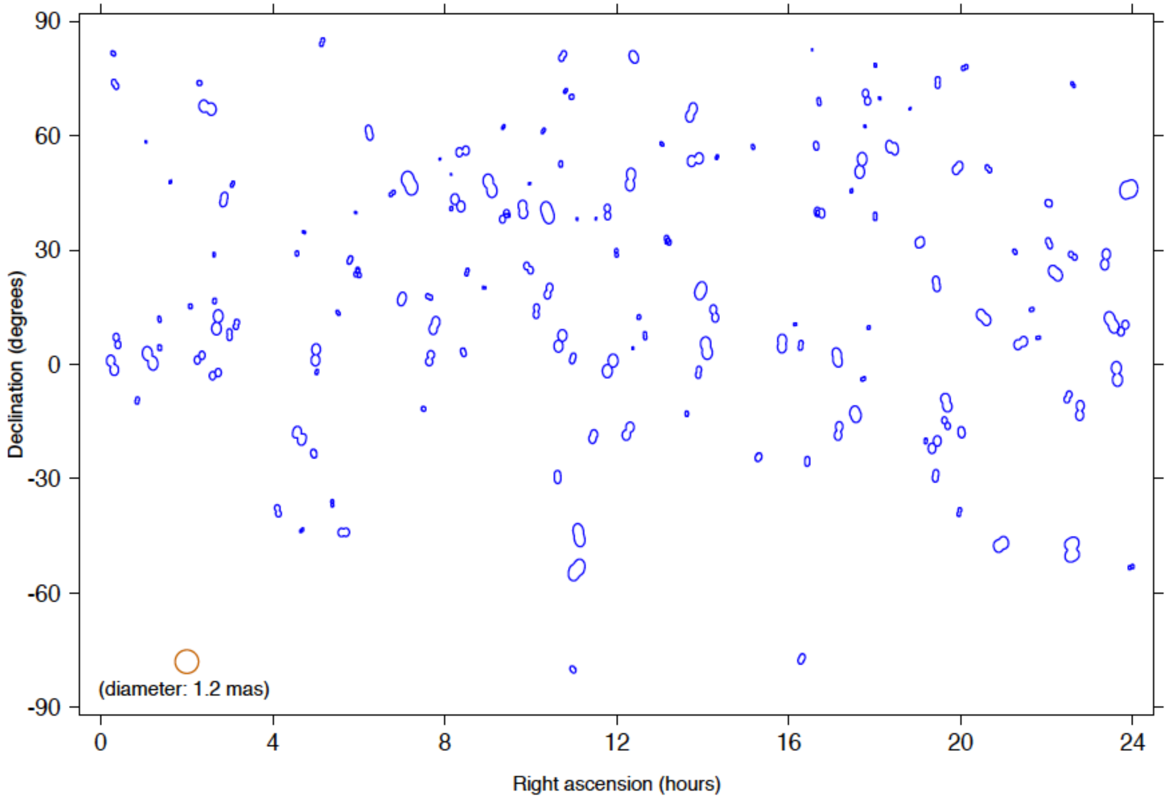
$$\Delta\theta = -\frac{0.1\lambda}{d\,\sin\theta}$$

- For a baseline of 5000 Km and an antenna operating at λ=3.6 cm (8.4 GHz) one obtains a variation of the source direction of ~ 0.14 mas/sinθ, on the average better than 0.2 mas



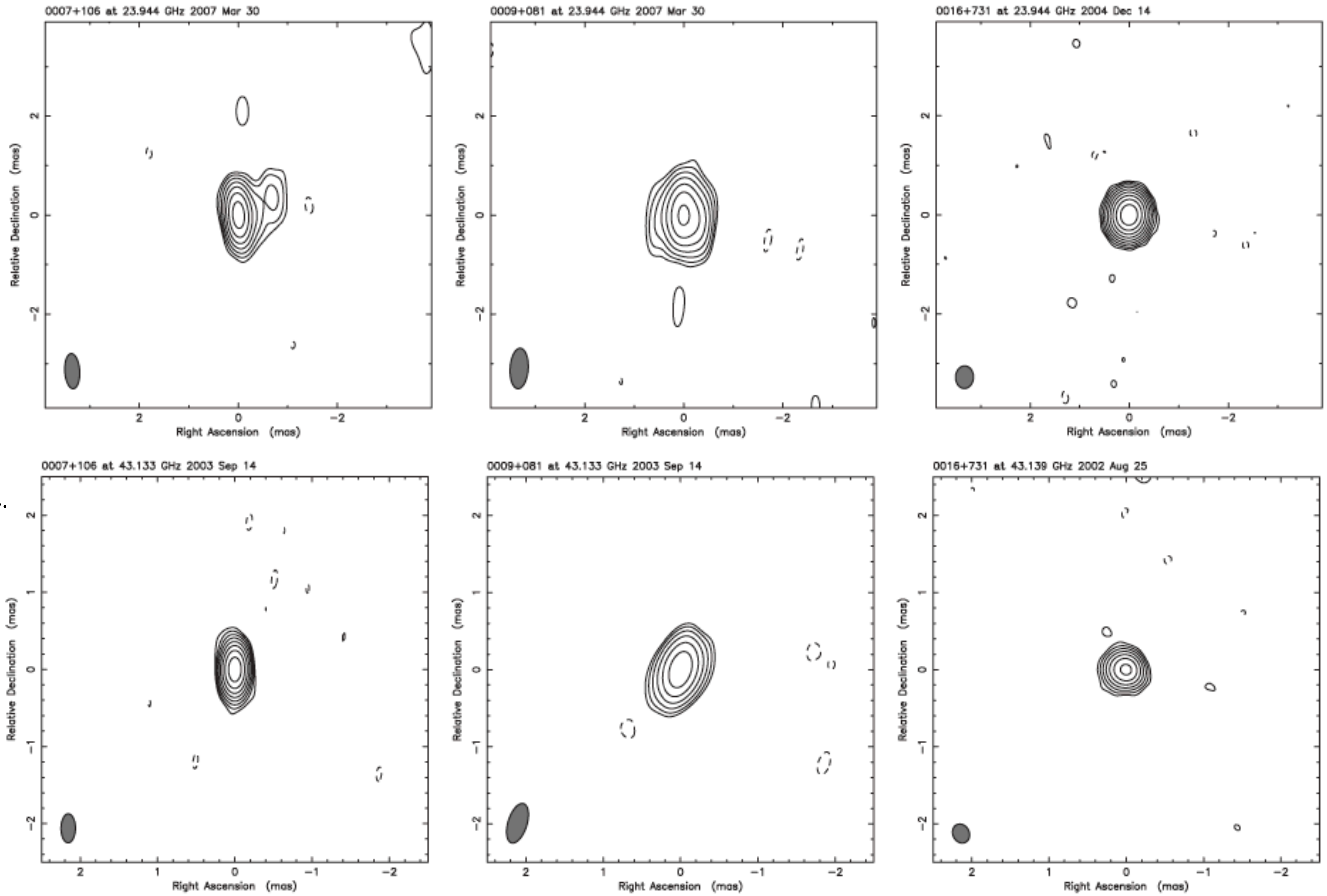
Radio Reference Frame Stability

- There are two major causes of *limitation* in ***accuracy*** of VLBI positions:
  - ***Tropospheric delay***: uncertainty in the modelling of the signal propagation due to the wet component of the troposphere, the lowest layer of Earth's atmosphere
  - ***Source structure***: if the radio source is extended or not circular, its apparent direction changes as function of the length and orientation of the baseline; source structure also can change with time (but this effect can be corrected if repeated maps of the source are available)
- QSO ***variability*** takes usually the form of ***jets***, i.e. aligned emissive structures.
- The figure from Gontier et al. (2001) shows the envelopes of the *standard deviations* over 0.5 years for *stable* and *moderately stable* sources , < 0.6 mas
- The alignment of x-axis with declination for -20°<δ<+20° reflects the tropospheric mismodelling; this excess, much stronger for the more variable sources, can be modelled as a function of declination.
- Importance of *continous monitoring* of sources in order to improve their categorization as ***defining, candidates***, or ***other*** for their use in the realization of the reference frame
- Charlot et al. (2010) measured the *sub-mas* structure of 274 sources in the K band (24 GHz) and Q band (43 GHz) finding that they have less intrinsic structure and smaller flux variation of the core radio emission at higher frequency.



Contour plot of radio emission of 6 QSOs sources in the K band (24 GHz top) and Q band (43 GHz bottom) from Charlot et al. 2001

- The source structure looks more compact at higher (Q band) frequency.
- The ellipse in the lower left of each panel shows the FWHM gaussian beam applied in the image restoration process.



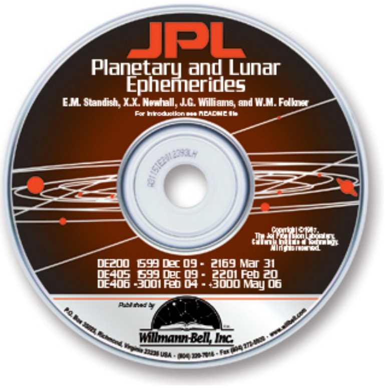
Steps towards the establishment of a new Standard Celestial Reference System and Frame

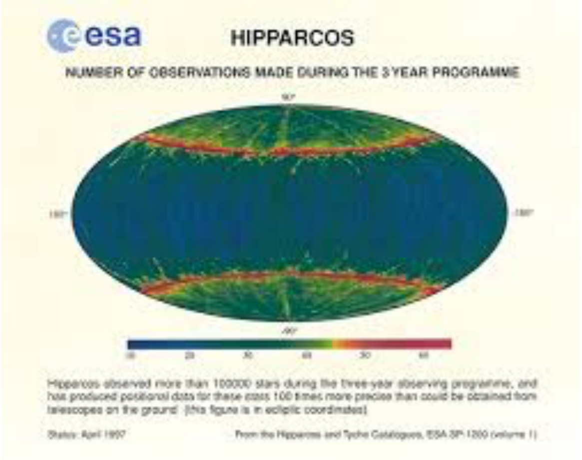
- A series of *Working Groups on Reference Systems* (WGRF) were organized by several IAU commissions to define a *list of objects* appropriate for VLBI observations at wavelengths of 13 cm (2.3 GHz, *S band*) and 3.6 cm (8.4 GHz, *X band*), reaching ***sub-mas accuracy***
- Between 1991 and 1994 the WGRF produced a list of about **600** radio sources; meanwhile, the *International Earth Rotation Service* (IERS) had developed the procedures to *maintain* the celestial reference system.
- Finally, in **1997** the IAU adopted the following **resolutions**:

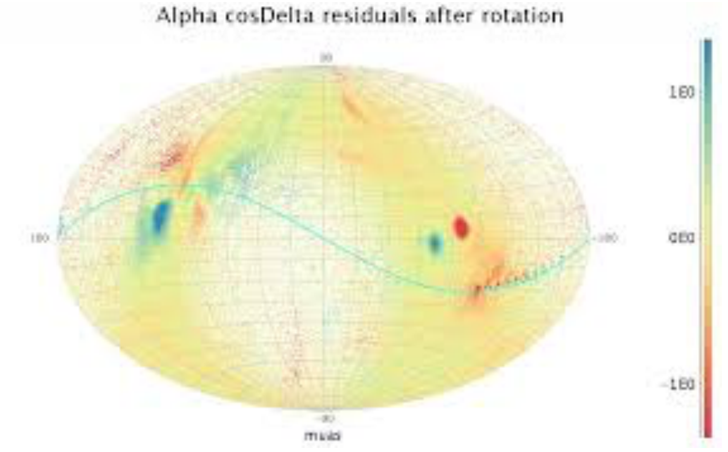
  - *«That, as from 1 January 1998, the IAU celestial reference system shall be the* ***International Celestial Reference System*** *(ICRS) as specified by the 1991 IAU resolution on Reference Systems and as defined by the IERS»*
  - *«That the corresponding fundamental reference frame shall be the* ***International Celestial Reference Frame*** *(ICRF) constructed by the IAU WGRF»*
  - *«That the Hipparcos Catalogue shall be the primary realization of the ICRS at optical wavelengths»*
  - *«That IERS should take appropriate measures, in conjunction with the IAU WGRF, to maintain the ICRF and its ties to the reference frames at other wavelengths»*

The International Celestial Reference System (ICRS)

- The ICRS complies with the conditions specified by IAU recommendations.
- The **origin** of the ICRS axes is located at the **barycenter of the solar system** and the axes **directions** are fixed relatively to distant extragalactic sources. For continuity with the **FK5 pole**, the ICRS pole is in the J2000 direction defined by the conventional IAU models for precession (1972) and nutation (1982).
- The **origin of right ascensions** is also defined **consistently with that of the FK5** by fixing the right ascension of radio source 3C 273B to the FK4 value transformed to the J2000 (FK5) system.
- The **ICRS axes** are meant to be space-fixed, i.e. **kinematically non-rotating**; therefore there is no date associated with the ICRS.





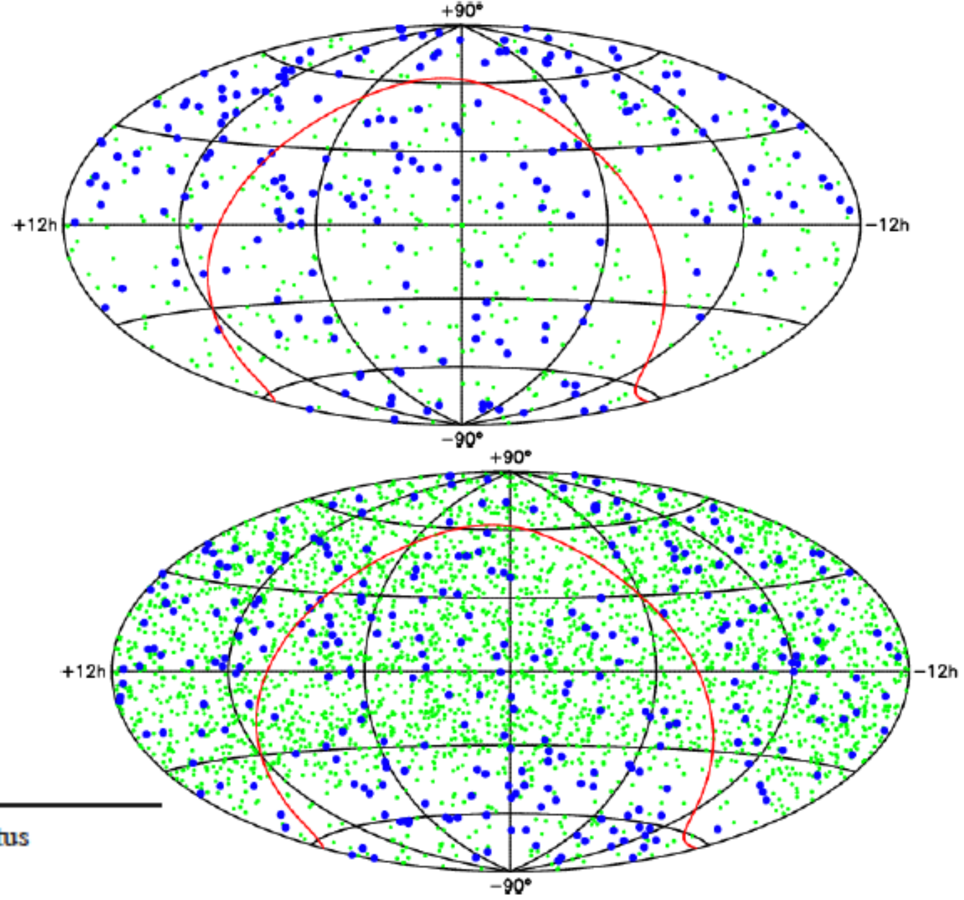


- The *Jet Propulsion Laboratory* (JPL) *ephemerides* are expressed in the ICRS (from release DE403 on).
- The *Hipparcos* star positions and proper motions (circa 120000 stars) were tied to the ICRF, representing therefore its first realization (HCRF) in the optical band.
- The intermediate and final **Gaia** catalog of positions, proper motions, and parallaxes constitute the realization of a non-rotating global optical frame meeting the ICRS prescrptions, and is directly linked to more than **500,000 QSOs**

The Evolution of the Celestial Reference Frame

- ICRF1 Officially adopted as of January 1998. It consists of **608** (later expanded to 717) radio sources derived from about *1.6 million observations* accumulated in the years 1979-1995 by a worldwide network
  - The typical **position error** is ~ 0.25 mas, while accuracy of frame axes is ~ 0.02 mas
  - ***limitations***: non-uniform distribution of defining sources; several successively found to be unstable
- ICRF2 Adopted as of January 1 2010. Thanks to **significant developments and improvements** in the technique and data analysis of geodetic/astrometric VLBI (*newer, more sensitive antennas/arrays, better observing strategies, dedicated programs, bettern geophysical modelling, faster computers*). It contains precise positions of **3414** compact radio sources, more uniformly distributed over the sky, derived from nearly 30 years (1979-2009) of accumulated geodetic/astrometric VLBI pobservations.
  - **Positional noise floor** is ~ 40 microarcseconds
  - Comparisons between ICRF1 and ICRF2 obtained using 138 common sources indicate that the **axes** are **stable to within 10 microarcseconds** (Fey et al. 2015)
- ICRF3 being realized under the IAU Working Group «Third Realization of the International Celestial Reference Frame»
  - A **prototype version** containing **4265 radio sources** based on the VLBI solution of the *Goddard Space Flight Center* (GSFC) was made available to the *Gaia DPAC Consortium*. Of these, **2820** sources were **used to align Gaia axes** with the radio frame (*orientation* parameters); moreover, **555934** sources found by cross-matching with the AllWISE AGN Catalog were **used to define the non-rotating frame** (*spin* parameters)
  - *Vector Spherical Harmonics* (VSH) analysis of DR2 astrometry has shown that the GCRF-2 accuracy matches the current ICRF radio frame

The ICRF Series



Top map: ICRF1 sources (1997)
Bottom map: ICRF2 sources (2009);
Blue dots: *defining* sources
Green dots: *other* sources

(from Capitaine N. 2012, Res. Astron. Astrophys, 12, 1162)

Name	Fiducial objects	Number	Magnitude limit	Mean time of observations	Technique of observation	Uncertainties in: pos. proper motion (yr^{-1})	Status
FK5	stars	1535 3117	< 7 $< 9,5$	1940 to 1950	Optical astrometry	$0.02''$ $0.0008''$ $0.08''$ $0.002''$	Fundamental catalog from 1976 to 1997
ICRF1	Extragalactic radiosources	608 (212 defining)		1987	VLBI	$0.001''$ $(0.0004'')$	Celestial reference frame from 1998
Hipparcos catalog	stars	118 218	< 12	1991.25	Astrometric satellite Hipparcos	$0.001''$ $0.001''$	HCRF: Optical counterpart of ICRF from 2000
ICRF2	Extragalactic radiosources	3414 (295 defining)		1999	VLBI	$0.001''$ $(0.0004'')$	Celestial reference frame from 2010

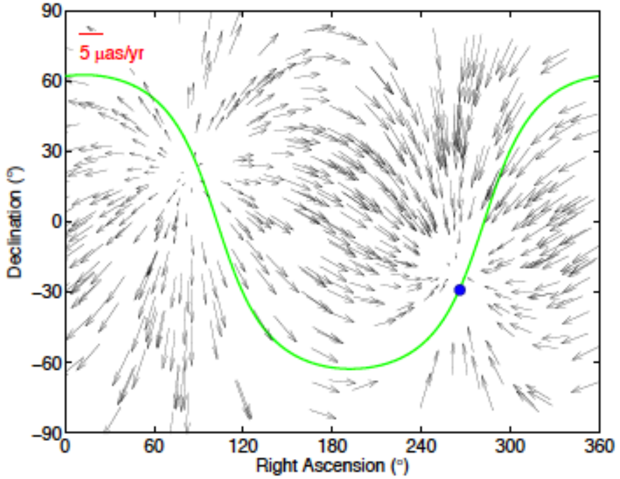
Impact of QSO variability on Gaia CRF

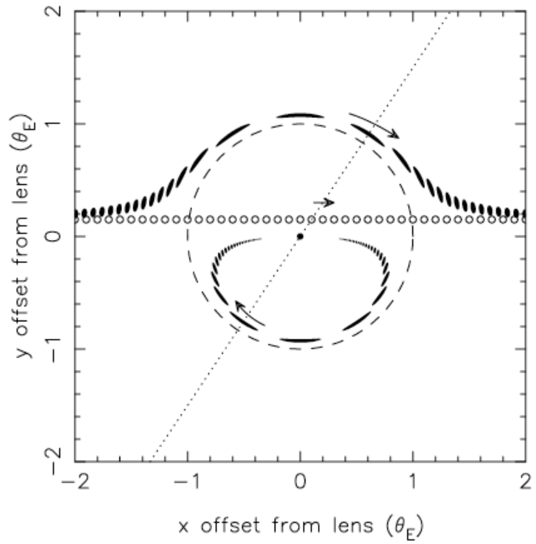
- *Motion of the optical photocenter*: the internal structure of the QSO, induces an astrometric variability typically less than $\sim$ **60 muas**, but up to $\sim$ 100 muas in extreme cases; timescales of this variability are of the order of 3-15 years, peaking between 6-9 years

- *Galactic secular aberration*: the Solar System orbital velocity of $\sim$ 220 Km/s around the galactic center results in a change of velocity aberration generating an apparent proper motion dipole field of amplitude $\sim$**4 muas/year** in the direction of the Galactic center

- *Astrometric microlensing*: shift of the source photocenter due to gravitational microlensing from intervening massive bodies. It it estimated that more than 25000 sources will have a significant astrometric variation during the course of the Gaia mission; in the case of **stellar microlensing of quasars**, the centroid shift can amount to **tens of muas** (Lewis and Ibata 1998)

Galactic velocity aberration vector field



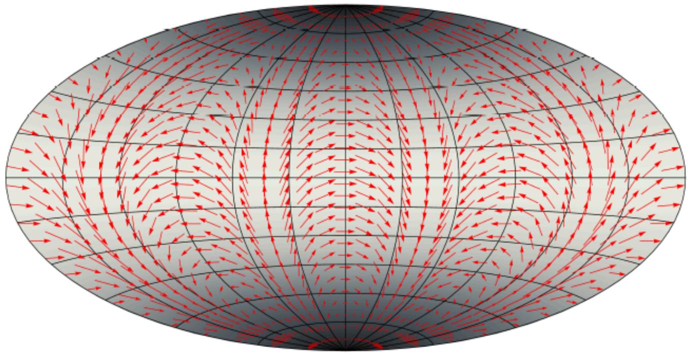


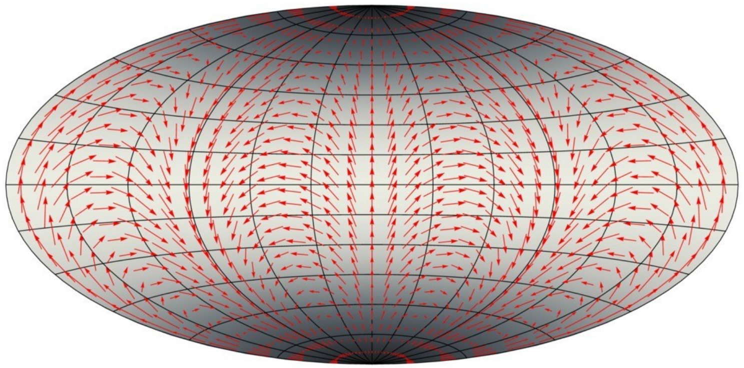
Astrometric microlensing effect

Impact of QSO variability on Gaia CRF

- *Cosmological (parallactic) proper motion*: the velocity *V* of the solar system with respect to the observable Universe produces a dipole pattern in the CMB temperature ($\Delta T/T=V/c$). Observations of the CMB indicate a velocity $V \sim 369$ Km/s in the galactic direction $l \sim 264°$, $b \sim 49°$. This motion should produce a parallactic shift of all QSOs towards the *antiapex* at an angular rate that depends on the cosmological redshift *z* via the comoving distance. For very low redshifts ($z<<1$) → $\mu \propto VH_0/cz$, e.g. **1-2 muas/yr** for z=0.01.

- *Primordial gravitational waves*: space-time metric perturbations due to gravitational waves (GW) propagation produce oscillations in the apparent position of the source. If the interval of observation is shorter than the period of the GW, the perturbation generates an *apparent pattern of proper motions* in the sky, composed primarily of second-order *vector spherical harmonics*. It is anticipated that Gaia is not sufficiently sensitive to detect primordial GW, but it should be able to place upper limits on the GW energy density spectrum at frequencies $f \sim 1$ yr^{-1} at the order of accuracy of 10^{-6}, comparable with pulsar timing measurements (Book and Flanagan 2011).





2nd order vector spherical hamonics