

中国科学院上海天文台

Shanghai Astronomical Observatory, Chinese Academy of Science



中国科学院大学

University of Chinese Academy of Sciences

轨道确定工程案例分析

宋叶志
2020年秋季

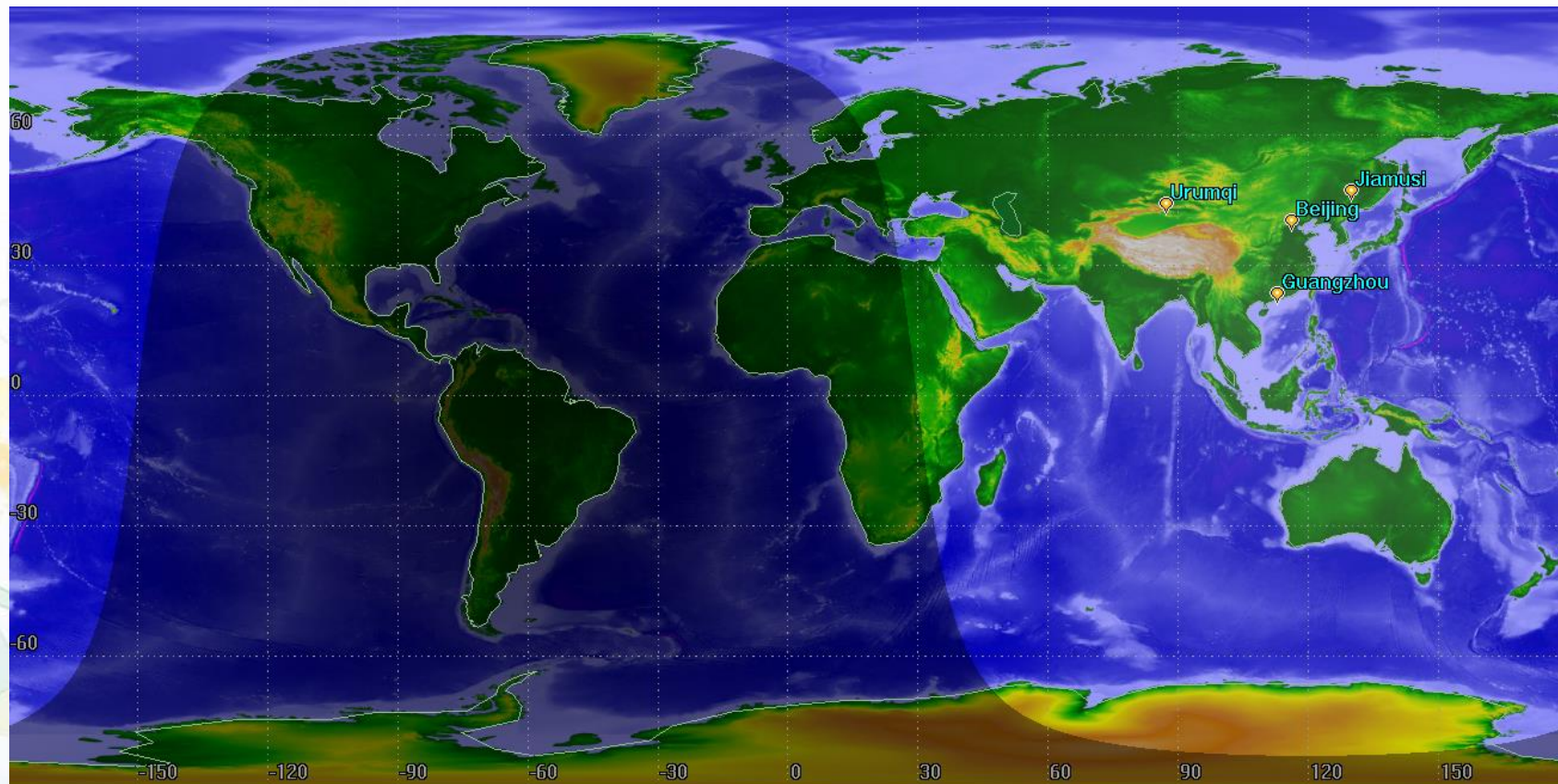
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主要内容

- 案例一：风云四号精密定轨系统
- 案例二：LEO星载GNSS精密定轨
- 案例三：近地自然小天体的星基平台光学定轨

风云四号精密定轨系统



FY-4 series is China's second generation geostationary meteorological satellites. The new generation satellites are designed with an enhanced imagery scanning capability, desirable for monitoring small and medium scale weather systems.

风云四号概况

- ▶ 风云四号卫星实现了我国静止轨道气象卫星升级换代和技术跨越，将对我国及周边地区的大气、云层和空间环境进行高时间分辨率、高空间分辨率、高光谱分辨率的观测，大幅提高天气预报和气候预测能力。
- ▶ 我国首颗地球同步轨道三轴稳定定量遥感卫星，使用全新研制的SAST5000平台，设计寿命7年。
- ▶ 更加精确地开展天气监测与预报预警、数值预报、气候监测。卫星装载的闪电成像仪能1秒钟拍500张闪电图，探测区域范围内的闪电频次和强度，在国内首次提供闪电预警。
- ▶ 台风分析和预报方面，能够3每分钟对台风区域进行观测，高频次观测可提供台风云结构及其演变的精细化动态信息。

风云二号测距模式

风云二号地面跟踪站

测站编号	站址	天线
1	北京	1号、2号和3号
2	广州	1号和2号
3	乌鲁木齐	1号、2号、3号、4号和5号

副站不主动发射信号。而是由主站发射信号经过卫星转发到副站，再由副站转发到卫星，再转发到主站，由此扣除主站测距值得到副站测距值。

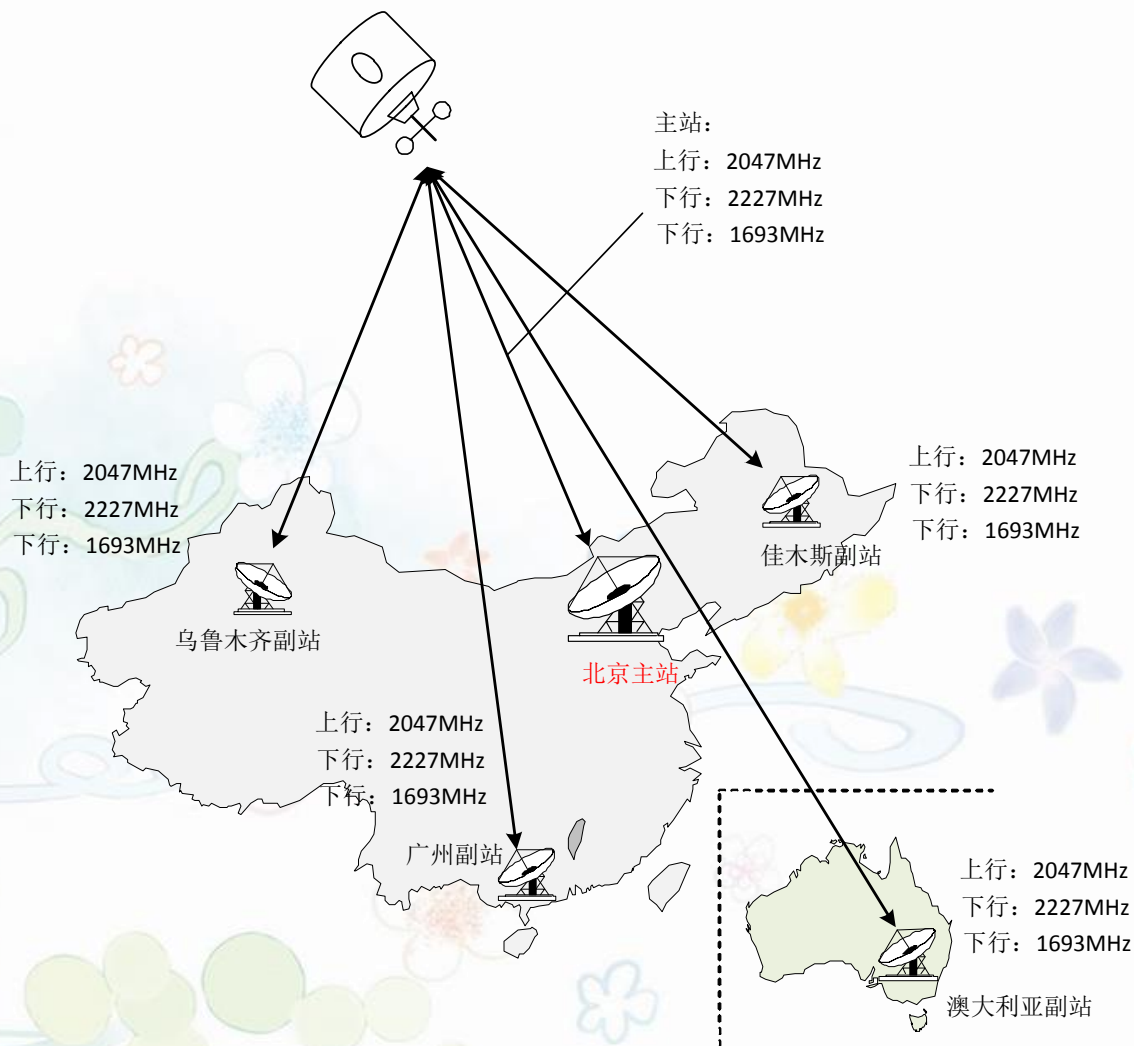
主站双程测距模式

副站“鹰四程”测距模式双向转发测距
(双向传输测距BTR)



风云四号测控网

测距站采用码分多址技术体制，上行为 S 波段测距信号，经卫星接收后变为 L 和 S 双频下行信号，经过接收、解码获得距离值。每个副站将设备工作状态和距离值、时间等按照一定的格式装载在基带数据中，通过 S 波段信号向卫星发射，卫星接收后不断地进行 L 和 S 双频转发，主站在测距的同时，解调副站的基带信号获取相应的测距值。



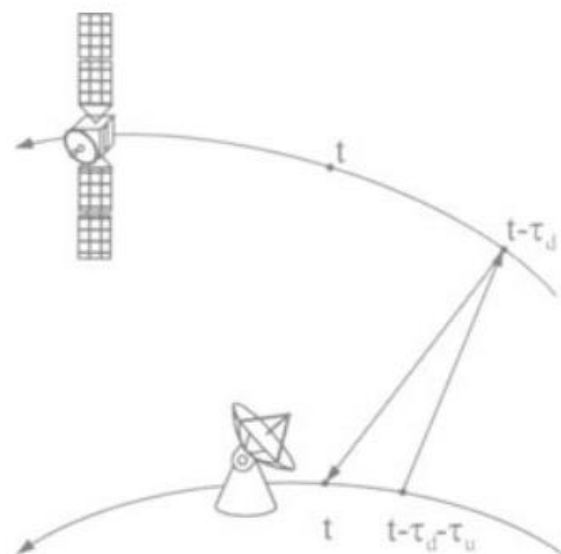
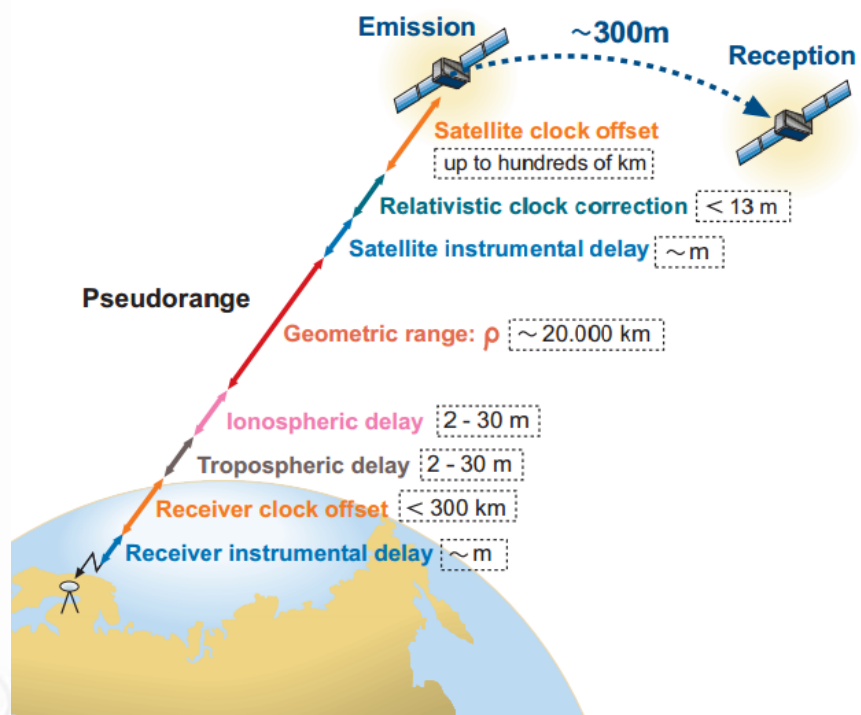
双程测距

$$\rho_t = \frac{\rho_d + \rho_u}{2} \quad \rho_d = \left| \mathbf{r}(t - \Delta t_2) - \mathbf{R}(t) \right| + TR_d + ION_d + GR_d + \varepsilon_d$$

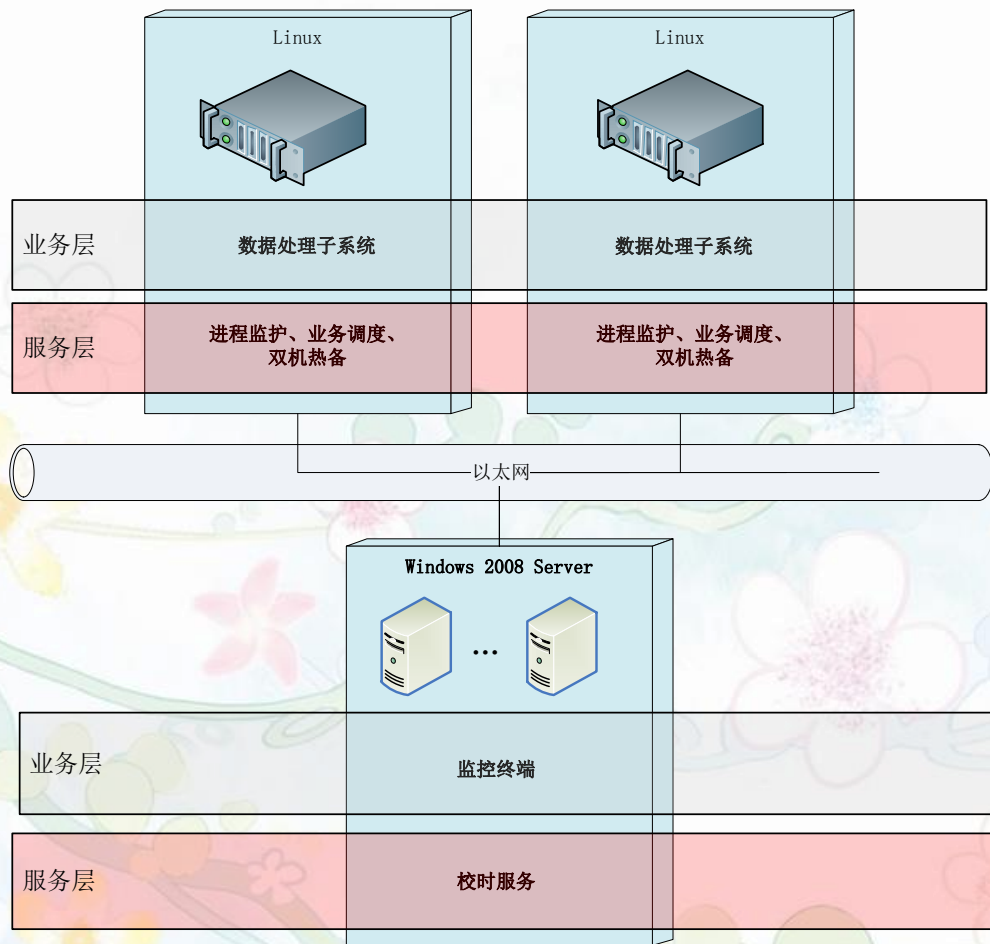
$$\rho_u = \left| \mathbf{r}(t - \Delta t_2) - \mathbf{R}(t - \Delta t_1 - \Delta t_2) \right| + TR_u + ION_u + GR_u + \varepsilon_u$$

$$\begin{aligned} \Delta t_2^{i+1} &= \rho_d(\Delta t_2^i) \\ &= \frac{1}{c} \left[\left| \mathbf{r}(t - \Delta t_2^i) - \mathbf{R}(t) \right| + \delta \rho_d(\Delta t_2^i) \right] \end{aligned}$$

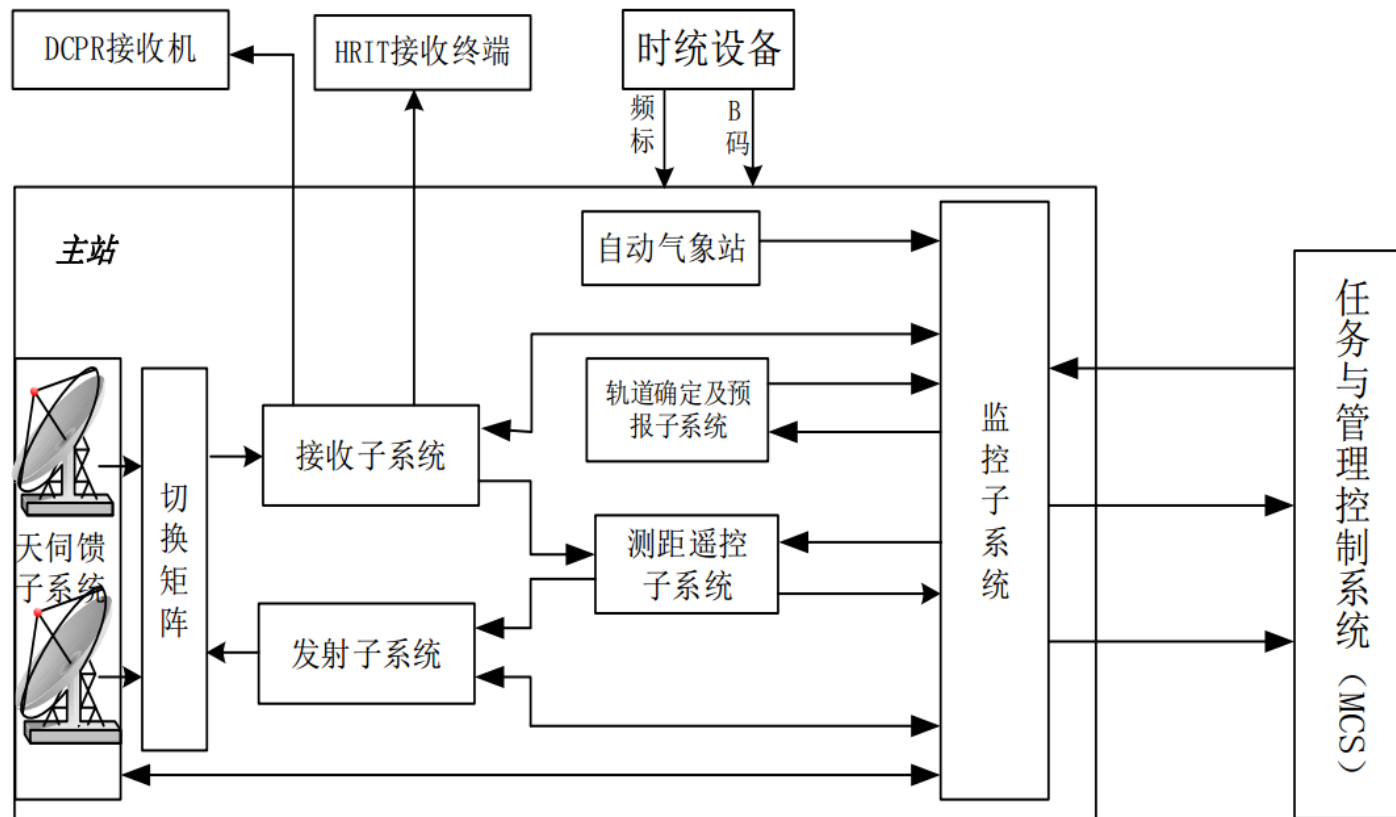
$$\begin{aligned} \Delta t_1^{i+1} &= \rho_u(\Delta t_2, \Delta t_1^i) \\ &= \frac{1}{c} \left[\left| \mathbf{r}(t - \Delta t_2) - \mathbf{R}(t - \Delta t_1^i - \Delta t_2) \right| + \delta \rho_u(\Delta t_2, \Delta t_1^i) \right] \end{aligned}$$



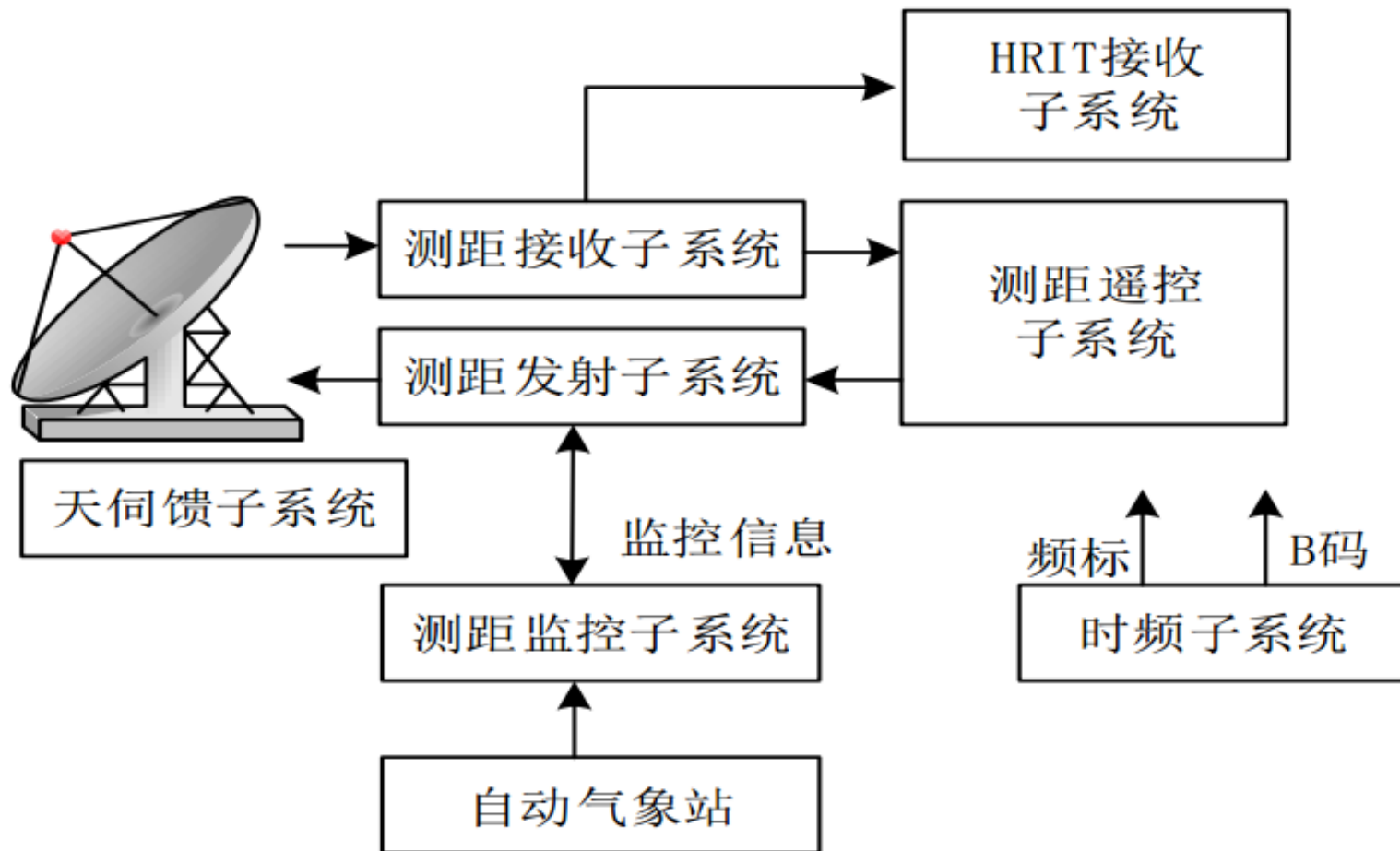
软硬件部署



主站设备组成



副站设备组成

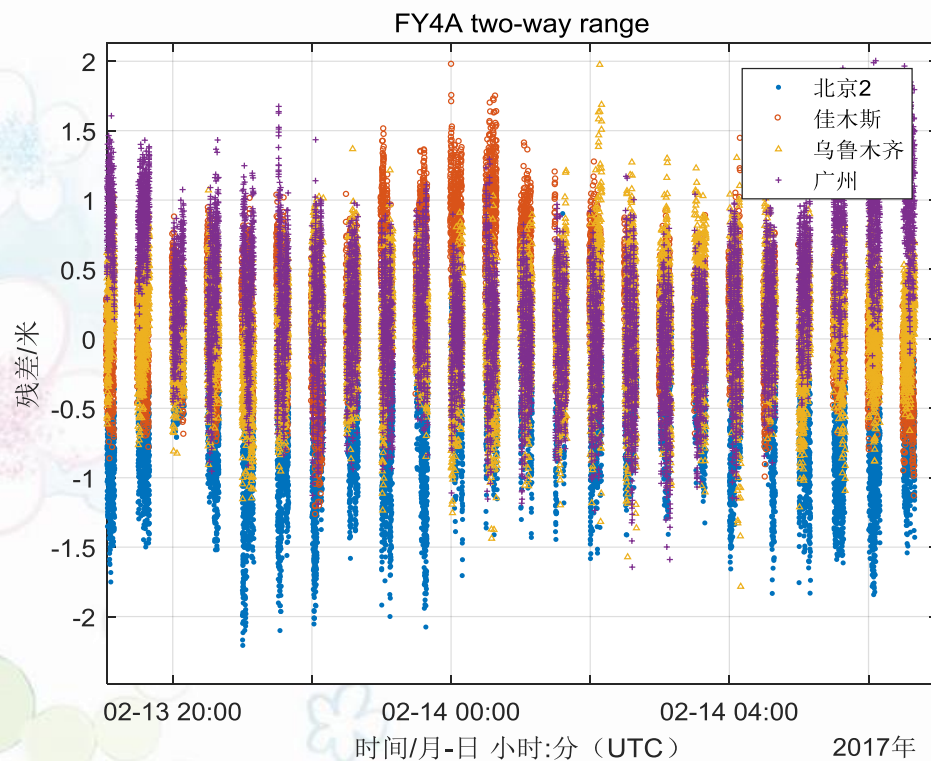


长弧定轨

测站	北京02+佳木斯+乌鲁木齐+广州
数据	2017.2.13 19:00:00 2017.2.14 7:00:00
解算参数	轨道+光压系数

定轨后残差RMS: **0.54844 m**, 各站残差统计如下:

测站	残差RMS/m	数量	残差均值/m
北京2	0.70028	14096	-0.54650
佳木斯	0.48363	13651	0.21753
乌鲁木齐	0.37726	14253	0.07425
广州	0.57959	14200	0.26261



重叠弧段分析

	开始	结束
1	2017.02.13 19:00:00	2017.02.14 01:00:00
2	2017.02.14 00:00:00	2017.02.14 06:00:00
3	2017.02.14 05:00:00	2017.02.14 11:00:00
4	2017.02.14 10:00:00	2017.02.14 16:00:00

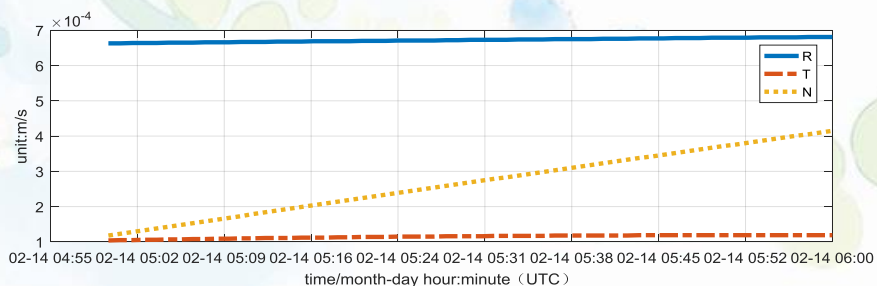
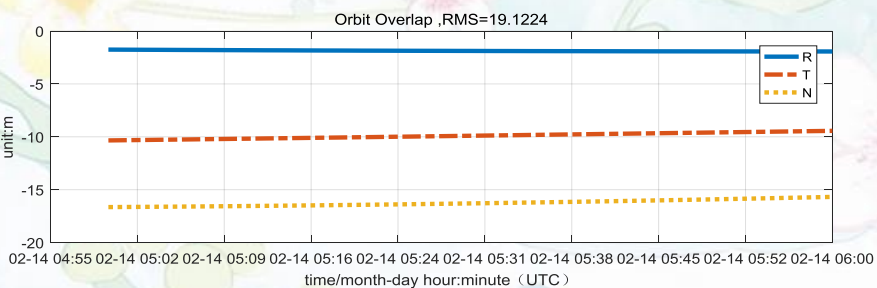
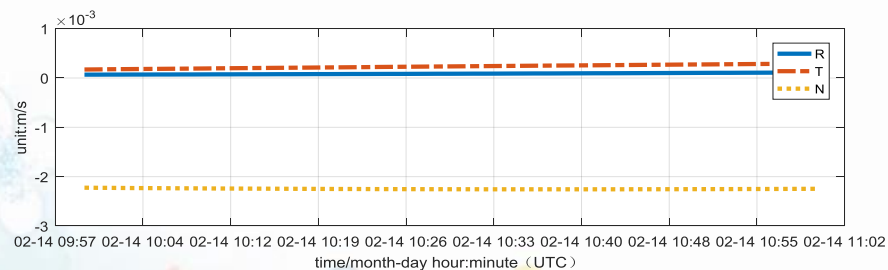
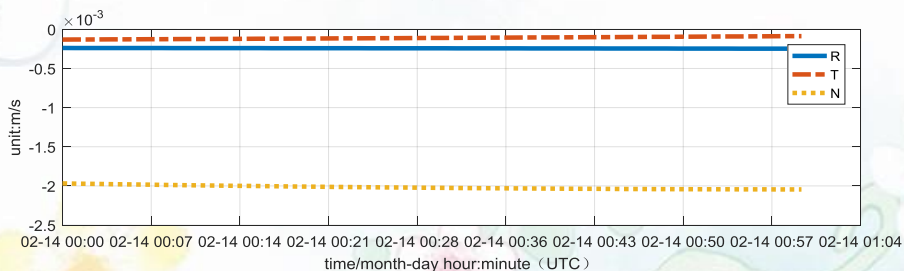
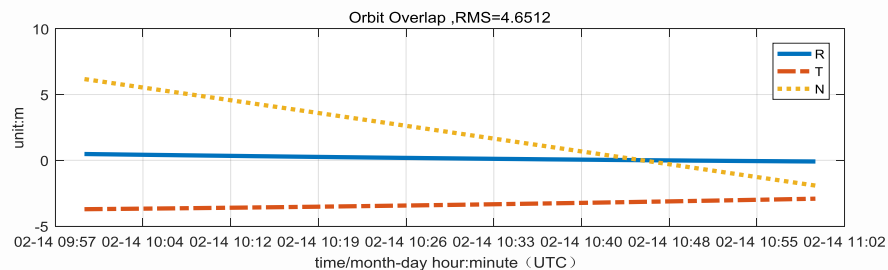
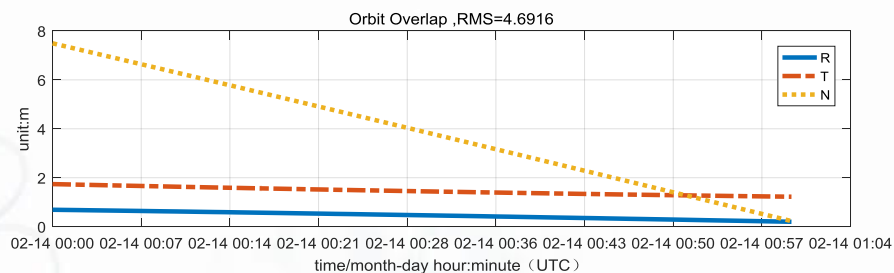
测站	残差RMS/m	数量	残差均值/m
北京2	0.71647	6975	-0.57449
佳木斯	0.52702	7116	0.35309
乌鲁木齐	0.40802	7121	0.11397
广州	0.40548	7121	0.09621

测站	残差RMS/m	数量	残差均值/m
北京2	0.61851	7076	-0.48650
佳木斯	0.47916	6541	0.31378
乌鲁木齐	0.35519	7135	0.09949
广州	0.39847	7123	0.10866

测站	残差RMS/m	数量	残差均值/m
北京2	0.59120	7069	-0.43697
佳木斯	0.41327	6534	0.25740
乌鲁木齐	0.43969	7112	0.08595
广州	0.43951	7119	0.12836

测站	残差RMS/m	数量	残差均值/m
北京2	0.68665	6997	-0.55083
佳木斯	0.50654	7124	0.32943
乌鲁木齐	0.41966	7122	0.11016
广州	0.33782	7126	0.10784

轨道重叠



重叠弧段	R/m	T/m	N/m	Total/m
1-2	0.4811	1.4654	4.4309	4.6916
2-3	1.8708	9.9010	16.2523	19.1224
3-4	0.2360	3.3718	3.1952	4.6512

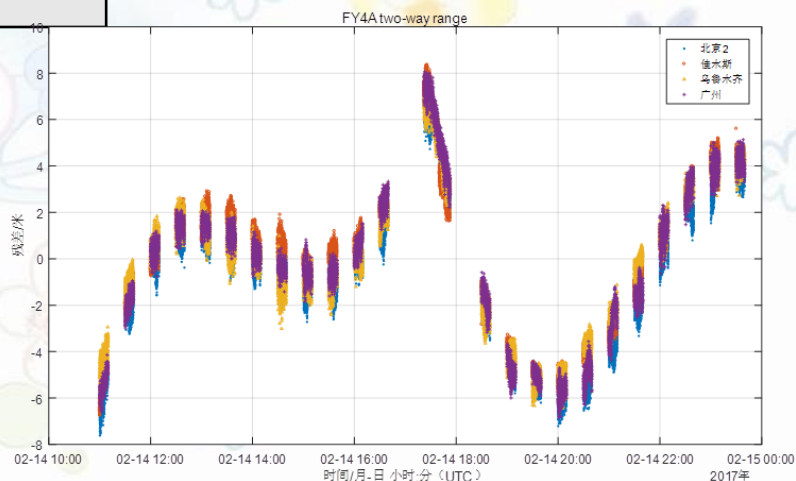
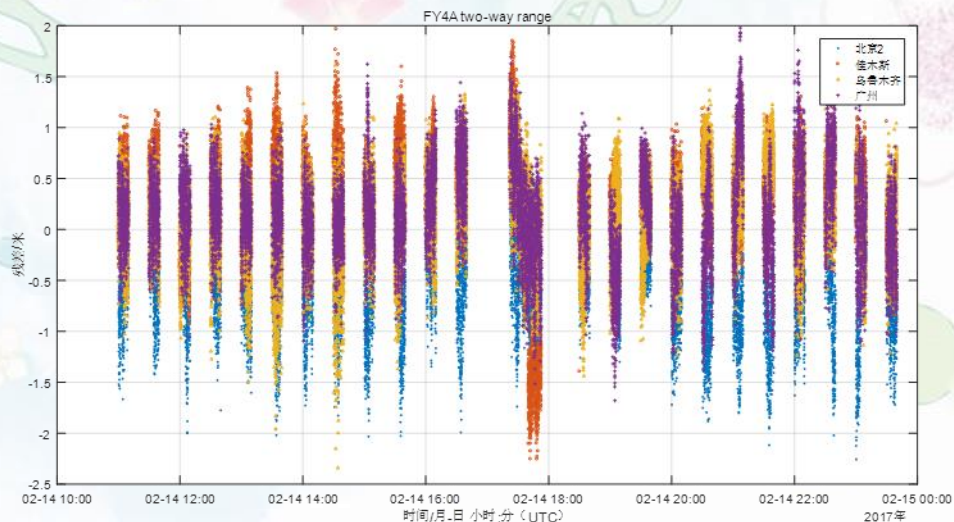
动量轮卸载期间定轨试验（长弧试验）

14日动量轮卸载结束时间为201702141738。持续时间约15分钟。

测站	北京02+佳木斯+乌鲁木齐+广州
数据	2017.2.14 11:00:00 2017.2.15 00:00:00
加经验力弧段	2017.2.14 17:22:00 2017.2.14 17:38:00

解算经验力（RTN都解）

测站	残差RMS/m	数量	残差均值/m
北京2	0.69337	15410	-0.53275
佳木斯	0.60210	15366	0.31361
乌鲁木齐	0.45704	15493	0.10774
广州	0.47828	15496	0.14584

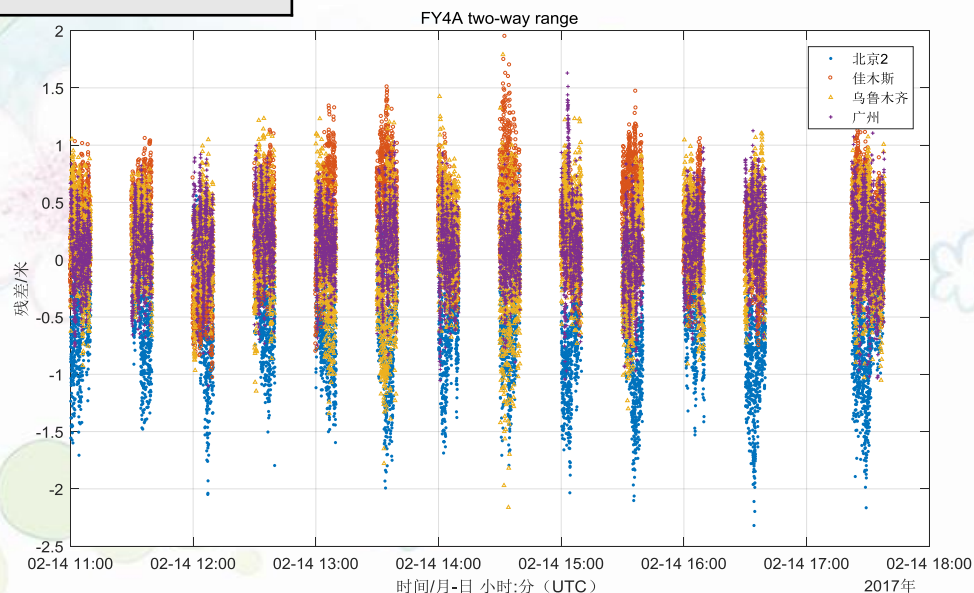


动量轮卸载期间定轨试验（快速恢复试验）

若要轨道机动结束后立即获得轨道，选用数据到轨道机动结束为止。

测站	北京02+佳木斯+乌鲁木齐+广州	
数据	2017.2.14 11:00:00	2017.2.14 17:38:00
加经验力弧段	2017.2.14 17:22:00	2017.2.14 17:38:00

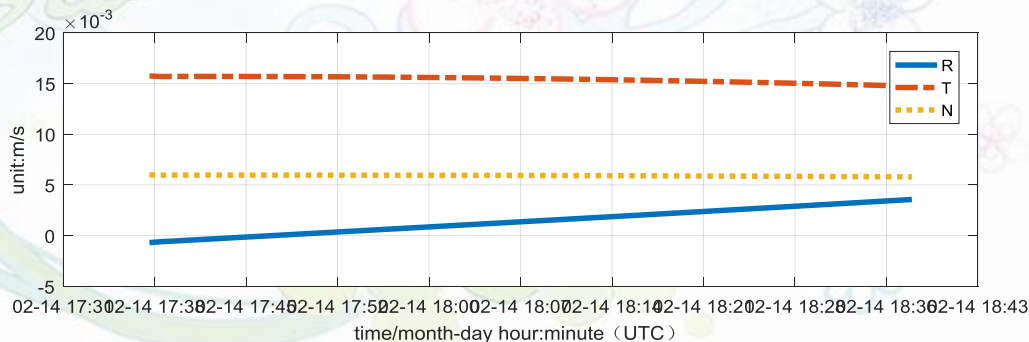
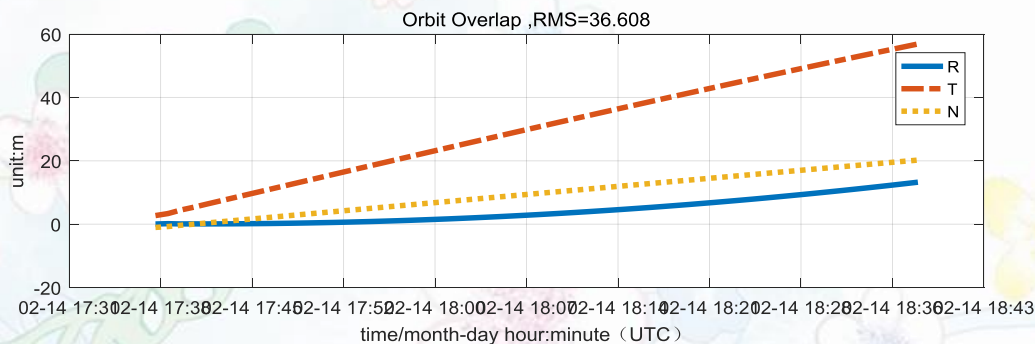
测站	残差RMS/m	数量	残差均值/m
北京2	0.69565	7883	-0.55423
佳木斯	0.50690	8073	0.32700
乌鲁木齐	0.42100	8074	0.10985
广州	0.34616	8079	0.11176



轨道机动期间定轨的预报轨道与长弧定轨比较（一）

轨道1	快速恢复试验预报的轨道
轨道2	2017.2.14 17:38:00 — 2017.2.15 00:00:00 数据进行确定的轨道
比较弧段	2017.2.14 17:38:00 — 2017.2.14 18:38:00

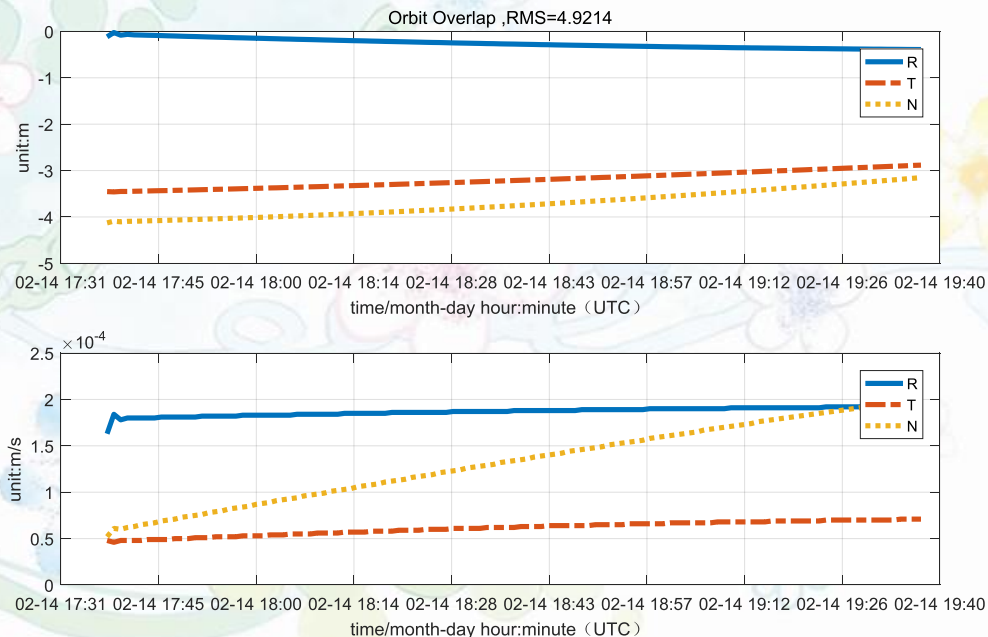
轨道比较统计	R/m	T/m	N/m	Total/m
	5.8705	34.2583	11.4916	36.6080



轨道机动期间定轨的预报轨道与长弧定轨比较（二）

轨道1	动量轮卸载期间长弧轨道
轨道2	2017.2.14 17:38:00 —— 2017.2.15 00:00:00 数据进行确定的轨道
比较弧段	2017.2.14 17:38:00 —— 2017.2.14 18:38:00

轨道比较统计	R/m	T/m	N/m	Total/m
	0.2753	3.2042	3.7253	4.9214



结论

- ▶ 无轨道机动情况下，定轨残差1米以下，重叠弧段分析精度约20-30米。
- ▶ 轨道机动期间如果进行定轨，解算经验力，内符精度无异常。从机动到结束期间，定轨结果对位置的确定误差不算太大。但是速度即便是有较小的偏差，后续的预报轨道与事后精密轨道相比也会引起卫星轨道的较大偏离。
- ▶ 包含机动弧段前后跨度各几个小时的数据进行轨道确定得到的轨道，与机动结束后数据进行轨道确定的轨道进行比较，则差异在几米以内。
- ▶ 后续卫星发射后系统兼容试验。

主要内容

- 案例一：风云四号精密定轨系统
- 案例二：LEO星载GNSS精密定轨
- 案例三：近地自然小天体的星基平台光学定轨

星载GNSS接收机轨道确定

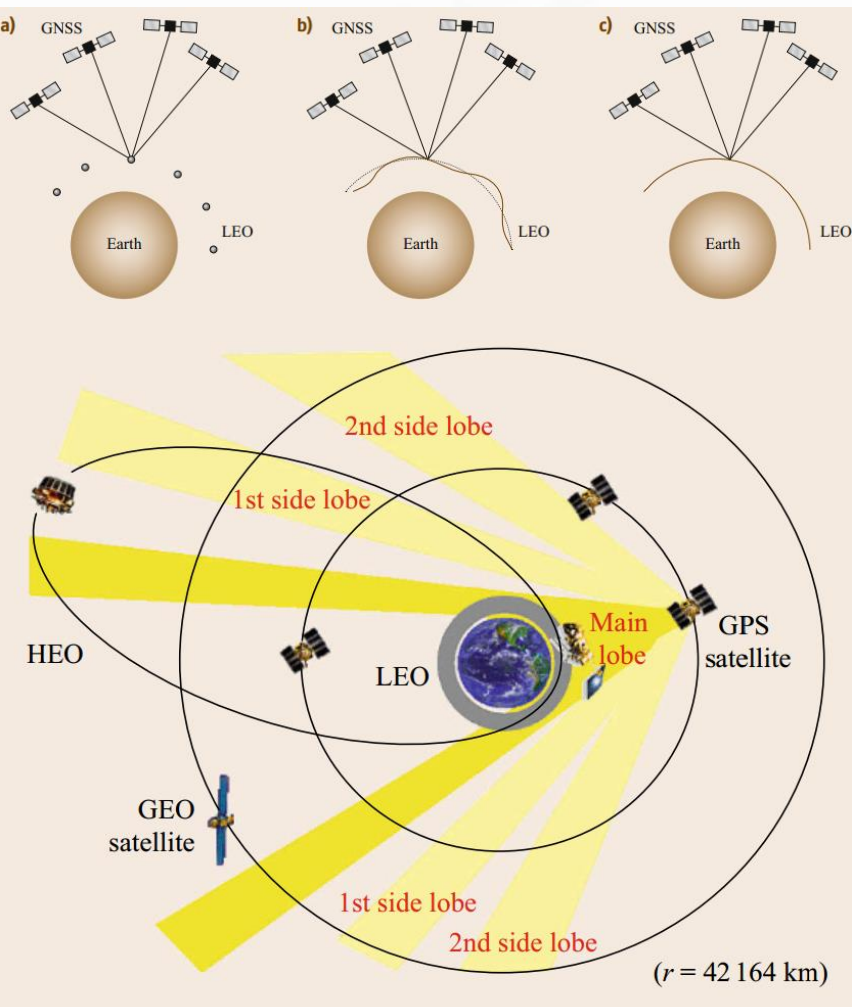








Table 32.1 Single- and dual-frequency GNSS receivers for space applications

Receiver	Manufacturer (country)	Channels signals	Antennas	Power mass	TID (krad)	Missions
SGR-10	SSTL (UK)	24 GPS L1 C/A	2	5.5 W 1 kg	10	Tsinghua-1, BILSAT, DART
Mosaic GNSS	Airbus DS (D)	8 GPS L1 C/A	1	10 W 4 kg	> 30	SARLupe, TerraSAR-X, Aeolus
TopStar 3000	Thales-Alenia (F)	12-16 GPS L1 C/A	1-4	1.5 W 1.5 kg	> 30	Demeter, Kompsat-2
Viceroy	General Dynamics (US)	12-18 GPS L1 C/A	1-2	7 W 1.1 kg	15	MSTI-3, Seastar, MIR, Orbview
Navigator	NASA/GSFC (US)	12 GPS L1 C/A	1	< 30 W < 11 kg	100	Shuttle HSM-4, MMS
Phoenix	DLR (D)	12 GPS L1 C/A	1	0.9 W 0.1 kg	15	PROBA-2 & -V, PRISMA, TET
GNSS S/W Rcv.	Sylinks (F)	9 GPS L1 C/A, GAL E1	1	5 W 1 kg	10	Taranis
IGOR	Broadreach Eng. (US)	16 × 3 GPS L1 C/A, L1/L2 P(Y)	4	10 W 4.6 kg	20	COSMIC, TerraSAR-X, TanDEM-X
GPS POD	RUAG (A)	8 × 3 GPS L1 C/A, L1/L2 P(Y)	1	8.5 W 2.8 kg	> 20	SWARM, Sentinel, ICESat-2
Lagrange	Thales-Alenia (I)	12 × 3 GPS L1 C/A, L1/L2 P(Y)	1	30 W 5.2 kg	20	Radarsat-2, COSMO-Skymed, GOCE
TriG	JPL, MOOG Broadreach (US)	24 × 2 GPS/GLO L1/L2, (GAL E1/E5a)	4	55 W 6 kg		Formosat-7/COSMIC-2
LION	Airbus DS (D)	36 GPS L1/L2/L5, GAL E1/E5a	1-4	15 W 6 kg	50	SARah, CSO, Metop-SG
PODRIX	RUAG (A)	18 × 2 GPS L1/L2/L5, GAL E1/E5a	1-4	15 W 3 kg	50	SARah, Sentinel

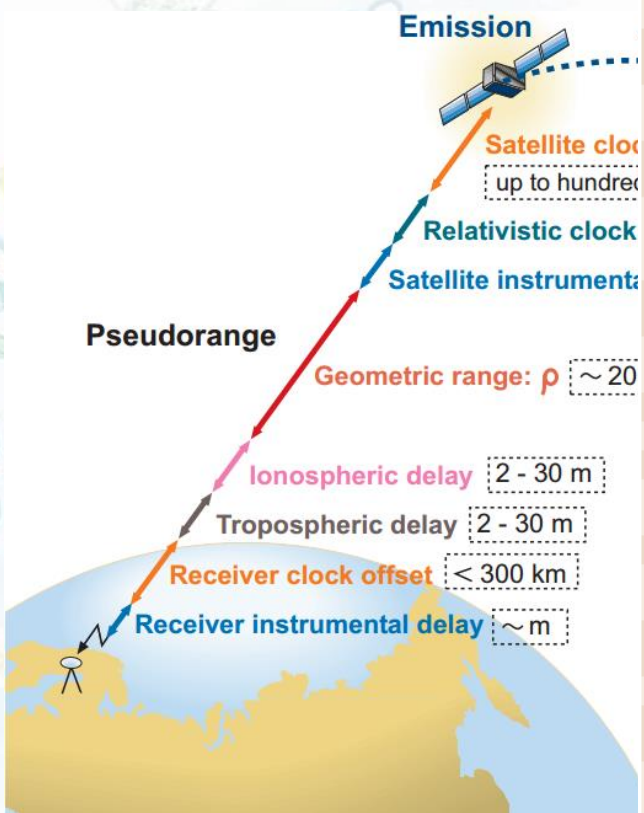
Fig. 32.1 Schematic view of GNSS visibility conditions for LEO, HEO and GEO satellites

全球主要卫星导航系统

System	GPS 	GLONASS 	BeiDou 	Galileo 	QZSS 	IRNSS/NavIC 
Orbit	MEO	MEO	MEO, IGSO, GEO	MEO	IGSO, GEO	IGSO, GEO
Nominal number of satellites	24	24	27, 3, 5	30	3, 1	4, 3
Constellation	6 planes 56° inclination	Walker (24/3/1) 64.8° inclination	Walker (24/3/1) 55° inclination	Walker (24/3/1) 56° inclination	IGSOs with 43° inclination	IGSOs with 29° inclination
Services	SPS, PPS	SPS, PPS	OS, AS, WADS, SMS	OS, CS, PRS	GCS, GAS, PRS, EWS, MCS	SPS, RS
Initial service	Dec 1993	Sep 1993	Dec 2012	2016/2017 (planned)	2018 (planned)	2016 (planned)
Origin	USA	Russia	China	Europe	Japan	India
Coverage	Global	Global	Global	Global	East Asia Oceania region	$-30^\circ < \phi < 50^\circ$ $30^\circ < \lambda < 130^\circ$
Frequency (MHz)	L1 1575.42 L2 1227.60 L5 1176.45	L1 1602.00 L2 1246.00 L3 1202.025	B1 1561.098 B2 1207.14 B3 1268.52	E1 1575.42 E5a 1176.45 E5b 1207.14 E6 1278.75	L1 1575.42 L2 1227.60 L5 1176.45 E6 1278.75	L5 1176.45 S 2492.028

SPS: Standard Positioning Service; PPS: Precise Positioning Service; OS: Open Service; AS: Authorized Service; WADS: Wide Area Differential Service; SMS: Short Message Service; CS: Commercial Service; PRS: Public Regulated Service; GCS: GPS Complementary Service; GAS: GPS Augmentation Service; EWS: Early Warning Service; MCS: Message Communications Service; PS: Precision Service; RS: Restricted Service

典型PPP误差源估计



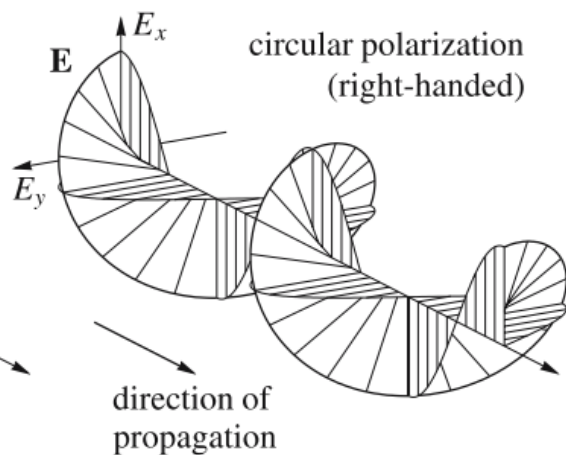
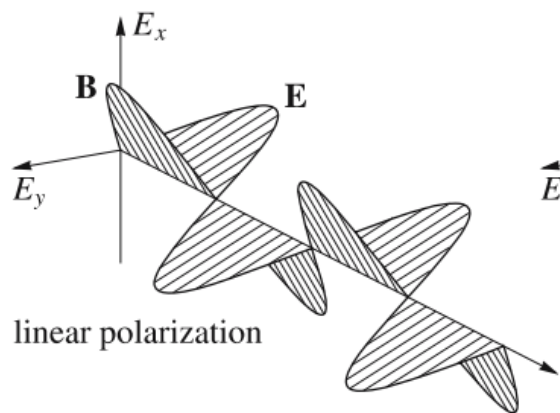
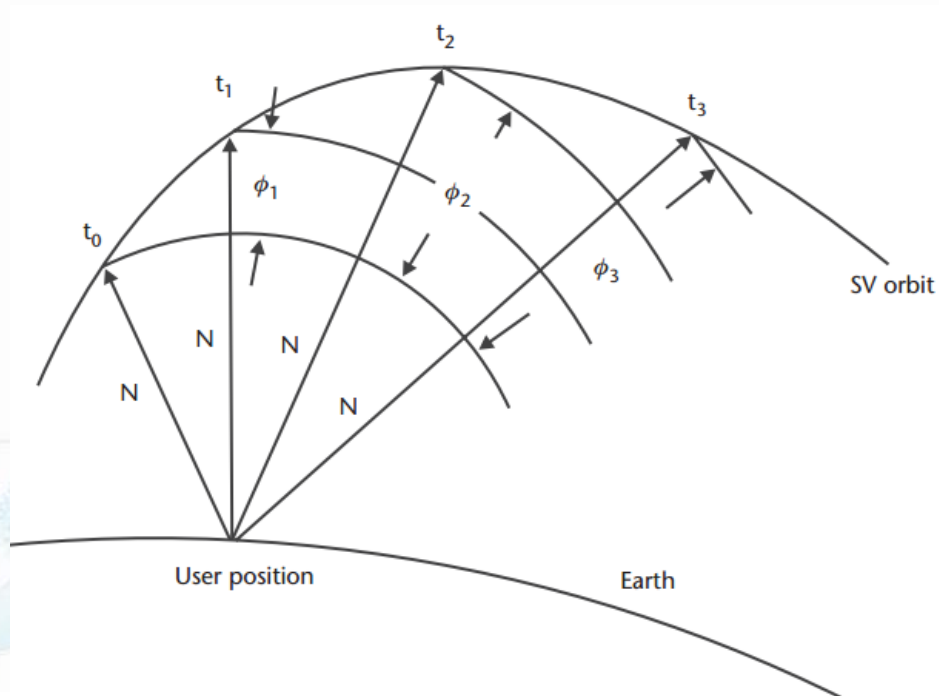
Model component		Magnitude	Uncertainty	Notes
Satellite	Center-of-mass position		2.5 cm (GPS)	Interpolated from precise orbit product in standard product 3 (format) (SP3) format with typical sampling of 15 min
	Antenna phase center offset	0.5–3 m	10 cm	Antenna offset vector in spacecraft system (IGS antenna exchange (ANTEX)) and GNSS specific attitude models [25.5, 6]
	Phase center variations	5–15 mm (GPS)	0.2–1 mm	IGS ANTEX model [25.5]
	Clock offset	< 1 ms	75 ps, 2 cm (GPS)	Interpolated from precise clock product with typical sampling of 30 s to 5 min
	Relativistic clock effects	10–20 m	–	Eccentricity-dependent effect [25.7, 8]
		2 cm	–	J_2 -dependent contribution [25.8]; consistently neglected in current precise GNSS clock products and PPP models
	Differential code biases	up to 15 ns, 5 m	0.1–1 ns	Required biases depend on tracked signals and clock product [25.9, 10]
Atmosphere	Fractional phase biases	up to 0.5 cy	0.01 cy	For undifferenced ambiguity resolution [25.11]
	Troposphere (dry)	2.3 m	5 mm	Vertical delay [25.12], up to 10× larger for low elevations. Models: see, e.g., [25.13, Sect. 9.2], [25.14, 15]
	Troposphere (wet)	up to 0.3 m	up to 100%	Vertical delay [25.12]; estimated due to insufficient a priori models
	Ionosphere (1 st -order)	up to 30 m	– / 1 m	Vertical delay, up to 3× larger for low elevations. Corrected through ionosphere-free combination (2-freq. PPP) or global ionosphere maps ([25.16]; 1-freq. PPP)
Site displacement	Ionosphere (higher-order)	0–2 cm	1–2 mm	References [25.17] and [25.13, Sect. 9.4.1]
	Plate motion	up to 0.1 m/y	0.3 mm/y	Corrections for expressing measured positions in a conventional terrestrial reference frame Reference [25.18]
Receiver	Solid Earth tide	up to 0.4 m	1 mm	References [25.19] and [25.13, Sect. 7.1.1]
	Ocean loading (tidal)	1–10 cm	1–2 mm	References [25.13, Sect. 7.1.2], [25.20, 21]
	Ocean loading (nontidal)	up to 15 mm	1 mm	Nonconventional correction; [25.22]
	Pole tide	25 mm	–	Reference [25.13, Sect. 7.1.4]
	Atmospheric loading (tidal)	up to 1.5 mm	–	Reference [25.13, Sect. 7.1.3]
	Atm. loading (nontidal)	up to 20 mm	15%	Nonconventional correction; [25.23]
	Phase center offset	5–15 cm	–	IGS ANTEX model (conventional values)
Others	Phase center variations	up to 3 cm	1–2 mm	IGS ANTEX model; [25.24]
	Phase wind-up	10 cm	see notes	Wavelength dependent; correction subject to knowledge of satellite/receiver antenna orientation; [25.25, 26]

导航信号

$$\varphi(t) - \varphi(t_0) = \int_{t_0}^t f dt$$

$$\nabla^2 \mathbf{E} = \varepsilon \mu \frac{\partial^2 \mathbf{E}}{\partial t^2}$$

$$\nabla^2 \mathbf{H} = \varepsilon \mu \frac{\partial^2 \mathbf{H}}{\partial t^2}$$



观测方程

$$\begin{aligned}\phi_i^j = & \rho_i^j - c\delta t_i + c\delta t^j + \lambda_i N_i^j - d_I^j \\ & + d_{tro}^j + d_{rel}^j + \lambda(\phi_0 - \phi_0^j) \\ & + d_{hd,\phi}^j + d_{hd,\phi}^j + d_{mult,\phi}^j + \varepsilon_{i,\phi}^j\end{aligned}$$

$$\begin{aligned}P_i^j = & \rho_i^j - c\delta t_i + c\delta t^j + d_I^j + d_{tro}^j + d_{hd,P}^j \\ & + d_{hd,P}^j + d_{rel}^j + d_{mult,P}^j + \varepsilon_{i,P}^j\end{aligned}$$

i 为测站标志;

j 为卫星标志;

ϕ_i^j, P_i^j 分别表示相位和伪距观测量 (m);

x_i, y_i, z_i 为接收机坐标 (m);

X^j, Y^j, Z^j 为卫星坐标 (m);

N_i^j 为整周模糊度 (cycle);

ϕ_0, ϕ_0^j 分别为接收机和卫星的初始相位 (cycle);

d_I^j 为电离层延迟 (m);

d_{tro}^j 为对流层延迟(m);

$d_{hd,P}, d_{hd,\phi}$ 为接收机硬件延迟(m);

$d_{hd,P}^j, d_{hd,\phi}^j$ 为卫星硬件延迟 (m);

d_{rel}^j 为相对论效应 (m);

$d_{mult,P}^j, d_{mult,\phi}^j$ 为多路径误差 (m);

$\varepsilon_{i,P}^j, \varepsilon_{i,\phi}^j$ 为观测噪声 (m)。

周跳探测与模糊度问题

- 定轨采用的观测量为伪距相位观测数据的无电离层LC组合：

$$PC = \frac{f_1^2}{f_1^2 - f_2^2} P_1 - \frac{f_2^2}{f_1^2 - f_2^2} P_2 \quad LC = \frac{f_1^2}{f_1^2 - f_2^2} L_1 - \frac{f_2^2}{f_1^2 - f_2^2} L_2$$

$$\varphi_{mn} = \varphi_1 - \frac{f_1}{f_2} \varphi_2 = \left(\frac{f_1^2 - f_2^2}{cf_1 f_2} \right) \times 40.3TEC - \left(N_1 - \frac{f_1}{f_2} N_2 \right)$$

Wide-laning combinations: These combinations are used to create a measurement with a significantly wide wavelength. This long wavelength is useful for carrier phase cycle-slip detection and fixing ambiguities:

$$\Phi_W = \frac{f_1 \Phi_1 - f_2 \Phi_2}{f_1 - f_2}, \quad R_W = \frac{f_1 R_1 - f_2 R_2}{f_1 - f_2} \quad (4.1)$$

Narrow-laning combinations: These combinations create measurements with a narrow wavelength. The measurement in this combination has a lower noise than each separate component:

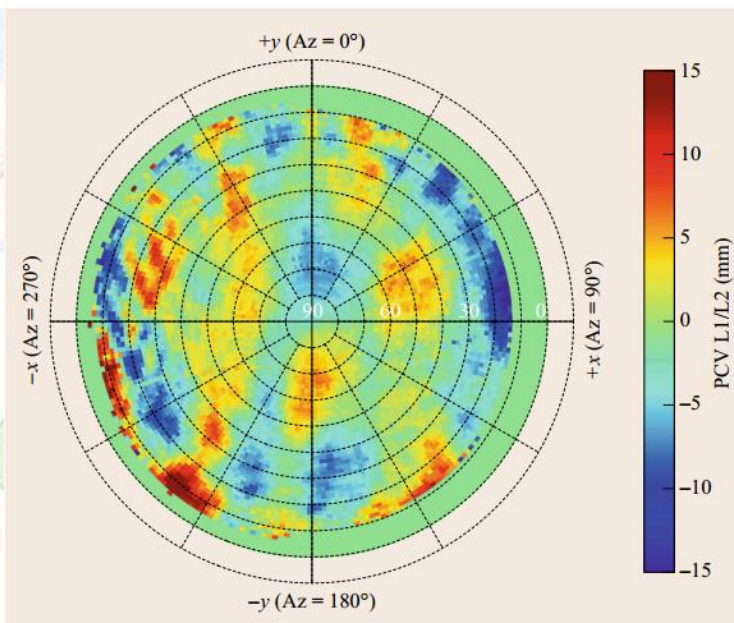
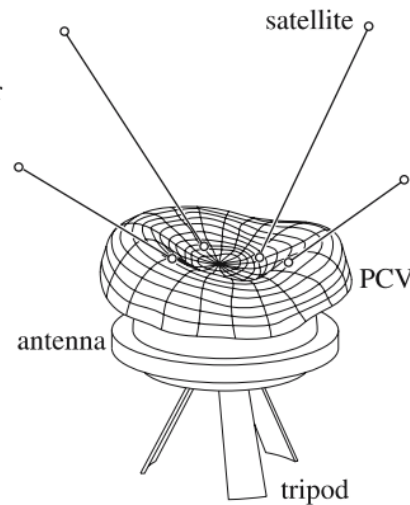
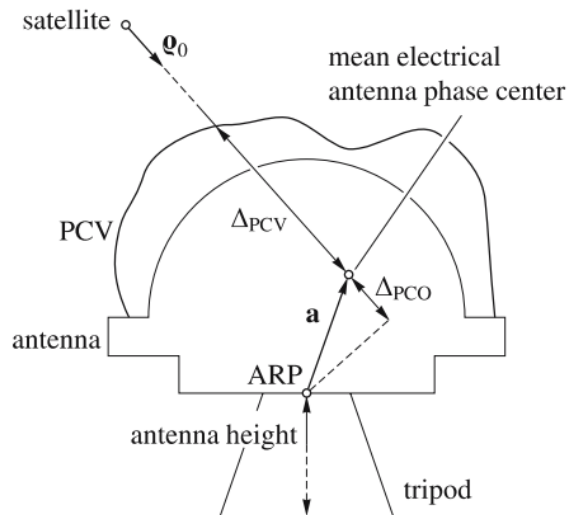
$$\Phi_N = \frac{f_1 \Phi_1 + f_2 \Phi_2}{f_1 + f_2}, \quad R_N = \frac{f_1 R_1 + f_2 R_2}{f_1 + f_2}$$

The Melbourne–Wübbena combination is a linear combination of both, carrier phase (L_1 and L_2) and code (P_1 and P_2) observables as described by Wübbena (1985) and Melbourne (1985). This combination eliminates the effect of the ionosphere, the geometry, the clocks, and the troposphere. The combination is given by

$$L_6 = \frac{1}{f_1 - f_2} (f_1 L_1 - f_2 L_2) - \frac{1}{f_1 + f_2} (f_1 P_1 + f_2 P_2) . \quad (2.28)$$

天线相位中心偏差与相位中心变化

伪距和载波相位值都是在星载GNSS接收机相位中心到GNSS卫星发射相位中心之间，计算出的LEO卫星坐标也是对应于LEO卫星质心而不是相位中心。GNSS卫星和LEO卫星相位中心与其质心一般并不重合，存在一定偏差。



相位缠绕

GPS 发射天线或星载 GPS 接收天线绕极化轴向的旋转会改变相位观测值，这一效应称为相位缠绕。相位缠绕是 GPS 载波相位观测数据的误差源之一，会对相位观测数据产生分米量级的误差。

$$\Delta\Phi = \delta\phi + 2N\pi \quad (5.71)$$

where $\delta\phi$ is the fractional part of a cycle given by

$$\delta\phi = \text{sign}(\zeta) \arccos\left(\frac{\mathbf{d}' \cdot \mathbf{d}}{\|\mathbf{d}'\| \|\mathbf{d}\|}\right), \text{ with } \zeta = \hat{\rho} \cdot (\mathbf{d}' \times \mathbf{d}) \quad (5.72)$$

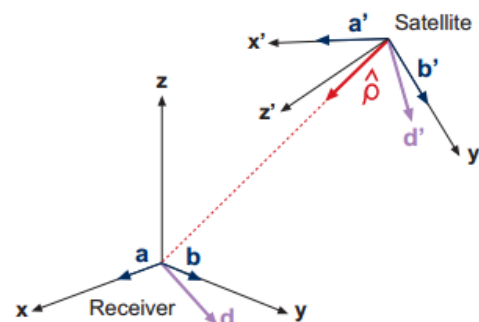
and N is an integer number given by

$$N = \text{nint}\left[\frac{\Delta\Phi_{prev} - \delta\phi}{2\pi}\right] \quad (N \text{ can be initialised as zero}) \quad (5.73)$$

where $\Delta\Phi_{prev}$ is the previous value of the phase correction, nint stands for the *nearest integer* and \mathbf{d} , \mathbf{d}' are two effective dipoles for the receiver and transmitter:

$$\begin{aligned} \mathbf{d} &= \hat{\mathbf{a}} - \hat{\rho}(\hat{\rho} \cdot \hat{\mathbf{a}}) + \hat{\rho} \times \hat{\mathbf{b}} \\ \mathbf{d}' &= \hat{\mathbf{a}}' - \hat{\rho}(\hat{\rho} \cdot \hat{\mathbf{a}}') - \hat{\rho} \times \hat{\mathbf{b}}' \end{aligned} \quad (5.74)$$

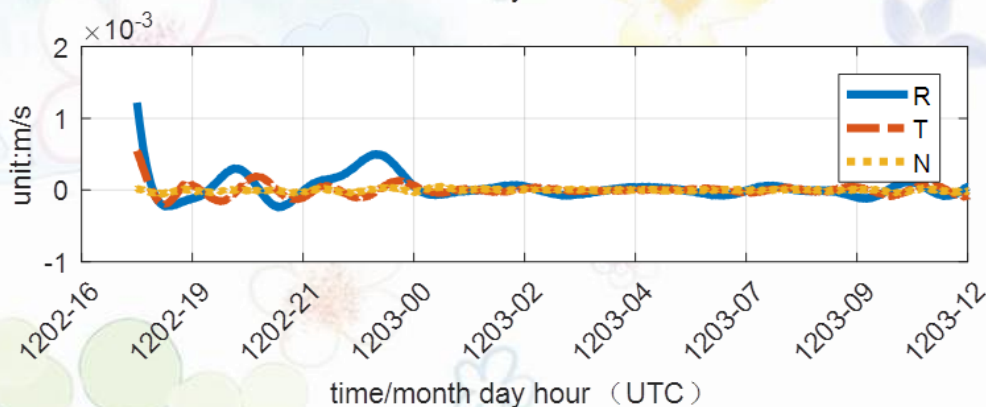
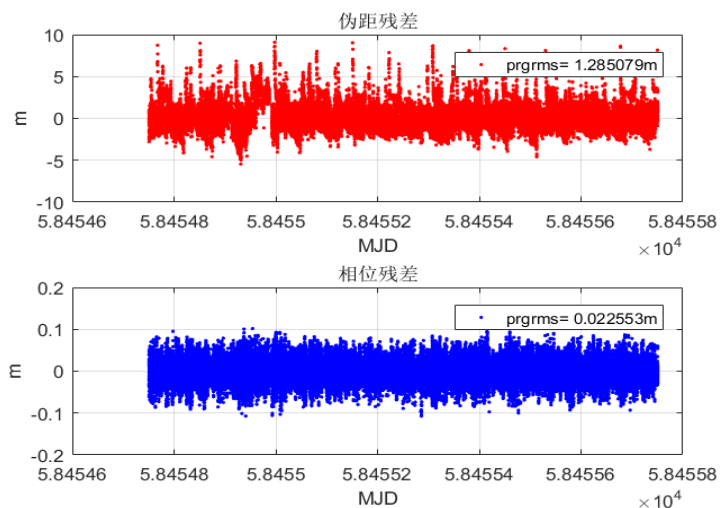
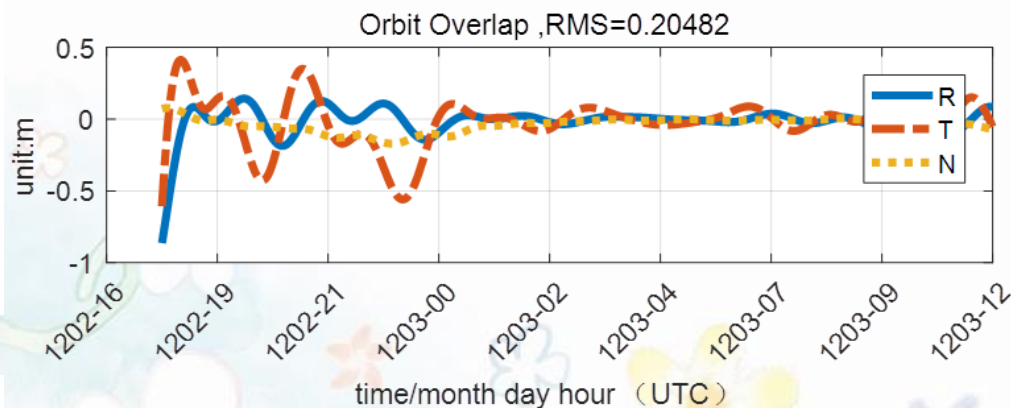
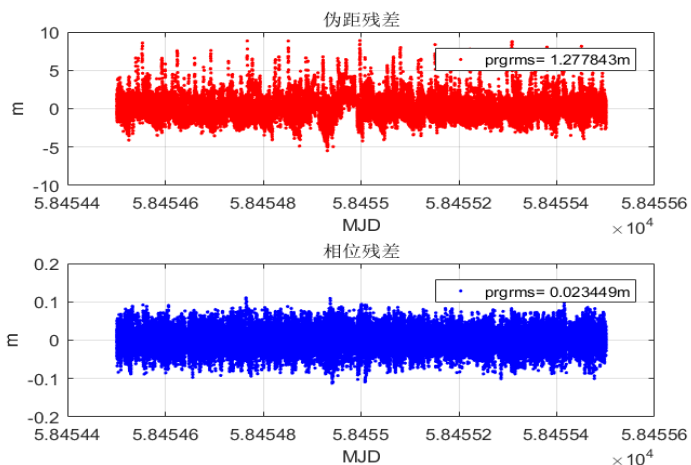
where the unit vectors $\hat{\mathbf{a}}$, $\hat{\mathbf{b}}$, $\hat{\mathbf{a}}'$, $\hat{\mathbf{b}}'$ and $\hat{\rho}$ are defined in Fig. 5.19 and below.



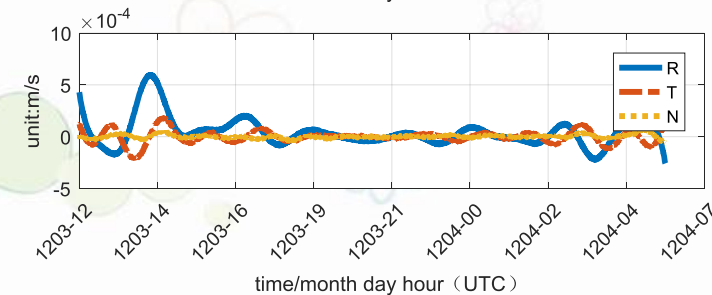
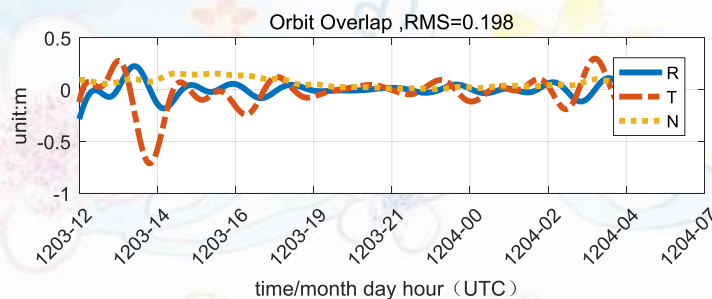
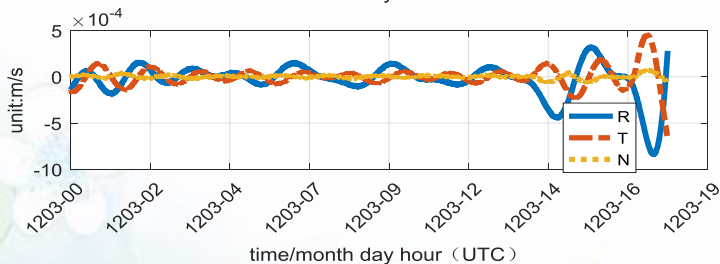
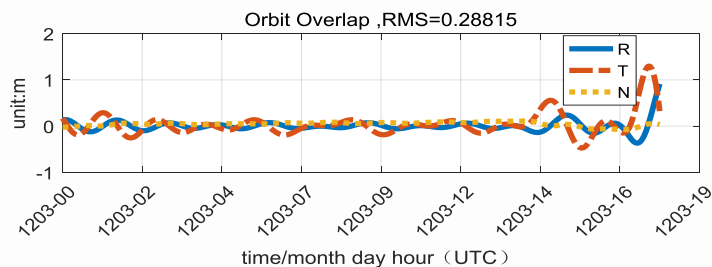
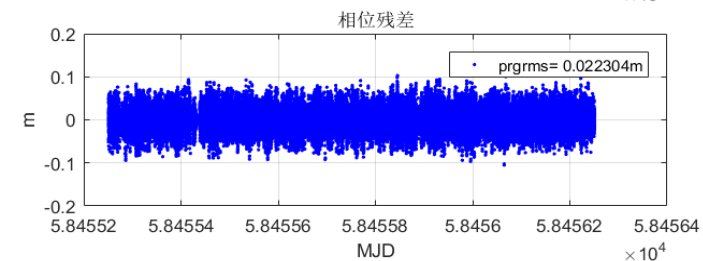
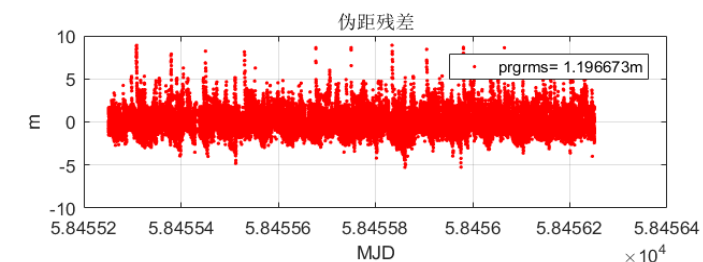
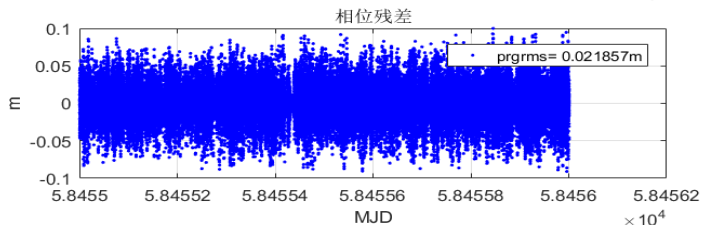
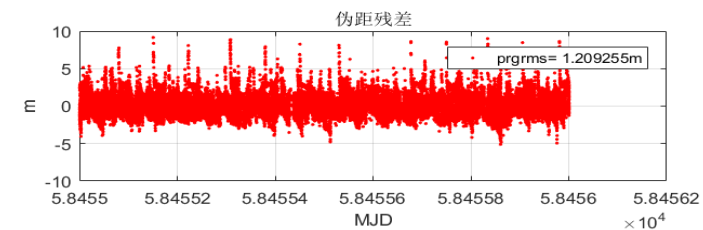
天平一号卫星试验数据处理结果

弧段	起始与结束时间（月日时分秒）										重叠弧段（1-2, 2-3,）									
1	12	2	12	0	0	12	3	12	0	0										
2	12	2	18	0	0	12	3	18	0	0	12	2	18	0	0	12	3	12	0	0
3	12	3	0	0	0	12	4	0	0	0	12	3	0	0	0	12	3	18	0	0
4	12	3	6	0	0	12	4	6	0	0	12	3	6	0	0	12	4	0	0	0
5	12	3	12	0	0	12	4	12	0	0	12	3	12	0	0	12	4	6	0	0
6	12	3	18	0	0	12	4	18	0	0	12	3	18	0	0	12	4	12	0	0

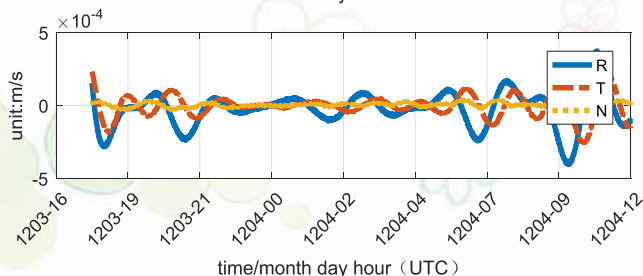
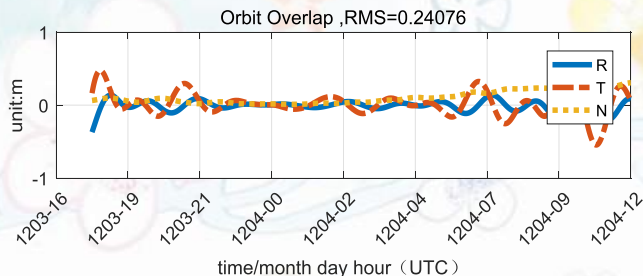
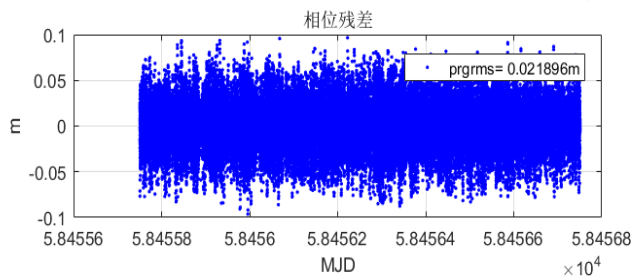
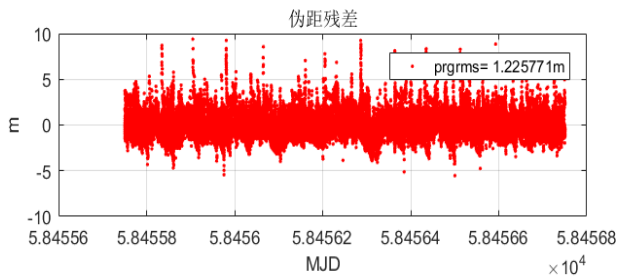
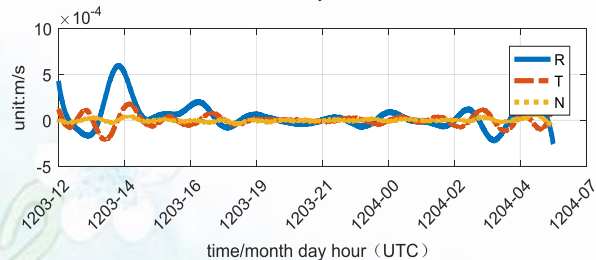
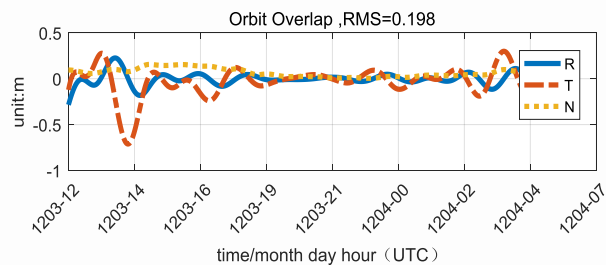
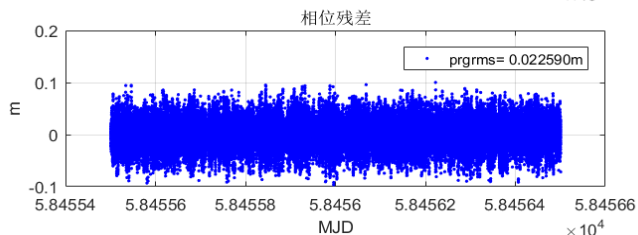
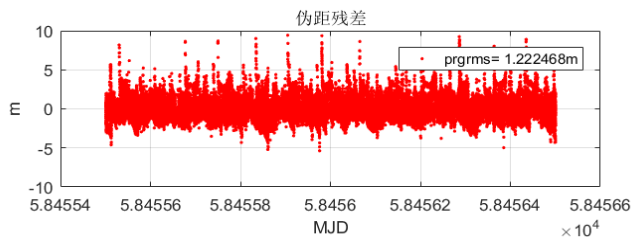
弧段1、2残差与轨道重叠



弧段2-3轨道重叠, 3-4重叠



弧段4-5轨道重叠, 5-6重叠



估计参数回顾

- 轨道参数6个
- 钟差参数（1秒采样率86400个/天，一般重采样，如10s）
- 天线相位中心PCO
- RTN方向周期经验力
- 分段大气阻尼cd
- 分段光压系数cr
- 模糊度参数根据数据分析一般1000以内（与弧段与数据质量有关）

星载GNSS接收机LEO轨道确定小结

- 定轨弧长24小时，每6小时向后滑动，定轨残差一般2-3cm，轨道重叠通常在3dm以下。数据质量有问题时会偏大。
- 提升性能提升：PCV处理，周跳探测进一步分析、残差编辑。
- 功能提升：PPP处理、导航星多星定轨系统等。

主要内容

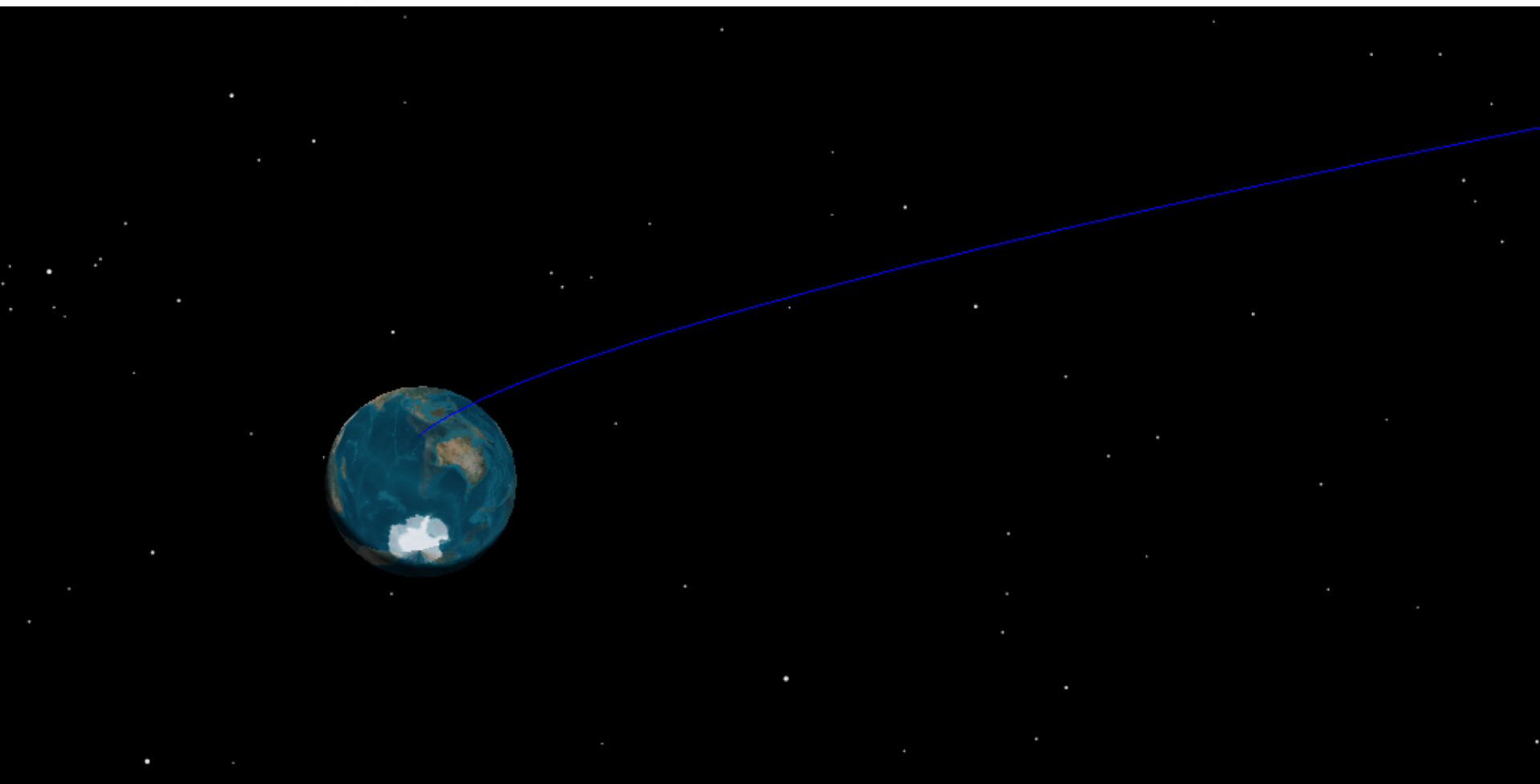
- 案例一：风云四号精密定轨系统
- 案例二：LEO星载GNSS精密定轨
- 案例三：近地自然小天体的星基平台光学定轨

撞击小天体初轨

初始根数

初始根数			
年	2019	半长径	106247.000000
月	11	偏心率	0.990000
日	17	倾角	28.500
时	4	升交点赤经	0.000
分	0	近地点幅角	90.0
秒	0	平近点角	60.000

空间轨迹



天基平台光学测量单星定初轨

```
# stdin for initial orbit determination
# if the first character of a line is "#" then this line is just for comment
# arc ---- the length of the arc , unit is minute
# obsfile --- the obs file name
# sateph --- the platform satellite's ephemeris file
```

```
arc      :      20
obsfile  :      obs\obsdat.txt
sateph   :      xyz_prn001.eph
reportfile :      report
```

```
#the end of stdin
```

```
the first obs : 2019 11 17 10 0 0.000 263.90840 -28.92180
the last obs  : 2019 11 17 10 20 3.000 262.68740 -27.26700
nobs : 401
```

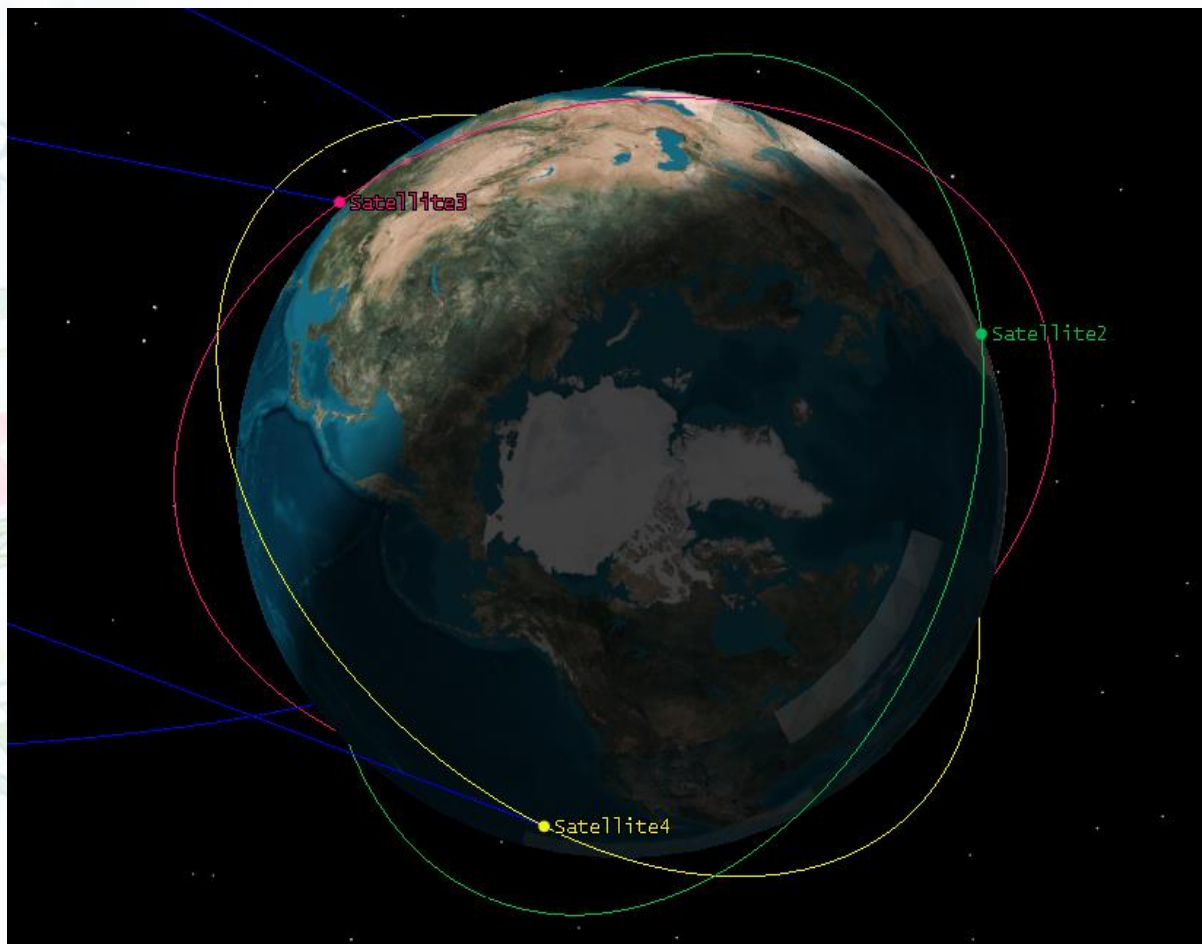
```
epoch1      2019.0      11.0      17.0
epoch2      10.0      0.0      0.000
pos  0      -14667126.393      -73219785.795      -39755066.060
vel  0      -70.531      -2091.040      -1135.379
```

```
initial ----- (UTC) -----
```

```
epoch1      2019.0      11.0      17.0
epoch2      10.0      00.0      00.000
# sat0
pos  0      -14667067.229      -73219305.824      -39754832.673
vel  0      -70.633      -2092.045      -1135.888
```

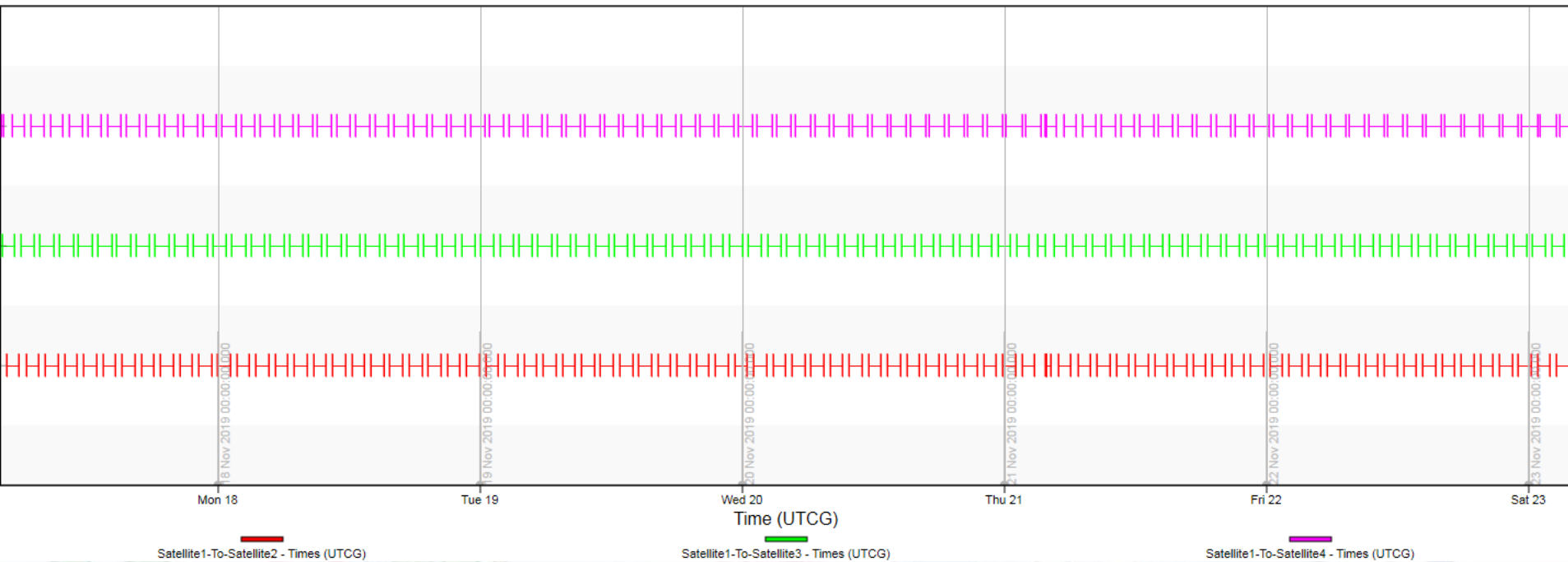
三星低轨星座监测自然卫星

轨道高度1000km，倾角 45° ，升交点赤经 0° ， 120° ， 240° 。



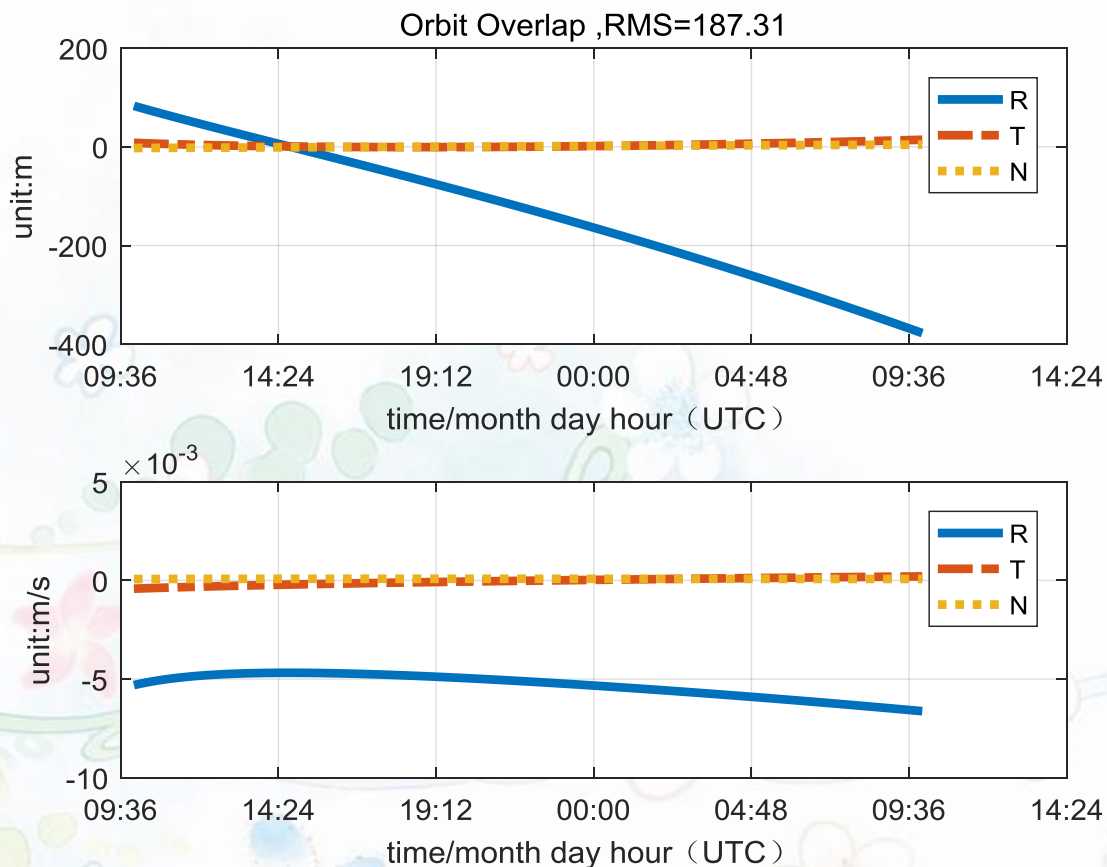
凝视模式下可视性分析

Access Times - 18 Nov 2019 00:43:02



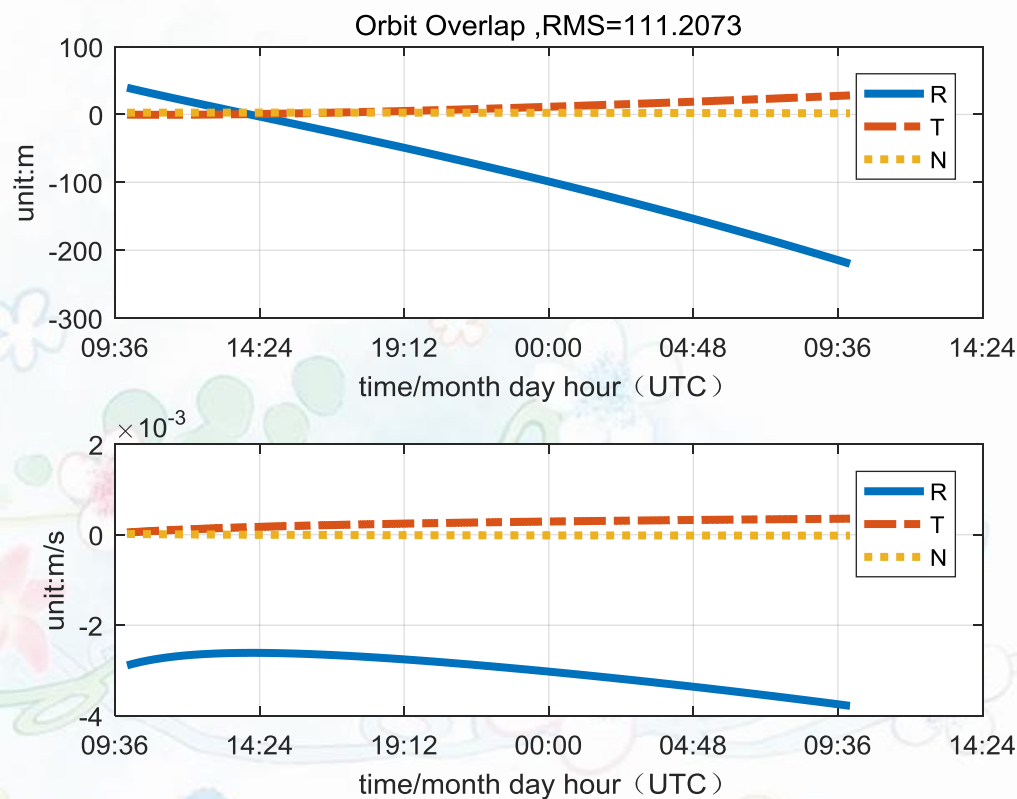
Access	Start Time (UTCG)	Stop Time (UTCG)	Duration (sec)
1	17 Nov 2019 04:41:20.584	17 Nov 2019 05:46:17.488	3896.904
2	17 Nov 2019 06:26:14.788	17 Nov 2019 07:33:43.576	4048.788
3	17 Nov 2019 08:11:35.538	17 Nov 2019 09:19:52.166	4096.629
4	17 Nov 2019 09:56:53.767	17 Nov 2019 11:05:36.295	4122.528
5	17 Nov 2019 11:42:09.674	17 Nov 2019 12:51:08.861	4139.187
6	17 Nov 2019 13:27:23.903	17 Nov 2019 14:36:34.853	4150.950
7	17 Nov 2019 15:12:36.930	17 Nov 2019 16:21:56.648	4159.718
8	17 Nov 2019 16:57:49.047	17 Nov 2019 18:07:15.585	4166.538
9	17 Nov 2019 18:43:00.481	17 Nov 2019 19:52:32.442	4171.961

单星定轨结果与仿真轨道比较



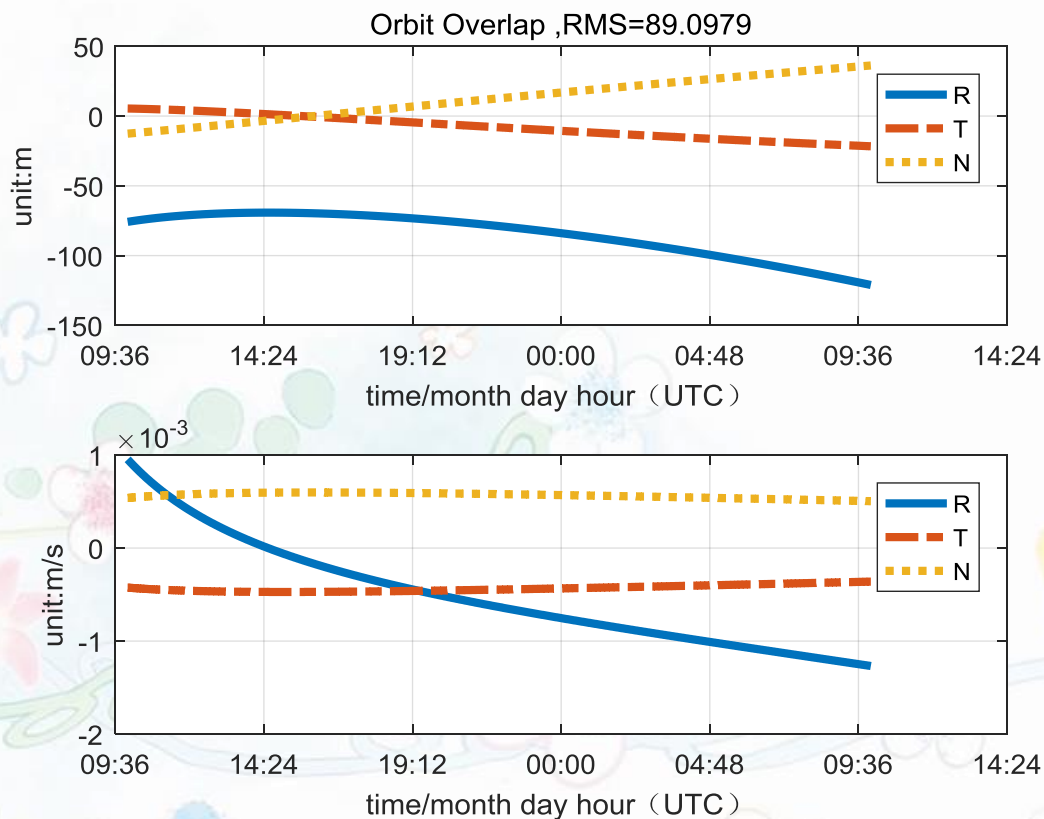
定轨资料弧长10小时，预报14小时。事后轨道与仿真轨道重叠。

双星定轨结果与仿真轨道比较



定轨资料弧长10小时，预报14小时。事后轨道与仿真轨道重叠。

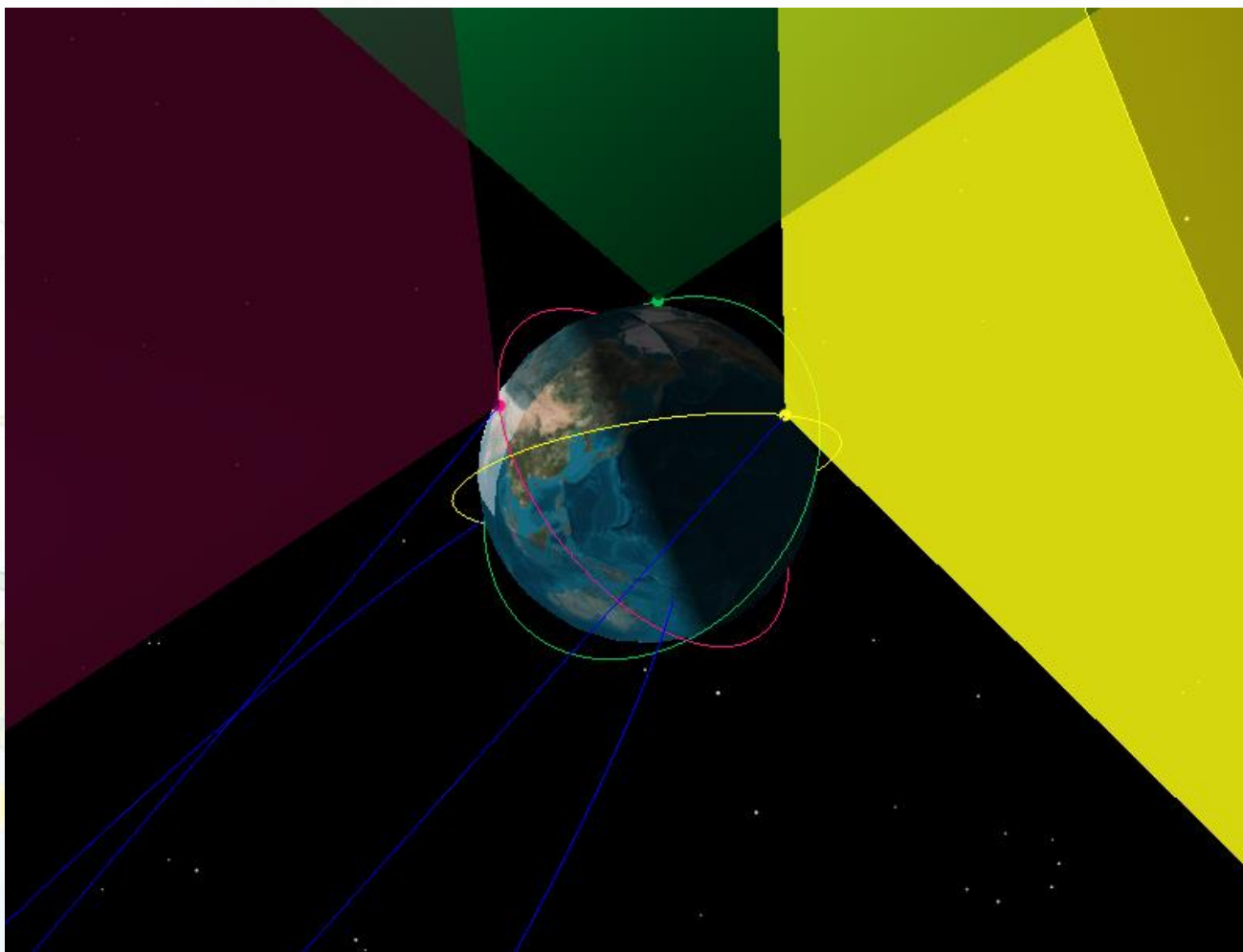
三星联合定轨结果与仿真轨道比较



定轨资料弧长10小时，预报14小时。事后轨道与仿真轨道重叠。

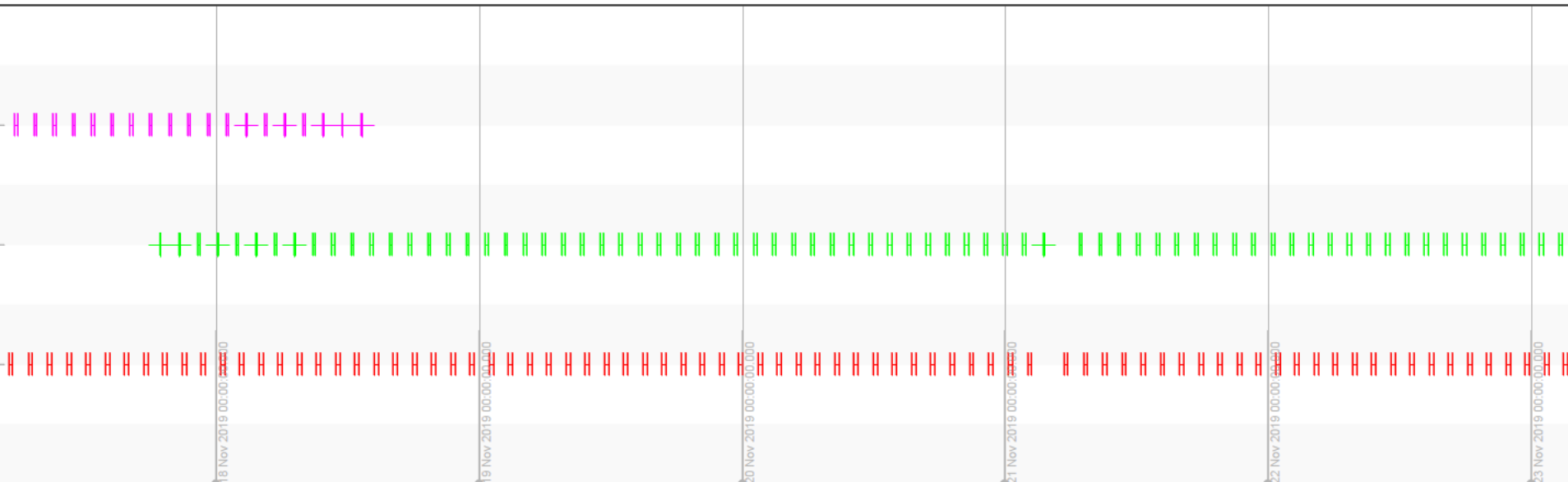
巡天模式

- ▶ 视场指向地心反方向，半角 45° 。



可视性分析

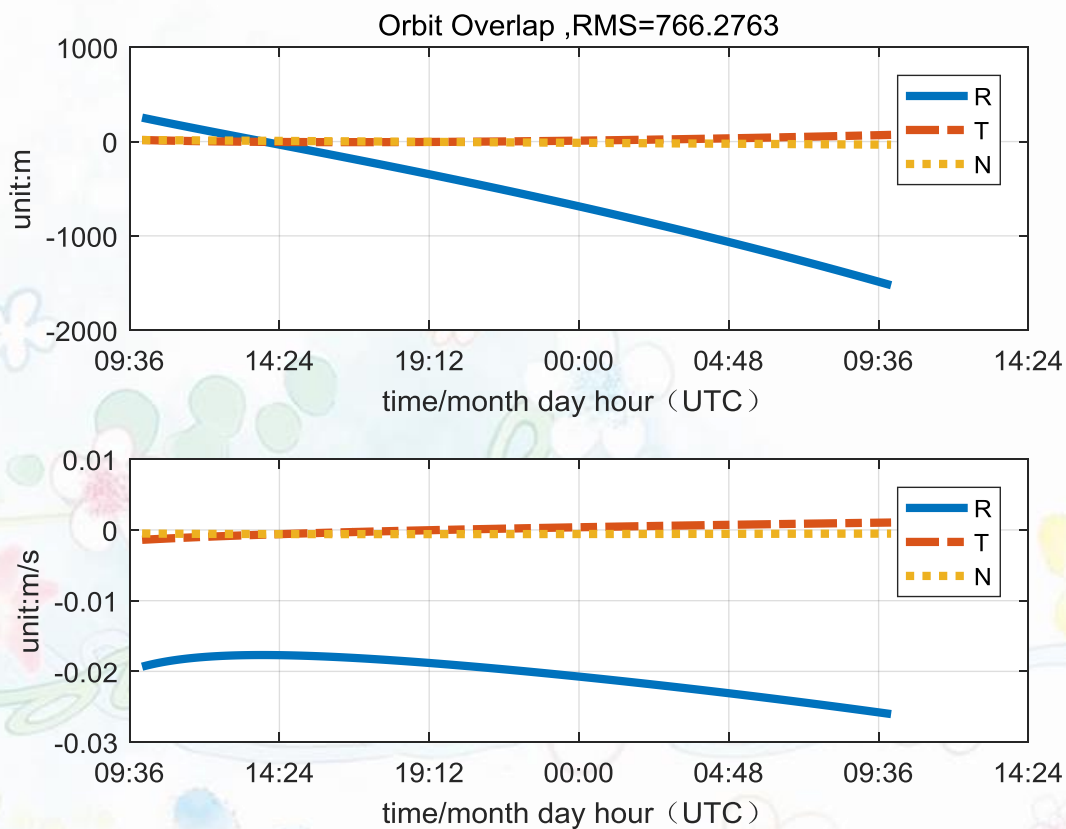
Access Times - 18 Nov 2019 00:55:13



Satellite1-To-Sensor4

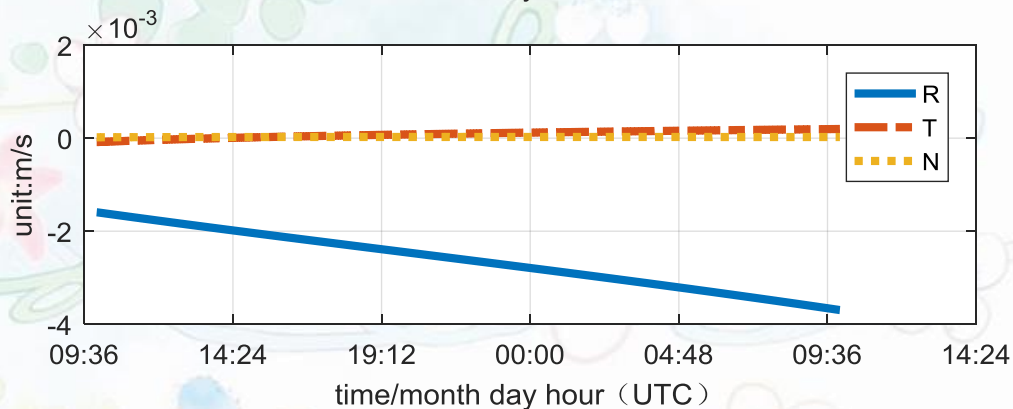
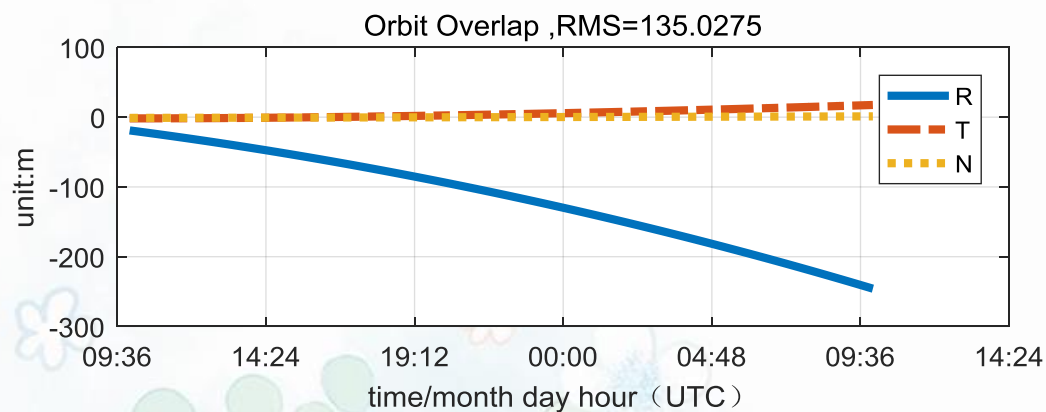
Access	Start Time (UTC)	Stop Time (UTC)	Duration (sec)
1	17 Nov 2019 05:03:29.492	17 Nov 2019 05:22:43.743	1154.250
2	17 Nov 2019 06:49:02.422	17 Nov 2019 07:10:37.843	1295.420
3	17 Nov 2019 08:34:29.165	17 Nov 2019 08:56:50.113	1340.947
4	17 Nov 2019 10:19:50.140	17 Nov 2019 10:42:34.964	1364.824
5	17 Nov 2019 12:05:07.691	17 Nov 2019 12:28:07.566	1379.876
6	17 Nov 2019 13:50:23.033	17 Nov 2019 14:13:33.395	1390.362
7	17 Nov 2019 15:35:36.848	17 Nov 2019 15:58:54.998	1398.150
8	17 Nov 2019 17:20:49.549	17 Nov 2019 17:44:13.746	1404.197
9	17 Nov 2019 19:00:00.000	17 Nov 2019 19:00:00.000	0.000

单星巡天定轨



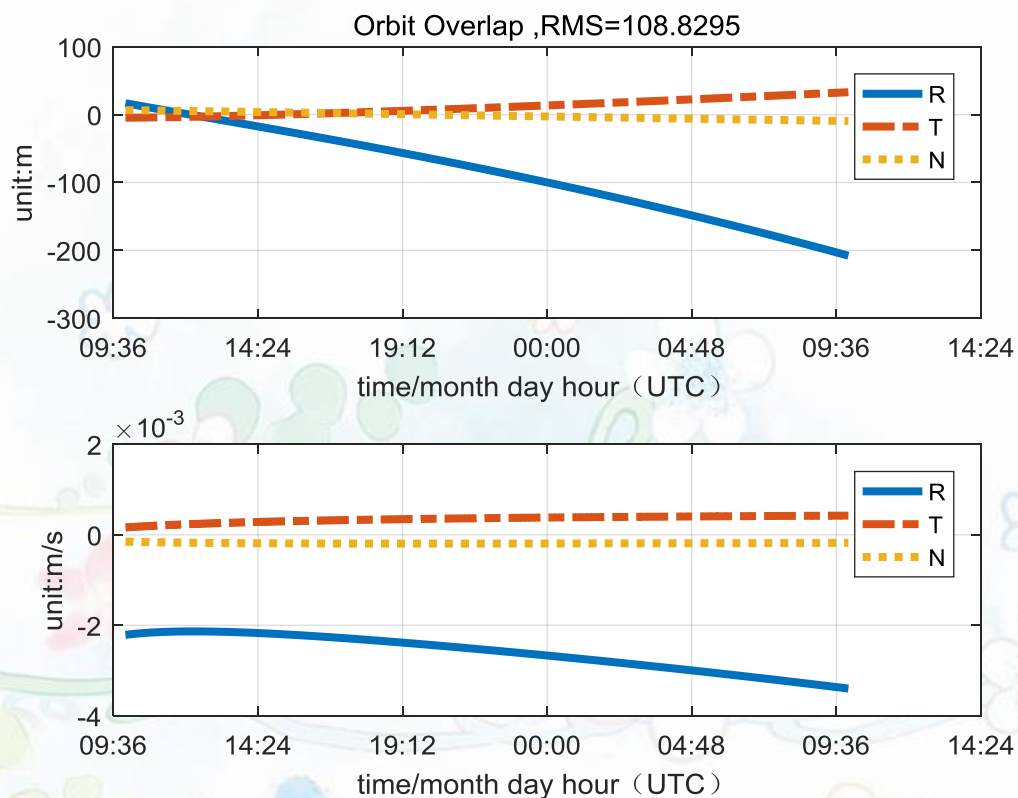
定轨资料弧长12小时，预报12小时。事后轨道与仿真轨道重叠。

双星巡天定轨



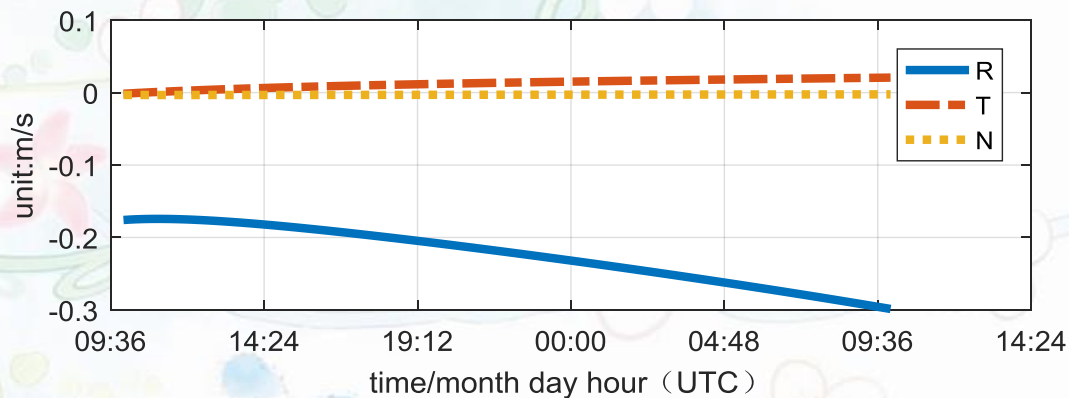
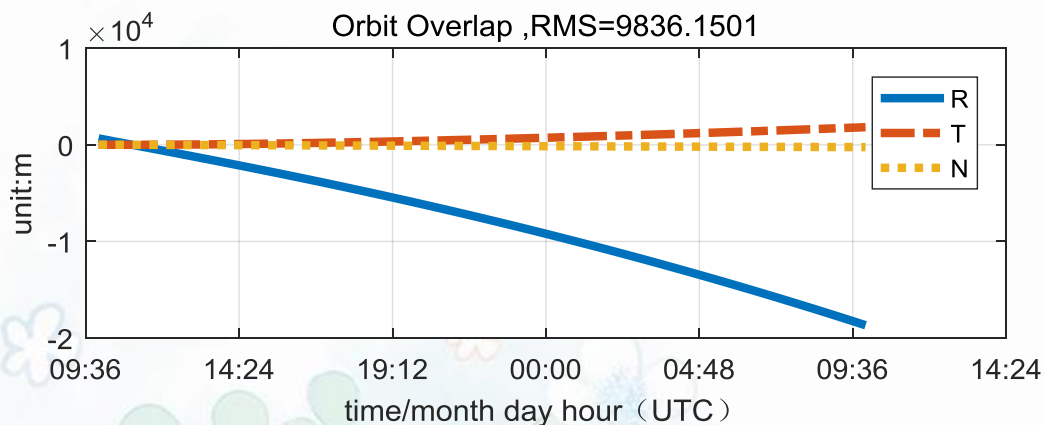
定轨资料弧长12小时，预报12小时。事后轨道与仿真轨道重叠。

三星巡天模式定轨



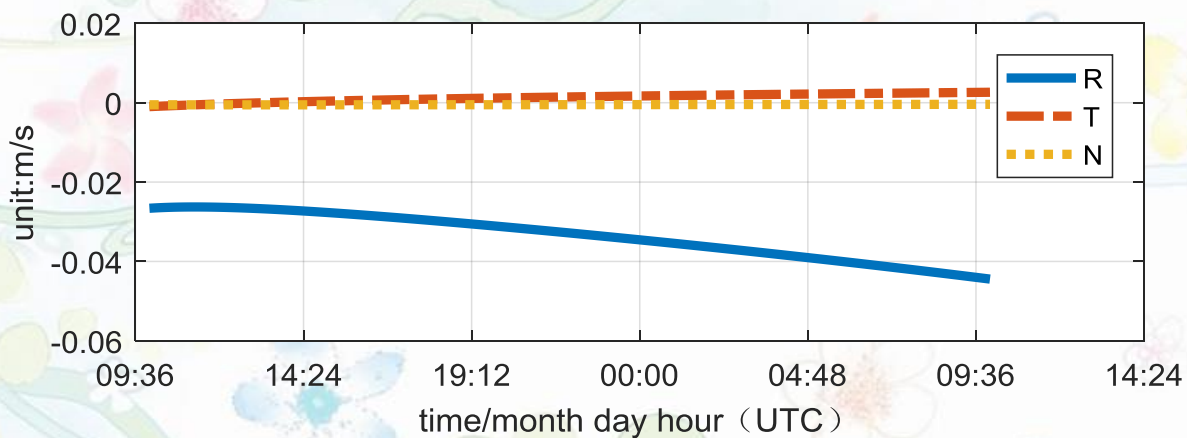
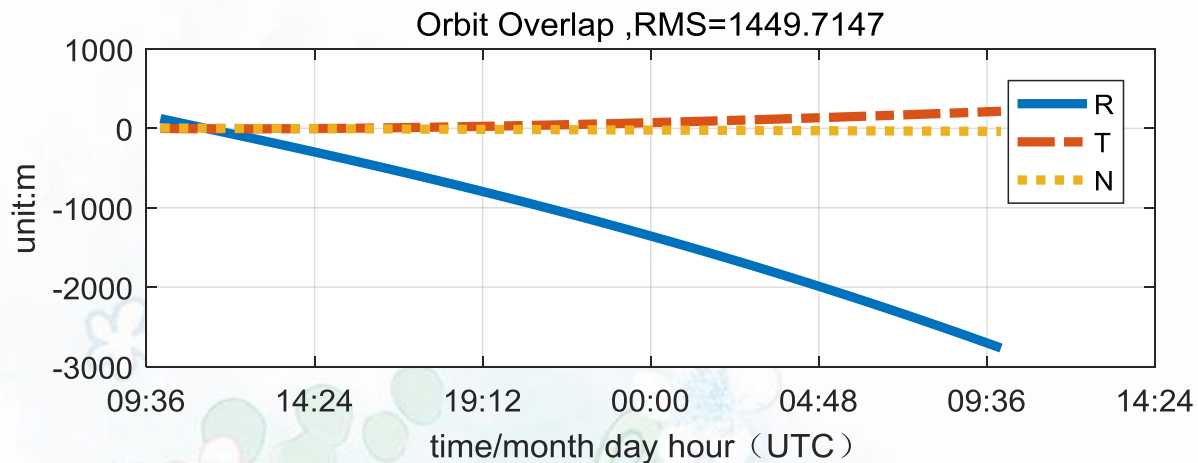
定轨资料弧长12小时，预报12小时。事后轨道与仿真轨道重叠。

单星巡天2小时快速定轨

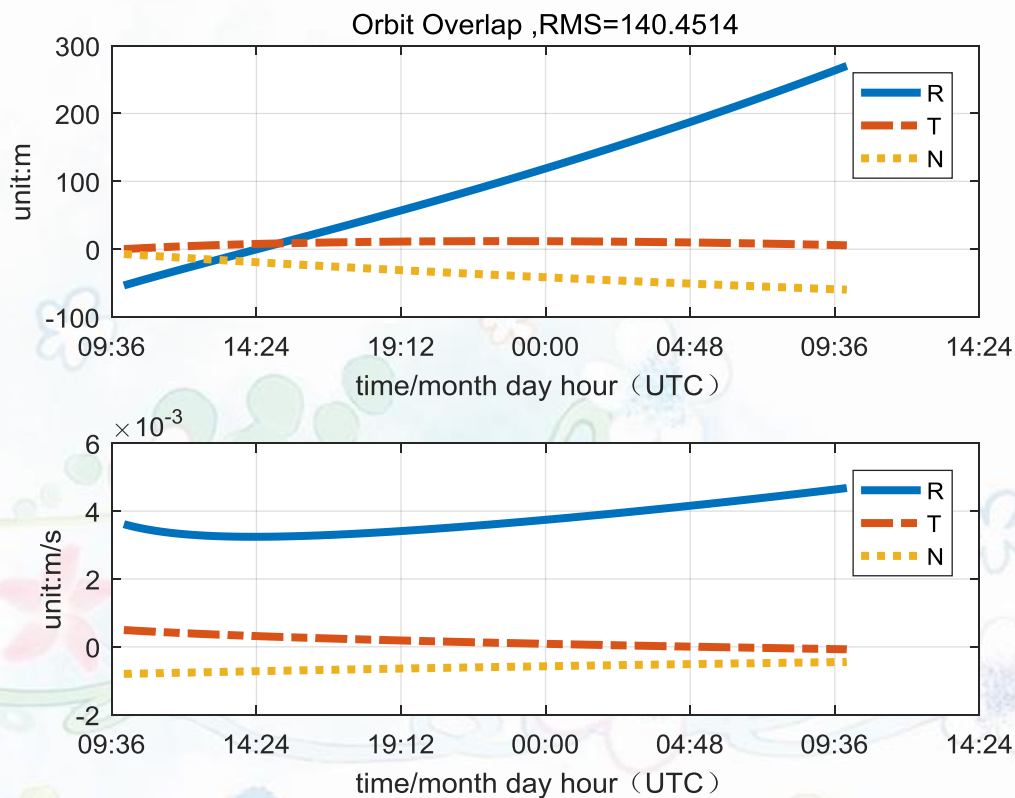


定轨资料弧长2小时，预报22小时。事后轨道与仿真轨道重叠。

双星巡天2小时快速定轨



三星巡天2小时快速定轨



定轨资料弧长2小时，预报22小时。事后轨道与仿真轨道重叠。

结论

- 低轨跟踪低轨，针对仿真算例，轨道周期约1个半小时。1小时观测已经覆盖2/3周期弧段。目标与平台较近，在0.5角秒测量精度下，较为容易达到百米以下定轨精度。由于其轨道周期短，因此预报的1-2小时精度损失也较小。实际情况下，由于400km高度受大气影响较为严重，长弧段预报轨道精度会迅速衰减。因此，实际情况会比仿真精度要低。在超高精度轨道确定中，大气模型往往采用经验加速度吸收，由于要进行轨道预报，这里并不适合为追求内符精度而采用过多的经验模型。
- GEO跟踪GEO单星问题，轨道精度较低。通过分析定轨协方差矩阵，高度相关，造成其法矩阵接近秩亏。有时长弧段反而精度略有下降，较难满足工程需求。
- 双GEO联合跟踪测量GEO，轨道精度在测量1-2小时后，较为容易达到百米级。对其分析其定轨协方差矩阵，在双星条件下该矩阵良好。
- 在对近地自然小天体进行轨道确定确定时，单星在短时较难快速响应，而多星则可能较快速的进行轨道确定。

A satellite is shown in orbit above the Earth. The satellite has a central body covered in gold thermal insulation, two large rectangular solar panel arrays extending outwards, and a large white parabolic dish antenna. The Earth's surface is visible below, showing dark landmasses and bright city lights at night. The text "本学期课程完，谢谢！" is overlaid in the bottom left corner.

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