Systematic effect of the Galactic aberration on the ICRS realization and EOP

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Outline

- Introduction
- Effect of the Galactic aberration on the ICRS realization
- Effect of the Galactic aberration effect on the Earth Orientation Parameters
- Discussion and conclusion
1. Galactic aberration

The origin of the effect under consideration: acceleration of the SSB around the Galactic center (simplification: circular orbit, Kovalevsky 2003; Kopeikin & Makarov 2006; Titov 2010; Titov 2011)

Figure: The apparent proper motions of ICRF sources.

First order: dipole pattern; the magnitude is

\[ A = \frac{\omega_0 V_0}{c} \approx 5 \text{ \(\mu\)as yr}^{-1} \]

which can be called the “Galactic aberration constant” (Malkin 2011).
2. Global rotation of the ICRS

- What is the systematic effect of the GA effect on the ICRS realization?

- Is the realization of the ICRS rotating due to the dipole proper motion?

Proper motions due to the GA can be written as:

In the Galactic coordinate system
\[
\begin{align*}
\Delta \mu_\ell \cos b &= -A \sin \ell, \\
\Delta \mu_b &= -A \cos \ell \sin b.
\end{align*}
\]

where \( A = 5 \mu \text{as yr}^{-1} \)

In the Equatorial coordinate system:
\[
\begin{align*}
\Delta \mu_\alpha \cos \delta &= -d_1 \sin \alpha + d_2 \cos \alpha, \\
\Delta \mu_\delta &= -d_1 \cos \alpha \sin \delta - d_2 \sin \alpha \sin \delta + d_3 \cos \delta,
\end{align*}
\]

where \( d_1 = A \cos \alpha_0 \cos \delta_0 \), \( d_2 = A \sin \alpha_0 \cos \delta_0 \), and \( d_3 = A \sin \delta_0 \).

This effect has been measured by VLBI by Titov et al. (2011)
Fit to theoretical proper motions due to the Galactic aberration based on the sources of the ICRF1 and ICRF2 catalogs using the following equations (no weights were used):

\[
\Delta \mu_\alpha \cos \delta = -\omega_x \cos \alpha \sin \delta - \omega_y \sin \alpha \sin \delta + \omega_z \cos \delta \\
\Delta \mu_\delta = +\omega_x \sin \alpha - \omega_y \cos \alpha,
\]

<table>
<thead>
<tr>
<th>Catalog</th>
<th>No.</th>
<th>(\omega_x)</th>
<th>(\omega_y)</th>
<th>(\omega_z)</th>
<th>(\omega_{\text{tot}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICRF1 def</td>
<td>212</td>
<td>+1.07 ± 0.08</td>
<td>−0.20 ± 0.08</td>
<td>+0.18 ± 0.09</td>
<td>1.10 ± 0.14</td>
</tr>
<tr>
<td>ICRF1</td>
<td>608</td>
<td>+0.22 ± 0.05</td>
<td>−0.03 ± 0.05</td>
<td>+0.04 ± 0.05</td>
<td>0.22 ± 0.09</td>
</tr>
<tr>
<td>ICRF2 def</td>
<td>295</td>
<td>+0.01 ± 0.07</td>
<td>−0.14 ± 0.07</td>
<td>+0.28 ± 0.07</td>
<td>0.31 ± 0.12</td>
</tr>
<tr>
<td>ICRF2</td>
<td>3414</td>
<td>+0.89 ± 0.02</td>
<td>−0.08 ± 0.02</td>
<td>+0.04 ± 0.02</td>
<td>0.89 ± 0.03</td>
</tr>
</tbody>
</table>

**Conclusion 1:** The effect depends on the distribution of sources.

Compare with ICRF axes stabilities \(0.1 \mu\text{as yr}^{-1} < \omega_{xyz} < 1 \mu\text{as yr}^{-1}\)

ICRF1: 20 \(\mu\text{as}\)  \quad ICRF2: 10 \(\mu\text{as}\)

**Conclusion 2:** The effect is not negligible after a few tens of years.
Geometrical feature of the GA effect

Use the Galactic coordinate system \([X_G, Y_G, Z_G]\) help us to best characterize the geometry of the global rotation resulting from GA effect.

Transform the results in the Equatorial coordinate system, or fit directly the proper motions in the Galactic coordinate system, we have:

The direction of the total rotation can be described in the highlighted plane by the angle:

\[
\theta = \arctan \left( \frac{\omega_{ZG}}{\omega_{YG}} \right)
\]

unit: \(\mu\text{as yr}^{-1}\)

<table>
<thead>
<tr>
<th>Catalog</th>
<th>No.</th>
<th>(\omega_{XG})</th>
<th>(\omega_{YG})</th>
<th>(\omega_{ZG})</th>
<th>(\omega_{tot})</th>
<th>(\theta)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICRF1 def</td>
<td>212</td>
<td>+0.03 ± 0.08</td>
<td>+0.73 ± 0.08</td>
<td>-0.82 ± 0.09</td>
<td>1.09 ± 0.14</td>
<td>-48°.3</td>
</tr>
<tr>
<td>ICRF1</td>
<td>608</td>
<td>-0.01 ± 0.05</td>
<td>+0.15 ± 0.05</td>
<td>-0.18 ± 0.05</td>
<td>0.23 ± 0.09</td>
<td>-50°.2</td>
</tr>
<tr>
<td>ICRF2 def</td>
<td>295</td>
<td>-0.01 ± 0.07</td>
<td>+0.26 ± 0.07</td>
<td>+0.15 ± 0.07</td>
<td>0.30 ± 0.12</td>
<td>+30°.0</td>
</tr>
<tr>
<td>ICRF2</td>
<td>3414</td>
<td>-0.00 ± 0.02</td>
<td>+0.51 ± 0.02</td>
<td>-0.74 ± 0.02</td>
<td>0.90 ± 0.03</td>
<td>-55°.4</td>
</tr>
<tr>
<td>uniform</td>
<td>2500</td>
<td>+0.00 ± 0.02</td>
<td>+0.00 ± 0.02</td>
<td>+0.00 ± 0.02</td>
<td>0.00 ± 0.03</td>
<td>- - -</td>
</tr>
</tbody>
</table>

Conclusion 3: There is almost no rotation around the \(X_G\) axis.
Conclusion 4: With uniform distribution, there is no global rotation.

For the Galactic coordinate system, please see the poster by Zhu & Liu (No. JD7-3-1363).
The revised ICRS

To keep the orthogonality of the ICRS, only global rotation can be applied.

The revised ICRS, denoted ICRS’ is such that

$$[\text{ICRS’}] = M_{\text{rot}}(\psi_x, \psi_y, \psi_z) \cdot [\text{ICRS}]$$

where the rotation angles:

$$\psi_x = \omega_x(t - t_0), \quad \psi_y = \omega_y(t - t_0), \quad \psi_z = \omega_z(t - t_0)$$

are small quantities over several thousand centuries.

The rotation matrix can be written as:

$$M_{\text{rot}}(\psi_x, \psi_y, \psi_z) = \begin{pmatrix} 1 & +\psi_z & -\psi_y \\ -\psi_z & 1 & +\psi_x \\ +\psi_y & -\psi_x & 1 \end{pmatrix}$$
3. Effect of GA on the EOP

**ICRS**

\[(X, Y, \text{ERA}) \xrightarrow{\text{GA effect on the radio sources}} (X + \Delta X, Y + \Delta Y, \text{ERA} + \Delta \text{ERA})\]

**ICRS’**

Terrestrial–to–Celestial reference system transformation:

\[
[\text{ITRS}] = \mathcal{W}(x_p, y_p) \cdot R_3(\text{ERA} - s) \cdot M_{\Sigma}(X, Y) \cdot [\text{ICRS}]
\]

in the ICRS’

\[
M_{\Sigma}(X, Y) = \begin{pmatrix}
1 - aX^2 & -aXY & -X \\
-aXY & 1 - aY^2 & -Y \\
x & y & 1 - a(X^2 + Y^2)
\end{pmatrix}
\]

\[
[\text{ITRS}] = \mathcal{W}(x_p, y_p) \cdot R_3(\text{ERA} - s + \Delta(\text{ERA} - s)) \cdot M_{\Sigma}(X + \Delta X, Y + \Delta Y) \cdot [\text{ICRS’}]
\]

Note: there is no effect on the ITRS and polar motion

and apply \[\text{ICRS’} = M_{\text{rot}}(\psi_x, \psi_y, \psi_z) \cdot [\text{ICRS}]\]

\[
M_{\Sigma}(X, Y) = R_3(\Delta(\text{ERA} - s)) \cdot M_{\Sigma}(X + \Delta X, Y + \Delta Y) \cdot M_{\text{rot}}(\psi_x, \psi_y, \psi_z)
\]

solution \(\Delta X, \Delta Y, \text{and } \Delta(\text{ERA} - s)\)
Theoretical solution:

\[ \Delta X = +\psi_z Y - \psi_y Z, \]
\[ \Delta Y = -\psi_z X + \psi_x Z, \]
\[ \Delta (\text{ERA} - s) = -\psi_x - \psi_y X - \psi_y Y. \]

\begin{center}
\begin{tabular}{lcccccccc}
\hline
 & \multicolumn{3}{c}{values after one century} & \multicolumn{3}{c}{mean rates between J1500 and J2500} \\
 & \multicolumn{3}{c}{unit: \(\mu\text{as}\)} & \multicolumn{3}{c}{unit: \(\mu\text{as yr}^{-1}\)} \\
Catalog & \(\Delta X\) & \(\Delta Y\) & \(\Delta (\text{ERA} - s)\) & \(\text{d}\Delta X/\text{dt}\) & \(\text{d}\Delta Y/\text{dt}\) & \(\text{d}\Delta (\text{ERA} - s)/\text{dt}\) \\
\hline
ICRF1 def & 20.0 ± 8.0 & \textbf{107.1} ± 8.1 & -19.0 ± 9.6 & 0.20 ± 0.08 & 1.07 ± 0.08 & -0.18 ± 0.09 \\
ICRF1 & 3.3 ± 4.9 & 22.1 ± 5.0 & -4.1 ± 5.3 & 0.03 ± 0.05 & 0.22 ± 0.05 & -0.04 ± 0.05 \\
ICRF2 def & 14.4 ± 7.1 & 0.7 ± 5.2 & -28.0 ± 7.3 & 0.14 ± 0.07 & 0.01 ± 0.05 & -0.28 ± 0.07 \\
ICRF2 & 7.8 ± 2.1 & 88.9 ± 2.2 & -5.1 ± 2.4 & 0.08 ± 0.02 & 0.89 ± 0.02 & -0.04 ± 0.02 \\
\hline
\end{tabular}
\end{center}

The Galactic aberration effect is very different from precession, however the spurious global rotation of the ICRS (realized by these sources) contributes to the linear trend of the celestial pole offsets; this slightly distorts the precession rate estimated from VLBI observations.

1. Compare with Malkin (2011) results based on VLBI EOP series

\[
\text{(d}\Delta X/\text{dt})_{\text{Malkin}} = +0.1 ± 0.5 \, \mu\text{as yr}^{-1}
\]
\[
\text{(d}\Delta Y/\text{dt})_{\text{Malkin}} = +0.2 ± 0.6 \, \mu\text{as yr}^{-1}
\]

2. Compare with the accuracy of the precession–nutation model

The accuracy for predicting the CIP location is expected to be better than 100 \(\mu\text{as}\) after one century in the near future.
\[ \Delta X = +\psi_z Y - \psi_y Z, \]
\[ \Delta Y = -\psi_z X + \psi_x Z \]
\[ \Delta(\text{ERA} - s) = -\psi_z - \psi_x X - \psi_y Y. \]

- Time interval: 1000 years
- IAU 2006/2000 precession-nutation model

- Time interval: 4000 centuries
- Vondrak et al. (2011) precession expressions valid for long time intervals
4. Conclusion and discussion

- GA effect is responsible for slow rotation of the ICRS realization.
- The systematic effect depends on the distribution of sources and there is no effect in case of uniform distribution.
- The use of Galactic coordinate system can best characterize the global rotation.
- The effect is not negligible after about 30 years (in the next ICRF)

1. Other methods to derive the global rotation of the ICRS realization?
2. How to deal with the deformation effect?
3. Considered as a contribution in the precession–nutation model?
   
   No, because it is not known with sufficient precision.

- Is a Galactocentric Celestial Reference System (GalCRS) possible?
  
  No, because the corresponding transformation between the GalCRS and the BCRS is not available.
Nomenclature issue

- Secular aberration
  - Kopeikin & Makarov (2006)

- Secular aberration drift
  - Tivov (2010); Titov et al. (2011)

- Aberration in proper motion
  - Kovalevsky (2003)

- Galactic aberration
  - Malkin (2011); This study

- Galactocentric aberration drift
  - ??

A convention should be adopted.