天文参考系

Astronomical Reference Systems

刘　牛
南京大学　天文与空间科学学院
niu.liu@nju.edu.cn

2022 年 1 月 10 日

盖亚天体测量

Gaia Astrometry

章节安排

1. *Gaia* 空间望远镜观测
2. *Gaia* 参考架的建立与精度分析
3. 未来天体测量

Gaia 空间望远镜观测

Gaia 项目 [1]

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2. 科学目标
3. 探测器和有效载荷的设计和特性
4. 卫星发射和调试
5. 观测运行
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7. DPAC 结构和处理数据流程
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Special issue

Gaia Data Release 1

The *Gaia* mission*

Gaia Collaboration, T. Prusti[1,**], J. H. J. de Bruijne[1], A. G. A. Brown[2], A. Vallenari[3], C. Babusiaux[4], C. A. L. Bailer-Jones[5], U. Bastian[6], M. Biermann[6], D. W. Evans[7], L. Eyer[8], F. Jansen[9], C. Jordi[10], S. A. Klioner[11], U. Lammers[12], L. Lindegren[13], X. Luri[10], F. Mignard[14], D. J. Milligan[15], C. Panem[16], V. Poinsignon[17], D. Pourbaix[18,19], S. Randich[20], G. Sarri[21], P. Sartoretti[4], H. I. Siddiqui[22], C. Soubiran[23], V. Valette[16], F. van Leeuwen[7], N. A. Walton[7], C. Aerts[24,25], F. Arenou[4], M. Cropper[26], R. Drimmel[27], E. Høg[28], D. Katz[4], M. G. Lattanzi[27], W. O'Mullane[12], E. K. Grebel[6], A. D. Holland[29], C. Huc[16], X. Passot[16], L. Bramante[30], C. Cacciari[31], J. Castañeda[10], L. Chaoul[16], N. Cheek[32], F. De Angeli[7], C. Fabricius[10], R. Guerra[12], J. Hernández[12], A. Jean-Antoine-Piccolo[16], E. Masana[10], R. Messineo[30], N. Mowlavi[8], K. Nienartowicz[33], D. Ordóñez-Blanco[33], P. Panuzzo[4], J. 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* http://www.cosmos.esa.int/gaia
** Corresponding author: T. Prusti, e-mail: tprusti@cosmos.esa.int

Gaia 项目历史回顾

- 1990 年代早期 Høg 提出了 Rømer 项目提案，Lindegren 和 Perryman 随后于 1993 年提出了 *Gaia* 项目，之后 Perryman 等人在 2001 年描述了相应的科学任务和航天器概念。
- 在 2000 年,*Gaia* 项目被确定为只有欧洲航天局参与的任务，并于 2006 年开始进入实施阶段。
- *Gaia* 卫星于 2013 年 12 月发射，经过半年的调试后，2014 年夏季开始开始正式进入预期为 5 年的科学运行阶段。
- 项目周期延长 5 年，一直到 2024 年年中，最终数据预计在 2027 年发布。
- 起初，*Gaia* 拼写为 *GAIA* (Global Astrometric Interferometer for Astrophysics)，但最终的工作原理是基于单片反射镜和直接成像（与 Rømer 项目类似）而非干涉测量，拼写才改为现在的形式。

Gaia 项目的科学目标

Gaia 的主要科学目标是银河系，依赖于天体测量巡天，并结合了光度测量和光谱测量巡天。

- 银河系的结构、动力学和演化
- 银河系的恒星形成历史
- 恒星物理和演化
- 恒星光变和距离尺度
- 双星和多星系统
- 系外行星
- 太阳系内天体
- 本星系群
- 无法分辨的星系、类星体和参考系
- 基本物理学

Gaia 航天器和有效载荷

Gaia 卫星由三部分组成:

- 有效载荷模块（payload module, PLM）
- 机械服务模块（mechanical service module，M-SVM）
- 电子服务模块（electrical service module，E-SVM）

右图为 *Gaia* 卫星的分解示意图

(a) 有效载荷保温罩

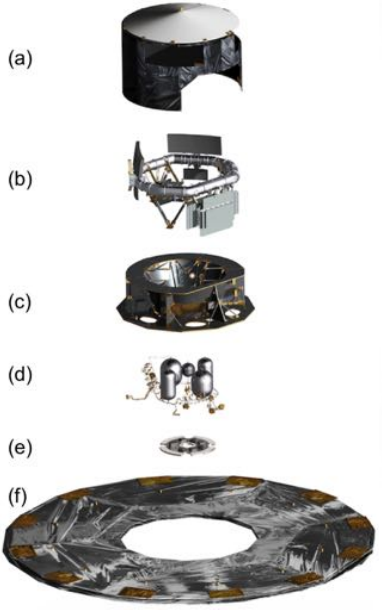
(b) 有效载荷模块：光学平台、望远镜、仪器和焦平面组件

(c) 服务模块，还包含一些电子有效载荷设备，例如：授时单元、视频处理单元和有效载荷数据处理单元

(d) 推进剂系统

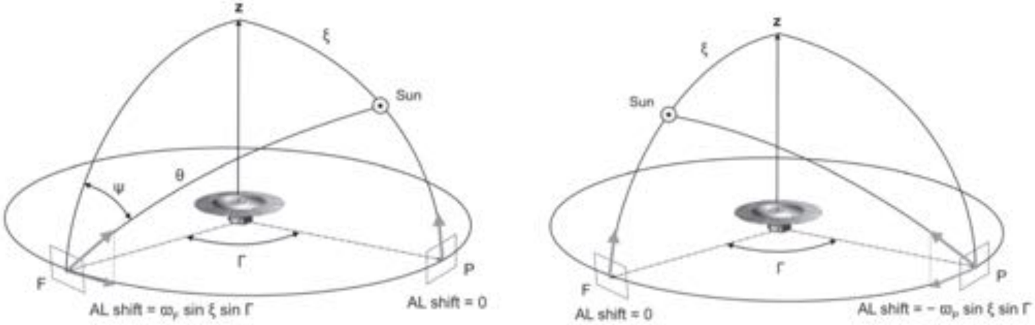
(e) 相控阵 (phased-array) 天线

(f) 可展开的遮阳板组件，包括太阳能电池板



Gaia 测量是一种扫描空间天体测量（scanning space astrometry）。*Gaia* 卫星在空间中缓慢自转，测量目标通过焦平面的的时刻，这些观测时刻代表天体相对于仪器轴的沿扫描方向 (ALong-scan) 的一维位置。观测量与天体的位置、仪器指向关于时间的函数（姿态）以及焦平面像素通过望远镜投影到天球上的光学映射（几何校准）相关，通过天体测量全局迭代解 (AGIS) 得到最终的 *Gaia* 天体测量星表。

基本角 $\Gamma = 106.5°$，望远镜自转轴与太阳夹角 $\xi = 45°$。



Gaia 光学系统

Gaia 望远镜口径为 $1.45\,\mathrm{m}\times 0.50\,\mathrm{m}$，焦距为 35 m。整个光路由六面反射镜组成：前三个（M1–M3 和 M1′–M3′）形成三镜反像散望远镜 (three-mirror anastigmatic telescopes, TMA)，第四个是平面光束组合器（M4 和 M4′），最后两个是平面折叠镜，用于公共光路

Gaia 光学系统 [2]

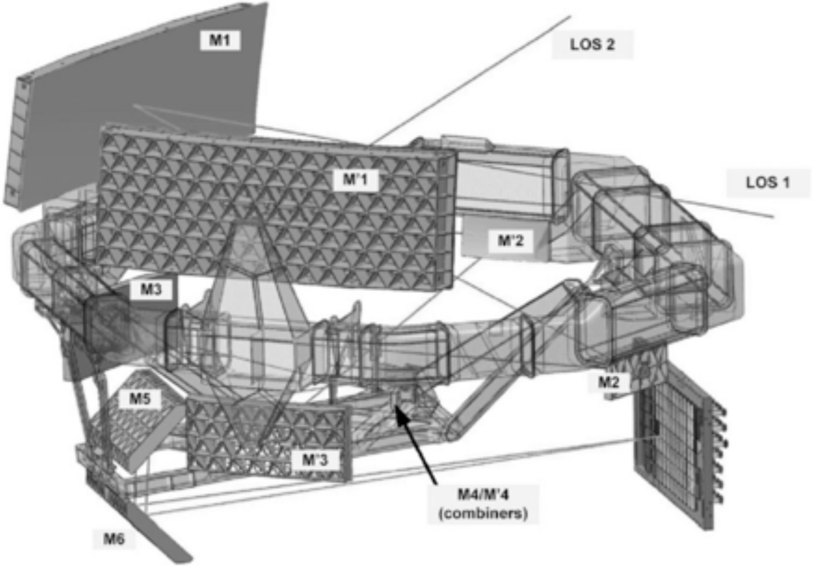


Fig. 2.3 The optical instrument of Gaia, comprising two telescopes (mirrors M1–M6 and M′1–M6), with a common focal plane, on a ring-shaped optical bench of ∼3.5 m diameter. M4/M′4 is the beam combiner situated at the exit pupil. LOS 1 and LOS 2 are the lines of sight for the two optical systems. (Image credit: EADS Astrium.)

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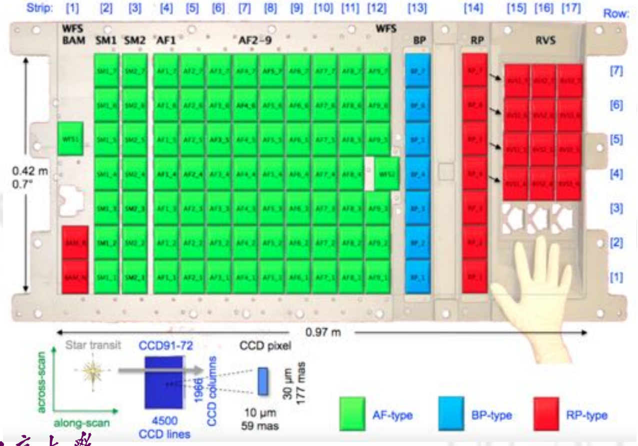
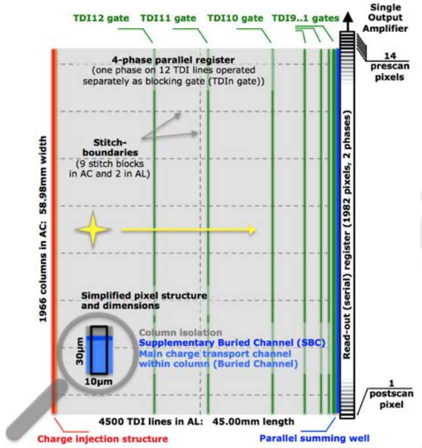
焦平面

1. 仪器监测系统：波前传感器（wave-front sensing，WFS）和基本角度监测（basic angle monitoring，BAM）
2. 天体检测系统（sky mapper，SM）
3. 天体测量系统（astrometric field，AF）
4. 低分辨率测光系统，分为蓝光（blue photometer，BP）和红光（red photometer，RP）
5. 径向速度光谱仪（radial-velocity spectrometer，RVS）





Gaia 窗口等级（Windows Class, WC）[3]

Table 1. Specification of the downlinked window geometry by onboard estimated G magnitude and CCD strip.

Strip	$G<13$	$13<G<16$	$16<G$
SM	WC0: 40×6 (2×2) PSF	WC1: 20×3 (4×4) PSF	
AF1	WC0: 18×6 (1×2) PSF	WC1: 12×1 (1×12) LSF	WC2: 6×1 (1×12) LSF
AF2–9	WC0: 18×12 (1×1) PSF	WC1: 18×1 (1×12) LSF	WC2: 12×1 (1×12) LSF

Notes. In each case the window class (WC) is given followed by the number of samples in the AL and AC directions, the number of pixels in the AL and AC directions that have been binned to produce each sample (in brackets), and whether the resulting observation corresponds to the LSF or PSF. The solid black lines indicate the geometry of each sample and their arrangement to form the window; the faint dashed lines indicate the pixels that have been binned to produce each sample. A combination of on-chip and numerical (software) binning is applied to optimise onboard performance and telemetry budget.

卫星发射和调试

Gaia 卫星于 2013 年 12 月 19 日 09:12:19.6（UTC）发射，用了 26 天转移到 L2 点。

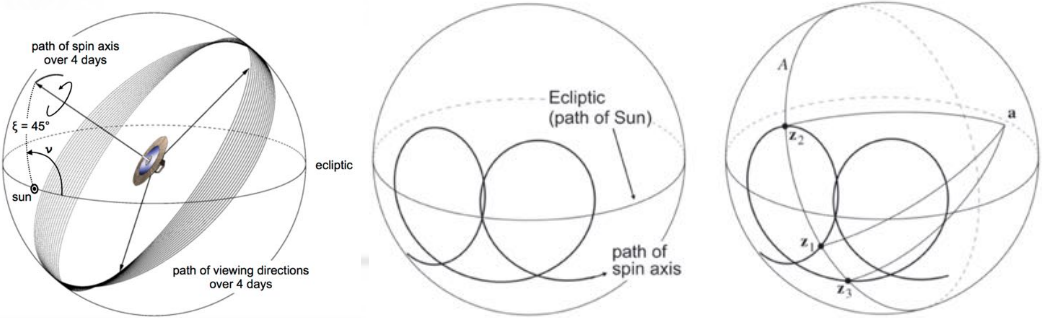
早期的观测用于仪器调试和性能验证，发现各个系统都正常工作，但也有一些小问题：

- 化学推进器 3B 的锁阀门卡在关了闭位置
- 微推进推进器（micro-propulsion thrusters）的质量传感器有偏差
- Micro-clanks 现象：卫星的自转速度有周期性跃变（约每分钟一次），通常高达每秒几毫角秒，然后迅速恢复到偏移前的速度

此外，还发现影响有效载荷性能的三个问题：

- 水汽污染，导致光学器件的透射率随时间变化
- 来自于太阳和银河系的杂散光
- 基本角存在周期性变化

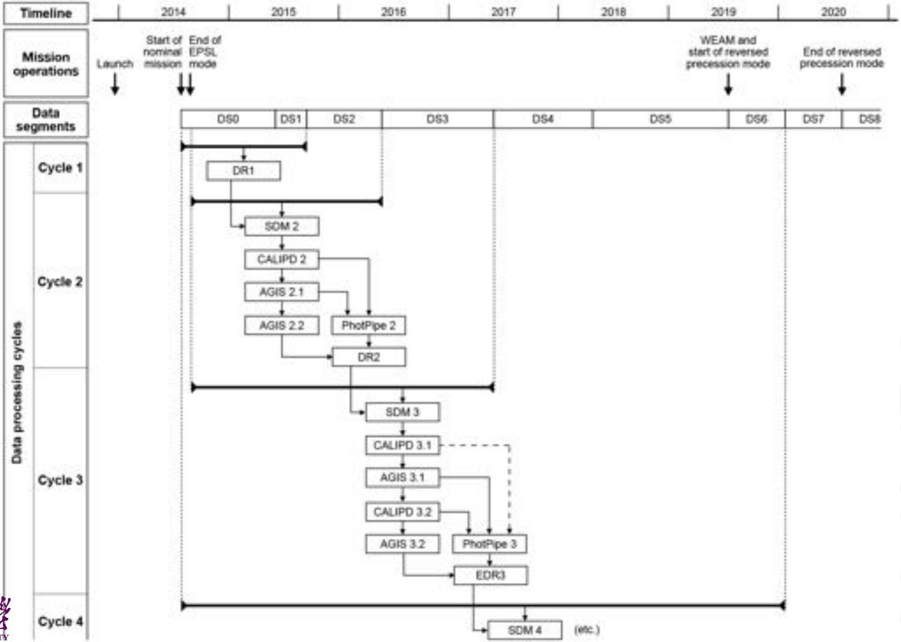
Gaia 观测运行模式



扫描定律（scanning law）可以由下列方程描述：

$$
\begin{aligned}
\dot{\upsilon}\sin\xi &= \dot{\lambda}_\odot\sqrt{S^2-\cos^2\upsilon}+\dot{\lambda}_\odot\cos\xi\sin\upsilon \\
\dot{\Omega} &= \omega_z-\dot{\lambda}_\odot\sin\xi\sin\upsilon-\dot{\upsilon}\cos\xi \\
S &= |\omega\times z|\dot{\lambda}_\odot^{-1}=4.220745
\end{aligned}
\tag{1}
$$

Gaia 数据处理和发布 [4]



Gaia 计划预期的天体测量数据质量

对于五年的观测计划，以**视差测量精度** σ_ϖ来作为衡量数据质量的指标。

对于 $3 \le G \le 20.7\,\mathrm{mag}$ 的天体，

$$
\begin{aligned}
\sigma_\varpi[\mu\mathrm{as}] &= c(V-I)\sqrt{-1.631 + 680.766 z_{12.09} + 32.732 z_{12.09}^2},\\
z_x(G) &= \max\left[10^{0.4(x-15)}, 10^{0.4(G-15)}\right], c(V-I) = 0.986 + (1-0.986)(V-I).
\end{aligned}
\tag{2}
$$

其他天体测量参数（中间历元）的精度为

$$
\begin{aligned}
\sigma_0 &= 0.743\sigma_\varpi\\
\sigma_{\alpha*} &= 0.787\sigma_\varpi\\
\sigma_\delta &= 0.699\sigma_\varpi\\
\sigma_\mu &= 0.526\sigma_\varpi\\
\sigma_{\mu_{\alpha*}} &= 0.556\sigma_\varpi\\
\sigma_{\mu_\delta} &= 0.496\sigma_\varpi
\end{aligned}
\tag{3}
$$

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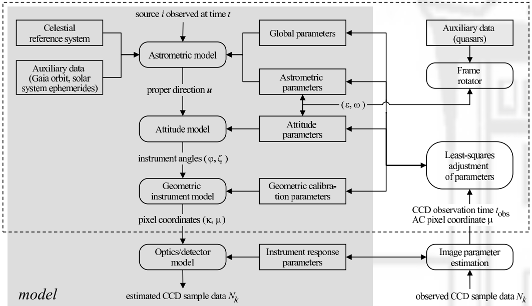
Table 1. Numerical factor to be applied to the sky-averaged astrometric standard errors of Eqs. (4) and (7) for the five astrometric parameters as a function of ecliptic latitude β, including the effect of the variation of the end-of-mission number of transits over the sky.

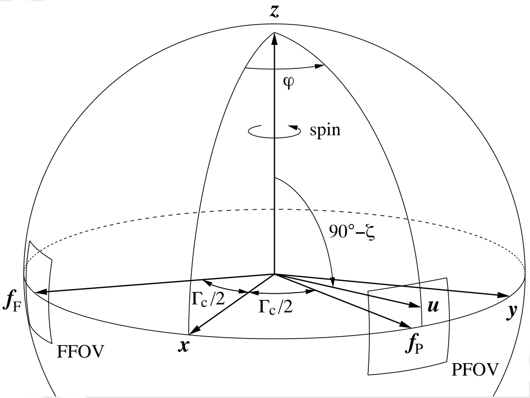
$\lvert\sin\beta\rvert$	$\beta_{\min}$ [°]	$\beta_{\max}$ [°]	$N_{\rm obs}$	$\alpha*$	δ	ϖ	$\mu_{\alpha*}$	μ_δ
0.025	0.0	2.9	61	1.026	0.756	1.180	0.725	0.542
0.075	2.9	5.7	61	1.021	0.757	1.180	0.722	0.542
0.125	5.7	8.6	62	1.002	0.751	1.169	0.710	0.537
0.175	8.6	11.5	62	0.993	0.752	1.167	0.703	0.539
0.225	11.5	14.5	63	0.973	0.751	1.158	0.689	0.538
0.275	14.5	17.5	65	0.952	0.742	1.143	0.673	0.533
0.325	17.5	20.5	66	0.934	0.740	1.136	0.662	0.533
0.375	20.5	23.6	68	0.901	0.730	1.119	0.640	0.525
0.425	23.6	26.7	71	0.861	0.718	1.098	0.614	0.515
0.475	26.7	30.0	75	0.819	0.705	1.072	0.584	0.506
0.525	30.0	33.4	80	0.765	0.691	1.043	0.548	0.493
0.575	33.4	36.9	87	0.701	0.673	1.009	0.500	0.477
0.625	36.9	40.5	98	0.631	0.650	0.970	0.541	0.461
0.675	40.5	44.4	122	0.535	0.621	0.922	0.381	0.437
0.725	44.4	48.6	144	0.469	0.607	0.850	0.327	0.423
0.775	48.6	53.1	106	0.554	0.636	0.808	0.386	0.443
0.825	53.1	58.2	93	0.603	0.654	0.779	0.422	0.456
0.875	58.2	64.2	85	0.641	0.669	0.755	0.447	0.467
0.925	64.2	71.8	80	0.668	0.680	0.731	0.466	0.473
0.975	71.8	90.0	75	0.688	0.706	0.713	0.481	0.490
Sky-average	0.0	90.0	81	0.787	0.699	1.000	0.556	0.496

Notes. The quantity $N_{\rm obs}$ in Col. 4 denotes the end-of-mission number of focal plane passages for AF, BP, and RP (both fields of view combined; recall that *Gaia* DR1 is based on 14 months of data, corresponding on average to 16 field-of-view transits). For RVS, the number of focal plane transits is a factor $4/7 = 0.57$ smaller (Sect. 3.3.7). The transit numbers in Col. 4 are based on an assumed 6% dead time (data loss). For the faintest objects ($G \gtrsim 20$ mag or $G_{\rm RVS} \gtrsim 14$ mag), the actual losses are larger (Sect. 5.3.1).

Gaia 参考架的建立与精度分析

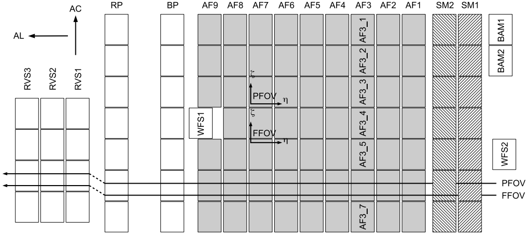
Gaia 的观测模型





- 太阳系质心天球参考系（BCRS）
- *Gaia* 质心参考系（Centre-of-Mass Reference System，CoMRS），记为 **C**
- *Gaia* 扫描参考系（Scanning Reference System，SRS），记为 **S**

$$x = \langle f_F + f_P \rangle, \quad z = \langle f_F \times f_P \rangle, \quad y = z \times x \tag{4}$$



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在 BCRS 中，假设天体运动遵循标准模型，则其视方向为

$$\overline{\boldsymbol{u}}_i(t)=\left\langle \boldsymbol{r}_i+(t_{\mathrm{B}}-t_{\mathrm{ep}})\left(\boldsymbol{p}_i\mu_{\alpha*i}+\boldsymbol{q}_i\mu_{\delta i}+\boldsymbol{r}_i\mu_{ri}\right)-\varpi_i\boldsymbol{b}_{\mathrm{G}}(t)/A_{\mathrm{u}}\right\rangle \tag{5}$$

其中

$$\mathrm{C}'\left[\boldsymbol{p}_i\ \boldsymbol{q}_i\ \boldsymbol{r}_i\right]=\begin{bmatrix}-\sin\alpha_i & -\sin\delta_i\cos\alpha_i & \cos\delta_i\cos\alpha_i\\ \cos\alpha_i & -\sin\delta_i\sin\alpha_i & \cos\delta_i\sin\alpha_i\\ 0 & \cos\delta_i & \sin\delta_i\end{bmatrix} \tag{6}$$

假设天体测量参数记为 $\boldsymbol{s}_i$（包括 α_i，δ_i，ϖ_i，$\mu_{\alpha*i}$，$\mu_{\delta i}$，并假设视向速度由 RVS 给出），全局参数为 $\boldsymbol{g}$（如 PPN 参数 γ），外部数据记为 $\boldsymbol{h}$（如历表），则在 CoMRS 中天体的视方向为

$$\boldsymbol{u}_i(t)=\boldsymbol{u}\left(\boldsymbol{s}_i,\boldsymbol{g}\mid t,\boldsymbol{h}\right) \tag{7}$$

SRS（$S = \begin{bmatrix} x & y & z \end{bmatrix}$）相对于 CoMRS（$\mathrm{C} = \begin{bmatrix} X & Y & Z \end{bmatrix}$）的旋转可以用一个姿态矩阵来表示

$$\boldsymbol{A} \equiv \begin{bmatrix} A_{xx} & A_{xy} & A_{xz} \\ A_{yx} & A_{yy} & A_{yz} \\ A_{zx} & A_{zy} & A_{zz} \end{bmatrix} = \mathrm{S}'\mathrm{C} = \begin{bmatrix} x'X & x'Y & x'Z \\ y'X & y'Y & y'Z \\ z'X & z'Y & z'Z \end{bmatrix} \tag{8}$$

也可以用单位四元数来表征

$$\boldsymbol{q} = \{q_x, q_y, q_z, q_w\} \tag{9}$$

则任一矢量 $\boldsymbol{v}$ 在两个坐标系统之间的转换为

$$\{S'\boldsymbol{v}, 0\} = \boldsymbol{q}^{-1}\{C'\boldsymbol{v}, 0\}\,\boldsymbol{q} \tag{10}$$

卫星姿态与时间的关系可以用 B 样条函数来表示

$$\boldsymbol{q}(t) = \left\langle \sum_{n=\ell-M+1}^{\ell} \boldsymbol{a}_n B_n(t) \right\rangle \tag{11}$$

姿态参数记为 $\boldsymbol{a}$。

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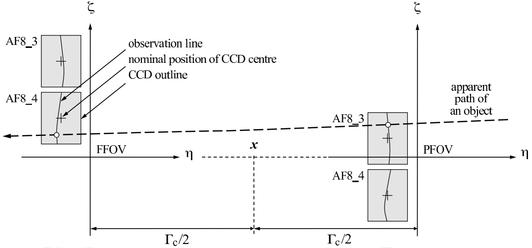
仪器几何模型

仪器几何模型表征的是 CCD 像素坐标 μ 的关系为与视场坐标（η,ζ）之间的关系，与下列因素有关

- 每块 CCD 的物理几何特征
- CCD 在焦平面的位置
- 光学系统，如扭曲和像差
- 基本角 Γ_c



$$\left.\begin{aligned}\eta_{fng}(\mu,t) &= \eta^0_{ng} + \textstyle\sum_{r=0}^{2} \Delta\eta_{rfngj} L^*_r\left(\frac{\mu-13.5}{1966}\right) + \delta\eta_{ngkm} \\ \zeta_{fng}(\mu,t) &= \zeta^0_{fng}(\mu) + \textstyle\sum_{r=0}^{2} \Delta\zeta_{rfngk} L^*_r\left(\frac{\mu-13.5}{1966}\right)\end{aligned}\right\} \tag{12}$$

其中，n 为 CCD 编号，g 为快门编号，f 为视场编号，$L^*_r(x)$ 为 Legendre 多项式。仪器几何参数记为 $\boldsymbol{c}$。

最原始的观测量为光电子信号，与 CCD 像素坐标 κ 的关系为

$$\lambda_k \equiv \mathrm{E}\left(N_k\right) = \beta + \alpha L(k-\kappa) \tag{13}$$

全局优化问题

$$\begin{aligned}
&\min_{s,a,c,g} Q = \sum_{l\in \mathrm{AL}} \frac{\left(R_l^{\mathrm{AL}}\right)^2 w_l^{\mathrm{AL}}}{\left(\sigma_l^{\mathrm{AL}}\right)^2+\left(\epsilon_l^{\mathrm{AL}}\right)^2} + \sum_{l\in \mathrm{AC}} \frac{\left(R_l^{\mathrm{AC}}\right)^2 w_l^{\mathrm{AC}}}{\left(\sigma_l^{\mathrm{AC}}\right)^2+\left(\epsilon_l^{\mathrm{AC}}\right)^2} \\
&R_l^{\mathrm{AL}}(\boldsymbol{s},\boldsymbol{a},\boldsymbol{c},\boldsymbol{g}) = \eta_{fng}\left(\mu_l, t_l \mid \boldsymbol{c}\right) - \eta\left(t_l \mid \boldsymbol{s},\boldsymbol{a},\boldsymbol{g}\right) \\
&R_l^{\mathrm{AC}}(\boldsymbol{s},\boldsymbol{a},\boldsymbol{c},\boldsymbol{g}) = \zeta_{fng}\left(\mu_l, t_l \mid \boldsymbol{c}\right) - \zeta\left(t_l \mid \boldsymbol{s},\boldsymbol{a},\boldsymbol{g}\right)
\end{aligned} \tag{14}$$

正规方程（Normal equation）为

$$\left[\sum_l \frac{\partial R_l}{\partial x}\frac{\partial R_l}{\partial x'} W_l\right] x = -\sum_l \frac{\partial R_l}{\partial x} R_l\left(s^{\mathrm{ref}}, a^{\mathrm{ref}}, c^{\mathrm{ref}}, g^{\mathrm{ref}}\right) W_l \tag{15}$$

解算过程分为四块，依次迭代（SACSAC...G）

- S: 星表更新，天体测量参数 s 得到改进
- A: 卫星姿态更新，姿态参数 a 得到改进
- C: 仪器校准更新，校准参数 c 得到改进
- G: 全局更新，全局参数 g 得到改进

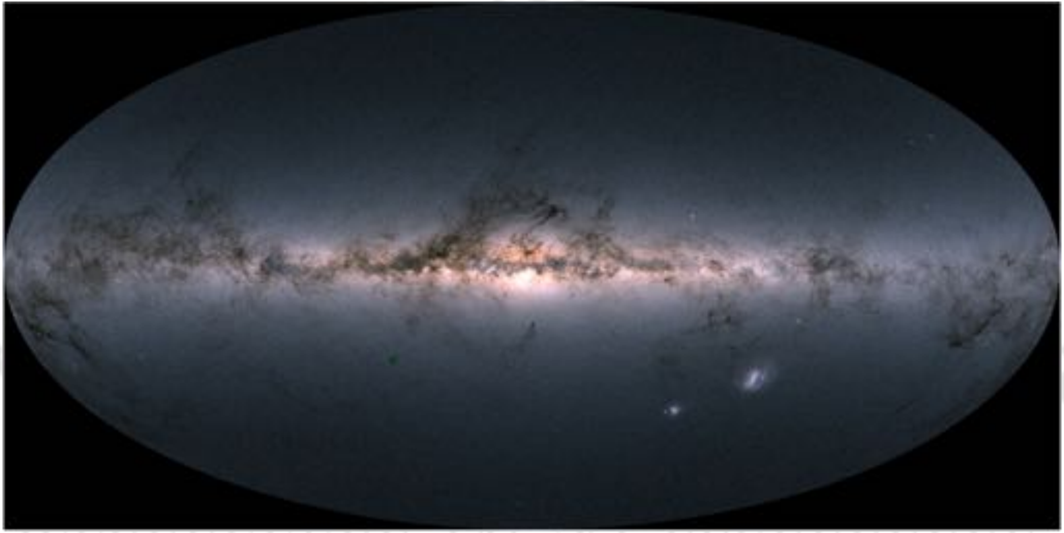


图 1: 约 17 亿颗类星体在银道坐标系中的全天分布

Gaia-CRF 建立在类星体的位置上，并且连接到 ICRS 上。

目前 *Gaia* 的类星体是通过与外部星表 (ICRF3、AllWISE 等) 交叉认证得出，此外还施加筛选条件以移除可能的银河系内恒星，如在 DR2[6] 中

(i) `astrometric_matched_observations` ≥ 8

(ii) $\varsigma_w < 1\mathrm{mas}$

(iii) $|\varpi/\varsigma_\varpi| < 5$

(iv) $(\mu_{\alpha*}/S_{\mu\alpha*})^2 + (\mu_\delta/S_{\mu\delta})^2 < 25$

(v) $|\sin b| > 0.1$

Gaia-CRF2

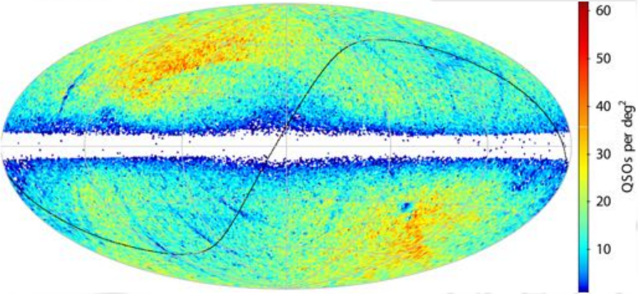
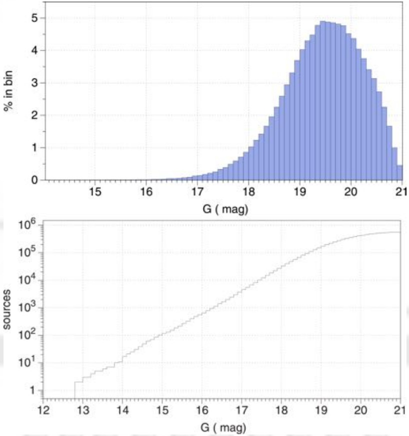
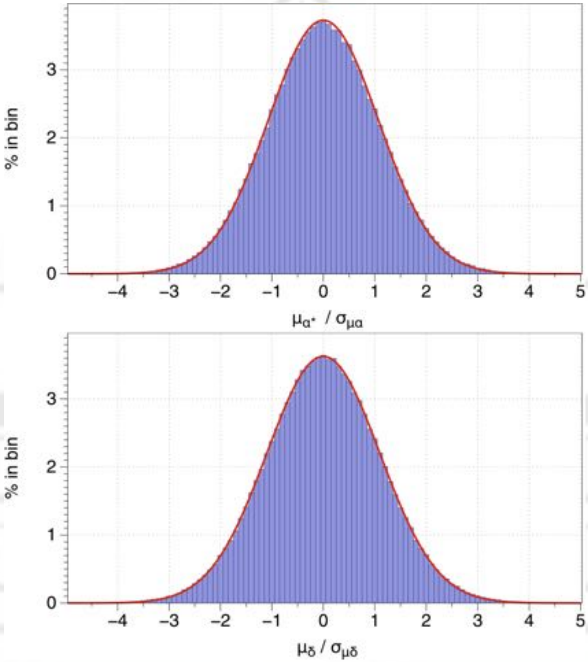


图 2: 55 万多颗类星体在银道坐标系中的全天分布



Gaia-CRF2 的自行系统



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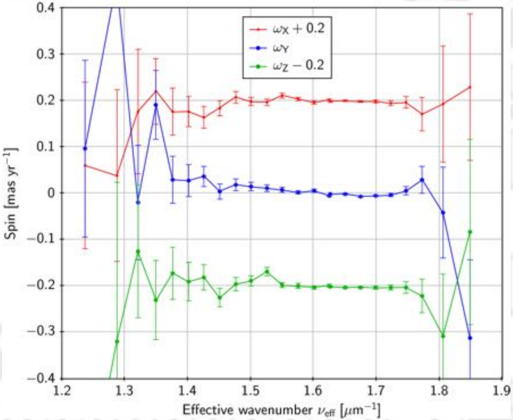
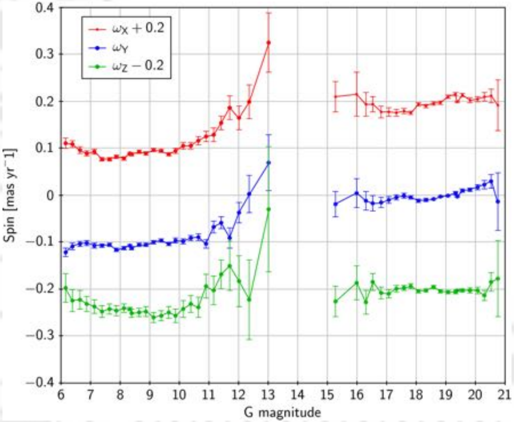
Gaia-CRF2 性质与颜色和星等的关系





亮段参考架存在明显的自转。

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Gaia-CRF2 的视差系统

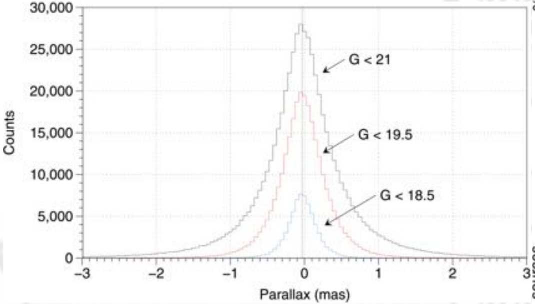
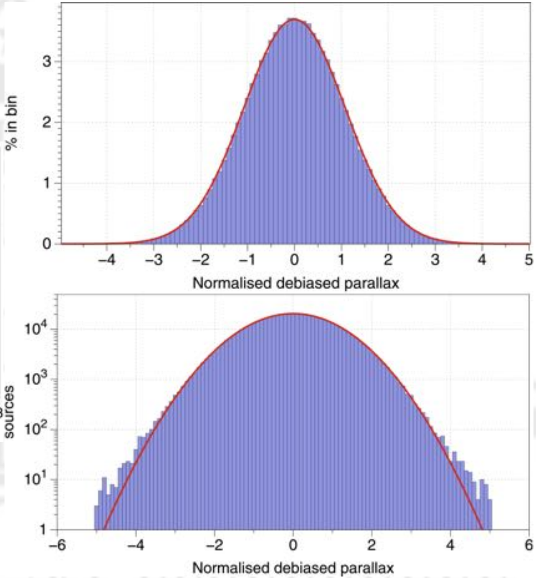
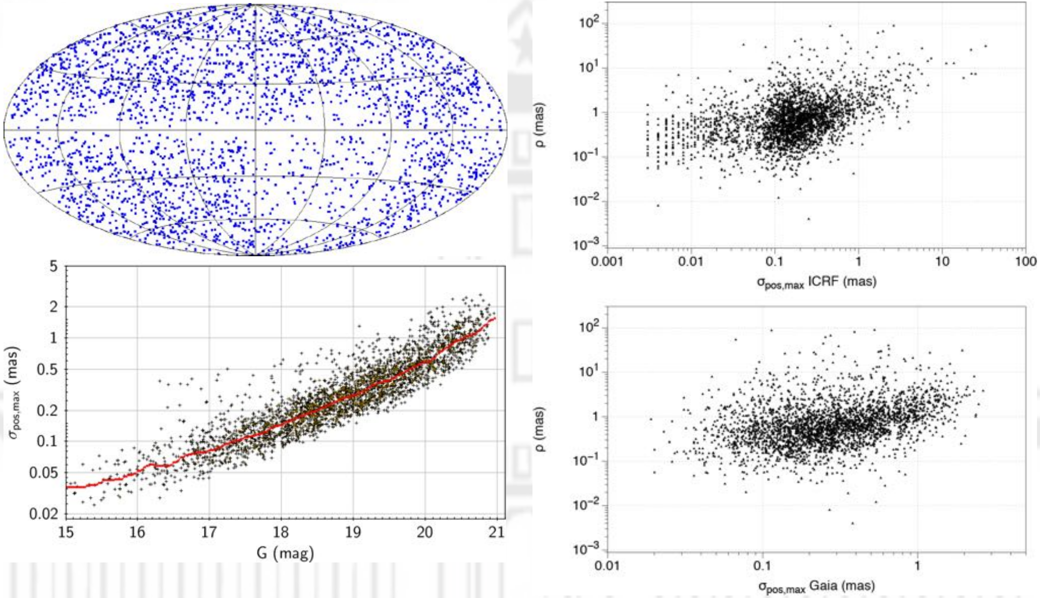
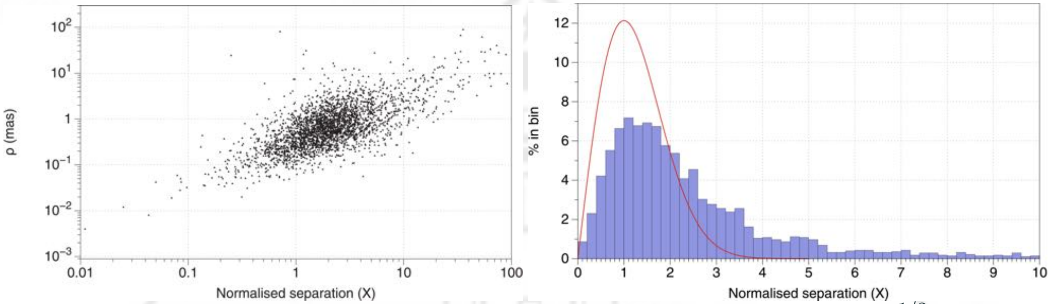


图 3: 视差零点问题：$-29\,\mu$as



Gaia-CRF2 的位置系统: *Gaia*-CRF2 vs. ICRF3





$$\Delta\alpha* = (\alpha_{\mathrm{Gaia}} - \alpha_{\mathrm{ICRF}})\cos\delta, \quad \Delta\delta = \delta_{\mathrm{Gaia}} - \delta_{\mathrm{ICRF}}, \quad \rho = \left(\Delta\alpha_*^2 + \Delta\delta^2\right)^{1/2} \tag{16}$$

$$X_\alpha = \frac{\Delta\alpha*}{\sqrt{\sigma^2_{\alpha*,\,\mathrm{Gaia}} + \sigma^2_{\alpha*,\,\mathrm{ICRF}}}}, \quad X_\delta = \frac{\Delta\delta}{\sqrt{\sigma^2_{\delta,\,\mathrm{Gaia}} + \sigma^2_{\delta,\,\mathrm{ICRF}}}} \tag{17}$$

$$X^2 = \begin{bmatrix} X_\alpha & X_\delta \end{bmatrix} \begin{bmatrix} 1 & C \\ C & 1 \end{bmatrix}^{-1} \begin{bmatrix} X_\alpha \\ X_\delta \end{bmatrix}, C = \frac{\sigma_{\alpha*,\,\mathrm{Gaia}}\,\sigma_{\delta,\,\mathrm{Gaia}}\,C_{\mathrm{Gaia}} + \sigma_{\alpha*,\,\mathrm{ICRF}}\,\sigma_{\delta,\,\mathrm{ICRF}}\,C_{\mathrm{ICRF}}}{\sqrt{\left(\sigma^2_{\alpha*,\,\mathrm{Gaia}} + \sigma^2_{\alpha*,\,\mathrm{ICRF}}\right)\left(\sigma^2_{\delta,\,\mathrm{Gaia}} + \sigma^2_{\delta,\,\mathrm{ICRF}}\right)}} \tag{18}$$

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未来天体测量

关于未来光学天体测量的讨论

- Zacharias N. Astrometric surveys in the Gaia era[J]. Proceedings of the International Astronomical Union, 2017, 12(S330): 49-58.[7]
- Høg E. Absolute astrometry in the next 50 years[J]. arXiv preprint arXiv:1408.2190, 2014.[8]
- Høg E. Absolute Astrometry in the next 50 Years-II[C]//Revista Mexicana de Astronomia y Astrofisica Conference Series. 2018, 50: 1-4.[9]
- Hobbs D, Høg E. GaiaNIR–A future all-sky astrometry mission[J]. Proceedings of the International Astronomical Union, 2017, 12(S330): 67-70.[10]
- Hobbs D, Brown A, Høg E, et al. All-sky visible and near infrared space astrometry[J]. Experimental Astronomy, 2021: 1-61.[11]
- Boehm C, Krone-Martins A, Amorim A, et al. Theia: Faint objects in motion or the new astrometry frontier[J]. arXiv preprint arXiv:1707.01348, 2017.[12]
- Malbet F, Boehm C, Krone-Martins A, et al. Faint objects in motion: the new frontier of high precision astrometry[J]. Experimental Astronomy, 2021, 51(3): 845-886.[13]
- Kopeikin S M, Makarov V V. The Science of Fundamental Catalogs[J]. Frontiers in Astronomy and Space Sciences, 2021, 8: 9.[14]

Norbert Zacharias: Astrometric surveys in the Gaia era[7]

astrometric research not fully covered by Gaia

(1) very bright stars (G <= 3.x), until near final Gaia DR, likely after 2020

(2) faint objects (G >= 20.7) = main open area

(3) other than optical bandpass (like near-IR)

(4) complex motion or variable centroid objects, i.e. "time domain astronomy" require observations at multiple, specific epochs or long time-line observations:

(a) orbital motions of natural satellites (USNO + Paris Observatory)

(b) asteroid mass determination (close encounters)

(c) many double and multiple star systems, companions, exo-planets

(d) some AGN, extragalactic reference frame objects (variability induced center motion)

2017 Apr 24 IAU S 330, Nice, astrom.surveys 23

Table 3. Current and future, deep, wide-field surveys.

survey name	first light	survey begin	telescope aperture	bandpass	camera size Mpx	field of view sq.deg	R mag range
SDSS	1998	2000	2.5 m	u,g,r,i,z	120	1.5	14-23
Skymapper	2008	2014	1.3 m	u,v,g,r,i,z	268	5.7	13-22
PanSTARRS	2008	2009	1.8 m	g,r,i,z,y	1000	7.0	14-23
CFHT	2003		3.6 m	u,g,r,i,z +	340	1.0	15-24
DECam	2012	2013	4.0 m	u,g,r,i,z,Y	520	3.0	15-24
ZTF	2017	2018	1.2 m	g, R	576	47.0	14-21
LSST	2020	2022	8.4 m	U,G,R,I,Z,Y	3000	9.6	18-26
Vista	2009	2010	4.1 m	near-IR	67	0.6	

Note: Limiting magnitudes given here are for stacked images except for ZTF. The saturation limit is approximate, strongly depending on exposure time and seeing conditions.

> "The era of traditional, ground-based, wide-field astrometry with the goal to provide accurate reference stars has come to an end. Future ground-based astrometry will fill in some gaps (very bright stars, observations needed at many or specific epochs) and mainly will go fainter than the Gaia limit, like the PanSTARRS and the upcoming LSST surveys."

- *Gaia* 星表的未来精确度
  在 $G = 20\,\mathrm{mag}$ 处，自行精确度为 $0.175\,\mathrm{mas/yr}$，在 2016 年位置精确度约为 $0.247\,\mathrm{mas}$ 则未来的位置精确度为：在 2026 年为 $1.76\,\mathrm{mas}$，在 2036 年为 $3.5\,\mathrm{mas}$，在 2066 年为 $8.8\,\mathrm{mas}$。
- 未来天文学对于位置的需求
  场景：仅使用位置信息来叠加不同波段的图像从而进行比较分析
  位置精确度：假设一架口径为 $D = 50\,\mathrm{m}$ 的光学望远镜，工作波长为 $\lambda = 560\,\mathrm{nm}$，则角分辨率为

$$\theta = 1.22 \times \frac{\lambda}{D} \approx 2.8\,\mathrm{mas}, \tag{19}$$

  星象定位精确度 $0.1\theta = 0.28\,\mathrm{mas}$。
- 需要一架和*Gaia* 类似性能的空间天体测量卫星，在 *Gaia* 项目结束的 20 年后发射。

具体方案（左）和预期性能（右）[8]

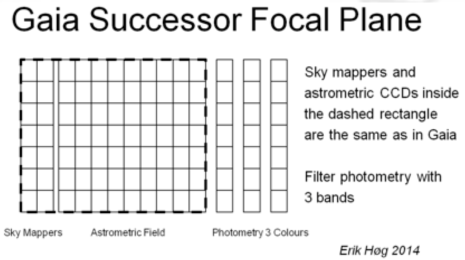


Figure 1. The proposed focal plane assembly. The filter photometry is required to enable correct chromatic corrections of the astrometric observations at every field crossing. The 3 filter bands shown here may well be augmented to 4 bands if wanted. Observations of bright stars to 3rd mag are obtained by way of special gates on the CCDs, see Gaia (2011: 2).

The astrometric foundation of astrophysics

Top science

from a new Gaia-like mission vs. a single Gaia:

- *Imaging of radio/optical sources etc.:*
  Positions 50 years from now >20 times smaller errors
- *Dynamics of Dark Matter etc. from stellar proper motions:*
  Tangential velocities with 10 times smaller errors
  in 30 times larger volume
- *Stellar distances in >3 times larger volume*
- *Exoplanets: Periods up to 40 years, vs. Gaia P<10 yrs*
- *Quasars solely by zero motions: 100 times cleaner sample*
- *Solar system: orbits, asteroid masses…*
- *Astrometry and photometry with 0."1 resolution*
- *Astrometric binaries. Common proper motion pairs. Etc. etc.*

Figure 2. A long-lasting astrometric foundation of astrophysics will be obtained by a new Gaia-like mission launched 20 years after the first. For example, in 2066, 50 years from now, the positions from the two missions will have 20 times smaller errors than from Gaia alone. With 10 times smaller errors on proper motions and tangential velocities, the volume covered with a certain accuracy for a given type of stellar tracer becomes 30 times larger, and even more than that because the long-term proper motions are less affected by motion in binaries. The possibility to perform astrometry with all sensors covering 400 nm to NIR belongs in this list thus penetrating obscured regions as molecular clouds and the Galactic centre.

与 *Gaia* 焦平面的不同之处在于:

- 用滤波片测光替代低分辨率 BP/RP 测光，提高角分辨率（在 $G = 15\,\mathrm{mag}$ 处，140 mas vs 2650 mas）
- 移除了径向速度光谱仪

GaiaNIR = Gaia Near-InfraRed[11]

假设 *Gaia* 和 GaiaNIR 计划各自观测 5 年，间隔 20 年，位置精度为 $25\ \mu as$

$$
\begin{aligned}
\sigma_{\mu_{\alpha *}} &= \frac{\sqrt{\sigma^2_{\alpha^*_{\rm N}} + \sigma^2_{\alpha^*_{\rm G}}}}{t_{\rm N} - t_{\rm G}} = \frac{\sqrt{25^2 + 25^2}}{20} \sim 1.77 \mu{\rm as yr}^{-1}, \\
\sigma_{\mu_{\delta}} &= \frac{\sqrt{\sigma^2_{\delta_{\rm N}} + \sigma^2_{\delta_{\rm G}}}}{t_{\rm N} - t_{\rm G}} = \frac{\sqrt{25^2 + 25^2}}{20} \sim 1.77 \mu{\rm as yr}^{-1}
\end{aligned}
\tag{20}
$$

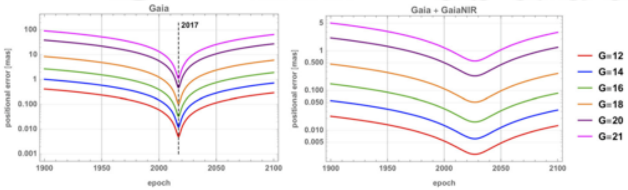


Fig. 3 Degradation of the astrometric accuracy of the individual sources in the Gaia catalogue (left pane) and of the common solution using 10 years of Gaia and 10 years of GaiaNIR data (right pane) depending on the G magnitude and time from the reference epoch (J2017 for the Gaia catalogue and a mean epoch of Gaia and GaiaNIR taken here as J2027). Note the very different vertical scales

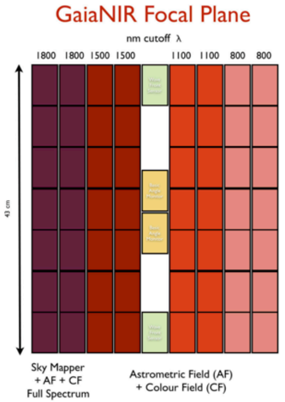
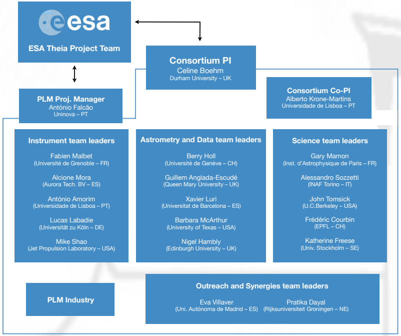
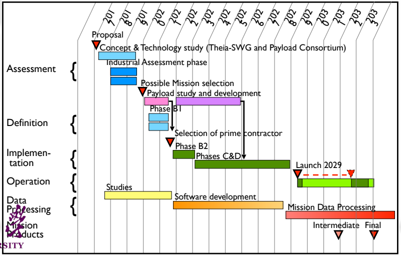


Fig. 4 Proposed focal plane array and filter bands used in the GaiaNIR CDF study (see page 203 in https://sci.esa.int/s/8a65kZA). The array consists of 60 NIR detectors, arranged in 7 across-scan rows and 9 along-scan strips (out of which 8 are for the astrometric/photometric field, divided into 4 photometric fields (i.e. 4 different cut-off wavelengths each starting from ~ 400 nm). The new array is less than half the size of Gaia's

Theia: Faint objects in motion or the new astrometry frontier

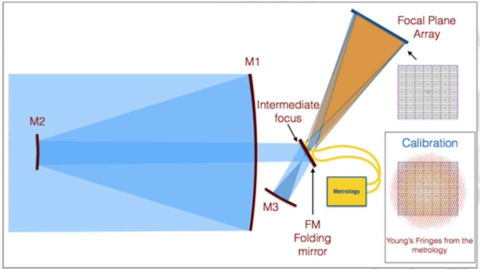


Possible program schedule

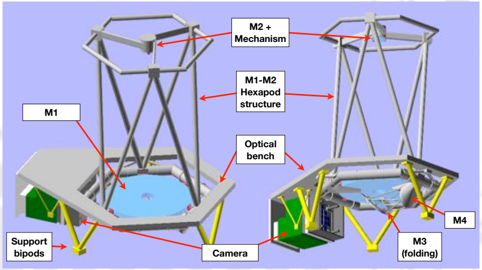


Science case	Dark Matter, Exoplanets, Neutron stars and Binary Black Holes.
Science objectives	• To discover the nature of dark matter; • To find nearby habitable Earths; • To probe Nature's densest environments.
Overview	• Spacecraft at L2 for 4.5 years; • Optical telescope (350nm-1000nm); • Micro-arcsecond astrometry, sub-percent photometry; • Point and stare strategy, to enable relative (differential) astrometry; • Built on *Gaia*'s "absolute" reference frame.
What makes *Theia* unique?	• Ultra-high-precision astrometry, only reachable from space: from 10 μas (dark matter) down to 0.15 μas (exoplanets); • Dedicated payload design to achieve the required astrometric precision; • Unprecedented sensitivity to DM targets, enabling particle physics tests; • True masses and orbital architecture of habitable-zone terrestrial planets, and complete orbital characterization of planetary systems; • Measurements of orbits and distances to probe the interiors of neutron stars and the structure of black hole accretion discs.
Main observational targets	• dwarf spheroidals & ultra-faint dwarf galaxies, hyper-velocity stars; • nearby A, F, G, K, M stellar systems; • neutron stars in X-ray binaries; • Milky Way disc + open observatory targets.
Payload	• Korsch on-axis TMA telescope with controlled optical aberrations; • Primary mirror: $D = 0.8$ m diameter; • Long focal length, $f = 32$ m; • FoV ~0.5 deg, with 4 to 6 reference stars with magnitude $R \leq 10.8$ mag; • Focal plane with 24 CCD detectors (~402 Mpixels, 350nm-1000nm); • Nyquist sampling of the point-spread-function; • Metrology calibration of the focal plane array: relative positions of pixels at the micropixel level using Young's interferometric fringes; • Interferometric monitoring of the telescope: picometer level determination of the telescope geometry using laser interferometric hexapods.
Spacecraft	• Spacecraft dry mass with margin: 1063 kg. Total launch Mass: 1325 kg; • Attitude Control System: synergistic system with hydrazine, reaction wheels and cold-gas thrusters. RPE: 20 mas rms in a few minutes (1σ); • Thermal Control System: active thermal control of telescope; dedicated radiator for the payload; • Telecommand, Telemetry and Communication: Ka-band, ~95 GBytes of science data per day. High Gain Antenna and 35m stations.
Launcher and operations	• Ariane 6.02. Lissajous orbit at L2. Launch in 2029; • Nominal mission: 4 yrs + 6 months transit, outgassing & commissioning; • MOC at ESOC, SOC at ESAC.
Data policy	• Instrument Science Data Centers at consortium member states; • Short proprietary period and 2 data releases.
Consortium	• > 180 participants from 22 countries; UK, France, Germany, Italy, Spain, Switzerland, Poland, Portugal, Sweden, The Netherlands, Hungary, Greece, Denmark, Austria, Finland, USA, Brazil, China, Canada, India, Israel, Japan.
Estimated cost	• 536 M€ for the spacecraft and telescope, including launcher (70), ground segment (85), project (53) and payload contribution (56). • 51.3 M€ for the payload (consortium member states only)

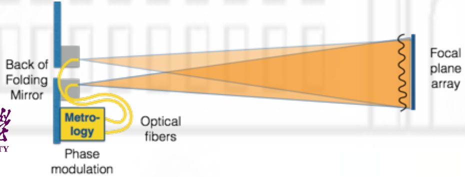
Theia 观测设计



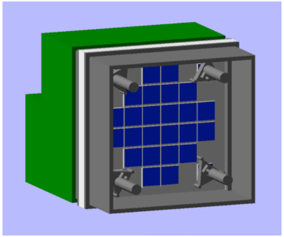
Focal Plane Array
M1
Intermediate focus
M2
Calibration
Metrology
M3
FM Folding mirror
Young's Fringes from the metrology

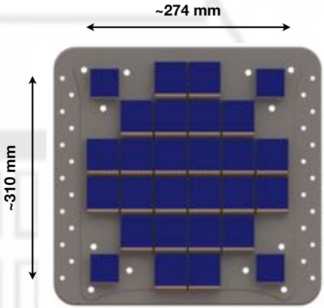


M2 + Mechanism
M1-M2 Hexapod structure
M1
Optical bench
M4
Support bipods
Camera
M3 (folding)



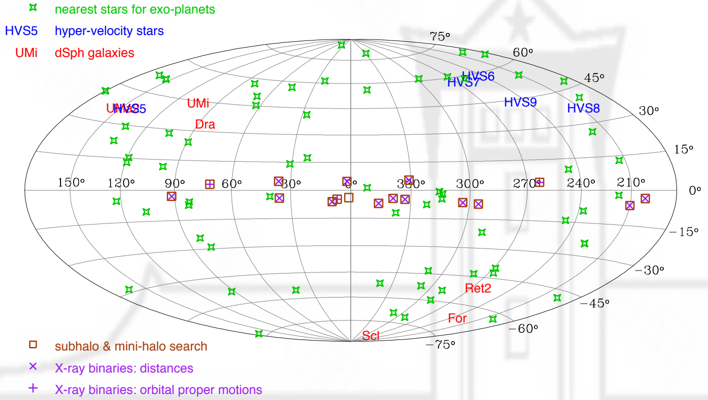
Back of Folding Mirror
Focal plane array
Metro-logy
Optical fibers
Phase modulation





~274 mm
~310 mm

Theia 项目的观测目标



- 近邻系外行星系统：
  50 targets × 0.8 h/obs × 50 obs
- 遥远的矮星系：
  6 targets × 1000 h
- 银晕中的高速移动天体:5 targets × 1000 h/yr × 4 yr
- 银盘上的恒星：9 个视线方向，
  18 FoVs × 400 h/FoV

Program	Used time (h)	Mission fraction	Nb of objects per field	Benchmark target R mag (and range)	EoM precision (at ref. mag.)
Dark Matter & compact objects	17 000	0.69	10^2–10^5	20 (14–22)	10 μas
Nearby Earths & follow-up	3 500	0.14	<20	5 (1–18)	0.15 μas
Open observatory	4 000	0.17	10-10^5	6 (1-22)	1.0 μas
Overall requirements	24 500	1.00	10^1-10^5	6 (1-22)	0.15-10 μas

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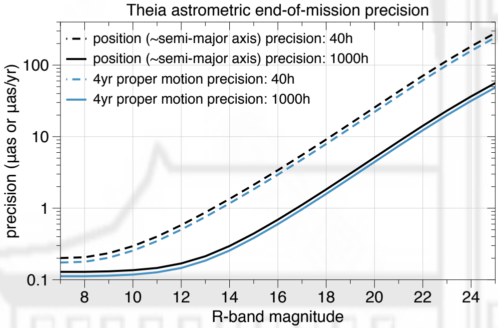
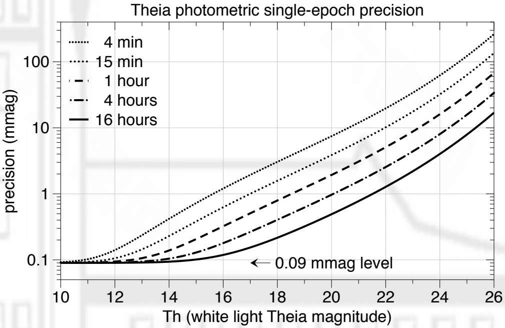
Theia 项目的预期精度





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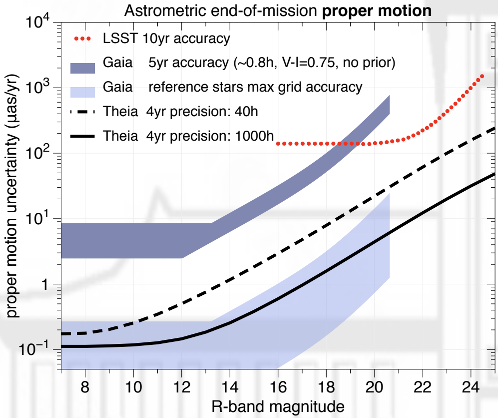
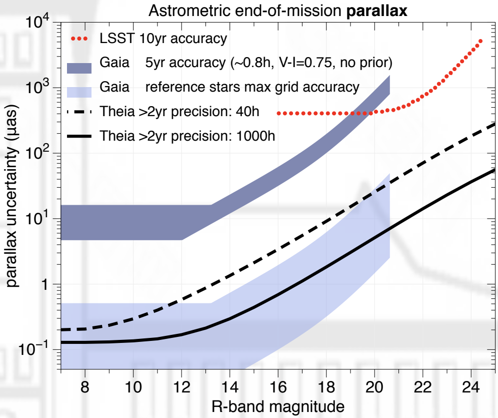
Theia 与其他项目的比较





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> "… significantly improved models and estimation techniques in conjunction with sufficient data accumulation will lead quite naturally to the construction of a new and self-contained celestial reference frame. As before, this reference frame will be a human artifact reflecting the latest level of knowledge at the time of its coming into being."
>
> ——Walter & Sovers (2000) [15]

附录

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南京大学
NANJING UNIVERSITY