User requirements for ICRF applications of a co-location satellite

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GENESIS-1 Online Workshop
April 26, 2022

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1. ICRF at various frequencies
2. General assumptions and requirements for VLBI transmitter
3. ICRF applications and special requirements
   a) Local tie in space
   b) Determination of AGN core shift
   c) Determination of AGN core shift – VGOS
   d) Positive effects for EOP
4. Recapitulation

1. ICRF at various frequencies

- ICRS is the celestial reference system realized by observations of **distant active galactic nuclei (AGN)**
- **Current realizations:** ICRF3 (S/X, K, X/Ka) and Gaia-CRF3 (optical)
- **Future:** ICRFs will include VGOS (2.5-14 GHz) and maybe higher frequencies
- Currently each ICRF is derived **independently → aligned** afterwards
- Higher frequency ICRFs → higher accuracy with less observations
- Combination of AGN positions among the various wavebands is challenging due to **frequency-dependent structure** and **core shift**

→ Geodesy and astrometry must go hand in hand

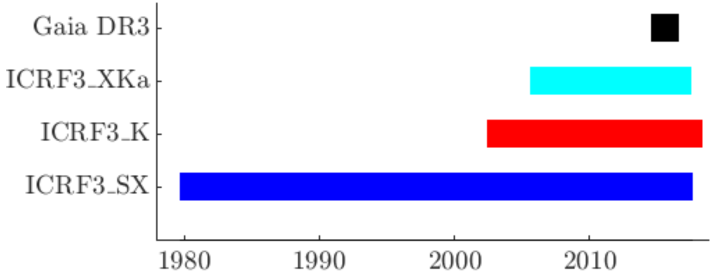
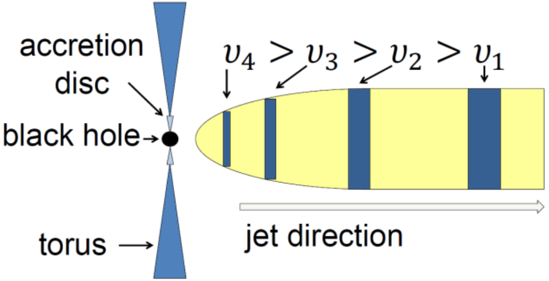


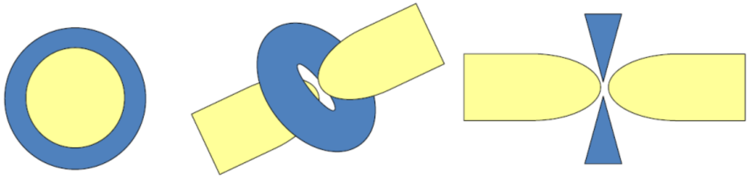
Fig.: Observation time spans of the ICRFs.

ICRF3: Charlot et al. (2020): A&A Vol. 644, A159, 10.1051/0004-6361/202038368
Gaia: IAU Resolution B3 (2021): https://www.iau.org/static/archives/announcements/pdf/ann21040c.pdf

1. ICRF at various frequencies

- Core shift





- Frequency-dependent structure

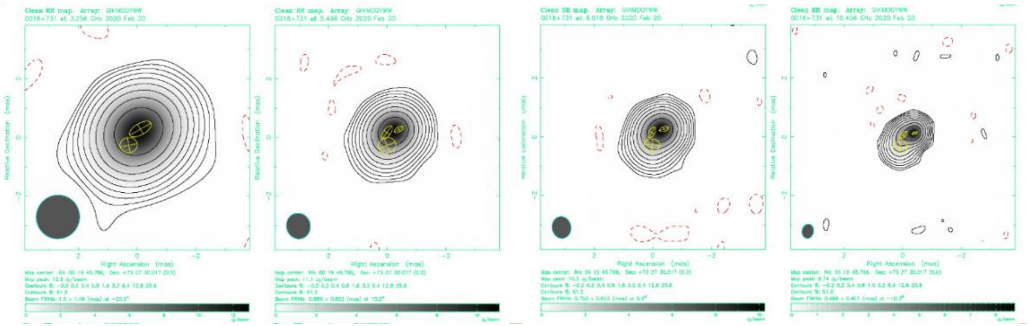
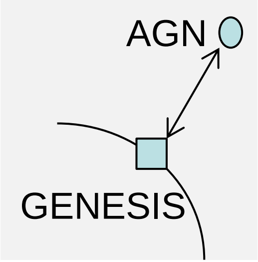


Fig.: Source model of 0016+731 for the 4 VGOS bands (Xu et al., 2021b, submitted to A&A).

* Both core shift and structure can also be variable in time.

2. General assumptions and requirements



- **VLBI Transmitter:** weak broadband noise (similar to AGN)
  → no change at VLBI sites needed
- **Satellite speed:** slow enough for phase-referencing (nodding-style)
- **Transmitting antenna requirements:**
  - One antenna is probably best option for ICRF applications
  - Operating multiple antennas will cause position offsets of several milliarcseconds (mas) of the respective antenna position in ICRF → Extended VLBI modeling requirements?
  - Calibration of PCO at various frequencies on ground is essential in case of multiple antennas or varying antenna behavior → frequency-dependent 'core shift' must be determined
  - Satellite antenna pattern must be calibrated in case it is resolved; otherwise point source
  - Satellite orientation in space has to be known precisely

Depending on the frequencies, various applications are possible, as follows…

3.a Local tie in space

- VLBI networks used for ICRF determination **observe independently** at different frequencies (S/X | K | X/Ka | VGOS)
- **Satellite** emitting the various frequencies = **calibrator source to align a multi-wavelength ICRF** (based on group delays)
- Contrast to AGN: satellite antenna is **ideal point source** and **frequency-dependent position is known** (after calibration)

→ Combination of VLBI networks by **con-straining the satellite position** to be equal **for all frequencies** applying the **local tie in space**

→ Combination of independent ICRF realizations

→ User requirement: S/X/K/Ka/VGOS antenna capability

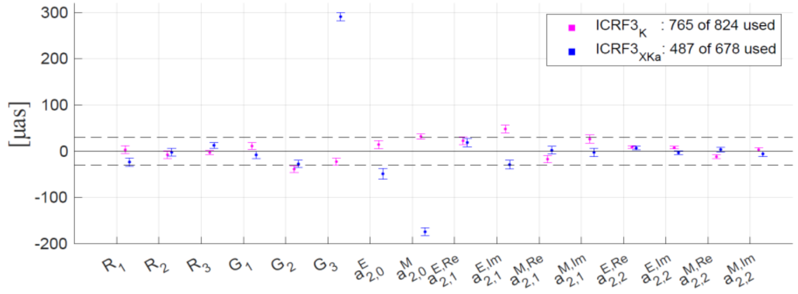
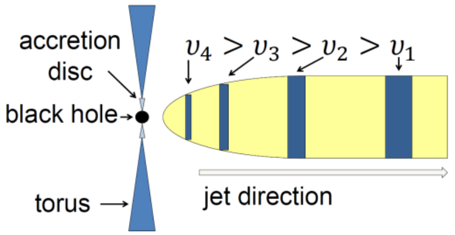


Fig.: Global deformation parameters for orientation off-set between the ICRF3 K & X/Ka towards ICRF3 S/X.

3.b Determination of AGN core shift

- Satellite = calibrator source for **precise relative** observations (phase-referencing, phase delays) **to AGN at various frequencies**
  → **AGN core at the various frequencies** can be determined **relative to each other** (for all types of AGN!)
  → Unsolved problem in astrometric VLBI, unique opportunity
- Absolute position of satellite known → AGN core positions can be transferred to the absolute frame



→ Astrophysical studies of AGN

→ Approve defining sources for CRF alignment

→ Determination of AGN phase- vs. group delay position offsets, e.g. for **observations of radio-faint objects (e.g. radio stars)** or for spacecraft tracking

Example: Alignment of Gaia DR to ICRF3

- Observations of **radio stars** are used for **verifying** the **alignment** of the bright (G < 13 mag) **Gaia** frame to **ICRF3** S/X: orientation offset and residual spin
- Optically bright stars are usually too faint to be observed by geodetic (group delay) VLBI
  → Solution: **phase-referencing** between star (faint) and AGN (bright)
- **Relative** star positions towards AGN position at specific frequency core:
  - Can be very precisely derived
  - Estimates for models of stellar motion
  - Precise proper motion is used for determination of the Gaia DR residual spin

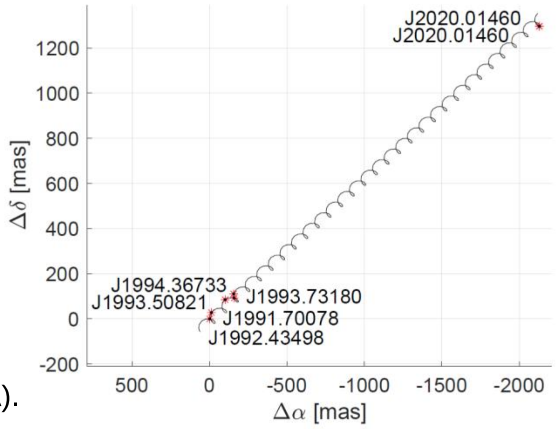


Fig.: Estimated model of stellar motion for star AR Lac. The relative positions labelled by red asterisks (Lunz et al., 2021b, submitted to A&A).

Example: Alignment of Gaia DR to ICRF3

- **Absolute** star positions in ICRF3 S/X:
  - Commonly used procedure: add absolute calibrator position in ICRF3 S/X based on group delays
  - Used for determination of the orientation offset and the residual spin
- **One of the largest error sources of absolute position is the (unkown) difference between phase delay position and group delay position of the AGN**
  → on average 0.2 milliarcseconds
  → directly affects the formal error of the Gaia/ICRF3 alignment test

→ User requirement: S/X(/C) antenna capability, S/X/K/Ka/VGOS for astrophysical studies

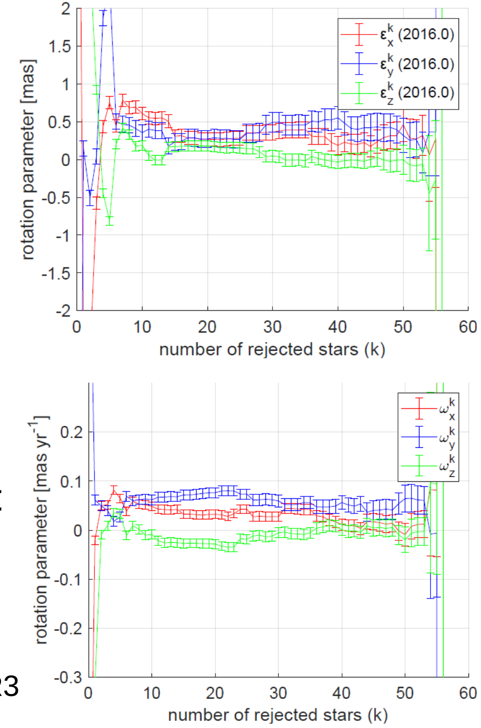


Fig.: Orientation offset (top) and residual spin (bottom) between Gaia EDR3 and ICRF3 from data of 60 stars (Lunz et al., 2021b, submitted to A&A).

Lunz et al., 2021a, submitted to A&A
Lunz et al., 2021b, submitted to A&A

3.c Determination of AGN core shift - VGOS

- VGOS observes AGN at 4 widely separated broad frequency bands
- **Source structure and core shift are typically different at the 4 bands**
- VGOS observations have very low thermal noise → **source structure is dominant systematic error** that has to be corrected for in the data analysis

  → Relative source structure can be modeled from observations directly

  → **Alignment of the images** relative to each other depends on assumptions (core shift is unknown!)

→ Observations of **AGN at VGOS bands relative to the satellite** are a unique chance to accurately address and solve this error source

→ User requirement: VGOS antenna capability

Xu et al., 2021b, JoG, 95, 51
Xu et al., 2021a, submitted to A&A
Xu et al. IVS General Meeting 2022

3.d Positive effects for EOP

- Earth Orientation Parameters (EOP) link the ITRF and ICRF
- Full set of EOP can only be determined by **VLBI to AGN**
- **Celestial pole offsets (CPO; dX and dY) and dUT1 estimation is improved** from enhanced CRF

$R_1 \triangleq$ -dY; $R_2 \triangleq$ dX; $R_3 \triangleq$ dUT1/r′+ A_Z

r′ … ratio between solar and siderial time; A_Z … part of global rotation wrt. TRF

- Polar motion is **correlated** to CPO and dUT1→ improved pole coordinates (x_P, y_P)

→ Overall improved consistency of EOP and CRF

→ User requirement: S/X/K/Ka/VGOS antenna capability

4. Recapitulation

- GENESIS can serve several applications for ICRF:
  - Simultaneous observations by various VLBI networks (e.g. S/X, K, X/Ka and VGOS)
    → **Local tie in space**
  - Unique chance to determine **core shifts for all AGN** precisely through phase-referencing between satellite and AGN
    → Astrophysical studies and enhancement of the Gaia/VLBI frame alignment
    → Correction of **source structure effects in VGOS**
  - Enhanced CRF has **positive effects on all EOP**
    → Overall improvement of any satellite application that requires POD

- Required frequencies:
  - S/X can be considered legacy, but important for ICRF stability and connection to ITRF
  - Include VGOS → future of geodetic VLBI
  - Include K-band and other higher frequencies (Ka) → future of ICRF, spacecraft tracking

4. Recapitulation

- Design requirements:
  - Weak broadband noise (similar to AGN)
  - One antenna which emits all frequencies is optimal
  - Calibration at all frequencies on ground essential (position, structure of the emission)
  - Satellite orientation in space has to be determined precisely
  - Satellite speed: slow enough for phase-referencing (nodding-style)

Conclusion: A co-location satellite is an outstanding opportunity to enhance the CRF and thereby indirectly obtain improved EOP

→ General improvement of all satellite applications that require POD

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Thank you very much for your attention.

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We are looking forward to the collaboration.

Current DFG Project: Alignment of Gaia-optical and radio reference frames (AGORA)

Backup: polarization difference between legacy and VGOS sites

- **Legacy antennas (S/X):** right circular polarization (RCP)

  → Transmitting antenna onboard satellite must produce left circular polarization (LCP) for optimal gain of the system
- **VGOS antennas:** two perpendicular linear polarizations

  → Transmitting antenna onboard satellite must be unpolarized for optimal gain of the system

  → not possible → use circular polaization

→ Best for co-location satellite is LCP (Jaradat et al. 2021)

→ Two arms Archimedian Spiral Antenna is best as the fractional bandwith can be up to 40:1 (e.g. 1-40 GHz → covers all geodetic VLBI frequ.) without significant frequency dependence of radiation pattern and polarization (Klimya and Prakash 2015)

Jaradat, A., Jaron, F., Gruber, J., Nothnagel, A. (2021): Considerations of VLBI transmitters on **Galileo** satellites, AiSR 68 (3), 1281-1300.
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