天文参考系

Astronomical Reference Systems

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国际天球参考系
International Celestial Reference System (ICRS)

章节安排

1. VLBI 天体测量

2. ICRF 的建立和发展

3. ICRF 的性质研究

VLBI 天体测量

NASA | Using Quasars to Measure the Earth: A Brief History of VLBI

视频来源： NASA Goddard.

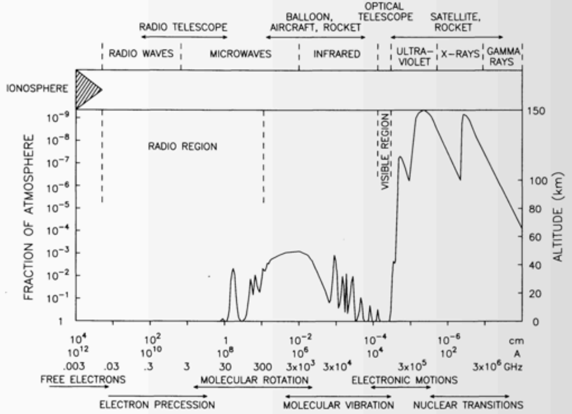

Fig. 4.1. Transparency of the Earth's atmosphere to electromagnetic radiation showing the radio and visible regions. The diagram gives the height of the atmosphere at which the intensity of radiation is attenuated by a factor of 2 (After Rohlfs & Wilson 2000)

图 1: 大气窗口（Atmospheric Windows）[1]

大气窗口:
电磁辐射中能穿透大气的一些波段/频段

射电窗口:

$$\nu = 15\,\mathrm{MHz} \quad \sim \quad \nu = 300\,\mathrm{GHz}$$
$$\lambda = 20\,\mathrm{m} \quad \sim \quad \lambda = 1\,\mathrm{mm}$$

高频处的截断是由于对流层中水汽、氧气和臭氧分子的分子共振吸收:

$$H_2O \quad \sim \quad 22.2\,\mathrm{GHz}/184\,\mathrm{GHz}$$
$$O_2 \quad \sim \quad 60\,\mathrm{GHz}/118\,\mathrm{GHz}$$

低频处的截断是由于电离层中自由电子对特定频率辐射的吸收:
$\nu < \nu_p$, $\nu_p/\mathrm{Hz} = 9\sqrt{N_e/\mathrm{m}^{-3}}$ 为电子的等离子体频率 (Plasma frequency)

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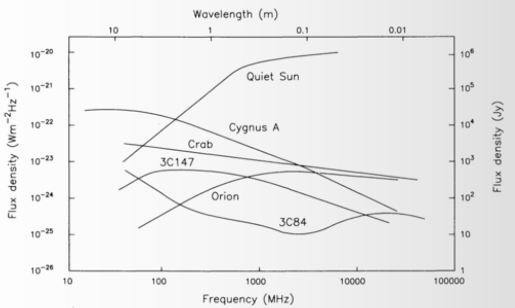

Fig. 4.2. Radio spectra of some prominent radio sources. The quiet Sun and the Orion nebula are thermal sources. The non-thermal sources include a supernova remnant (the Crab nebula), a quasar (3C 147) and two radio galaxies, Cygnus A and 3C 84 (After Christiansen and Högbom 1985)

图 2: 一些典型天体的射电光谱 [1]

1 Jy = $10^{-26}\ \mathrm{W\,m^{-2}\,Hz^{-1}}$

手机在月球上的辐射约为 1.5 Jy。

有射电辐射的天体包括:

1. 太阳系内天体 (solar system bodies)
2. 星间分子云 (interstellar clouds)
3. 脉泽 (masers)
4. 脉冲星 (pulsars)
5. 射电星 (radio stars)
6. 河外源 (extragalactic sources), 多数为活动星系核（AGNs，active galactic nucleus)

适合定义河外参考架的天体为类星体（quasar）（在射电波段上的致密点源），射电亮度 (radio brightness) 约为 ~0.1-10 Jy。

活动星系核 (Active Galactic Nuclei, AGN) 和类星体（Quasar）

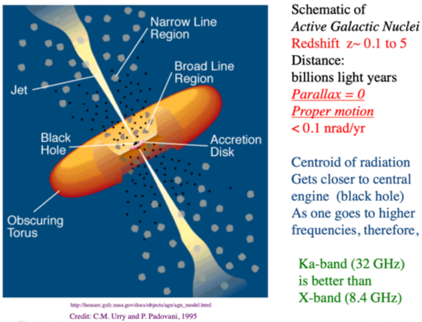

图 3: 活动星系核的物理模型

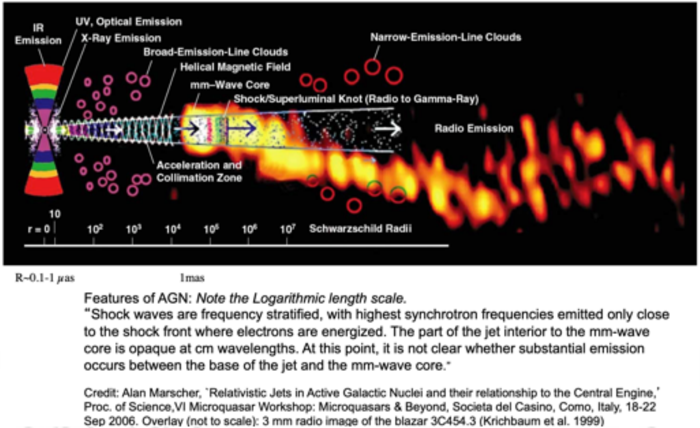

图 4: 活动星系核的辐射区域

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射电望远镜

图 5: Karl Jansky 在 1931 年的射电天线（复刻版）

图 7: 位于阿根廷 La Plata 的 AGGO 6 米望远镜

图 6: 上海佘山 25 米望远镜

图 8: 南极的 O’Higgins 9 米望远镜

对于遥远的天体（银河系外天体），测量位置实际上是测量角坐标，因此角分辨率决定了位置测量精度（二者至少应在同一数量级）。

单天线的角分辨率为

$$\theta \simeq 1.22\,\frac{\lambda}{D} \tag{1}$$

思考

以典型的射电望远镜为例，假设其口径为 30 m，接收机频率为 5 GHz（相当于波长为 6 cm），这台望远镜的角分辨率为多少？(约为 $8'$)

如何提升角分辨率到毫角秒水平甚至更高，以满足现代天体测量的需求？

1. 增大 D $\longrightarrow$ 更大口径天线、干涉仪和干涉阵
2. 减小 λ $\longrightarrow$ 在更高的频率上观测

甚长基线干涉测量（VLBI = Very Long Baseline Interforemetry）

> “A connected element interferometer is a close analog of the Michelson stellar interferometer, which manipulates signals with mirrors to produce a physical interference pattern at the detector.”
>
> ——Sovers et al. (1998) [2]

> “The technique known as Very Long Baseline Interferometry (VLBI) differs from connected interferometry in that the intermediate frequency (IF) signals are tape recorded independently at the two sites of observation. They are later cross-correlated to produce the interference pattern.”
>
> ——Green (1985) [3]

> “Interferometry at radio frequencies between Earth-based receivers separated by intercontinental distances ...”
>
> ——Sovers et al. (1998) [2]

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VLBI 观测站的分布 [4]

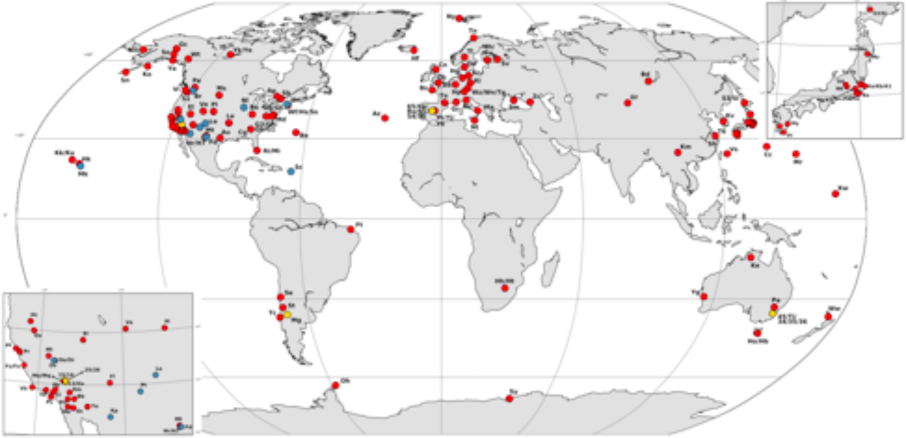


Fig. 1. World map showing the geographical location of the 167 antennas (situated on 126 different sites) that participated in the observations used for ICRF3. The red dots show the antennas from the IVS network (and pre-existing adhoc VLBI arrays that observed at *S/X* band), the blue ones those from the VLBA, and the yellow ones those from the DSN and ESA. The two-character codes printed near each dot correspond to the short names of the antennas, as defined in the IVS nomenclature. The two insets show enlargements of western US and Japan where a large number of antennas (including mobile VLBI stations) have been used to collect geodetic VLBI data over the years due to the seismic nature of these regions.

VLBI 实验流程

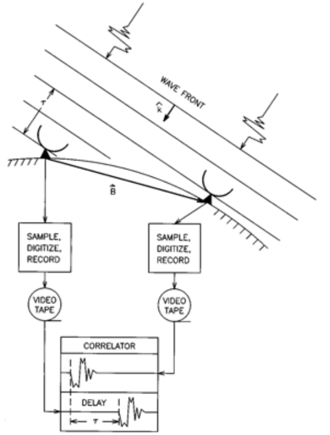


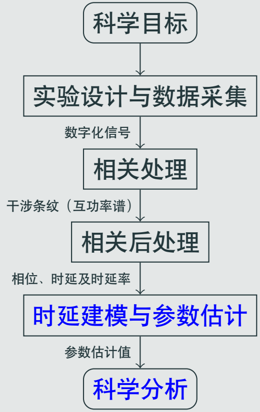
FIG. 1. Schematic diagram of a VLBI experiment. Wave forms are shown impinging from the direction $\hat{\mathbf{k}}$ on two antennas separated by a baseline **B** on the Earth's surface. They are followed through the data acquisition system to the point where the correlator determines the delay τ. The signal wave forms are exaggerated for effect. The actual wave forms are random Gaussian processes.

图 9: VLBI 观测示意图 [2]

VLBI 几何时延（零阶）

$$\tau = \frac{\hat{k} \cdot B}{c} = -\frac{\hat{s} \cdot B}{c} \quad (2)$$

VLBI 实验的一般流程



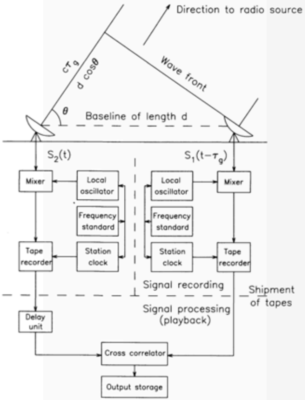


Fig. 4.4. A general block diagram of a VLBI recording system. The lower horizontal dotted line separates the terminals for signal recording from the processing terminal dedicated to the combination of the two signal streams

图 10: VLBI 数据记录系统 [1]

相关机的输出为相干函数 (Coherence function)

$$R = A_{\mathrm{f}} \cos\left(2\pi\nu_{\mathrm{f}} t + \phi_{\mathrm{f}}\right) \tag{3}$$

直接观测量（Direct Observables）

- 条纹幅度（fringe amplitude) A_{f}
- 条纹相位（fringe phase） ϕ_{f}

$$\phi_{\mathrm{f}}(t) = \frac{\omega}{c} B(t) \cdot \hat{s} + \phi_{\mathrm{media}}(t) + \phi_{\mathrm{instr}}(t) + 2\pi k \tag{4}$$

导出观测量（Derivative Observables）

- 相时延（phase delay) $\tau_\phi = \frac{n_\lambda \lambda}{v_\phi} = \frac{\phi_{\mathrm{f}}}{\omega}$
- 群时延（group delay) $\tau_{\mathrm{g}} = \frac{n_\lambda \lambda}{v_{\mathrm{g}}} = \frac{\partial \phi_{\mathrm{f}}}{\partial \omega}$
- 相时延率（phase delay rate) $\nu_{\mathrm{f}} = \omega \frac{\partial \tau_\phi}{\partial t}$
- 群时延率（group delay rate) $\dot{\tau}_{\mathrm{g}} = \frac{\partial \tau_{\mathrm{g}}}{\partial t}$

为何要进行 VLBI 观测？

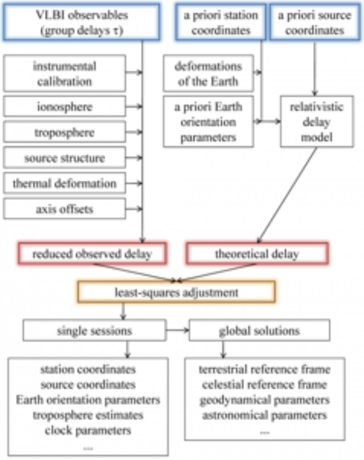


图 11: VLBI 数据分析链 [5]

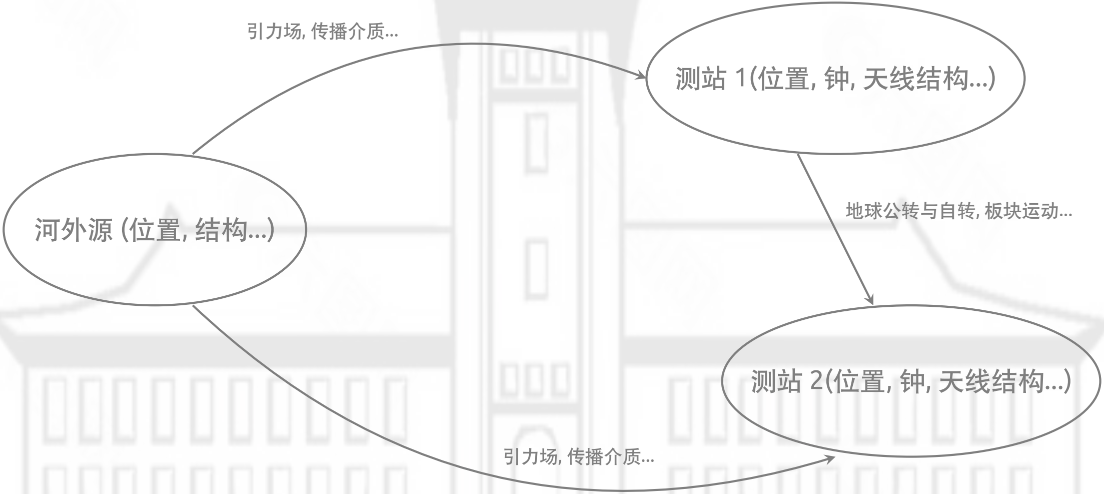
"现代观测资料的参数解析一般遵循这样的基本操作过程，即对待求参数赋予尽量准确的初值，依照有关模型计算观测量的理论值以及理论值对待求参数的偏导数，将观测值与理论值之差对待求参数初值的改正值进行泰勒展开，通过误差方程解算获得参数初值的改正值，进而获得经观测资料更新之后的参数值。形式地表示为:

$$O - C = \sum \frac{\partial C}{\partial X} \mathrm{d}X \tag{5}$$

上式即误差方程，其中 O 为观测值；C 为待求参数取初值时由观测模型计算得到的理论值；X 为待求参数集合；$\frac{\partial C}{\partial X}$ 为由观测模型推演得到的理论值对待求参数的偏导；$O - C$ 为观测值与理论值之差；$\mathrm{d}X$ 为解算参数集合，是待求参数初值的改正值；经误差方程解算获得 $\mathrm{d}X$，$X_0 + \mathrm{d}X$ 即为经观测更新的参数取值。"[6]

待估参数包括：射电源位置（空固系）、观测站位置（地固系）、地球定向参数（EOP）

VLBI 观测总览



引力场, 传播介质...
测站 1(位置, 钟, 天线结构...)
河外源 (位置, 结构...)
地球公转与自转, 板块运动...
测站 2(位置, 钟, 天线结构...)
引力场, 传播介质...

VLBI 理论时延模型（1 ps 精度）

理论时延模型，可以划分为数个组成部分：

$$\tau_c = \tau_{geo} + \tau_{ins} + \tau_{tro} + \tau_{ion} + \ldots, \tag{6}$$

$$\tau_{geo} = \tau + \tau_{gra} + \tau_{ant} + \tau_{str} + \ldots \tag{7}$$

等号右边各项依次表示几何时延、测站钟差和仪器时延、中性大气与电离层时延修正等，引力时延、源结构时延修正和天线时延修正都被包含在几何时延模型中。

几何时延（Geometric delay）τ_{geo}

定义 某射电信号在理想状态下到达两个分开的几何点的时间差，为理论时延的主项。

理想状态 包括理想的测量设备、理想的同步钟，而且射电源与地面仪器之间为理想的真空。

思考

假设地球为不透明的球体，对于地球表面的基线，一束来自无穷远处的信号所造成的几何时延的最大值约为多少？(约 20 ms）对应于怎样的情况？

几何时延模型（1）— 信号波前到达时间差（Wave-front Arrival-time Difference）

平面波前（Plane wave front）

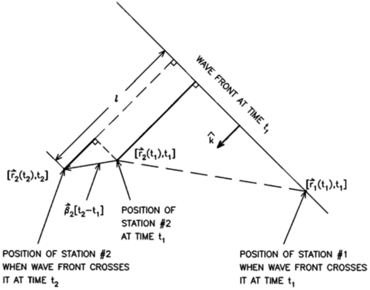


图 12: 平面波前的观测几何示意图 [2]

球面波前（Curved wave front）

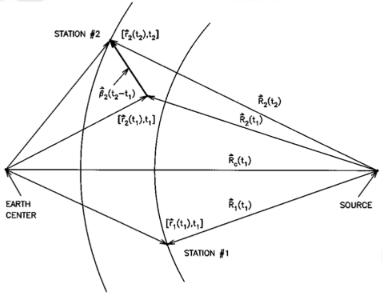


图 13: 球面波前的观测几何示意图 [2]

$$\tau = t_2 - t_1 = \frac{\hat{\boldsymbol{k}} \cdot [\boldsymbol{r}_2(t_1) - \boldsymbol{r}_1(t_1)]}{c \cdot [1 - \hat{\boldsymbol{k}} \cdot \boldsymbol{\beta}_2]} \quad (8)$$

$$\tau = \frac{\hat{\boldsymbol{r}}_c \cdot [\boldsymbol{R}_2(t_1) - \boldsymbol{R}_1(t_1)]}{c \cdot [1 - \hat{\boldsymbol{r}}_c \cdot \boldsymbol{\beta}_2]} + \frac{R_c \Delta_c(\tau)}{2c \cdot [1 - \hat{\boldsymbol{r}}_c \cdot \boldsymbol{\beta}_2]} \quad (9)$$

$$\boldsymbol{\epsilon}_1 = \boldsymbol{r}_1(t_1)/R_C(t_1)$$

$$\boldsymbol{\epsilon}_2 = [\boldsymbol{r}_2(t_1) + c\boldsymbol{\beta}_2\tau]/R_C(t_1)$$

$$\Delta_C(\tau) = [\epsilon_2^2 - \epsilon_1^2] - [(\hat{\boldsymbol{r}}_C \cdot \boldsymbol{\epsilon}_2)^2 - (\hat{\boldsymbol{r}}_C \cdot \boldsymbol{\epsilon}_1)^2] + (\hat{\boldsymbol{r}}_C \cdot \boldsymbol{\epsilon}_2)^3 - (\hat{\boldsymbol{r}}_C \cdot \boldsymbol{\epsilon}_1)^3] - (\hat{\boldsymbol{r}}_C \cdot \boldsymbol{\epsilon}_2)\epsilon_2^2 + (\hat{\boldsymbol{r}}_C \cdot \boldsymbol{\epsilon}_1)\epsilon_1^2]$$

引力时延（Gravitational delay）τ_{gra}

定义 指由于引力场对电磁信号传播的迟滞作用（包括传播路径的弯曲和时间的延缓）而引起的额外的信号波前到达时间差。

取信号最接近引力体 p 时 p 的位置为坐标原点，p 引起的引力坐标时延为:

$$\Delta_G = \frac{[1+\gamma_{PPN}]\mu_P}{c^3} \ln\left(\frac{r_s + r_2(t_2) + r_{s2}}{r_s + r_2(t_2) - r_{s2}} \cdot \frac{r_s + r_1(t_1) + r_{s1}}{r_s + r_1(t_1) - r_{s1}}\right) \tag{10}$$

对于遥远射电源的地基 VLBI 观测，$r_i/r_s \to 0, |\boldsymbol{r}_2 - \boldsymbol{r}_1|/r_1 \to 0$，(10) 式可简化为:

$$\Delta_{G_p} = \frac{[1+\gamma_{PPN}]\mu_P}{c^3} \ln\left(\frac{r_1 + \boldsymbol{r}_1 \cdot \hat{\boldsymbol{r}}_s}{r_2 + \boldsymbol{r}_2 \cdot \hat{\boldsymbol{r}}_s}\right) \tag{11}$$

转换到太阳系质心坐标系的引力本征时延为:

$$\Delta'_{G_p} = \Delta_{G_p} - [1+\gamma_{PPN}]U\tau \tag{12}$$

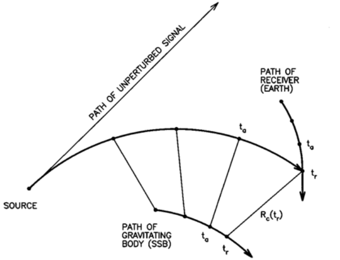


FIG. 7. Schematic representation of the motion of a gravitating object (Sun) during the transit time of a signal from the point of closest approach to reception by an antenna on Earth. Both move between the time t_a at closest approach $R(t_a)$ and the time t_r at reception. This motion needs to be taken into account for the highest accuracy.

图 14: 引力偏折示意图 [2]

引力时延为（考虑太阳系内的主要天体）

$$\tau_{\mathrm{gra}} = \sum_p \Delta'_{G_p} \tag{13}$$

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几何时延模型（3）— 测站坐标（Station location）

测站坐标一般在国际地固参考架中表示，记为 $\boldsymbol{r}_0$。以当前空间大地测量的精度水平可以测定各种类型的地壳运动，因此应尽可能对各种地壳运动建模。

地壳运动（Crustal motion）

- 板块运动（Tectonic plate motion） $\lesssim 10\,\mathrm{cm/yr}$
- 潮汐效应（Tidal station motion）
  - 地球固体潮（Solid Earth tides，主要影响）$\Delta_{\mathrm{sol}} \lesssim 50\,\mathrm{cm}$
  - 极潮（Pole tide，次级影响）$\Delta_{\mathrm{pol}} \lesssim 1-2\,\mathrm{cm}$
  - 海洋负荷潮（Ocean loading，次级影响）$\Delta_{\mathrm{ocn}} \lesssim 1-2\,\mathrm{mm}$
- 非潮汐效应（Nontidal station motion）
  - 大气负荷（Atmosphere loading）$\Delta_{\mathrm{atm}} \simeq \mathrm{mm}$
  - 冰期后反弹（Postglacial relaxation） $\simeq \mathrm{mm}$

总的改正可以记为

$$\boldsymbol{r}_t = \boldsymbol{r}_0 + \dot{\boldsymbol{r}}_t[t - t_0] + \Delta_{\mathrm{sol}} + \Delta_{\mathrm{pol}} + \Delta_{\mathrm{ocn}} + \Delta_{\mathrm{atm}} \tag{14}$$

几何时延模型（4）— 地球定向（Earth orientation）

从地固参考系（ITRS）到地心天球参考系（GCRS）的转换矩阵（IAU 2006 岁差/2000 章动模型）[7]

$$[GCRS] = Q(t)R(t)W(t)[ITRS] \tag{15}$$

其中，$Q(t)$，$R(t)$ 和 $W(t)$ 分别表示岁差–章动（Precession-Nutation）、地球自转（Earth rotation）和极移（Polar motion）。那么，地心天球参考系中的测站位置矢量为

$$\boldsymbol{r}_c = Q(t)R(t)W(t)\boldsymbol{r}_t \tag{16}$$

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洛伦兹变换（Lorentz transformation）

记地心相对于太阳系质心（SSB）的速度为 βc。ICRS 中的事件记为 $[\boldsymbol{r}(t), t]$，与之相对应的 GCRS 的事件记为 $[\boldsymbol{r}'(t'), t']$。两者之间的转换关系为

[ICRS] $\to$ [GCRS]，即 $[\boldsymbol{r}(t), t] \to [\boldsymbol{r}'(t'), t']$

$$\boldsymbol{r}'(t') = \boldsymbol{r}(t) + [\gamma - 1][\boldsymbol{r}(t) \cdot \boldsymbol{\beta}]\boldsymbol{\beta}/\beta^2 - \gamma \boldsymbol{\beta} t \tag{17}$$

$$t' = \gamma[t - \boldsymbol{r}(t) \cdot \boldsymbol{\beta}] \tag{18}$$

[GCRS] $\to$ [ICRS]，即 $[\boldsymbol{r}'(t'), t'] \to [\boldsymbol{r}(t), t]$

$$\boldsymbol{r}(t) = \boldsymbol{r}'(t') + [\gamma - 1][\boldsymbol{r}'(t') \cdot \boldsymbol{\beta}]\boldsymbol{\beta}/\beta^2 + \gamma \boldsymbol{\beta} t' \tag{19}$$

$$t = \gamma[t' + \boldsymbol{r}'(t') \cdot \boldsymbol{\beta}] \tag{20}$$

其中

$$\gamma = \left[1 - \boldsymbol{\beta}^2\right]^{-1/2} \tag{21}$$

在 ICRS 中观测到的几何时延为 $\tau = t_2 - t_1$，转换到 GCRS 中为

$$t'_2 - t'_1 = \gamma\left[t_2 - t_1\right] - \gamma\left[\boldsymbol{r}_2\left(t_2\right) - \boldsymbol{r}_1\left(t_1\right)\right]\cdot\boldsymbol{\beta} \tag{22}$$

假设在信号到达测站 #1 和到达测站 #2 这段时间内，测站 #2 在 ICRS 做线性运动且速度为 $\boldsymbol{\beta}_2$，则

$$t'_2 - t'_1 = \gamma\left[1 - \boldsymbol{\beta}_2\cdot\boldsymbol{\beta}\right]\left[t_2 - t_1\right] - \gamma\left[\boldsymbol{r}_2\left(t_1\right) - \boldsymbol{r}_1\left(t_1\right)\right]\cdot\boldsymbol{\beta} \tag{23}$$

考虑在 t'_1 时刻，GCRS 中同时发生的两个事件 $\left[\boldsymbol{r}_1{}'\left(t'_1\right), t'_1\right]$ 和 $\left[\boldsymbol{r}_2{}'\left(t'_1\right), t'_1\right]$，有

$$\boldsymbol{r}_2\left(t_2^*\right) = \boldsymbol{r}'_2\left(t'_1\right) + \left[\gamma - 1\right]\left[\boldsymbol{r}'_2\left(t'_1\right)\cdot\boldsymbol{\beta}\right]\boldsymbol{\beta}/\beta^2 + \gamma\boldsymbol{\beta}t'_1 \tag{24}$$

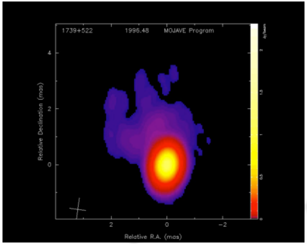
$$t_2^* - t_1 = \gamma\left[\boldsymbol{r}'_2\left(t'_1\right) - \boldsymbol{r}'_1\left(t'_1\right)\right]\cdot\boldsymbol{\beta} \tag{25}$$

$$\boldsymbol{r}_2\left(t_1\right) = \boldsymbol{r}_2\left(t_2^*\right) - \boldsymbol{\beta}_2\left(t_2^* - t_1\right) \tag{26}$$

最终

$$\begin{aligned}\boldsymbol{r}_2\left(t_1\right) - \boldsymbol{r}_1\left(t_1\right) =& \boldsymbol{r}'_2\left(t'_1\right) - \boldsymbol{r}'_1\left(t'_1\right) + \left[\gamma - 1\right]\left\{\left[\boldsymbol{r}'_2\left(t'_1\right) - \boldsymbol{r}'_1\left(t'_1\right)\right]\cdot\boldsymbol{\beta}\right\}\boldsymbol{\beta}/\beta^2 \\ & - \gamma\boldsymbol{\beta}_2\left[\boldsymbol{r}'_2\left(t'_1\right) - \boldsymbol{r}'_1\left(t'_1\right)\right]\cdot\boldsymbol{\beta}\end{aligned} \tag{27}$$

射电源结构及其变化（Source Structure），以 1739+522 为例



射电源 1739+522 的结构变化（来源：MOJAVE 项目）

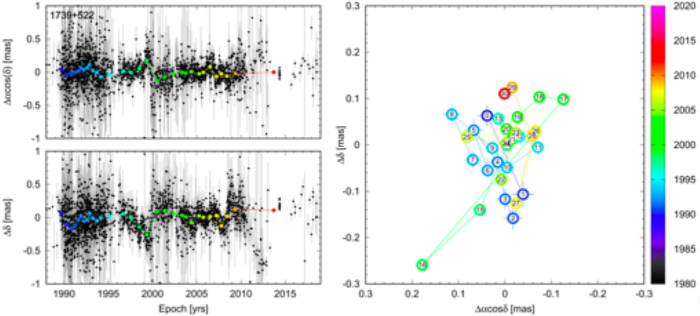


图 15: 射电源 1739+522 的位置变化 [8]

河外源在 S/X 波段上普遍表现为毫角秒尺度的结构，而这些结构会经常发生变化，从而使河外源的位置表现出随时间的漂移。

射电源结构及其变化（Source Structure），以 4C39.25 为例

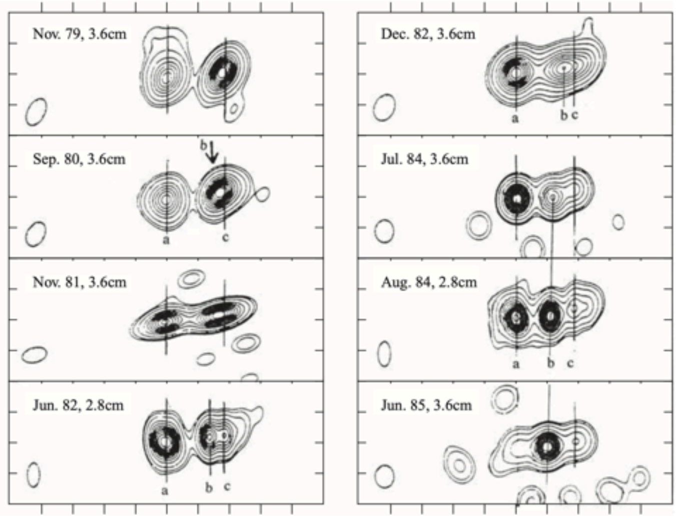


Fig. 7.2. Variation in the observed structure of the radio source 4C39.25. A new component (b) seems to have been ejected in 1980 (arrow) from the component (c) and to move towards the component (a) with a velocity of 0.16 ± 0.02 mas/year. The scale is 0.5 mas per interval of graduation (Shaffer and Marscher, 1987).

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图 16: 射电源 4C39.25 的结构变化 [9]

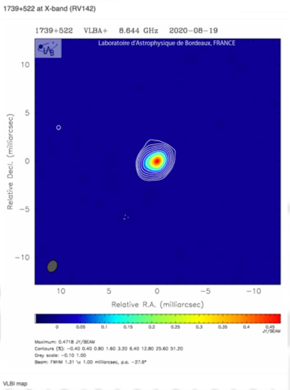

图 17: 射电源 1739+522 的图像（来源：BVID）

对射电图像建模（Dirac Delta/Gaussian functions）

$$I(\mathbf{s}) = \sum_k S_k \delta\left(x - x_k, y - y_k\right) \tag{28}$$

$$I(\mathbf{s}) = \sum_k \frac{S_k}{2\pi a_k b_k} \exp\left(-\{[x - x_k]\cos\theta_k + [y - y_k]\sin\theta_k\}^2/2a_k^2 \right.$$
$$\left. -\{[x - x_k]\sin\theta_k - [y - y_k]\cos\theta_k\}^2/2b_k^2\right) \tag{29}$$

计算因源结构产生的相位偏差（相对于点源）

$$Z_{\{^s_c\}} = \iint d\Omega I(\mathbf{s}, \omega, t) \left\{ \begin{array}{c} \sin \\ \cos \end{array} \right\} (2\pi \mathbf{B}\cdot\mathbf{s}/\lambda) \tag{30}$$

$$\phi_s = \arctan\left(-Z_s/Z_c\right) \tag{31}$$

结构群时延 $\tau_{\rm str}$ 为

$$\tau_{\rm str} = \partial\phi_s/\partial\omega \tag{32}$$

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图 18: 上海天文台天马 65 米望远镜

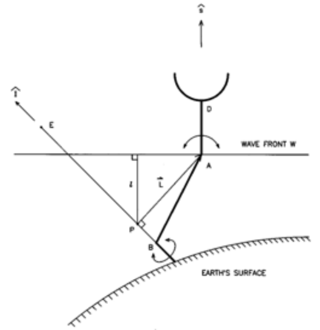


图 19: 天线结构示意图 [2]

当天线的两驱动轴不相交时，轴线偏差引起的附加几何时延为

$$\tau_{\mathrm{ax}} = l/c \tag{33}$$

$$\tau_{\mathrm{ant}} = \tau_{\mathrm{ax}_1} - \tau_{\mathrm{ax}_2} = (l_1 - l_2)/c \tag{34}$$

$$\boldsymbol{L} = \pm L \frac{\hat{\boldsymbol{I}} \times (\hat{\mathbf{s}} \times \hat{\boldsymbol{I}})}{|\hat{\boldsymbol{I}} \times (\hat{\mathbf{s}} \times \hat{\boldsymbol{I}})|}, l = \hat{\mathbf{s}} \cdot \boldsymbol{L} = \pm L \sqrt{1 - (\hat{\mathbf{s}} \cdot \hat{\boldsymbol{I}})^2} \tag{35}$$

$$\hat{\boldsymbol{I}} = \begin{pmatrix} \cos\phi\cos\lambda \\ \cos\phi\sin\lambda \\ \sin\phi \end{pmatrix} \tag{36}$$

VLBI 的钟（clock）误差

- 每个测站有独立的频率基准（“钟”），不同测站的钟一般通过 GPS 对钟的方式来实现同步，精度为 $\simeq 1\,\mu s$（时刻）和 $\simeq 10^{-13}$（速率）
- 钟经常会有跳跃和不稳定性，会降低干涉测量的精度
- 其他与仪器有关的可能对观测时延有贡献的因素，在形式上与钟误差类似，因此可以被钟模型吸收

为了改正这些钟误差，在观测时间段内一般将钟的行为近似为时间的分段二次函数（钟模型）

$$\tau_{\rm clo} = \tau_{{\rm clo}_1} + \tau_{{\rm clo}_2}\left[t - t_0\right] + \tau_{{\rm clo}_3}\left[t - t_0\right]^2/2 \tag{37}$$

测站的钟误差（及类似形式的其他仪器误差）对观测时延的贡献为

$$\Delta\tau_{\rm clo} = \tau_{\rm clo}(2) - \tau_{\rm clo}(1) \tag{38}$$

大气时延（Atmospheric delay）

定义 射电信号在地球的电离层和对流层行进时，这些介质中的成分会改变光的行进速度，从而产生了一个相对于真空介质的时延。

思考

大气折射对 VLBI 和地面照相测量观测的影响是否相同？

电离层（Ionosphere）时延

单频（如 K 波段）

$$\tau_{\mathrm{I}} = qS(E)/\nu^2,\ q = \frac{cr_0}{2\pi}\int \rho dl = \frac{cr_0 I_e}{2\pi} \tag{39}$$

双频（如 S/X 波段）

$$\tau = a\tau_{\nu 2} + b\tau_{\nu 1} \tag{40}$$

$$a = \nu_2^2/\left(\nu_2^2 - \nu_1^2\right),\ b = -\nu_1^2/\left(\nu_2^2 - \nu_1^2\right) \tag{41}$$

对流层（Troposphere）时延

对于俯仰角为 E 的观测

$$\tau_{\mathrm{T}} = \mathcal{M}_{\mathrm{d}}(E)Z_{\mathrm{d}} + \mathcal{M}_{\mathrm{w}}(E)Z_{\mathrm{w}} \tag{42}$$

$\mathcal{M}_{\mathrm{d,w}}$ 称为大气映射函数 (Mapping Function)，其中一种经验模型形式为

$$\mathcal{M} = \frac{1}{\sin E + \frac{a}{\sin E + \frac{b}{\sin E + c}}} \tag{43}$$

电离层时延模型中的信号传播路径

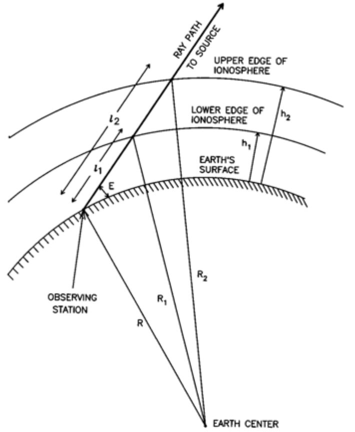


FIG. 11. Geometry of the spherical ionospheric shell used for ionospheric corrections. The slant range through the shell is $l_2 - l_1$ at elevation angle E.

图 20: 信号在大气中传播路径示意图 [2]

假设球对称大气和电离层模型，即

$$R_i = R + h_i \tag{44}$$

信号到达测站 #1 和 #2 的几何路径改正因子为

$$S(E) = \left(\sqrt{R^2 \sin^2 E + 2Rh_2 + h_2^2} - \sqrt{R^2 \sin^2 E + 2Rh_1 + h_1^2} \right) / (h_2 - h_1) \tag{45}$$

VLBI 时延成分占比

TABLE I. Maximum magnitudes and present uncertainties of portions of the VLBI delay model (mm).

Model component	Maximum delay	Present model uncertainty
BASELINE GEOMETRY		
Zero-order geometric delay	6×10^9	...
Earth orbital motion	6×10^5	1
Gravitational delay	2×10^3	2
STATION POSITIONS		
Tectonic motion	100	1
Tidal motion	500	3
Nontidal motion	50	5
EARTH ORIENTATION		
UTPM	2×10^4	2
Nutation/precession	3×10^5	3
SOURCE STRUCTURE	50	10
ANTENNA STRUCTURE	10^4	10
INSTRUMENTATION	3×10^5	5
ATMOSPHERE		
Ionosphere	10^3	1
Troposphere	2×10^4	20

图 21: VLBI 时延模型中各成分所占比例 [2]

总结如下：

1. 几何时延的零阶项占观测时延值的最主要部分
2. 目前理论时延模型的主要误差来源有：对流层大气时延、河外源结构时延、天线结构引起的时延、仪器时延和测站的非潮汐运动
3. 射电信号干扰（RFI）也是影响低频 VLBI 观测的主要因素

目前常规 VLBI 群时延观测量的噪声水平（WRMS）为 20-30 ps

下一代全球 VLBI 观测系统（VGOS, VLBI global observing system）致力于实现地表 1 mm 水平的定位精度和 1 mm/yr 的速度精度，河外源结构效应已成为主要的误差源。

理论时延的计算

计算理论时延的复杂性主要体现在多种坐标与时间系统之间的转换和测站坐标精修正。一般遵循如下的计算方式 [2]

1. 在信号到达测站 1 的时刻，确定两测站在地固参考架中的本征坐标。
2. 对测站坐标进行板块运动、潮汐效应等各项改正。
3. 将测站坐标转换至地心天球参考架。
4. 进行 Lorentz 变换，将测站本征坐标从地心天球参考架转换至太阳系质心天球参考架。
5. 在太阳系质心天球参考架中计算信号从测站 1 传播至测站 2 的本征时延，并进行源结构和引力时延改正。
6. 经 Lorentz 变换将时延转换至地心天球参考架，由此得到理论时延的几何时延
7. 对该几何时延进行中性大气、电离层时延改正和钟差改正，最终得到理论时延。

记录波前信号的时间戳为协调世界时 (Coordinated Universal Time, UTC)

↓

相关机给出的时延以地球时（Terrestrial Time, TT）来计量d_{TT}：
$TT = (TT - TAI) + (TAI - UTC) + UTC$

↓

转换为地心坐标时（Geocentric Coordinate Time, TCG）来计量：
$d_{TCG} = d_{TT}/(1 - L_G), L_G = 6.969290134 \times 10^{-10}$

↑

质心坐标系计算的几何时延对应于质心坐标时（Barycentric Coordinate Time, TCB）$d_{TCG} = d_{TCB} \times (1 + L_C), L_C = 1.48082686741 \times 10^{-8}$

在赤道坐标系下，河外源的位置矢量 $\hat{s}$ 和基线矢量 $\boldsymbol{r}_\mathrm{b}$ 分别为

$$\hat{s} = \begin{pmatrix} x_\mathrm{s} \\ y_\mathrm{s} \\ z_\mathrm{s} \end{pmatrix} = \begin{pmatrix} \cos\delta_\mathrm{s}\cos\alpha_\mathrm{s} \\ \cos\delta_\mathrm{s}\sin\alpha_\mathrm{s} \\ \sin\delta_\mathrm{s} \end{pmatrix}, \boldsymbol{r}_\mathrm{b}(t) = \begin{pmatrix} x_\mathrm{b} \\ y_\mathrm{b} \\ z_\mathrm{b} \end{pmatrix} = d\begin{pmatrix} \cos\delta_\mathrm{b}\cos\alpha_\mathrm{b} \\ \cos\delta_\mathrm{b}\sin\alpha_\mathrm{b} \\ \sin\delta_\mathrm{b} \end{pmatrix}, \omega_\mathrm{e} = \frac{\mathrm{d}\alpha_\mathrm{b}}{\mathrm{d}t} \tag{46}$$

则条纹相位和群时延为

$$\begin{aligned} \phi_\mathrm{g} &= \frac{\omega}{c}\boldsymbol{b}\cdot\boldsymbol{s} + 2\pi k = \frac{\omega d}{c}\left[\sin\delta_\mathrm{s}\sin\delta_\mathrm{b} + \cos\delta_\mathrm{s}\cos\delta_\mathrm{b}\cos\left(\alpha_\mathrm{b}-\alpha_\mathrm{s}\right)\right] + 2\pi k \\ \tau_\mathrm{g} &= \frac{\partial\phi_\mathrm{g}}{\partial\omega} = \frac{d}{c}\left[\sin\delta_\mathrm{s}\sin\delta_\mathrm{b} + \cos\delta_\mathrm{s}\cos\delta_\mathrm{b}\cos\left(\alpha_\mathrm{b}-\alpha_\mathrm{s}\right)\right] \end{aligned} \tag{47}$$

从而

$$\begin{aligned} \frac{\partial\tau_\mathrm{g}}{\partial\alpha_\mathrm{s}} &= \frac{d}{c}\cos\delta_\mathrm{s}\cos\delta_\mathrm{b}\sin\left(\alpha_\mathrm{b}-\alpha_\mathrm{s}\right) \\ \frac{\partial\tau_\mathrm{g}}{\partial\delta_\mathrm{s}} &= \frac{d}{c}\left[\cos\delta_\mathrm{s}\sin\delta_\mathrm{b} - \sin\delta_\mathrm{s}\cos\delta_\mathrm{b}\cos\left(\alpha_\mathrm{b}-\alpha_\mathrm{s}\right)\right] \end{aligned} \tag{48}$$

VLBI 观测量对 α_s 和 δ_s 变化的敏感程度

$$\sigma_{\alpha_\mathrm{s}}\cos\delta_\mathrm{s} = \left|\frac{c\sigma_{\tau_\mathrm{g}}}{d\cos\delta_\mathrm{b}\sin\left(\alpha_\mathrm{b}-\alpha_\mathrm{s}\right)}\right|, \sigma_{\delta_\mathrm{s}} = \left|\frac{c\sigma_{\tau_\mathrm{g}}}{d\left[\cos\delta_\mathrm{s}\sin\delta_\mathrm{b} - \sin\delta_\mathrm{s}\cos\delta_\mathrm{b}\cos\left(\alpha_\mathrm{b}-\alpha_\mathrm{s}\right)\right]}\right| \tag{49}$$

对于 $d = 5000\,\mathrm{km}$ 的基线，在 X 波段（$\lambda = 3.6\,\mathrm{cm}$）上观测，相关处理机的精度一般为 10 % 波长，从而群时延的测量精度为 $\sigma_{\tau_\mathrm{g}} = 0.01\,\mathrm{ns}$

图 22: 东西基线 ($\delta_\mathrm{b} = 0°$) 的定位灵敏度

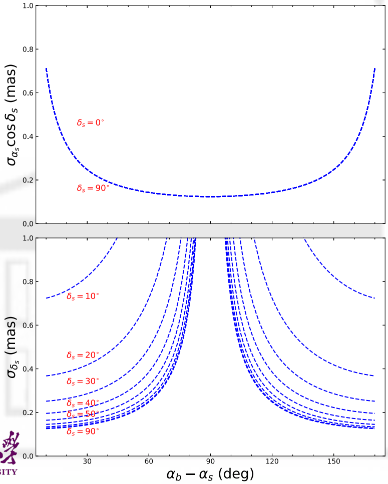
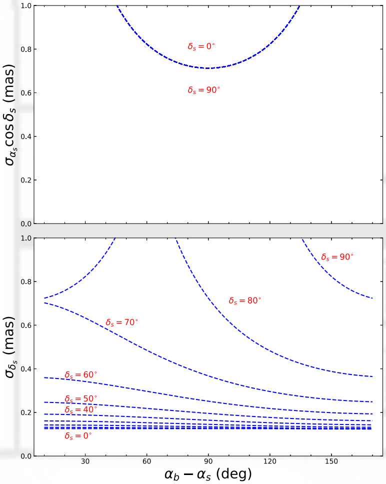


图 23: 南北基线 ($\delta_\mathrm{b} = 80°$) 的定位灵敏度



ICRF 的建立和发展

坐标系（Coordinate system）

定义 坐标系是用于描述物体的位置、运动和姿态的一种数学工具 [10]。

说明 对于欧氏空间，一个坐标系的定义包括坐标原点（origin）的位置、参考平面（reference plane）和零点（zero point）。

参考系（Reference system）

定义 具备“可实现性”的（准）惯性坐标系。

可实现性 参考系的原点、基本面和零点必须具备“可观测性”（determinability），且必须是不依赖于任何已知参考框架的“绝对可观测性”。例如，在没有任何已知数据的条件下，要能测量出一个天体（或一个测站）在该参考系中的坐标。

参考架（Reference frame）

定义 由标定了位置的一组基准点（fiducial point）组成的框架，如星表、历表。

说明 基准点（参考天体）的位置是根据参考系的定义对实测数据进行处理得到的。一个参考系可以由多种不同（如观测波段、仪器等）的参考架来实现。

以 VLBI 群时延的简化模型为例，不考虑任何误差

$$\tau = \frac{d}{c}\boldsymbol{r}_{\mathrm{b}} \cdot \boldsymbol{s} = \frac{d}{c}\left[\sin\delta_{\mathrm{s}}\sin\delta_{\mathrm{b}} + \cos\delta_{\mathrm{s}}\cos\delta_{\mathrm{b}}\cos\left(\alpha_{\mathrm{b}} - \alpha_{\mathrm{s}}\right)\right] \tag{50}$$

可以简写为常数项 + 周期项的形式：

$$\tau = B + A\cos(\omega_{\mathrm{e}}t + \phi) \tag{51}$$

其中

$$\begin{aligned} B &= \tfrac{d}{c}\sin\delta_{\mathrm{s}}\sin\delta_{\mathrm{b}}, \quad & A &= \tfrac{d}{c}\cos\delta_{\mathrm{s}}\cos\delta_{\mathrm{b}} \\ \omega_{\mathrm{e}}t + \phi &= \alpha_{\mathrm{b}}(t) - \alpha_{\mathrm{s}}, \quad & \phi &= \alpha_{\mathrm{b}}(t=0) - \alpha_{\mathrm{s}} \end{aligned} \tag{52}$$

一次 VLBI 观测 $\Longleftrightarrow$ 一个观测量 $\tau_i \Longrightarrow$ 三个未知量 (A_i, B_i, ϕ_i) ✗

三次 VLBI 观测 $\Longleftrightarrow$ 三个观测量 $\tau_i \Longrightarrow$ 三个未知量 (A_i, B_i, ϕ_i) ✓

通过单基线对同一颗源的多次观测，可以得到三个导出观测量 A_i, B_i, ϕ_i

但是，$(A_i, B_i, \phi_i) \Longrightarrow (\alpha_{\mathrm{s}}, \delta_{\mathrm{s}}, d, \alpha_{\mathrm{b}}(t=0)), \delta_{\mathrm{b}})$ ✗

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单基线观测多颗河外源：

河外源数目	所需观测数目	导出量数目	未知参数数目
1	3	3	5
	$A_1, B_1 \Longrightarrow$	δ_{s1}, d, δ_b ✗	
	$\phi_1 \Longrightarrow$	α_{s1}, α_b ✗	
2	6	6	7
	$A_1, B_1, A_2, B_2 \Longrightarrow$	$\delta_{s1}, \delta_{s2}, d, \delta_b$ ✓	
	$\phi_1, \phi_2 \Longrightarrow$	$\alpha_{s1}, \alpha_{s2}, \alpha_b$ ✗	
3	9	9	9
	$A_1, B_1, A_2, B_2, A_3, B_3 \Longrightarrow$	$\delta_{s1}, \delta_{s2}, \delta_{s3}, d, \delta_b$ ✓	
	$\phi_1, \phi_2, \phi_3 \Longrightarrow$	$\alpha_{s1}, \alpha_{s2}, \alpha_{s3}, \alpha_b$ ✗	
...	...	...	...

以上的分析可得河外源和基线的赤纬（δ_{si} 和 δ_b）、基线长度（d），以及河外源与基线、河外源与河外源之间的赤经差异 ($\alpha_s - \alpha_b$ 和 $\alpha_{si} - \alpha_{sj}$)，因此需要一个额外的参考信息：赤经零点。

确定河外源参考架的赤经零点

- 利用河外源的光学位置
  - 将 3C273B（1226+023）在 J2000 时刻的赤经值设为 $12^{\mathrm{h}}39^{\mathrm{m}}06^{\mathrm{s}}.6997$ [11]
  - 对于一组河外源 (ICRF1 选择了 23 颗), 通过取平均或者最优化方法

$$\frac{1}{N}\sum_i\left(\alpha^i_{\mathrm{radio}}-\alpha^i_{\mathrm{opt}}\right)=0$$
$$D(\Delta\alpha)=\frac{1}{N}\sum_i\left[\left(\alpha^i+\Delta\alpha\right)_{\mathrm{radio}}-\alpha^i_{\mathrm{opt}}\right]^2=\min \tag{53}$$

- 利用测站的 VLBI 和 LLR 位置
- 仅用射电资料
  - 对河外源和太阳系内行星、小行星或探测器的联合 VLA 观测
  - 对探测器和河外源的差分 VLBI 观测
- 利用脉冲星的 VLBI 位置 $\boldsymbol{r}_{\mathrm{VLBI}}$ 和计时位置 $\boldsymbol{r}_{\mathrm{PAT}}$

$$\boldsymbol{r}_{\mathrm{PAT}}(\lambda,\beta)=\mathrm{R}_x(\varepsilon+\Delta\varepsilon)\mathrm{R}_z(\Delta\alpha)\boldsymbol{r}_{\mathrm{VLBI}}(\alpha,\delta) \tag{54}$$

Accurate Radio and Optical Positions of 3C273B

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Royal Greenwich Observatory, Herstmonceux Castle, Sussex

New measurements have confirmed that 3C273B and the associated quasi-stellar object are coincident.

THE small angular size component (3C273B) of the radio source 3C273 is generally considered to coincide with the associated quasi-stellar object (QSO), and the most accurate published optical and radio positions[1] are consistent with this interpretation. Nevertheless, they do differ by 0.7 arc s, a discrepancy which is just outside the combined estimated errors, and the possibility of a small but significant displacement between the QSO and 3C273B cannot be excluded. In an attempt to reduce this uncertainty we have therefore carried out a new measurement of the position of 3C273B based on occultation observations using the CSIRO 210-foot telescope at Parkes, Australia, and the 1,000-foot telescope at Arecibo, Puerto Rico. We had not previously carried out this analysis because it was not possible to realize the full positional accuracy of which these high signal/noise observations were capable because of uncertainties in the Improved Lunar Ephemeris and in the difference (ΔT) between Ephemeris (ET) and Universal Time (UT). Recently, corrections to the Improved Lunar Ephemeris[2] have been proposed and, with accurate values for ΔT over the period 1963 to 1966 also now available, it seemed possible to reduce the error in the radio position to $\leq$0.2 arc s. As it turned out, our new position measurement only increased the discrepancy between the optical and radio positions. On examining the optical position, however, we found that the usually quoted value was based on observations made by Jefferys[1] for the purpose of proper motion studies and that no accurate optical position had been measured. We therefore carried out new position measurements of the QSO both at the Cambridge Observatories and at the Royal Greenwich Observatory (RGO) to permit an accurate comparison with the new radio position.

Radio Position

The method of observation and an account of the structural information obtained from an analysis of all the occultation curves have been given elsewhere[3,4]. For the present investigation we selected only those occultation curves for which the signal/noise ratio and the separation of the A and B components permitted a timing accuracy of better than 1 s, corresponding to an error in the location of the Moon's mean limb of $\leq$0.3 arc s. The relevant data relating to these selected curves are listed in Table 1 together with the estimated times of occultation, all of which have been corrected for delays introduced by the output time constants of the receiving equipment. In the case of the grazing occultation the quoted occultation time corresponds to the time of closest approach. For the other occultations the occultation times were determined using the restoration technique described by Scheuer[5], which gives the brightness distribution across the source as seen by a fan beam of arbitrary width. The widths of the restoring beams used ranged from a minimum of 0.18 arc s for the occultation of June 7, 1965, to a maximum of 3.5 arc s for the occultation of September 7, 1964, where the occultation occurred during the day and close to the Sun, and the observa-

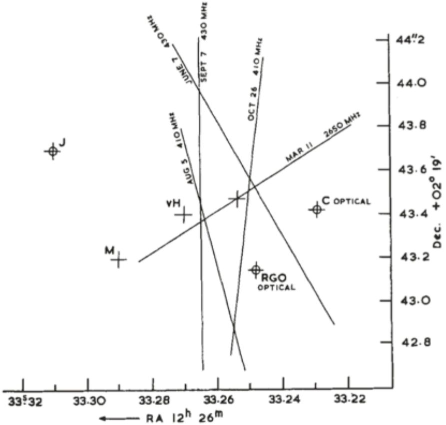

Fig. 1 Corrected lunar limb positions (1950.0) defining lines along which the source 3C273B must lie. (The position for September 7 has been discarded in deriving the final radio position.) The separate optical determinations are denoted by C and RGO (from Table 3). M and vH, The radio positions of Moffer and von Hoerner; J, The optical position given by von Hoerner[1] based on data by Jefferys.

图 24: 测量 3C273B 的光学（照相底片）和射电（计时）位置 [11]

如何定义一个（准）惯性参考系？

1. 动力学定义（Dynamical definition）

定义 如果在一个参考架中，一个物体不受科里奥利力（Coriolis force）和离心力（centrifugal force）的作用，其运动遵循牛顿第一和第二定律，则称这样的参考架是惯性的。

2. 运动学定义（kinematic/static definition）

定义 惯性的参考架相对于宇宙的其他部分是没有整体旋转的。

以河外源为参考源建立天球参考系的理论基础有两点

1. 在当前的观测精度下，宇宙整体没有旋转

THE ROTATION AND DISTORTION OF THE UNIVERSE

C. B. Collins and S. W. Hawking

(Communicated by D. W. Sciama)

(Received 1973 January 30)

SUMMARY

The isotropy of the microwave background is used to place upper limits on the large-scale anisotropies of the Universe. This is done by considering the behaviour of the microwave background in all types of spatially homogeneous models that could reasonably represent our Universe. If the Universe is closed, we find that it is rotating at a rate of less than 3×10^{-11} second of arc/century if the microwave background was last scattered at a redshift of about 7 and less than 2×10^{-14} second of arc/century if the last scattering was at a redshift of 1000. We also calculate how far back in time the Universe must have been nearly isotropic. In the case of one extreme hyperbolic model, it seems that it could have been highly anisotropic at a redshift greater than about 4. The significance of these results for galaxy formation is briefly discussed.

图 25: 根据 Collins 和 Hawking 的计算 [12], 宇宙的整体旋转小于 $10^{-9}\,\mathrm{mas\,yr^{-1}}$

2. 在当前的观测精度下，河外源没有真实的自行（proper motion）

假设河外源与我们的距离 $D = 100\,\mathrm{Mpc}$

取哈勃常数 $H_0 = 75\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$

则其径向速度为 $V_\mathrm{r} = H_0 \cdot D = 7.5 \times 10^3\,\mathrm{km\,s^{-1}}$

假设其横向速度与径向速度相当：$V_\mathrm{t} \simeq V_\mathrm{r}$

$$V_\mathrm{t} = 7.5 \times 10^3 \left(\frac{1.5 \times 10^8\,\mathrm{km}}{1\,\mathrm{AU}}\right)\left(\frac{365.25 \times 86400\,\mathrm{s}}{1\,\mathrm{yr}}\right)\mathrm{AU\,yr^{-1}}$$
$$= 1.6 \times 10^2\,\mathrm{AU\,yr^{-1}} \tag{55}$$

自行为

$$\mu = \frac{V_\mathrm{t}}{D} = \frac{1.6 \times 10^2}{10^8}\left(\frac{\mathrm{AU}}{\mathrm{pc}}\right)\mathrm{yr^{-1}} \lesssim 10^{-2}\,\mathrm{mas\,yr^{-1}} \tag{56}$$

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选择参考架的定义源

- 目的：挑选出位置稳定的河外源来作为天球上的基准点
- 筛选条件
  - 观测次数多（如 >20）且覆盖的历元跨度长（如 > 2 yr）
  - 位置随时间的变化小
    - 经验方法，如检查河外源天球坐标在较短时间内的变化，或在所有观测历元内估计天球坐标的时间变化率
    - 借助成图资料分析其源结构延展程度
  - 天球分布的均匀性

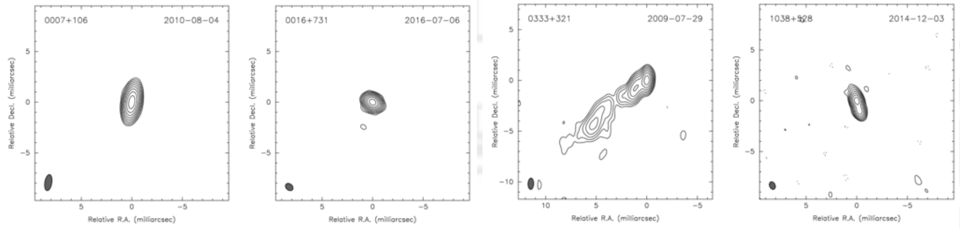
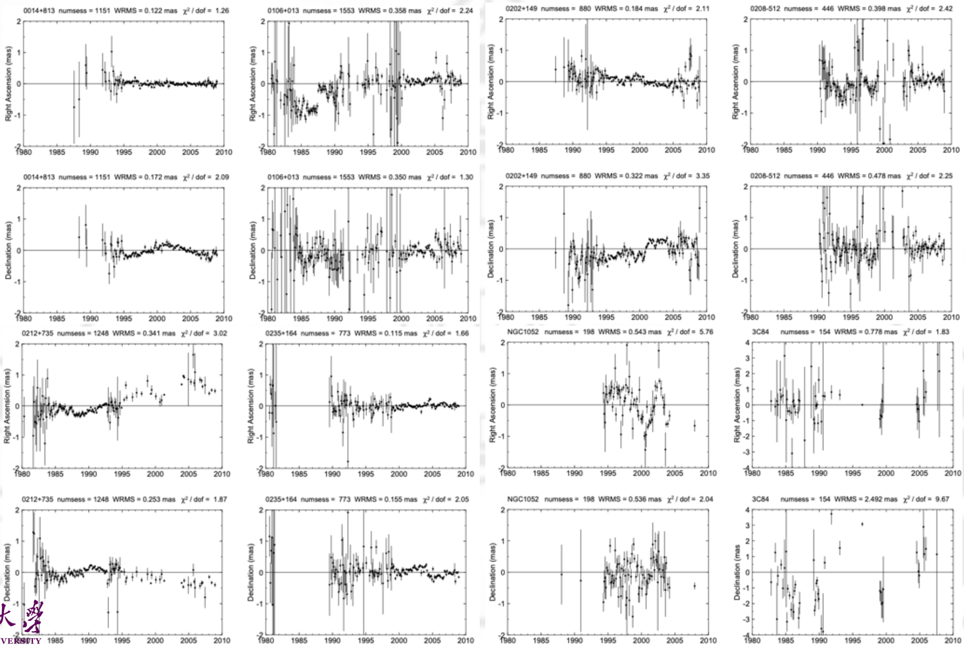


图 26: 致密源（左）与延展源（右）[4]

不稳定河外源的位置时间序列 [13]



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1991 年 IAU 大会关于参考系 (架) 的 A4 决议 (1)

Resolution No. A 4

Recommendations from the Working Group on Reference Systems

Recommandation du Groupe de Travail sur les Systèmes de référence

Recommendations I to IX

The XXIst General Assembly of the International Astronomical Union,

RECOMMENDATION I

considering,

that it is appropriate to define several systems of space-time coordinates within the framework of the General Theory of Relativity,

recommends,

that the four space-time coordinates ($x^0 = ct$, x^1, x^2, x^3) be selected in such a way that in each coordinate system centred at the barycentre of any ensemble of masses, the squared interval ds^2 be expressed with the minimum degree of approximation in the form:

$$ds^2 = -c^2 d\tau^2$$

$$= -\left(1 - \frac{2U}{c^2}\right)(dx^0)^2 + \left(1 + \frac{2U}{c^2}\right)\left[(dx^1)^2 + (dx^2)^2 + (dx^3)^2\right],$$

where c is the velocity of light, τ is proper time, and U is the sum of the gravitational potentials of the above mentioned ensemble of masses, and of a tidal potential generated by bodies external to the ensemble, the latter potential vanishing at the barycentre.

RECOMMENDATION II

considering,

a) the need to define a barycentric coordinate system with spatial origin at the centre of mass of the solar system and a geocentric coordinate system with spatial origin at the centre of mass of the Earth, and the desirability of defining analogous coordinate systems for other planets and for the Moon,

b) that the coordinate systems should be related to the best realization of reference systems in space and time, and,

c) that the same physical units should be used in all coordinate systems,

recommends that,

1. the space coordinate grids with origins at the solar system barycentre and at the centre of mass of the Earth show no global rotation with respect to a set of distant extragalactic objects,
2. the time coordinates be derived from a time scale realized by atomic clocks operating on the Earth,
3. the basic physical units of space-time in all coordinate systems be the second of the International System of Units (SI) for proper time, and the SI meter for proper length, connected to the SI second by the value of the velocity of light $c = 299792458\ \mathrm{ms}^{-1}$.

RECOMMENDATION III

considering,

the desirability of the standardisation of the units and origins of coordinate times used in astronomy,

recommends that,

1. the units of measurement of the coordinate times of all coordinate systems centred at the barycentres of ensembles of masses be chosen so that they are consistent with the proper unit of time, the SI second,
2. the reading of these coordinate times be 1977 January 1, $0^h\ 0^m\ 32.184^s$ exactly, on 1977 January 1, $0^h\ 0^m\ 0^s$ TAI exactly (JD = 2443144.5, TAI), at the geocentre,
3. coordinate times in coordinate systems having their spatial origins respectively at the centre of mass of the Earth and at the solar system barycentre, and established in conformity with the above sections (1) and (2), be designated as Geocentric Coordinate Time (TCG) and Barycentric Coordinate Time (TCB).

定义广义相对论框架下的
空时坐标系统

太阳系质心和地球质心
作为参考系统的原点,
相对于一组河外源无全局旋转

坐标时的单位和原点要统一
引入 TCB 和 TCG

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决议全文见 https://www.iau.org/static/resolutions/IAU1991_French.pdf

1991 年 IAU 大会关于参考系 (架) 的 A4 决议 (2)

RECOMMENDATION IV

considering,

a) that the time scales used for dating events observed from the surface of the Earth and for terrestrial metrology should have as the unit of measurement the SI second, as realized by terrestrial time standards,

b) the definition of the International Atomic Time, TAI, approved by the 14th Conférence Générale des Poids et Mesures (1971) and completed by a declaration of the 9th session of the Comité Consultatif pour la Définition de la Seconde (1980),

recommends that,

1) the time reference for apparent geocentric ephemerides be Terrestrial Time, TT,

2) TT be a time scale differing from TCG of Recommendation III by a constant rate, the unit of measurement of TT being chosen so that it agrees with the SI second on the geoid,

3) at instant 1977 January 1, $0^h\ 0^m\ 0^s$ TAI exactly, TT have the reading 1977 January 1, $0^h\ 0^m\ 32.184^s$ exactly.

RECOMMENDATION V

considering,

that important work has already been performed using Barycentric Dynamical Time (TDB), defined by IAU Recommendation 5 (1976) of IAU Commissions 4, 8 and 31, and Recommendation 5 (1979) of IAU Commissions 4, 19 and 31,

recognizes,

that where discontinuity with previous work is deemed to be undesirable, TDB may be used.

RECOMMENDATION VI

considering,

the desirability of implementing a conventional celestial barycentric reference system based upon the observed positions of extragalactic objects, and,

noting,

the existence of tentative reference frames constructed by various institutions and combined by the International Earth Rotation Service (IERS) into a frame used for Earth rotation series,

recommends,

1. that intercomparisons of these frames be extensively made in order to assess their systematic differences and accuracy,

2. that an IAU Working Group consisting of members of Commissions 4, 8, 19, 24, 31 and 40, the IERS, and other pertinent experts, in consultation with all the institutions producing catalogues of extragalactic radio sources, establish a list of candidates for primary sources defining the new conventional reference frame, together with a list of secondary sources that may later be added to or replace some of the primary sources, and,

requests,

1. that such a list be presented to the XXIInd General Assembly (1994) as a part of the definition of a new conventional reference system,

2. that the objects in this list be systematically observed by all VLBI and other appropriate astrometric programmes.

RECOMMENDATION VII

considering,

a) that the new conventional celestial barycentric reference frame should be as close as possible to the existing FK5 equator and equinox and the dynamical equinox which are referred to J2000.0,

b) that it should be accessible to astrometry in visual as well as in radio wavelengths,

recommends,

1. that the principal plane of the new conventional celestial reference system be as near as possible to the mean equator at J2000.0 and that the origin in this principal plane be as near as possible to the dynamical equinox of J2000.0,

2. that the positions of the extragalactic objects selected in accordance with Recommendation VI and representing the reference frame be computed initially for the equator and equinox J2000.0 using the best available values of the celestial pole offset with respect to the IAU expressions for precession and nutation,

3. that a great effort be made to compare reference frames of all types, in particular the FK5, solar system and extragalactic reference frames,

4. that observing programmes be undertaken or continued in order to relate planetary positions to radio and optical objects, and to determine the relationship between catalogues of extragalactic source positions and the best catalogues of star positions, in particular the FK5 and Hipparcos catalogues.

引入 TT
旧 TDB 时间系统的使用

建立基于河外源视位置定义
的基本质心天球参考系统

新参考系统的具体实现及与
旧参考系统 (FK5) 之间的关系

南京大学 NANJING UNIVERSITY

决议全文见 https://www.iau.org/static/resolutions/IAU1991_French.pdf

国际天球参考系 ICRS 的理论定义是运动学上的定义，需满足以下条件：

- ICRS 为质心系，即 ICRS 的空间坐标原点与太阳系质心重合；
- 代表 ICRS 的参考架相对于一组遥远的银河系外参考点没有整体（全局）旋转（global rotation）；
- 选取河外源作为参考点是 ICRS 定义的一部分；
- ICRS 的基本面要尽可能地靠近 J2000 时刻的平赤道，基本面上的零点要尽可能地靠近 J2000 时刻的动力学春分点（与 FK5 保持连续性）；
- 利用最准确的相对于 IAU 岁差章动模型的天极偏差资料，相对于 J2000 时刻的赤道和春分点，计算代表参考架的河外源位置；
- ICRS 要通过在光学和射电波段都可以使用的参考架来实现。

ICRS vs. FK5

ICRS

理论概念:

- 一组可观测的河外源来作为定义源
- 参考框架的坐标轴指向是固定的，由相对于宇宙静止的河外射电源的位置来定义
- 目标是建立一个惯性（无旋转）的参考系统

实现步骤:

无

模型:

- 无旋转宇宙模型
- 河外源相对于宇宙的运动模型
- 大气模型
- 光偏折模型

参数和常数:

无

FK5

理论概念:

- 参考系的基本方向标记如下：地月系统绕太阳的轨道运动定义黄道面，地球自转轴的方向定义赤道面，两个平面的交点定义春分点
- 目标是建立一个惯性的参考系统
- 参考系通过恒星星表来实现

实现步骤:

将地心视方向转换到太阳系质心视方向的处理算法

模型:

- 太阳系成员的运动模型
- 岁差和章动模型
- 银河系运动学模型
- 周年视差模型
- 光折射模型
- 光偏折模型

参数和常数:

- 恒星视差、恒星自行
- 日月岁差、行星岁差、测地岁差
- 黄经章动和交角章动系数
- 黄赤交角
- 其他出现在处理观测数据过程中的参数

1994 年 IAU 大会关于参考系 (架) 的 B5 决议

Resolution No. B 5
on the Working Group on Reference Frames
The participants of Symposium 166
sur le Groupe de Travail Reference Frames
Les participants au Symposium 166

The XXIInd General Assembly of the International Astronomical Union

Considering that the IAU Working Group on Reference Frames consisting of members of Commissions 4, 8, 19, 24 and 31, the International Rotation Service (IERS) and other pertinent experts has been formed to produce a list of candidate extragalactic radio sources for defining the new conventional reference frame and secondary sources that may later be added to the primary sources or replace some of the primary sources,

Noting that a list of sources which define the conventional reference frame together with list of candidate sources which may, at some future date, be added to or replace the defining sources has been made,

Recommends that this list of defining sources be adopted by the XXIInd General Assembly (1994) as the first stage in the definition of the new reference frame, and

Requests that the Working Group on Reference Frames be continued and its membership be reviewed by Commissions 4, 8, 19, 24 and 31 and the IERS to

1. define the positions of the radio sources on the list,
2. determine the relationship of this frame to an optical frame defined by stars, and
3. recommend to the XXIIIrd General Assembly (1997) that a way be found to organize the work for the maintenance and evolution of this frame and its extension to other frames at other wavelengths.

选取一批定义源，初步实现新参考架的定义

Annnexe to Resolution B5

List of extragalactic objects identifieds sources which define the new conventional celestial reference frame together with candidate sources which may, at some future date, be added or replace the defining sources:

d: defining sources
c: additional sources
o: optical objects

	Name			R.A.			Dec.	Alias
d	0003-066	0	6	13.89	-6	23	35.3	PKS 0003-066
d	0007+106	0	10	31.01	10	58	29.5	IIIZW2, PKS 0007+106
d	0007+171	0	10	33.99	17	24	18.8	4C+17.04
d	0008-264	0	11	1.25	-26	12	33.4	PKS 0008-264
d	0010+405	0	13	31.13	40	51	37.1	B3 0010+406
d	0013-005	0	16	11.09	0	-15	12.5	PKS 0013-005
d	0014+813	0	17	8.48	81	35	8.1	S5 0014+81
d	0016+731	0	19	45.79	73	27	30.0	S5 0016+73
d	0019+058	0	22	32.44	6	8	4.3	PKS 0019+058
d	0026+346	0	29	14.24	34	56	32.2	OB343, S4 0026+34
d	0039+230	0	42	4.55	23	20	1.1	PKS 0039+230
d	0047-579	0	49	59.47	-57	38	27.3	PKS 0047-579
d	0048-097	0	50	41.32	-9	29	5.2	PKS 0048-097
d	0056-572	0	58	46.58	-56	59	11.5	PKS 0056-572
d	0056-001	0	59	5.51	0	6	51.6	4C-00.06
d	0059+581	1	2	45.76	58	24	11.1	
d	0104-408	1	6	45.11	-40	34	20.0	
d	0106+013	1	8	38.77	1	35	0.3	4C+01.02
d	0109+224	1	12	5.82	22	44	38.8	
d	0111+021	1	13	43.14	2	22	17.3	
d	0112-017	1	15	17.10	-1	27	4.6	PKS 0112-014
d	0113-118	1	16	12.52	-11	36	15.4	PKS 0113-118
d	0119+115	1	21	41.59	11	49	50.4	PKS 0119+115
d	0119+041	1	21	56.86	4	22	24.7	IRAS F01177+
d	0123+257	1	26	42.79	25	59	1.3	
d	0131-522	1	33	5.76	-52	0	4.0	PKS 0131-522
d	0133+476	1	36	58.59	47	51	29.1	
d	0135-247	1	37	38.35	-24	30	53.9	
d	0134+329	1	37	41.30	33	9	35.1	3C48, 4C+39.25
d	0146+056	1	49	22.37	5	55	53.6	PKS 0146+056
d	0148+274	1	51	27.15	27	44	41.8	
d	0149+218	1	52	18.06	22	7	7.7	PKS 0149+218
d	0150-334	1	53	10.12	-33	10	25.9	PKS 0150-334
d	0153+744	1	57	34.96	74	42	43.2	
d	0159+723	2	3	33.38	72	32	53.7	
d	0201+113	2	3	46.66	11	34	45.4	PKS 0201+113
d	0202+149	2	4	50.41	15	14	11.0	4C+15.05
d	0202-172	2	4	57.67	-17	1	19.8	PKS 0202-172
d	0202+319	2	5	4.93	32	12	30.1	B2 0202+31
d	0208-512	2	10	46.20	-51	1	1.9	PKS 0208-512

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决议全文见 https://www.iau.org/static/resolutions/IAU1994_French.pdf

1997 年 IAU 大会关于参考系 (架) 的 B2 和 B5 决议

Resolution No B2
On the international celestial reference system (ICRS)
Sur le système céleste international de référence (ICRS)

The XXIIIrd International Astronomical Union General Assembly

Considering

a. That Recommendation VII of Resolution A4 of the 21st General Assembly specifies the coordinate system for the new celestial reference frame and, in particular, its continuity with the FK5 system at J2000.0;

b. That Resolution B5 of the 22nd General Assembly specifies a list of extragalactic sources for consideration as candidates for the realization of the new celestial reference frame;

c. That the IAU Working Group on Reference Frames has in 1995 finalized the positions of these candidate extragalactic sources in a coordinate frame aligned to that of the FK5 to within the tolerance of the errors in the latter (see note 1);

d. That the Hipparcos Catalogue was finalized in 1996 and that its coordinate frame is aligned to that of the frame of the extragalactic sources in (c) with one sigma uncertainties of ± 0.6 milliarcseconds (mas) at epoch J1991.25 and ± 0.25 mas per year in rotation rate;

Noting

That all the conditions in the IAU Resolutions have now been met;

Resolves

a. That, as from 1 January 1998, the IAU celestial reference system shall be the International Celestial Reference System (ICRS) as specified in the 1991 IAU Resolution on reference frames and as defined by the International Earth Rotation Service (IERS) (see note 2);

b. That the corresponding fundamental reference frame shall be the International Celestial Reference Frame (ICRF) constructed by the IAU Working Group on Reference Frames;

c. That the Hipparcos Catalogue shall be the primary realization of the ICRS at optical wavelengths;

d. That IERS should take appropriate measures, in conjunction with the IAU Working Group on reference frames, to maintain the ICRF and its ties to the reference frames at other wavelengths.

Note 1: IERS 1995 Report, Observatoire de Paris, p.II-19 (1996).
Note 2: "The extragalactic reference system of the International Earth Rotation Service (ICRS)", Arias, E.F. et al. A & A 303, 604 (1995).

Resolution No. B5
On the international celestial reference system (ICRS)
And the Hipparcos catalogue
Sur le nouveau système céleste international de référence (ICRS) et le catalogue Hipparcos

The XXIIIrd International Astronomical Union General Assembly

considering

1. that the International Astronomical Union (IAU) has adopted an International Celestial Reference System (ICRS) in which the axes are fixed relative to the distant background as implied by observations of extragalactic sources,
2. that the realization of the ICRS is based on observations made from the Earth, the axes of which precess and nutate relative to the ICRS,
3. that there are significant differences between the nutation adopted by the IAU in 1980 and astronomical observations,
4. that a rate of variation of the obliquity is observed, which is not predicted by the 1980 IAU precession-nutation theory,
5. that there is a difference in the precession rate of about -3.0 milliarcseconds per year (mas/year) between the observed and adopted values,

recommends

1. that Division I form a new Working Group to report to the IAU General Assembly in 2000 which will
   a. examine and clarify the effects on astrometric computations, of changes such as the adoption of the International Celestial Reference System, the availability of the Hipparcos catalogue, and the change expected in the conventional precession-nutation model, and
   b. make recommendations regarding the algorithms to be used,
2. that this Working Group study these questions jointly with the International Earth Rotation Service (IERS) and maintain a close connection with the IAU Working Group on Reference Frames, the IAU Working Group on Astronomical Constants, and the IAU-IUGG Working Group on Non-rigid Earth Nutation Theory (up to its discontinuation at the 1999 IUGG General Assembly), through exchange of representatives.

正式采用 ICRS 和 ICRF 作为新的基本参考系统

决议全文见 https://www.iau.org/static/resolutions/IAU1997_French.pdf

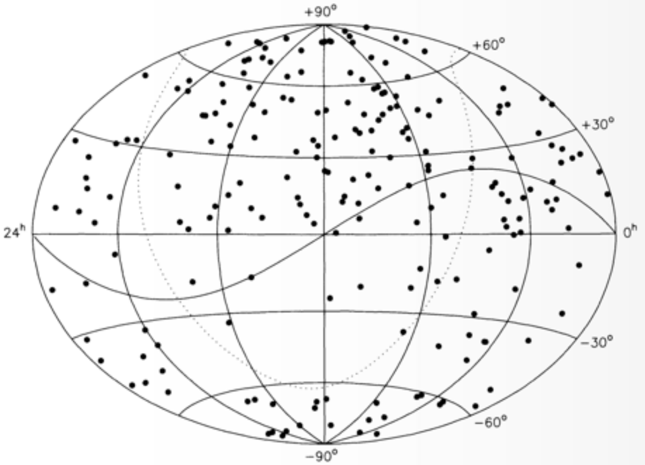


Fig. 6.1. Distribution of the 212 best-observed extragalactic sources comprising the new IAU celestial reference frame (ICRF). An Aitoff equal-area projection is used. Note the relatively sparse population at negative declinations (After Ma et al. 1998)

图 27: 212 颗 ICRF1 定义源的全局分布 [1]

ICRF1 星表包含 608 颗河外射电源的位置、射电波段形态等信息，观测波段为 S/X 波段（2.3/8.4 GHz），单颗射电源的位置精度最好水平为0.25 mas，参考架轴稳定水平为0.02 mas。

2000 年 IAU 大会关于参考系 (架) 的 B1 决议

Resolution No. B1.1
Maintenance and establishment of reference frames and systems
Suivi et construction de repères Et de systèmes de référence

The XXIVth International Astronomical Union General Assembly,

Noting

1. that Resolution B2 of the XXIIIrd General Assembly (1997) specifies that "the fundamental reference frame shall be the International Celestial Reference Frame (ICRF) constructed by the IAU Working Group on Reference Frames",

2. that Resolution B2 of the XXIIIrd General Assembly (1997) specifies "That the Hipparcos Catalogue shall be the primary realisation of the International Celestial Reference System (ICRS) at optical wavelengths", and

3. the need for accurate definition of reference systems brought about by unprecedented precision, and

Recognising

1. the importance of continuing operational observations made with Very Long Baseline Interferometry (VLBI) to maintain the ICRF,

2. the importance of VLBI observations to the operational determination of the parameters needed to specify the time-variable transformation between the International Celestial and Terrestrial Reference Frames,

3. the progressive shift between the Hipparcos frame and the ICRF, and

4. the need to maintain the optical realisation as close as possible to the ICRF,

Recommends

1. that IAU Division I maintain the Working Group on Celestial Reference Systems formed from Division I members to consult with the International Earth Rotation Service (IERS) regarding the maintenance of the ICRS,

2. that the IAU recognise the International VLBI service (IVS) for Geodesy and Astrometry as an IAU Service Organisation,

3. that an official representative of the IVS be invited to participate in the IAU Working Group on Celestial Reference Systems,

4. that the IAU continue to provide an official representative to the IVS Directing Board,

5. that the astrometric and geodetic VLBI observing programs consider the requirements for maintenance of the ICRF and linking to the Hipparcos optical frame in the selection of sources to be observed (with emphasis on the Southern Hemisphere), design of observing networks, and the distribution of data, and

6. that the scientific community continue with high priority ground- and space- based observations (a) for the maintenance of the optical Hipparcos frame and frames at other wavelengths and (b) for links of the frames to the ICRF.

Resolution No. B1.2
Hipparcos celestal reference frame
Le repère de référence céleste Hipparcos

The XXIVth International Astronomical Union General Assembly,

Noting

1. that Resolution B2 of the XXIIIrd General Assembly (1997) specifies, "That the Hipparcos Catalogue shall be the primary realisation of the International Celestial Reference System (ICRS) at optical wavelengths",

2. the need for this realisation to be of the highest precision,

3. that the proper motions of many of the Hipparcos stars known, or suspected, to be multiple are adversely affected by uncorrected orbital motion,

4. the extensive use of the Hipparcos Catalogue as reference for the ICRS in extension to fainter stars,

5. the need to avoid confusion between the International Celestial Reference Frame (ICRF) and the Hipparcos frame, and

6. the progressive shift between the Hipparcos frame and the ICRF,

Recommends

1. that Resolution B2 of the XXIIIrd IAU General Assembly (1997) be amended by excluding from the optical realisation of the ICRS all stars flagged C, G, O, V and X in the Hipparcos Catalogue, and

2. that this modified Hipparcos frame be labelled the Hipparcos Celestial Reference Frame (HCRF).

决议全文见 https://www.iau.org/static/resolutions/IAU2000_French.pdf

2006 年 IAU 大会关于参考系 (架) 的决议

Resolution 1
Adoption of the P03 Precession Theory and Definition of the Ecliptic

The XXVIth International Astronomical Union General Assembly,

Noting

1. the need for a precession theory consistent with dynamical theory,
2. that, while the precession portion of the IAU 2000A precession-nutation model, recommended for use beginning on 1 January 2003 by resolution B1.6 of the XXIVth IAU General Assembly, is based on improved precession rates with respect to the IAU 1976 precession, it is not consistent with dynamical theory, and
3. that resolution B1.6 of the XXIVth General Assembly also encourages the development of new expressions for precession consistent with the IAU 2000A precession-nutation model, and

Recognizing

1. that the gravitational attraction of the planets make a significant contribution to the motion of the Earth's equator, making the terms lunisolar precession and planetary precession misleading,
2. the need for a definition of the ecliptic for both astronomical and civil purposes, and
3. that in the past, the ecliptic has been defined both with respect to an observer situated in inertial space (inertial definition) and an observer comoving with the ecliptic (rotating definition),

Accepts

the conclusions of the IAU Division I Working Group on Precession and the Ecliptic published in Hilton et al. (2006, *Celest. Mech.* 94, 351), and

Recommends

1. that the terms lunisolar precession and planetary precession be replaced by precession of the equator and precession of the ecliptic, respectively,
2. that, beginning on 1 January 2009, the precession component of the IAU 2000A precession-nutation model be replaced by the P03 precession theory, of Capitaine et al. (2003, *A&A*, 412, 567-586) for the precession of the equator (Eqs. 37) and the precession of the ecliptic (Eqs. 38); the same paper provides the polynomial developments for the P03 primary angles and a number of derived quantities for use in both the equinox based and CIO based paradigms,
3. that the choice of precession parameters be left to the user, and
4. that the ecliptic pole should be explicitly defined by the mean orbital angular momentum vector of the Earth-Moon barycenter in the Barycentric Celestial Reference System (BCRS), and this definition should be explicitly stated to avoid confusion with other, older definitions.

Notes

1. Formulas for constructing the precession matrix using various parameterizations are given in Eqs. 1, 6, 7, 11, 12 and 22 of Hilton et al. (2006). The recommended polynomial developments for the various parameters are given in Table 1 of the same paper, including the P03 expressions set out in expressions (37) to (41) of Capitaine et al. (2003) and Tables 3-5 of Capitaine et al. (2005).
2. The time rate of change in the dynamical form factor in P03 is

$dJ_2/dt = 0.3001 \times 10^{-9}$ century^{-1}

References

Capitaine, N., Wallace, P.T., & Chapront, J. 2003, *A&A*, 412, 567
Capitaine, N., Wallace, P.T., & Chapront, J. 2005, *A&A*, 432, 355
Hilton, J.L., Capitaine, N., Chapront, J., Ferrandiz, J.M., Fienga, A., Fukushima, T., Getino, J., Mathews, P., Simon, J.-L., Soffel, M., Vondrak, J., Wallace, P., & Williams, J. 2006, *Celest. Mech.*, 94, 351

Actions to be taken by the General Secretary upon adoption of the Resolution:

Adoption of the P03 Precession Theory and Definition of the Ecliptic

The following institutions should receive formal notification of the action:

Her Majesty's Nautical Almanac Office, Institute de mécanique céleste et de calcul des éphémérides, Institute of Applied Astronomy of the Russian Academy of Sciences, International Association of Geodesy, (IAG), International Earth Rotation and Reference Systems Service (IERS), International Union of Geodesy and Geophysics (IUGG), International VLBI Service for Geodesy and Astrometry (IVS), Japan Coast Guard (JCG), National Astronomical Observatory of Japan (NAOJ), Nautical Almanac Office of the United States Naval Observatory.

Resolution 2
Supplement to the IAU 2000 Resolutions on reference systems

RECOMMENDATION 1. Harmonizing the name of the pole and origin to "intermediate"

The XXVIth International Astronomical Union General Assembly,

Noting

1. the adoption of resolutions IAU B1.1 through B1.9 by the IAU General Assembly of 2000,
2. that the International Earth Rotation and Reference Systems Service (IERS) and the Standards Of Fundamental Astronomy (SOFA) activity have made available the models, procedures, data and software to implement these resolutions operationally, and that the Almanac Offices have begun to implement them beginning with their 2006 editions, and
3. the recommendations of the IAU Working Group on "Nomenclature for Fundamental Astronomy" (IAU Transactions XXVIA, 2005), and

Recognizing

1. that using the designation "intermediate" to refer to both the pole and the origin of the new systems linked to the Celestial Intermediate Pole and the Celestial or Terrestrial Ephemeris origins, defined in Resolutions B1.7 and B1.8, respectively would improve the consistency of the nomenclature, and
2. that the name "Conventional International Origin" with the potentially conflicting acronym CIO is no longer commonly used to refer to the reference pole for measuring polar motion as it was in the past by the International Latitude Service,

Recommends

1. that, the designation "intermediate" be used to describe the moving celestial and terrestrial reference systems defined in the 2000 IAU Resolutions and the various related entities, and
2. that the terminology "Celestial Intermediate Origin" (CIO) and "Terrestrial Intermediate Origin" (TIO) be used in place of the previously introduced "Celestial Ephemeris Origin" (CEO) and "Terrestrial Ephemeris Origin" (TEO), and
3. that authors carefully define acronyms used to designate entities of astronomical reference systems to avoid possible confusion.

RECOMMENDATION 2. Default orientation of the Barycentric Celestial Reference System (BCRS) and Geocentric Celestial Reference System (GCRS)

The XXVIth International Astronomical Union General Assembly,

Noting

1. the adoption of resolutions IAU B1.1 through B1.9 by the IAU General Assembly of 2000,
2. that the International Earth Rotation and Reference Systems Service (IERS) and the Standards Of Fundamental Astronomy (SOFA) activity have made available the models, procedures, data and software to implement these resolutions operationally, and that the Almanac Offices have begun to implement them beginning with their 2006 editions,
3. that, in particular, the systems of space-time coordinates defined by IAU 2000 Resolution B1.3 for (a) the solar system (called the Barycentric Celestial Reference System, BCRS) and (b) the Earth (called the Geocentric Celestial Reference System, GCRS) have begun to come into use,
4. the recommendations of the IAU Working Group on "Nomenclature for Fundamental Astronomy" (IAU Transactions XXVIA, 2005), and
5. a recommendation from the IAU Working Group on "Relativity in Celestial Mechanics, Astrometry and Metrology",

Recognizing

1. that the BCRS definition does not determine the orientation of the spatial coordinates,
2. that the natural choice of orientation for typical applications is that of the ICRS, and
3. that the GCRS is defined such that its spatial coordinates are kinematically non-rotating with respect to those of the BCRS,

Recommends

that the BCRS definition is completed with the following: "For all practical applications, unless otherwise stated, the BCRS is assumed to be oriented according to the ICRS axes. The orientation of the GCRS is derived from the ICRS-oriented BCRS."

Note on Resolution 2:

Resolution 2, adopted by the 26th IAU General Assembly states in its "Noting" 2, that the International Earth Rotation and Reference Systems Service (IERS) and the Standards Of Fundamental Astronomy (SOFA) activity have made available the models, procedures, data and software to implement the IAU 2000 resolutions operationally, and that the almanac offices have begun to implement them beginning with their 2006 editions.

2006 is the year of the edition for which most of the worldwide-accessible almanacs have implemented the IAU 2000 resolutions. However, it should be noted that the Polish Almanac of the Institute of Geodesy and Cartography (Warsaw, Poland), began implementing the IAU 2000 resolutions in their 2004 edition. We are pleased to acknowledge the efforts that our Polish colleagues made to implement the changes with so little delay.

Nicole Capitaine, Chair of the IAU Division 1 Working Group on Nomenclature for Fundamental Astronomy (NFA) (2003-2006)

决议全文见 https://www.iau.org/static/resolutions/IAU2006_French.pdf

2009 年 IAU 大会关于参考系 (架) 的 B3 决议

IAU 2009 RESOLUTION B3
on
the Second Realization of the International Celestial Reference Frame

The International Astronomical Union XXVII General Assembly,

noting

1. that Resolution B2 of the XXIII General Assembly (1997) resolved "That, as from 1 January 1998, the IAU celestial reference system shall be the International Celestial Reference System (ICRS)",

2. that Resolution B2 of the XXIII General Assembly (1997) resolved that the "fundamental reference frame shall be the International Celestial Reference Frame (ICRF) constructed by the IAU Working Group on Reference Frames",

3. that Resolution B2 of the XXIII General Assembly (1997) resolved "That IERS should take appropriate measures, in conjunction with the IAU Working Group on reference frames, to maintain the ICRF and its ties to the reference frames at other wavelengths",

4. that Resolution B7 of the XXIII General Assembly (1997) recommended "that high-precision astronomical observing programs be organized in such a way that astronomical reference systems can be maintained at the highest possible accuracy for both northern and southern hemispheres",

5. that Resolution B1.1 of the XXIV General Assembly (2000) recognized "the importance of continuing operational observations made with Very Long Baseline Interferometry (VLBI) to maintain the ICRF",

recognizing

1. that since the establishment of the ICRF, continued VLBI observations of ICRF sources have more than tripled the number of source observations,

2. that since the establishment of the ICRF, continued VLBI observations of extragalactic sources have significantly increased the number of sources whose positions are known with a high degree of accuracy,

3. that since the establishment of the ICRF, improved instrumentation, observation strategies, and application of state-of-the-art astrophysical and geophysical models have significantly improved both the data quality and analysis of the entire relevant astrometric and geodetic VLBI data set.,

4. that a working group on the ICRF formed by the International Earth Rotation and Reference Systems Service (IERS) and the International VLBI Service for Geodesy and Astrometry (IVS), in conjunction with the IAU Division I Working Group on the Second Realization of the International Celestial Reference Frame has finalized a prospective second realization of the ICRF in a coordinate frame aligned to that of the ICRF to within the tolerance of the errors in the latter (see note 1),

5. that the prospective second realization of the ICRF as presented by the IAU Working Group on the Second Realization of the International Celestial Reference Frame represents a significant improvement in terms of source selection, coordinate accuracy, and total number of sources, and thus represents a significant improvement in the fundamental reference frame realization of the ICRS beyond the ICRF adopted by the XXIII General Assembly (1997),

resolves

1. that from 01 January 2010 the fundamental astrometric realization of the International Celestial Reference System (ICRS) shall be the Second Realization of the International Celestial Reference Frame (ICRF2) as constructed by the IERS/IVS working group on the ICRF in conjunction with the IAU Division I Working Group on the Second Realization of the International Celestial Reference Frame (see note 1),

2. that the organizations responsible for astrometric and geodetic VLBI observing programs (e.g. IERS, IVS) take appropriate measures to continue existing and develop improved VLBI observing and analysis programs to both maintain and improve ICRF2,

3. that the IERS, together with other relevant organizations continue efforts to improve and densify high accuracy reference frames defined at other wavelengths and continue to improve ties between these reference frames and ICRF2.

Note 1: The Second Realization of the International Celestial Reference Frame by Very Long Baseline Interferometry, Presented on behalf of the IERS / IVS Working Group, Alan Fey and David Gordon (eds.). (IERS Technical Note ; 35) Frankfurt am Main: Verlag des Bundesamts für Kartographie und Geodäsie, 2009. See <www.iers.org/MainDisp.csl?pid=46-25772> or <hpiers.obspm.fr/icrs-pc/> .

采用 ICRF2 作为新的基本天球参考框架

南京大學 NANJING UNIVERSITY

决议全文见 https://www.iau.org/static/resolutions/IAU2009_English.pdf

ICRF2 定义源

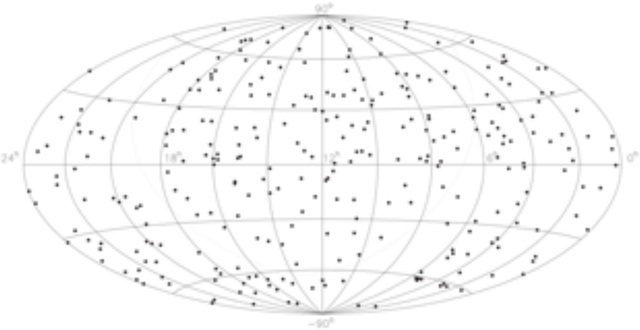


Figure 4. Distribution of the 295 ICRF2 "defining" sources on an Aitoff equal area projection of the celestial sphere. The dashed line represents the galactic equator.

图 28: 295 颗 ICRF2 定义源的全局分布 [14]

ICRF2 星表包含 3414 颗河外射电源的位置等信息，观测波段为 S/X 波段（2.3/8.4 GHz），单颗射电源的位置精度最好水平为0.04 mas，参考架轴稳定水平为0.01 mas。

2018 年 IAU 大会关于参考系 (架) 的 B2 决议

Transactions IAU, Volume XXXB
Proc. XXX IAU General Assembly, August 2018
Teresa Lago, ed.

DOI: 00.0000/X000000000000000X

THIRTHIETH GENERAL ASSEMBLY

RESOLUTIONS PRESENTED TO THE XXXth GENERAL ASSEMBLY

RESOLUTION B2

on The Third Realization of the International Celestial Reference Frame

Proposed by the IAU Working Group on the Third Realization of the International Celestial Reference Frame

The XXX General Assembly of the International Astronomical Union,

noting

1. that Resolution B2 of the XXIIIrd General Assembly (1997) resolved "that, as from 1 January 1998, the IAU celestial reference system shall be the International Celestial Reference System (ICRS)";

2. that Resolution B3 of the XXVIIth General Assembly (2009) resolved "that, as from 1 January 2010, the fundamental astrometric realization of the International Celestial Reference System (ICRS) shall be the Second Realization of the International Celestial Reference Frame (ICRF2)";

3. that Resolution B3 of the XXVIIth General Assembly (2009) resolved "that the organizations responsible for astrometric and geodetic VLBI observing programs (e.g. IERS, IVS) take appropriate measures to continue existing and develop improved VLBI observing and analysis programs to both maintain and improve ICRF2";

recognizing

4. that since the establishment of ICRF2, continued and new VLBI observing programs conducted by relevant organizations (e.g. IVS, the International VLBI Service for geodesy and astrometry) and individuals on various VLBI arrays and at multiple radio frequencies, have almost doubled the volume of astrometric and geodetic VLBI data collected on ICRF2 and add-on radio sources;

5. that since the establishment of ICRF2, improved instrumentation, network coverage, observation strategies, and astronomical and geophysical modeling have significantly improved the VLBI data quality and subsequent astrometric analysis of those data;

6. that an IAU Working Group was formed in 2012 to generate the Third Realization of the International Celestial Reference Frame using the entire astrometric and geodetic VLBI data set and state-of-the-art astronomical and geophysical modeling, with the mandate to complete that realization for presentation at the XXXth General Assembly (2018);

7. that the aforementioned Working Group has generated a prospective Third Realization of the International Celestial Reference Frame, in a coordinate frame aligned onto ICRF2, which represents a significant improvement in terms of source characterization, position accuracy and total number of sources, and thus represents a significant improvement in the fundamental realization of the ICRS, compared to ICRF2 adopted at the XXVIIth General Assembly (2009);

resolves

8. that, as from 1 January 2019, the fundamental realization of the International Celestial Reference System (ICRS) shall be the Third Realization of the International Celestial Reference Frame (ICRF3), as constructed by the IAU Working Group on the Third Realization of the International Celestial Reference Frame;

9. that the organizations responsible for astrometric and geodetic VLBI observing programs (e.g. IVS) take appropriate measures to continue and develop such programs, at multiple radio frequencies and with a specific effort on the southern hemisphere, to both maintain and improve ICRF3;

10. that the organizations responsible for defining high-accuracy reference frames at other wavelengths take appropriate measures, together with the International Earth Rotation and Reference Systems Service (IERS), to align those reference frames onto ICRF3 with the highest possible accuracy.

采用 ICRF3 作为新的基本天球参考框架

决议全文见 https://www.iau.org/static/resolutions/IAU2018_ResolB2_English.pdf

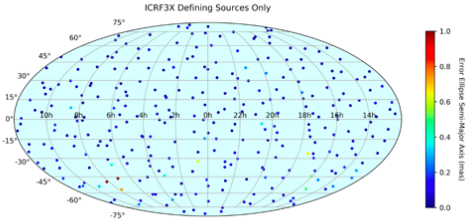


Fig. 13. Sky distribution of the 303 ICRF3 defining sources. Each source is plotted as a dot color-coded according to its position uncertainty in the *S/X* band frame (where the position uncertainty is defined as the semi-major axis of the error ellipse in position).

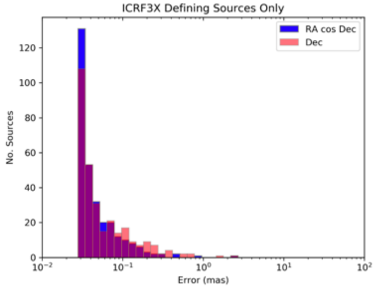


Fig. 14. Distribution of coordinate uncertainties of the 303 ICRF3 defining sources at *S/X* band. Right ascension is shown in blue while declination is shown in salmon. The superimposed portion of the two distributions is shown in purple.

图 29: 303 颗 ICRF3 定义源的全天分布 [4]

ICRF3 星表包含 4588 颗河外射电源的位置等信息，观测波段为 S/X 波段（2.3/8.4 GHz）、K 波段 (24 GHz)、X/Ka 波段 (8.4/32 GHz), 单颗射电源的位置精度最好水平为0.03 mas，参考架轴稳定水平为0.01 mas。

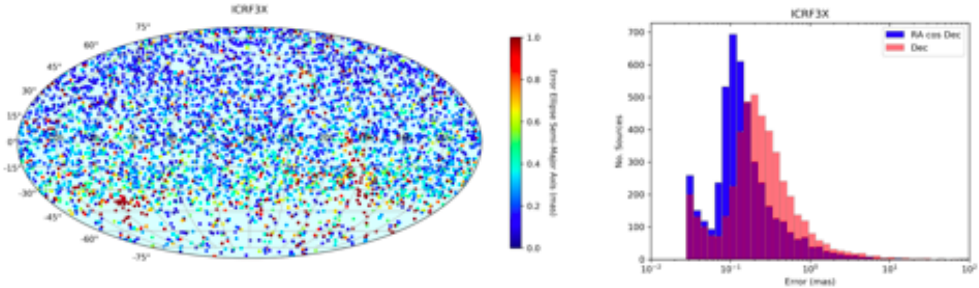


Fig. 6. *Left:* distribution of the 4536 sources included in the ICRF3 *S/X* band frame on a Mollweide projection of the celestial sphere. Each source is plotted as a dot color-coded according to its position uncertainty (defined as the semi-major axis of the error ellipse in position). *Right:* distribution of coordinate uncertainties for the same 4536 sources. Right ascension is shown in blue while declination is shown in salmon. The superimposed portion of the two distributions is shown in purple.

图 30: ICRF3 S/X 波段星表统计情况 [4]

ICRF3 S/X 波段星表包含 4536 颗河外射电源的位置等信息。

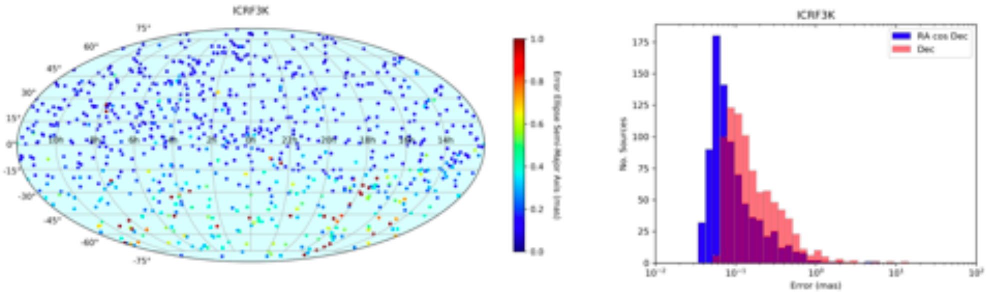


Fig. 7. *Left:* distribution of the 824 sources included in the ICRF3 *K* band frame on a Mollweide projection of the celestial sphere. Each source is plotted as a dot color-coded according to its position uncertainty (defined as the semi-major axis of the error ellipse in position). *Right:* distribution of coordinate uncertainties for the same 824 sources. Right ascension is shown in blue while declination is shown in salmon. The superimposed portion of the two distributions is shown in purple. It must be noted that the scale for the *y*-axis (number of sources) is different from that in Fig. 6.

图 31: ICRF3 K 波段星表统计情况 [4]

ICRF3 K 波段星表包含 824 颗河外射电源的位置等信息。

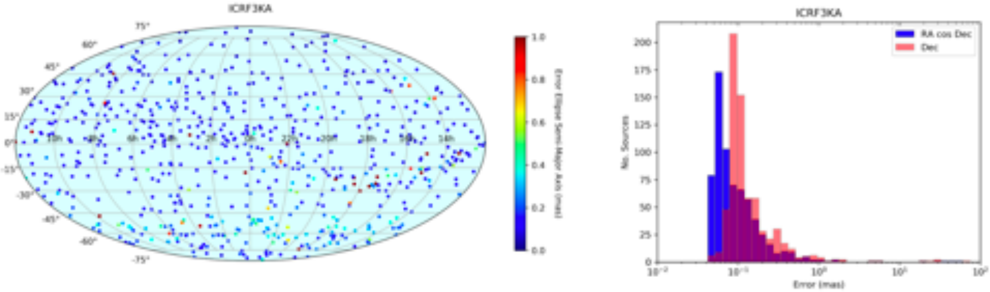


Fig. 8. *Left:* distribution of the 678 sources included in the ICRF3 *X/Ka* band frame on a Mollweide projection of the celestial sphere. Each source is plotted as a dot color-coded according to its position uncertainty (defined as the semi-major axis of the error ellipse in position). *Right:* distribution of coordinate uncertainties for the same 678 sources. Right ascension is shown in blue while declination is shown in salmon. The superimposed portion of the two distributions is shown in purple. It must be noted that the scale for the y-axis (number of sources) is different from that in Fig. 6.

图 32: ICRF3 X/Ka 波段星表统计情况 [4]

ICRF3 X/Ka 波段星表包含 678 颗河外射电源的位置等信息。

2021 年 IAU 大会关于参考系 (架) 的 B3 决议

RESOLUTION B3

On the Gaia Celestial Reference Frame

Proposed by the IAU Division A WG 'Multi-waveband Realizations of the International Celestial Reference System'

The XXXI General Assembly of the International Astronomical Union,

noting

1. that Resolution B2 of the XXIIIrd General Assembly (1997) resolved "that, as from 1 January 1998, the IAU celestial reference system shall be the International Celestial Reference System(ICRS)";
2. that Resolution B2 of the XXIIIrd General Assembly (1997) resolved 'that the Hipparcos Catalogue shall be the primary realization of the ICRS at optical wavelengths';
3. that Resolution B2 of the XXXth General Assembly (2018) resolved "that, as from 1 January 2019, the fundamental realization of the International Celestial Reference System (ICRS) shall be the Third Realization of the International Celestial Reference Frame (ICRF3), as constructed by the IAU Working Group on the Third Realization of the International Celestial Reference Frame";

recognizing

4. that since the establishment of the ICRF3, the ESA space telescope Gaia has conducted relevant optical observations of extragalactic sources and made available a high quality astrometric catalogue for these sources;
5. that the observational principles of Gaia regarding the extragalactic sources meet the ICRS requirements;
6. that the Gaia reference frame in the visible (Gaia-CRF3) and the radio ICRF3 are aligned to each other thanks to a set of common sources in the optical and radio bands;
7. that the Gaia-CRF3 and the stellar Gaia catalogue have largely superseded the Hipparcos Catalogue;
8. that the Gaia-CRF3 is de facto the optical realization of the Celestial Reference Frame in use within the astronomical community;
9. that the Gaia-CRF3 data has been released in December 2020 within the Gaia EDR3 and is accessible in the Gaia archive;

resolves

10. that as from 1 January 2022, the fundamental realization of the International Celestial Reference System (ICRS) shall comprise the Third Realization of the International Celestial Reference Frame (ICRF3) for the radio domain and the Gaia-CRF3 for the optical domain.

Reference

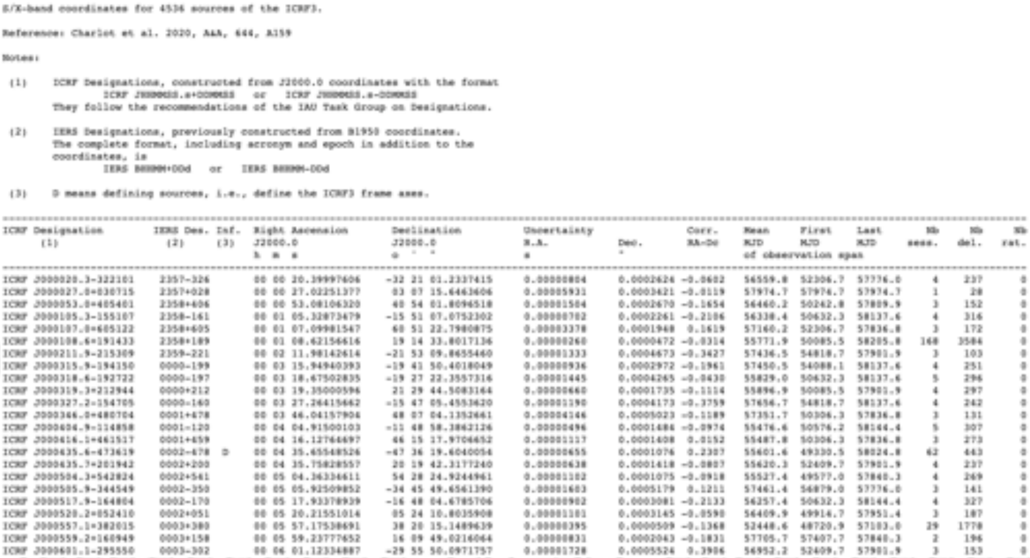
Gaia Collaboration, Gaia Early Data Release 3. Summary of the contents and survey properties, A&A, 649, A1 (2021), https://doi.org/10.1051/0004-6361/202039657

Gaia-CRF3 作为 ICRS 在光学波段的实现

决议全文见 https://www.iau.org/static/archives/announcements/pdf/ann21040c.pdf

ICRF 的性质研究

ICRF3 星表预览



S/X-band coordinates for 4536 sources of the ICRF3.

Reference: Charlot et al. 2020, A&A, 644, A159

Notes:

(1) ICRF Designations, constructed from J2000.0 coordinates with the format
ICRF JHHMMSS.s+DDMMSS or ICRF JHHMMSS.s-DDMMSS
They follow the recommendations of the IAU Task Group on Designations.

(2) IERS Designations, previously constructed from B1950 coordinates.
The complete format, including acronym and epoch in addition to the coordinates, is
IERS BHHMM+DDd or IERS BHHMM-DDd

(3) D means defining sources, i.e., define the ICRF3 frame axes.

ICRF Designation (1)	IERS Des. (2)	Inf. (3)	Right Ascension J2000.0 h m s	Declination J2000.0 ° ' "	Uncertainty R.A. s	Dec. "	Corr. RA-Dc	Mean MJD	First MJD	Last MJD (of observation span)	Nb sess.	Nb del.	Nb rat.
ICRF J000020.3-322101	2357-326		00 00 20.39997606	-32 21 01.2337415	0.00000804	0.0002624	-0.0602	56559.8	52306.7	57776.0	4	237	0
ICRF J000027.0+030715	2357+028		00 00 27.02251377	03 07 15.6463606	0.00005931	0.0003421	-0.0119	57974.7	57974.7	57974.7	1	28	0
ICRF J000053.0+405401	2358+406		00 00 53.08106320	40 54 01.8096518	0.00001504	0.0002670	-0.1654	56460.2	50242.8	57809.9	3	152	0
ICRF J000105.3-155107	2358-161		00 01 05.32873479	-15 51 07.0752302	0.00000702	0.0002261	-0.2106	56338.4	50632.3	58137.6	4	316	0
ICRF J000107.0+605122	2358+605		00 01 07.09981547	60 51 22.7980875	0.00003378	0.0001968	0.1619	57160.2	52306.7	57836.8	3	172	0
ICRF J000108.6+191433	2358+189		00 01 08.62156616	19 14 33.8017136	0.00000260	0.0000472	-0.0314	55771.9	50085.5	58205.8	168	3584	0
ICRF J000211.9-215309	2359-221		00 02 11.98142614	-21 53 09.8655460	0.00001333	0.0004673	-0.3427	57436.5	54818.7	57901.9	3	103	0
ICRF J000315.9-194150	0000-199		00 03 15.94940393	-19 41 50.4018049	0.00000936	0.0002972	-0.1961	57450.5	54088.1	58137.6	4	251	0
ICRF J000318.6-192722	0000-197		00 03 18.67502835	-19 27 22.3557316	0.00001445	0.0004265	-0.0430	55829.0	50632.3	58137.6	5	296	0
ICRF J000319.3+212944	0000+212		00 03 19.35000596	21 29 44.5083164	0.00000660	0.0001735	-0.1114	55896.9	50085.5	57901.9	4	297	0
ICRF J000327.2-154705	0000-160		00 03 27.26415662	-15 47 05.4553620	0.00001190	0.0004173	-0.3759	57656.7	54818.7	58137.6	4	242	0
ICRF J000346.0+480704	0001+478		00 03 46.04157906	48 07 04.1352661	0.00004146	0.0005023	-0.1189	57351.7	50306.3	57836.8	3	131	0
ICRF J000404.9-114858	0001-120		00 04 04.91500103	-11 48 58.3862126	0.00000496	0.0001486	-0.0974	55476.6	50576.2	58144.4	5	307	0
ICRF J000416.1+461517	0001+459		00 04 16.12764697	46 15 17.9706652	0.00001117	0.0001408	0.0152	55487.8	50306.3	57836.8	3	273	0
ICRF J000435.6-473619	0002-478	D	00 04 35.65548526	-47 36 19.6040054	0.00000655	0.0001076	0.2307	55601.6	49330.5	58024.8	62	443	0
ICRF J000435.7+201942	0002+200		00 04 35.75828557	20 19 42.3177240	0.00000638	0.0001418	-0.0807	55620.3	52409.7	57901.9	4	237	0
ICRF J000504.3+542824	0002+541		00 05 04.36334611	54 28 24.9244961	0.00001102	0.0001075	-0.0918	55527.4	49577.0	57840.3	4	269	0
ICRF J000505.9-344549	0002-350		00 05 05.92509852	-34 45 49.6561390	0.00001603	0.0005179	0.1211	57461.4	56879.0	57776.0	3	141	0
ICRF J000517.9-164804	0002-170		00 05 17.93378939	-16 48 04.6785706	0.00000902	0.0003081	-0.2133	56257.4	50632.3	58144.4	4	327	0
ICRF J000520.2+052410	0002+051		00 05 20.21551014	05 24 10.8035908	0.00001101	0.0003145	-0.0590	56409.9	49914.7	57951.4	3	187	0
ICRF J000557.1+382015	0003+380		00 05 57.17530691	38 20 15.1489639	0.00000395	0.0000509	-0.1368	52448.6	48720.9	57103.0	29	1778	0
ICRF J000559.2+160949	0003+158		00 05 59.23777652	16 09 49.0216064	0.00000831	0.0002063	-0.1831	57705.7	57407.7	57840.3	2	196	0
ICRF J000601.1-295550	0003-302		00 06 01.12334887	-29 55 50.0971757	0.00001728	0.0005524	0.3906	56952.2	52409.7	57901.9	3	153	0

图 33: 来源：https://hpiers.obspm.fr/icrs-pc/newwww/icrf/icrf3sx.txt

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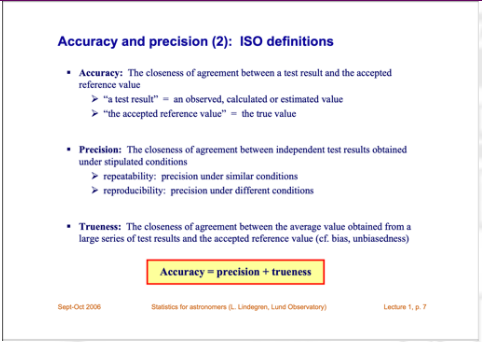
Number		Descriptor: epoch J1991.25					Position: epoch J1991.25			Par.	Proper Motion	
HIP		RA	Dec	V			α (ICRS)	δ		π	$\mu_{\alpha*}$	μ_δ
		h m s	±° ′ ″	mag			deg	deg		mas	mas/yr	
1	2	3	4	5	6	7	8	9	10	11	12	13
1		00 00 00.22	+01 05 20.4	9.10		H	0.000 911 85	+01.089 013 32		3.54	−5.20	−1.88
2		00 00 00.91	−19 29 55.8	9.27		G	0.003 797 37	−19.498 837 45	+	21.90	181.21	−0.93
3		00 00 01.20	+38 51 33.4	6.61		G	0.005 007 95	+38.859 286 08		2.81	5.24	−2.91
4		00 00 02.01	−51 53 36.8	8.06		H	0.008 381 70	−51.893 546 12		7.75	62.85	0.16
5		00 00 02.39	−40 35 28.4	8.55		H	0.009 965 34	−40.591 224 40		2.87	2.53	9.07
6		00 00 04.35	+03 56 47.4	12.31		G	0.018 141 44	+03.946 488 93		18.80	226.29	−12.84
7		00 00 05.41	+20 02 11.8	9.64		G	0.022 548 91	+20.036 602 16		17.74	−208.12	−200.79
8		00 00 06.55	+25 53 11.3	9.05	3	H	0.027 291 60	+25.886 474 45		5.17	19.09	−5.66
9		00 00 08.48	+36 35 09.4	8.59		H	0.035 341 89	+36.585 937 77		4.81	−6.30	8.42
10		00 00 08.70	−50 52 01.5	8.59		H	0.036 253 09	−50.867 073 60		10.76	42.23	40.02
11		00 00 08.95	+46 56 24.0	7.34		H	0.037 296 95	+46.940 001 54		4.29	11.09	−2.02
12		00 00 09.82	−35 57 36.8	8.43		H	0.040 917 56	−35.960 224 82		4.06	−5.99	−0.10
13		00 00 10.00	−22 35 40.9	8.80		H	0.041 679 70	−22.594 680 60		3.49	8.45	−10.07
14		00 00 11.59	−00 21 37.5	7.25		G	0.048 271 89	−00.360 421 19		5.11	61.75	−11.67
15		00 00 12.07	+50 47 28.2	8.60		H	0.050 308 90	+50.791 173 84		2.45	13.88	5.47
+16		00 00 12.34	−54 54 50.9	11.71		G	0.051 408 52	−54.914 128 19		0.53	257.39	−96.63
+17		00 00 12.26	−40 11 32.4	8.15		H	0.051 099 57	−40.192 328 42		6.15	−34.46	−26.37
18		00 00 12.75	−04 03 13.5	11.03		G	0.053 139 23	−04.053 738 13		19.93	−127.22	23.78
19		00 00 12.80	+38 18 14.7	6.53		H	0.053 316 96	+38.304 086 36		4.12	−2.50	−15.07
20		00 00 15.11	+23 31 45.4	8.51		G	0.062 960 50	+23.529 283 97		10.76	36.00	−22.98
21		00 00 15.90	+08 00 26.0	7.55		H	0.066 235 69	+08.007 234 37		5.84	61.89	−0.22
22		00 00 16.83	−49 21 08.2	8.69		H	0.070 135 93	−49.352 266 86		4.47	−7.90	0.46
23		00 00 17.86	+13 18 44.0	7.57		G	0.074 429 30	+13.312 210 83		12.21	54.15	9.65
24		00 00 18.25	−23 27 09.9	9.05		H	0.076 049 79	−23.452 749 13		9.73	127.15	22.22
25	H	00 00 19.05	−44 17 25.1	6.28		G	0.079 365 37	−44.290 297 41	A	13.74	58.36	−108.64
26		00 00 20.24	−13 23 35.9	9.13		H	0.084 345 79	−13.393 296 86		9.19	−103.33	−33.35
27		00 00 20.51	−41 17 51.1	9.32		H	0.085 469 76	−41.297 536 96		9.66	135.96	−113.67
28		00 00 20.94	−43 21 42.5	8.83		H	0.087 248 71	−43.361 799 62		5.64	−10.96	−8.69
29		00 00 22.11	−49 06 28.6	9.14		H	0.092 131 06	−49.107 955 05		2.85	26.86	4.05
30		00 00 23.07	+42 08 29.4	8.26		H	0.096 135 63	+42.141 498 82		3.79	−8.44	−10.14
31		00 00 23.54	+02 40 31.7	7.63		H	0.098 093 90	+02.675 477 68		1.84	−4.88	−0.20
32		00 00 23.66	+51 56 22.2	9.09		H	0.098 583 75	+51.939 490 50		3.10	−0.39	−1.38
33		00 00 23.80	−10 27 44.8	8.10		H	0.099 180 83	−10.462 454 45		8.94	−3.62	28.71
34		00 00 23.87	+26 55 05.7	6.43		H	0.099 469 73	+26.918 238 21		12.71	42.20	−53.47
35		00 00 24.61	−14 29 25.7	9.07		H	0.102 560 52	−14.490 480 72		5.96	162.25	−1.47
36		00 00 24.79	+12 16 01.5	7.68		H	0.103 275 50	+12.267 093 03		6.30	49.71	14.27
37	H	00 00 25.28	−47 10 46.5	10.44		H	0.105 351 90	−47.179 583 82	+	3.74	−6.92	7.03
38		00 00 26.65	−79 03 42.6	8.65		H	0.111 046 94	−79.061 831 33		23.84	162.30	−62.40
39		00 00 26.85	−16 41 48.9	7.46		G	0.111 861 48	−16.696 930 20		10.98	169.72	−32.54
+4[illegible]	H	00 00 29.27	+67 13 00.4	10.61	2	G	0.121 969 71	+67.216 791 25	A	−3.40	−2.99	−3.18

Number	Standard Errors					Astrometric Correlations (%)										Soln	
HIP	$\alpha*$	δ	π	$\mu_{\alpha*}$	μ_δ	δ/$\alpha*$	π/$\alpha*$	π/δ	$\mu_{\alpha*}$/$\alpha*$	$\mu_{\alpha*}$/δ	$\mu_{\alpha*}$/π	μ_δ/$\alpha*$	μ_δ/δ	μ_δ/π	μ_δ/$\mu_{\alpha*}$	F1	F2
	mas		mas	mas/yr												%	
1	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
1	1.32	0.74	1.39	1.36	0.81	+32	−7	−11	−24	+9	−1	+10	−1	+1	+34	0	0.74
2	1.28	0.70	3.10	1.74	0.92	+12	−14	−24	−29	+1	+21	−2	−19	−28	+14	2	1.45
3	0.53	0.40	0.63	0.57	0.47	+6	+9	+4	+43	−1	−6	+3	+24	+7	+21	0	−0.45
4	0.53	0.59	0.97	0.65	0.65	−22	−9	−3	+24	+20	+8	+18	+8	−31	−18	0	−1.46
5	0.64	0.61	1.11	0.67	0.74	+10	+24	+6	+26	−10	+20	−16	−30	−19	+6	0	−1.24
6	4.03	2.18	4.99	6.15	3.20	+35	−1	+3	−11	−2	+47	−2	+3	+31	+35	4	2.85
7	1.01	0.79	1.30	1.13	0.82	+32	+8	−2	−4	+12	+6	+11	+0	+16	+43	0	0.21
8	1.70	0.93	1.95	1.54	0.88	+27	−66	−36	−38	−12	+36	−21	−24	+32	+18	0	0.88
9	0.86	0.55	0.99	1.02	0.65	+3	+16	−1	+0	+7	−2	+8	+4	+10	+13	3	−1.26
10	0.77	0.73	1.10	0.98	0.82	−13	−24	+11	+1	−7	+6	+0	−18	−22	−13	0	0.82
11	0.52	0.51	0.84	0.53	0.54	+9	+20	+31	−30	+0	−11	+6	+21	+26	+5	0	−0.23
12	0.81	0.58	1.16	1.02	0.72	+13	−9	−17	−36	+0	+16	−1	−41	+29	+2	2	0.76
13	1.21	0.67	1.48	1.44	0.59	+15	+23	+24	+9	+9	+24	−5	−37	−4	−10	0	−0.46
14	0.88	0.54	0.99	1.12	0.59	+34	+1	−21	+23	−3	+11	+1	−24	+27	+40	0	−0.31
15	0.66	0.70	1.16	0.78	0.70	−27	+8	+27	+22	+5	+9	+6	−6	+14	−19	0	0.35
+16	1.49	1.67	2.63	1.81	1.95	−27	−7	−13	+2	+3	+4	+5	−8	−9	−22	0	0.76
+17	0.57	0.55	1.00	0.61	0.65	+18	+24	+13	+29	−7	+11	−15	−35	−18	+11	0	−0.62
18	2.18	1.20	2.36	2.69	1.15	+24	+19	+4	−8	+3	+15	+3	−30	+26	+18	3	0.05
19	0.55	0.40	0.64	0.60	0.45	+9	−5	+3	+53	−8	−10	−4	+21	+8	+23	0	−0.84
20	0.88	0.59	1.06	0.92	0.59	+30	+39	+19	+10	+2	+8	+9	−5	+20	+32	0	0.50
21	0.84	0.51	0.95	0.84	0.56	+20	+13	−9	−10	+1	+3	+6	−16	+30	+36	2	2.05
22	0.63	0.79	1.15	0.71	0.93	−6	−1	−10	−16	−14	+8	−12	−26	−6	+7	0	−0.40
23	0.90	0.52	0.95	0.91	0.55	+17	+10	+12	−23	+19	+9	+15	−1	+10	+36	0	0.32
24	1.00	0.61	1.21	1.21	0.55	+3	−12	+21	−10	+12	+27	+1	−37	−2	−13	1	0.24
25	0.88	0.81	0.98	0.73	0.68	−32	+18	−7	+2	−14	+2	−10	−25	+10	−2	2	−0.52
26	1.00	0.83	1.34	1.42	0.75	+42	−13	−12	−12	−16	+33	−24	−55	+25	+31	0	−0.56
27	0.82	0.73	1.38	0.95	0.94	−2	−6	+7	+19	−3	+6	−4	−34	−15	−4	2	−0.07
28	0.71	0.60	1.05	0.83	0.78	+5	−3	−11	+17	−15	+26	−14	−45	+8	+8	0	−0.76
29	0.75	0.92	1.40	0.79	1.09	−9	−11	−18	−24	−8	−3	−11	−24	+8	+0	0	−0.23
30	0.53	0.53	0.88	0.72	0.54	+7	+11	+26	−9	−5	−14	+2	+14	+16	−8	0	0.03
31	1.06	0.61	1.05	1.49	0.69	+19	+17	−4	−33	+14	−2	+22	+10	+7	−7	0	−0.07
32	0.78	0.74	1.29	0.94	0.79	−18	+7	+18	+4	+8	+8	+8	+2	+19	−12	2	0.61
33	0.90	0.48	1.09	1.39	0.47	+30	−31	−6	−25	+2	+33	−14	−38	+30	+23	0	0.26
34	0.61	0.43	0.74	0.64	0.43	+15	+32	+13	+0	+4	+2	+7	−7	+15	+9	0	1.99
35	1.13	0.69	1.45	1.66	0.62	+29	−34	−22	−22	−7	+44	−14	−47	+26	+19	2	1.25
36	0.82	0.53	0.96	0.85	0.60	+26	+15	−5	−12	+3	−1	+7	−11	+23	+50	0	0.34
37	3.67	2.50	2.72	2.23	2.14	+10	−14	−8	−13	−9	+12	−9	−26	+11	−4	2	−0.24
38	0.64	0.68	0.78	0.74	0.84	+10	−4	−14	+5	+9	−5	+7	−4	+3	+13	0	−1.56
39	0.95	0.61	1.18	1.40	0.57	+30	−2	−2	−32	−6	+17	−12	−47	+14	+11	2	−0.03
+4[illegible]	3.83	3.95	4.25	4.14	3.75	−11	−9	+24	−4	+12	+17	+8	−21	+12	−10	7	1.79

图 34: Hipparcos 主星表 [15]



Accuracy and precision (2): ISO definitions

- **Accuracy:** The closeness of agreement between a test result and the accepted reference value
  - "a test result" = an observed, calculated or estimated value
  - "the accepted reference value" = the true value
- **Precision:** The closeness of agreement between independent test results obtained under stipulated conditions
  - repeatability: precision under similar conditions
  - reproducibility: precision under different conditions
- **Trueness:** The closeness of agreement between the average value obtained from a large series of test results and the accepted reference value (cf. bias, unbiasedness)

Accuracy = precision + trueness

Sept-Oct 2006 Statistics for astronomers (L. Lindegren, Lund Observatory) Lecture 1, p. 7

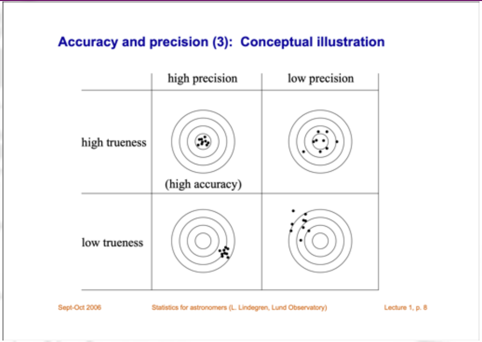
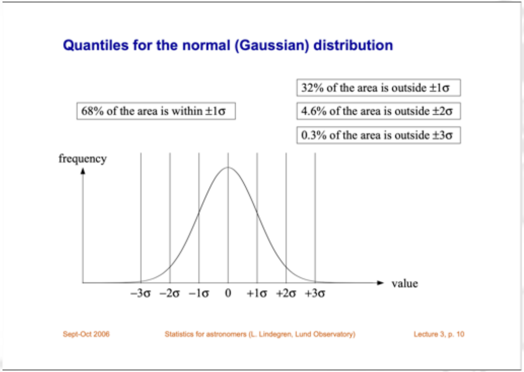


图 35: 相关概念示意图, 摘自`http://www.astro.lu.se/~lennart/statistics1.pdf`

- 精度是指误差分布的密集或离散程度，表征了观测结果的偶然误差大小程度。
- 准确度是指随机变量的真值与其数学期望之差，表征了观测结果的系统误差大小程度。
- 精确度是精度和准确度的合成，是指观测结果与其真值的接近程度，包括观测结果与其数学期望接近程度和数学期望与其真值的偏差。



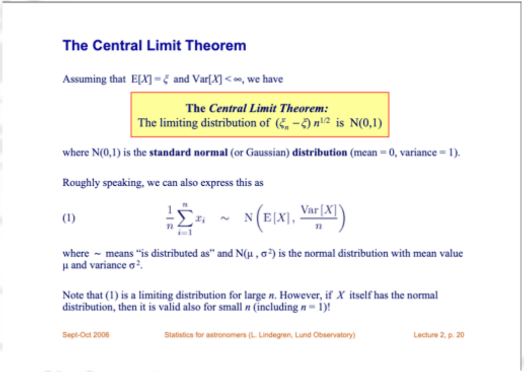


图 36: 摘自http://www.astro.lu.se/~lennart/statistics3.pdf（左）和http://www.astro.lu.se/~lennart/statistics2.pdf（右）

- 正态（高斯）分布的概率密度函数：$f(x;\mu,\sigma) = \frac{1}{\sigma\sqrt{2\pi}}\exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$;
- 随着观测次数 N 的增加，观测结果的精度 $\propto \frac{1}{\sqrt{N}}$.

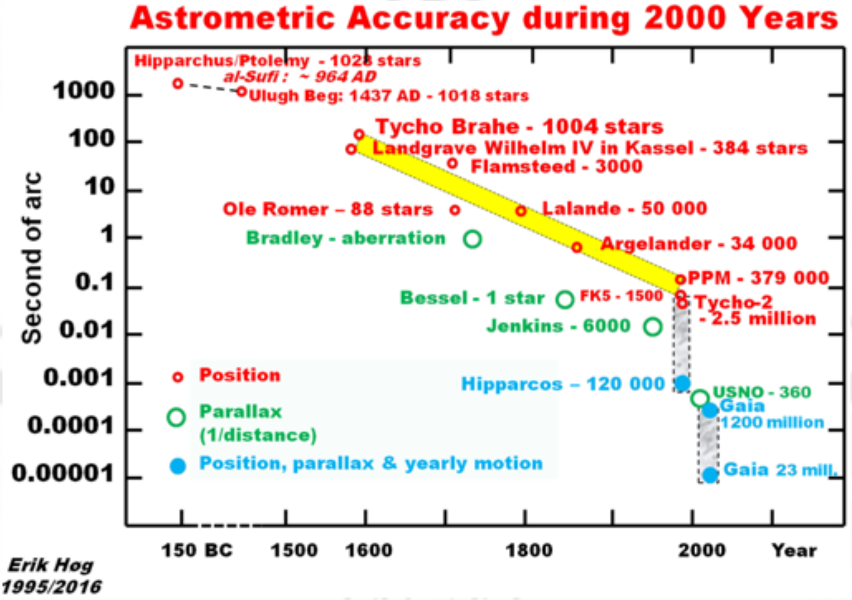


图 37: 星表精确度随时间的变化 [17]

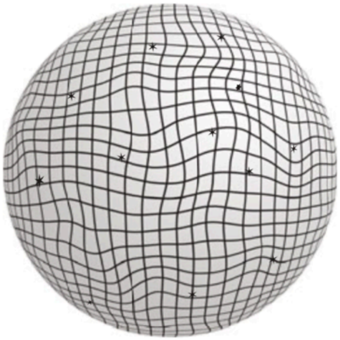


图 38: 参考架的“扭曲”，摘自https://www.astro.princeton.edu/~strauss/perryman/perryman1-astrometry-hipparcos

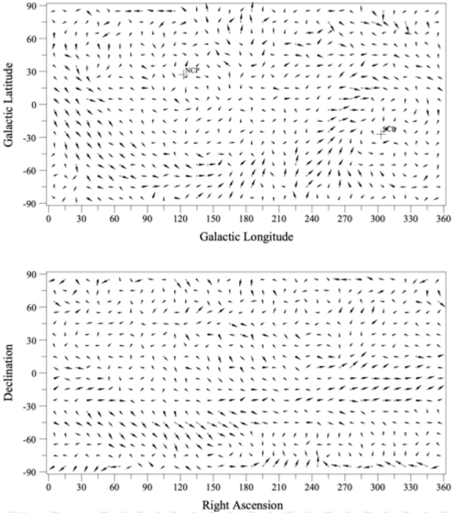


图 39: 地面 PPM 与 Hipparcos 星表的自行差异 [18]

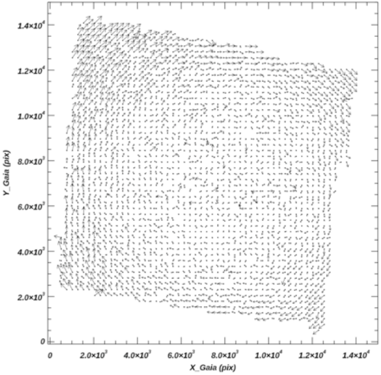


Figure 5: The difference in position between the Gaia and HST coordinates systems before applying global rotation and global offsets in X and Y positions. The maximum length of the vector is 19 pixels (950 mas) and each vector magnified by a factor 30. The tangent-plane positions X and Y are in units of the ACS/WFC pixels

图 40: HST/WFC3 与 *Gaia* EDR3 的位置比较 [19]

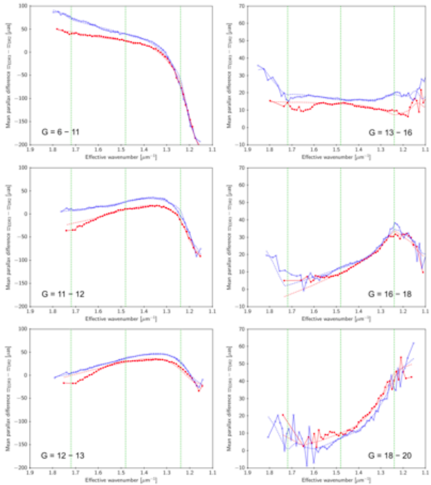


Fig. 4. Mean difference in parallax between EDR3 and DR2 as a function of effective wavenumber for several ranges of the G magnitude. Circles connected by solid lines are weighted mean values computed in bins of variable size, with at least 1000 sources per bin, and dashed lines are mean values of the fitted parametrised function ΔZ (Eq. (5)), binned as for the sources. Filled red circles are for sources with $\beta > 0$, and open blue circles for $\beta < 0$. The vertical dashed lines mark the breakpoints for the basis functions $c_j(\nu_{\rm eff})$ in Eq. (A.3), i.e. the clamping limits at 1.24 and 1.72 μm^{-1} and the midpoint at 1.48 μm^{-1}.

图 41: *Gaia* EDR3 视差零点与星等和有效波数的关系 [20]

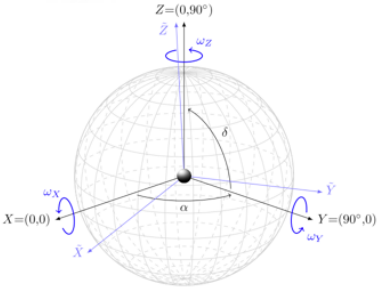


Fig. 3. ICRF modeled as an orthogonal vector triad C = [X Y Z]. The transformation from C to C̃ = [X̃ Ỹ Z̃] is obtained by applying the spin ω = [ωX ωY ωZ], which is a combination of rotations around the axes X, Y, and Z.

图 42: 参考架旋转示意图 [21]

- 参考架坐标轴的指向差异（orientation angle）– 旋转 (Rotation) 矢量 $\boldsymbol{R} = (R_X, R_Y, R_Z)^{\mathrm{T}}$，对天球坐标的影响为

$$
\begin{aligned}
\boldsymbol{V}^R &= \boldsymbol{R} \times \boldsymbol{u} \\
\Delta\alpha^* &= -R_X \sin\delta\cos\alpha - R_Y \sin\delta\sin\alpha + R_Z \cos\delta \\
\Delta\delta &= R_X \sin\alpha - R_Y \cos\alpha
\end{aligned} \tag{57}
$$

- 参考架的指向差异变化率 – 自转 (spin) 矢量 $\boldsymbol{\omega} = (\omega_X, \omega_Y, \omega_Z)^{\mathrm{T}}$, 对天球坐标的影响为

$$
\begin{aligned}
\boldsymbol{V}^R &= \boldsymbol{\omega} \times \boldsymbol{u} \\
\mu_{\alpha^*} &= -\omega_X \sin\delta\cos\alpha - \omega_Y \sin\delta\sin\alpha + \omega_Z \cos\delta \\
\mu_\delta &= \omega_X \sin\alpha - \omega_Y \cos\alpha
\end{aligned} \tag{58}
$$

ICRF 的精准度评估和维持 (maintenance)

ICRF 的精准度评估包括：

- 对系统误差的建模和优化
- VLBI 星表的内部符合水平
  VLBI 星表形式误差的真实性
  参考架轴稳定性评估
  模型误差
- VLBI 星表的外部符合水平
  系统误差的上限

对 ICRF 的精确度分析，可以指出理论模型中需要的改进之处，从而利用新的研究进展来弥补任何 ICRS 模型中的不足、减小系统误差指标。持续的模型改进和对参考天体的持续监测，就是 ICRF 的维持。

一般认为，河外射电源与我们的距离位于本星系群（Local group）和宇宙微波背景（Cosmic microwave background）之间。

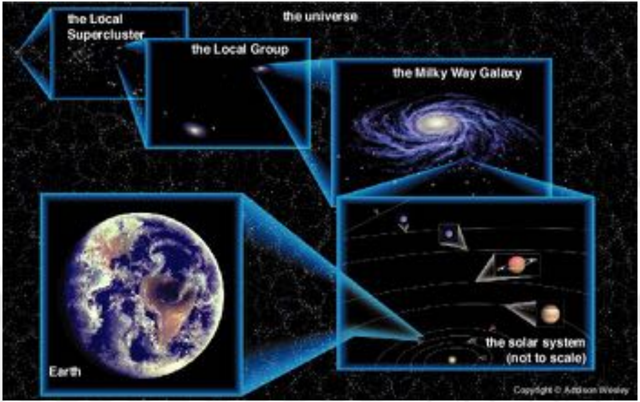


TABLE VI. Solar System velocity relative to various standards of rest.

Reference	Velocity (km/s)	l (deg)	b (deg)
Local standard of rest[a]	20±1	57	23
Galactic center[a,b]	240±5	90	0
Local group[c]	308±23	105	−7
Cosmic microwave background[d]	370±3	264	48

[a]Kerr and Lynden-Bell (1986).
[b]Fich *et al.* (1989).
[c]Yahil *et al.* (1977).
[d]Kogut *et al.* (1993).

图 43: 宇宙的分级模型[1]（左）和太阳系质心相对于多种静止标准的速度 [2]。

[1]https://www.pinterest.fr/pin/266556871673047219/

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ICRS 的系统误差（1）– 视差效应

太阳系绕银心的轨道运动周期约为 2.4 亿年，运动的角速度为

$$\omega_{\mathrm{SSB}} \approx \frac{2\pi}{2.4\times 10^{8}\ \mathrm{yr}} = 2.6\times 10^{-8}\ \mathrm{rad/yr} = 5.2\ \mathrm{mas/yr} \tag{59}$$

假设太阳系到银心的距离为

$$d = 8.5 \pm 1\ \mathrm{kpc} \approx 2.7\times 10^{4}\ \mathrm{ly} \tag{60}$$

对于银河系内银心距与 d 相当的恒星，视自行约为 $5.2\ \mathrm{mas/yr}$。
对于河外源，假设其距离为 $10^9\ \mathrm{ly}$，其视自行约为

$$5.2\ \mathrm{mas/yr} \times \frac{d}{10^{9}\ \mathrm{ly}} \approx 5.2\ \mathrm{mas/yr} \times 3\times 10^{-5} \leq 0.16\ \mu\mathrm{as/yr} \tag{61}$$

ICRS 的系统误差（2）– 长期光行差效应（Galacitc aberration effect）

长期光行差效应指由于太阳系质心相对于河外源背景的加速运动引起的河外源的视自行现象，若加速度为 $\boldsymbol{a}$，则视自行为 $\frac{\mathrm{d}(\delta\boldsymbol{u})}{\mathrm{d}t} = \frac{\boldsymbol{a}}{c} - \frac{\boldsymbol{a}\cdot\boldsymbol{u}}{c}\boldsymbol{u}$。

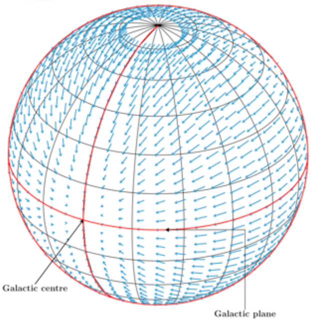

Fig. 2. Proper motion field of QSO-like objects induced by the centripetal galactic acceleration. There is no effect in the directions of the galactic centre and anti-centre, and a maximum in the plane passing through the galactic poles with nodes at 90–270° in galactic longitudes. The plot is in galactic coordinates with the Solar System at the centre of the sphere, and the vector field seen from the exterior of the sphere. Orthographic projection with viewpoint at $l = 30°, b = 30°$ and an arbitrary scale for the vectors. See also an online movie.

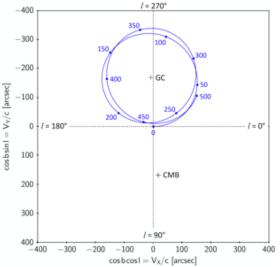

Fig. 1. Galactic aberration over 500 Myr for an observer looking towards Galactic north. The curve shows the apparent path of a hypothetical quasar, currently located exactly at the north galactic pole, as seen from the Sun (or solar system barycentre). The points along the path show the apparent positions after 0, 50, 100, . . . Myr due to the changing velocity of the Sun in its epicyclic orbit around the galactic centre. The point labelled GC is the position of the quasar as seen by an observer at rest with respect to the galactic centre. The point labelled CMB is the position as seen by an observer at rest with respect to the cosmic microwave background. The Sun's orbit was computed using the potential model by McMillan (2017) (see also Sect. 4), with current velocity components derived from the references in Sect. 4.1. The Sun's velocity with respect to the CMB is taken from Planck Collaboration III (2020).

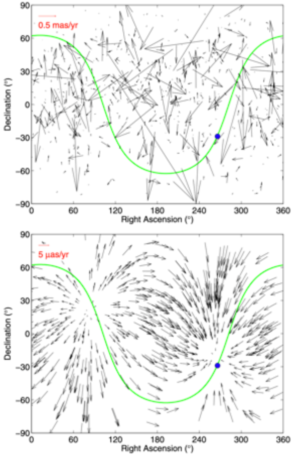

Fig. 3. (*Top*) The proper motions of the 555 sources, and (*bottom*) the estimated dipole component of the velocity field. The green line represents the equator of the Milky Way, whose center is indicated by the blue marker.

图 44: 长期光行差效应对河外源视位置的影响（左图和中图）[22] 以及 VLBI 的观测（右图)[23]

ICRS 的系统误差（3）– 银心的引力时延

- 对于地基 VLBI，一般只需要考虑太阳系主要天体（太阳、行星、地球和月球）的引力贡献。实际上，银河中心（$M_{\rm total} \simeq 1 \times 10^{11}\ M_{\odot}$）的引力也会有额外的贡献。

- 假设核球质量占整个银河系质量的 2/3，且银心距为 8.5 Kpc，可以估算知银心区的物质对电磁波信号的引力时延将是太阳的 40 倍左右。

- 当信号源距离银心区约 10° 以内时，银心引力作用将使信号源的视方向偏折约 4 角秒。

- 但是，由于太阳系绕银心旋转极慢（周期约为 2.4 亿年），这一光线偏折的变化很小。

- 因此，从实用角度出发，银心偏折只对天空中的信号传播产生准静态的偏折，这一影响被暗含在河外源位置中，即被吸收在参考架中。

ICRF 星表的内在符合水平检验

星表的内在符合水平检验包括:

- 同一数据的子数据集之间的符合程度
- 相同数据、不同理论模型之间的符合程度
- 相同数据、不同分析方法之间的符合程度
- ...

检测量包括:

- 基线长度
- 天极的位置
- ...

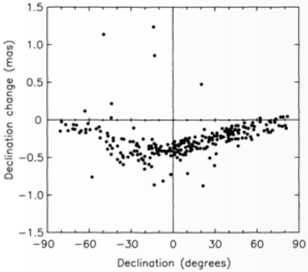

Fig. 6.3. The effect of tropospheric gradients on declinations as a function of declination. The sense is declination with gradients estimated minus declination without gradients estimated (After MacMillan & Ma 1997)

图 45: 大气模型（是否估算大气梯度参数）对星表位置的影响 [1]

最小二乘估计一般假设残差（$O-C$）服从正态分布，但实际上 VLBI 时延残差还存在与观测站相关的等其他形式误差，因而最小二乘拟合给出的参数形式误差通常是被低估的，即小于实际的测量精确度。

VLBI 星表是由对所有 VLBI 历史观测资料的单次最小二乘估计生成的，一般认为 VLBI 解算中的河外源位置误差 σ 需要被人为地放大，以接近实际的测量精确度 ξ:

$$\xi = \sqrt{(s \cdot \sigma)^2 + f^2} \tag{62}$$

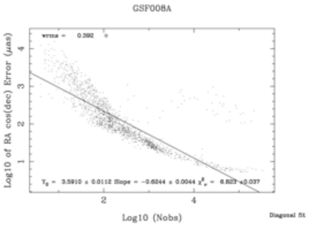

Figure 44: gsf008a catalogue's dependence of un-inflated $\sigma_{\alpha\cos(\delta)}$ on the number of observations for sources observed in at least two sessions. A slope of −0.5 would correspond to $1/\sqrt{N_{obs}}$ averaging of white noise. Calibrator survey's ≈ 2000 single-session densifying sources are not shown.

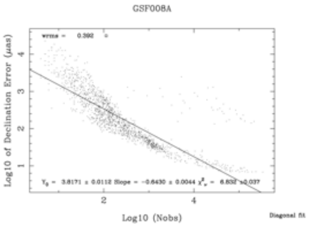

Figure 45: gsf008a catalogue's dependence of un-inflated σ_δ on the number of observations for sources observed in at least two sessions. A slope of −0.5 would correspond to $1/\sqrt{N_{obs}}$ averaging of white noise. Calibrator survey's ≈ 2000 single-session densifying sources are not shown.

图 46: VLBI 位置形式误差分布 [13]

通过将 VLBI 观测数据随机分为数量相等的两组，分别处理，以得到的 VLBI 星表位置之间的符合程度（如 WRMS）来表征真实测量精确度。

例如，对于 ICRF2，$s = 1.5$，$f = 40\,\mu as$。

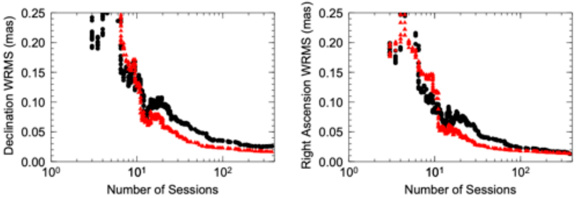

Figure 21: Wrms noise (solid circles) for subsets of 50 sources in each solution as a function of the minimum number of sessions a source was observed. The median formal uncertainty (red triangles) in each subset is shown for comparison. These were derived from differences between positions in the two decimation solutions.

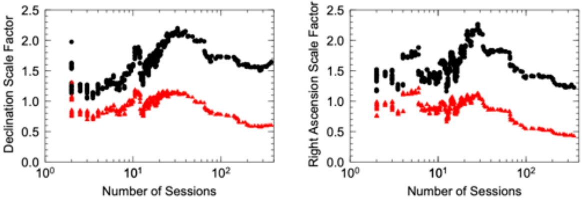

Figure 22: Error scaling factor (solid black circles) for each subset of 50 sources in each solution as a function of the minimum number of sessions a source was observed. The residual scaling factor (red triangles) after application of a scale factor of 1.5 to the formal uncertainties followed by a root-sum-square increase of 40 μas.

图 47: ICRF2 星表误差评估 [13]

ICRF 轴稳定性水平是指由于定义源视位置随时间的变化或选择不同的河外源作为定义源而导致的参考架坐标轴在空间晃动的水平。

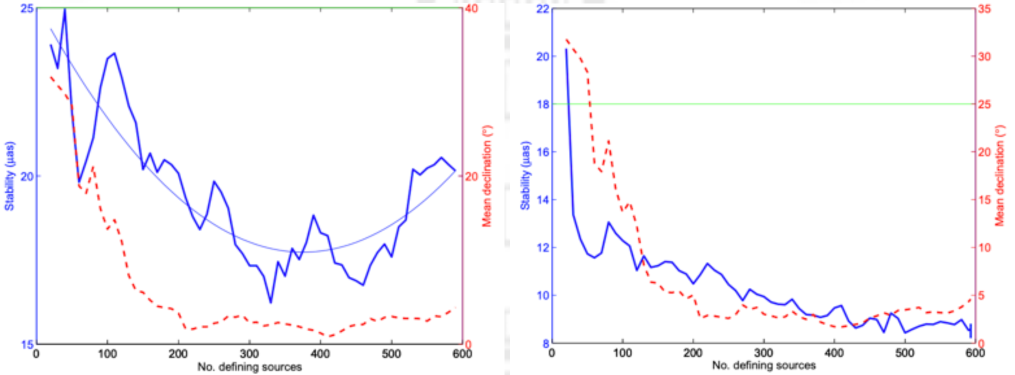

Figure 35: Axes stability and average declination of various subsets of sources of increasing size tested on annual catalogs.

Figure 36: Axes stability and average declination of various subsets of sources of increasing size checked on randomly-selected subsets.

图 48: ICRF2 轴稳定性评估 [13]

ICRF 星表的外在符合水平检验

星表的内在符合水平检验包括:

- 独立的数据集之间的符合程度
- 不同分析方法的符合程度
- 不同处理软件的符合程度
- ...

检测量与星表的内在符合水平检验的检测量相同。

右图反映出 JPL 观测站在南半球的分布少而导致的系统误差。

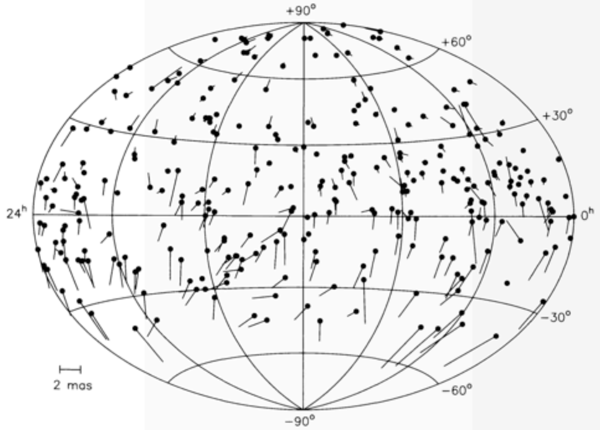

Fig. 6.4. Vector differences between JPL and GSFC catalogues. The lengths of the vectors represent the magnitude of the difference of the positions (as indicated by the key) while the orientations of the vectors represent the direction in which the positions differ on the sky

图 49: JPL 与 GSFC 的 VLBI 星表比较 [1]

- 经典方法:
  (1) 假设任一子星表的观测位置都包含系统误差：$\alpha_{\text{true}} + \Delta c^{\alpha} = \alpha_{\text{obs}}, \quad \delta_{\text{true}} + \Delta c^{\delta} = \delta_{\text{obs}}$
  (2) 假设一颗河外源有 n 个观测位置：

$$\Delta\alpha + \Delta c_i^{\alpha} = (\alpha_{\text{obs}})_i - \alpha_0, \Delta\delta + \Delta c_i^{\delta} = (\delta_{\text{obs}})_i - \delta_0, i = 1, \ldots, n \tag{63}$$

  (3) 假设星表位置的改正值服从正态分布: $\sum_{i=1}^{n} w_i^{\alpha} \Delta c_i^{\alpha} = 0, \quad \sum_{i=1}^{n} w_i^{\delta} \Delta c_i^{\delta} = 0$

- 观测方法:
  (1) 对每次观测进行单独解算，估计局部参数;
  (2) 固定局部参数值，利用所有的观测解算河外源的位置。

- IERS 星表综合方法:
  (1) 利用每一年的观测解算出年平均星表；
  (2) 假设年平均星表与综合星表之间存在旋转：$\boldsymbol{s}_i = \boldsymbol{R}^{(i)} \boldsymbol{s}_c$
  (3) 假设总的旋转为零：$\sum_{i=1}^{k} w_i R_s^{(i)} = 0, \quad s = 1, 2, 3$

附录

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