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博士论文摘要选登

区域导航卫星精密定轨研究

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摘要：区域卫星导航系统采用混合星座设计， GEO(地球同步轨道) 卫星是系统的重要组成部分，其精密定轨技术也是导航系统的关键技术之一。 GEO 卫星的高轨特性致使地面跟踪基线长度有限，定轨几何条件不佳；其静地特性致使卫星轨道与钟差存在强相关特性，对于基于伪距的 GEO 卫星定轨模式，需要星地与站间时间同步技术的支持。因此，如何利用区域卫星导航系统的多种测量技术实现多模式、多层次的导航卫星精密定轨，是一项值得深入研究的课题。

本文立足区域卫星导航系统的设计体制，对基于多技术、多模式下的导航卫星精密定轨进行了深入研究，提出了多种 GEO 卫星定轨方案，研究了时间同步体制下的定轨策略，实现了短弧跟踪条件下卫星轨道快速恢复。具体研究内容如下：

(1) 介绍了导航系统的基本理论，给出了钟差和伪距的详细定义，分析和讨论了不同类型测量数据的观测模型及其误差改正模型。

(2) 在 UTOPIA 软件的基础上，完善了一套综合多种测量数据的导航卫星联合定轨软件，能够处理多类型的观测数据，包括伪距、转发式测距、SLR 和星地时间同步上下行观测数据，实现了对卫星钟差和跟踪站钟差的灵活、有效的建模，实现了多种测量技术条件下的卫星精密定轨。

(3) 提出了两种设备时延的精确标定方法，即 SLR 并置比对法和联合定轨法，利用实测数据进行了标定试验，标定精度分别为 0.5 ns 和优于 1 ns，解决了设备时延的精确标定问题。

(4) 探讨与研究了基于 SLR 和转发式测距的 GEO 卫星联合定轨方案，利用 GEO 卫星的实测数据进行了定轨试验，结果表明： SLR 评估的外符视向精度为 0.133 m， 3 维位置精度优于 5 m，预报 2 h SLR 评估的外符视向精度为 0.373 m，实现了 GEO 卫星精密定轨。

(5) 探讨与研究了基于转发式测距和伪距的 GEO 卫星联合定轨方案，解决了转发式跟踪站数量和测距数据有限所带来的 GEO 定轨问题，找到了一种新的时间同步方法，实现了卫星星历与钟差的自洽，提高了导航服务性能。利用 GEO 卫星的实测数据进行了定轨试验， SLR 评估的外符视向精度为 0.076 m，预报 2 h 视向精度为 0.404 m，时间同步精度优于 1.5 ns。实现了在单个转发式站跟踪条件下的 C+L 联合定轨， SLR 评估的外符视向精度为 0.280 m，预报 2 h 视向精度为 0.888 m，解决了基于伪距的 GEO 定轨需要时间同步支持的问题。

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(6) 深入分析了多种测量技术条件下的 GEO 卫星定轨问题，利用仿真数据详细讨论了不同模式下定轨策略和轨道精度，包括“转发式测距 + 伪距”、“ SLR+ 伪距”和“ SLR+ 转发式” 3 种模式，讨论了钟差二次项对定轨精度的影响，详细分析了伪距跟踪站对 GEO 卫星定轨精度的影响，完成了卫星钟差和站钟差的统一估计，星历与钟差参数实现了自洽，分析和讨论了系统差对不同定轨模式的轨道精度影响，提出了单个转发式跟踪站约束条件下的 GEO 卫星联合定轨方案，从仿真角度分析了基于“ SLR+ 转发式”模式下系统差的解算精度，实现了系统差的精确标定。

(7) 研究了星地 / 站间、星地、站间 3 种模式下 GEO 定轨特性，利用仿真数据探讨了 3 种模式下的可行性，研究表明包含钟差误差和设备时延在内的系统差，是制约 GEO 定轨精度的关键因素，要达到 10 m 的定轨精度，系统差要控制在 2 ns 以内。基于站间时间同步条件下的 GEO 定轨模式要求至少两个时间同步站的支持，同时可以实现星地和站间时间同步，但是定轨精度不稳定，对钟差误差反映特别灵敏，从轨道精度和钟差精度来看，该策略要优于基于星地时间同步模式的定轨策略。不同模式下 GEO 定轨对定轨软件提出了很高的要求，要求具备处理钟差二次项、卫星钟差、测站钟差等功能。

(8) 立足短弧跟踪条件下导航卫星的轨道快速恢复问题，提出了 3 种运动学定轨方法，即基于单点定位多项式拟合法、基于伪距多项式拟合法和基于星历拟合法，建立了相应的理论模型，给出了 3 种方法的实现过程。 3 种方法克服了短弧跟踪条件下动力学法定轨和单点定位中各种问题，实现了短弧跟踪条件下卫星精密定轨。利用 MEO 和 GEO 卫星的实测数据，进行了短弧运动学定轨试验，在 10 min 跟踪弧段条件下， MEO 卫星的运动学定轨精度优于 10 m，速度精度为 2 cm/s，预报 5 min 轨道精度为 15.02 m； GEO 卫星的运动学定轨精度优于 19 m，速度精度为 4 mm/s，速度精度明显优于 MEO 卫星，预报 5 min 的位置精度为 17.76 m，预报 10 min 的位置精度为 18.168 m。

Studies on Precise Orbit Determination for the Regional Navigation Satellite

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Abstract: A mixed navigation constellation is employed in the regional satellite navigation system. The GEO (Geostationary Orbit) satellite plays a significant role in the system, and the POD (Precise Orbit Determination) is the key technology in the regional satellite navigation system. Therefore, how to employ several kinds of tracking techniques to achieve multi-mode and multi-level precise orbit determination for navigation satellites is worthy of in-depth study in regional satellite navigation system.

Based on the framework of regional satellite navigation system and multi-technology and multi-mode, POD for navigation satellites is studied in this paper. Several GEO satellite POD strategies are put forward, so are the POD strategies based on time synchronization framework. Based on the short-arc tracking, rapid orbit recovery has been achieved. Summarily, the main contents are as following:

(1) The basic theory of navigation systems is introduced, and definitions of the clock error and the pseudo-range are put forward. Measurement models and error correction models for different kinds of measurements are analyzed and discussed.

(2) Based on the UTOPIA software, a POD software for navigation satellites has been accomplished, which can deal with many types of measurements, including pseudo-range data, transfer ranging data, satellite laser ranging (SLR) data, and uplink/downlink measurements of satellite-ground time synchronization. In this software, clock offsets of satellites and stations are modeled flexibly and effectively, and POD for navigation satellites has been achieved combining different kinds of tracking data.

(3) Two approaches to calibrate ranging biases of the system are proposed, namely the co-location comparison of two tracking systems and the combined POD method, with calibration accuracies estimated to be 0.5 ns and better than 1 ns respectively. The calibration problem for time delays has been solved.

(4) A POD strategy based on the combination of SLR and C-band transfer ranging for GEO is presented. Using data from a C-band tracking network in China, POD experiments indicate that meter-level POD accuracy is achievable for GEO. Root-mean-square (RMS) of the post-fit C-band ranging data is about 0.205 m. The radial component errors of POD are evaluated with SLR data from a station in Beijing, with residual RMS of 0.133 m. Orbital overlapping experiments show the total orbit error is a few meters. Computations of SLR residuals also suggest that for 2-hour prediction, the predicted radial error is about 0.373 m. The POD for GEO has been achieved.

(5) Another GEO combined orbit determination strategy is studied in this paper, which combines pseudo-range data and C-band biased ranging data. This strategy successfully overcomes the C-band ranging data deficiency problem caused by limited stations and tracking time available. With the combination of biased ranging and psudorange data, clock offsets between the GEO and stations may be estimated simultaneously along with orbital parameters, maintaining self-consistency between the satellite ephemeris and clock offsets parameters. Using data collected for the GEO satellite of Regional satellite navigation system with 3 C-band biased ranging stations and 4 L-band pseudo-range tracking stations, POD experiments indicate that meter-level accuracy is achievable. Root-mean-square (RMS) of the post-fit C-band ranging data is about 0.203 m, and the RMS of the post-fit pseudo-range is 0.408m. Radial component errors of the POD experiments are independently evaluated with SLR data from a station in Beijing, with the residual RMS of 0.076 m. SLR validation also suggests that for 2-hour orbital predication, the predicted radial error is about 0.404 m, the clock offset error is better than 1.5 ns. Even for the combination of one C-band biased ranging station and 4 pseudo-range stations, POD is able to

achieve reasonable accuracy with radial error of 0.280 m and 2 h predicted radial error of 0.888 m. Clock synchronization between the GEO and tracking stations is achieved with an estimated accuracy better than 1.6 ns.

(6) By employing simulation data, the issue of GEO POD is studies based on several kinds of measurements, including “ transfer ranging and pseudo-range ”, “ SLR and pseudo-range ”, and “ SLR and transfer ranging ”. The POD strategies and accuracy are discussed based on the three different modes. Effects of the quadratic term of the clock offset and the effect of the pseudo-range stations on POD accuracy are discussed. Clock offsets of the satellite and stations are estimated simultaneously, maintaining self-consistency between the satellite ephemeris and clock offsets parameters. Effects of systematic errors on POD accuracy are analyzed and discussed based on different POD modes. POD has been achieved based on a constrain from a single transfer ranging station. Systematic errors are calibrated in the POD process combining the SLR and transfer ranging data.

(7) POD features of GEO satellites are discussed based on the undependant time synchronization framework in Regional satellite navigation, including the satellite-ground and ground-ground time synchronization modes, the single satellite-ground time synchronization mode, and the single ground-ground time synchronization mode. By employing simulation data, the POD possibilities are probed based on the three modes. Results show that systematic errors including clock offsets and time delays are the main factor for the GEO POD accuracy, and that 2 ns accuracy is required to achieve POD with the accuracy of better than 10 m. For the mode of ground-ground time synchronization, two time transfer stations are required at least, and time synchronization for satellite-ground and ground-ground of all stations could be achieved. But POD accuracy of this mode is not stable, with estimated parameters of highly relevant. In view of accuracy of the satellite orbit and clock offsets, the mode of satellite-ground and ground-ground time synchronization is much better than other two modes. The quadratic term of the clock offset and the clock offsets of both the satellite and stations are required to estimate for different POD modes.

(8) Three kinematic orbit determination approaches are brought forward to achieve rapid orbit recovery based on short-arc tracking, they are polynomial fitting approach based on the single point position determination, polynomial fitting approach based on pseudo-range, and ephemeris parameters fitting approach. These approaches overcome divergence of dynamical orbit determination approach, and obtain satellite velocity information, therefore POD is achieved based on the short-arc tracking. POD tests based on short-arc kinematic orbit determination approaches are carried out, using measurements from the MEO and GEO satellites with a 10 minutes tracking arc. Results show that: for the MEO satellite, the position accuracy is better than 10 m, and the velocity accuracy is 2 cm/s, and 5-min orbit prediction accuracy is 15.02 m; for the GEO satellite, the position accuracy is better than 19 m, and the velocity accuracy is 4 mm/s which is better than the MEO satellite, and 5-min orbit prediction accuracy is 17.76 m, 10-minute orbit prediction accuracy is 18.168 m.