第62卷 第6期 天 文 学 报 Vol.62 No.6
2021年11月 ACTA ASTRONOMICA SINICA Nov., 2021

doi: 10.15940/j.cnki.0001-5245.2021.06.012 博士学位论文摘要选登

ICRF与*Gaia*-CRF参考架特性分析

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天体测量学的核心任务之一就是建立一个高精度天文参考系, 以便利用这样的惯性参照系来描述天体的位置和运动、研究银河系的运动学特征及对同一天体在不同波段的对应体进行位置认证和比较. 当前的天文参考系是参照银河系外天体(主要是活动星系核)的位置来定义的, 称为国际天球参考系(ICRS). 在实测上, 与之相对应的基本星表为国际天球参考架(ICRF), 它由甚长基线干涉测量(VLBI)技术在S/X、K和X/Ka波段的观测资料解算而得, 位置精度达到数十微角秒(μas)水平. 另一方面, *Gaia*卫星的观测也将在光学波段建立类似精度的光学参考架(*Gaia*-CRF). ICRF与*Gaia*-CRF的连接成为天体测量领域需要解决的重大问题之一, 这要求对ICRF与*Gaia*-CRF参考架特性进行细致深入的分析.

首先, 分析了ICRF的整体特性. VLBI星表的内部符合精度估计值在10 μas和40 μas之间, 依赖于射电源的观测次数. 这一结果一方面验证了ICRF3星表给出的位置噪声水平, 也说明了VLBI技术在天体测量方面的潜力. 利用*Gaia*的河外源位置为参考, 分析了历代ICRF星表的外部符合精度, 指出ICRF3 X/Ka波段参考架存在约200 μas的系统误差. 最后, 发明了一种评估射电源全天分布均匀性的量化指标并改进了ICRF定义源筛选策略, 结果表明相较于ICRF2而言, 这一方法能将ICRF轴指向稳定性提高2至3倍. 这些工作很好地解释并补充了国际上ICRF3工作组的相关结果.

其次, 研究*Gaia*-CRF的参考架性质. 使用了相对于依巴谷参考架的全局旋转和结合银河系动力学分析两种方法来评估*Gaia*-CRF1的惯性水平, 指出*Gaia*-CRF1可能存在约0.3 $\mathrm{mas\cdot yr^{-1}}$的剩余旋转. 对于*Gaia*-CRF2, 研究了其系统精度与河外源样本极限星等的依赖关系, 发现*Gaia*-CRF2的整体精度几乎不受星等差的影响. 这一结果可作为未来ICRF与*Gaia*-CRF连接源选择的参考.

活动星系核的光学-射电位置差是影响参考架连接精度的重要因素之一. 本文首次将光学-射电位置差研究延伸到K和Ka波段, 并研究其与河外源性质参数的相关性, 发现: 光学-射电位置差与星等的相关性是由于星等差而非真实的物理原因造成的, 因此在前人工作中被忽略的暗源也有可能作为ICRF与*Gaia*-CRF连接源. 此外, 本文提出了一种新的参考架连接方法, 即在*Gaia*-CRF2框架下重新处理VLBI的历史观测资料. 先期结果发现使用*Gaia*-CRF2来替代ICRF3尚不足以显著提高VLBI产品的精度, 但未来在*Gaia*-CRF参考架精度进一步提高后, 此方法仍值得进一步检验.

本文的研究, 一方面指出了ICRF与*Gaia*-CRF参考架中可能存在的种种问题, 另一方面也为将来光学与射电参考架连接提供了第一手的参考资料.

Overall Properties of the ICRF and *Gaia*-CRF

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†2020-06-22获得博士学位, 导师: 南京大学朱紫教授和巴黎天文台Sébastien Lambert研究员; zhuzi@nju.edu.cn, sebastien.lambert@obspm.fr

The International Celestial Reference System (ICRS) now has realizations at several frequencies, all with an accuracy of several tens of mircoarcsecond (μas) level, including the International Celestial Reference Frame (ICRF) based on observations of the very long baseline interferometry (VLBI) at S/X, K, and X/Ka band, and the *Gaia* celestial reference frame (*Gaia*-CRF) built by the *Gaia* mission. The link between the ICRF and *Gaia*-CRF is a non-trivial task for constructing a multiwavelength reference frame. It requires detailed analyses of the overall properties of both the ICRF and *Gaia*-CRF for the sake of deepening our understanding of these frames, which is of the main interest of this thesis.

The first part is to investigate the internal and external accuracy of ICRF catalogs. The internal accuracy is estimated to range from $10\,\mu$as to $40\,\mu$as, depending on the number of observations to individual sources. This analysis provides an independent validation to the documented value ($30\,\mu$as) for the noise floor given by the ICRF3 Working Group, as well as indicates the potential accuracy VLBI catalogs could achieve. The external accuracy is studied by comparing all historic ICRF catalogs to the *Gaia*-CRF2 solution. The large-scale agreement is about $30\,\mu$as and $50\,\mu$as between the ICRF3 S/X band and K band and the *Gaia*-CRF2 catalogs. The X/Ka band catalog, however, presents deformations of about $200\,\mu$as, indicating severe zonal errors in the X/Ka band frame. The possible method of improving the stability of the ICRF axes is also explored, in term of defining source selection. A new selection algorithm considering both source positional stability and uniformness of source distribution is proposed, which is supposed to improve the axis stability by a factor of two compared to the ICRF2.

Secondly, different aspects related to the celestial frame in the *Gaia* Data Release 1 and 2 (DR1 and DR2) are concerned. The non-rotating of the stellar frame of the DR1 is investigated in the light of the global spin of *Gaia*-CRF1 with respect to the HIPPARCOS frames and using Galactic kinematical analysis. Both methods yield possible residual rotation of around $0.3\,\mathrm{mas}\cdot\mathrm{yr}^{-1}$ in the DR1 frame. As for the DR2, the magnitude-dependent error is estimated to have little influence on the global property of the *Gaia*-CRF2, suggesting that the overall accuracy of the *Gaia*-CRF might not degrade like the precision. It underlines a new aspect of the radio-to-optical frame link, which was thought to be taken place only among bright quasars.

In preparation for the radio-to-optical frame link, the correlation between the radio-to-optical offsets and source properties are tested statistically to understand its origin. The radio-to-optical offset is found to correlate strongly with the magnitude, however, this correlation would diminish when one consider the position formal error. As a result, large offsets for faint sources are likely resulted from the magnitude-dependent error rather than astrophysical cause. Besides, a method of the radio-to-optical frame link is proposed, whose idea is to introduce the *Gaia*-CRF in the VLBI data analysis. The preliminary tests suggest no benefit to do so, but it should be re-tested based on the future Gaia data releases with improved accuracy.

In conclusion, the agreement among the ICRF3 S/X band frame, K band frame, and *Gaia*-CRF2 is excellent. However, X/Ka band frame suffers from zonal errors and needs to be improved. More tests on the radio-to-optical frame-tie should be carried out based on the actual *Gaia* data.