doi: 10.15940/j.cnki.0001-5245.2015.04.012 博士学位论文摘要选登

我国月球探测工程中的定轨和定位

李培佳†

(中国科学院上海天文台 上海 200030)

本论文以我国月球探测工程为研究背景, 使用仿真分析和实测数据处理相结合的方法, 结合多种VLBI (very long baseline interferometry)技术在深空探测中的应用, 展开对探月飞行器精密定轨、定位的方法研究和精度分析. 本文主要做了以下几个方面的研究和探讨:

首先, 利用CE-2 (Chang'E-2)探测器实时任务期间的实测数据, 分析在我国现有的测量条件下月球探测器的轨道确定精度, 重点讨论了CE-2任务中观测精度有所提高的VLBI数据对提高探测器定轨精度的贡献. 对环月探测器短弧定轨计算分析表明, 联合VLBI和测距数据15 min短弧定轨精度比单独3 h测距数据定轨精度提高1～1.5个量级. 对环月探测器长弧定轨精度的重叠弧段分析表明, 在CE-2实时任务的测量条件下, 当环月探测器处于非通视状态时, VLBI数据的加入可以在量级上提高轨道精度, 提高主要在T和N方向上; 对100 km×100 km轨道, 18 h弧长联合定轨精度3维位置RMS可达30 m; 对15 km×100 km轨道, 18 h弧长联合定轨精度3维位置RMS可达45 m.

我国后续深空探测任务将采用X波段测控体制, 本论文对CE-2任务中首次进行的深空探测X波段测控体制试验数据的测量精度和定轨精度进行评定. 计算结果表明, X波段测控体制试验的ΔDOR时延数据噪声水平相比S波段VLBI时延提高1个量级以上, 优于0.1 ns, 且系统差问题得到显著改善.

月球引力场精度是影响环月飞行器定轨精度的主要误差源, CE-2探测器观测数据可以作为独立观测量, 对现有的几种月球引力场模型进行一定程度的外符合精度检验. 本文的计算结果表明现有的LP165P和SGM150Q引力场精度相当.

CE-2探测器在完成既定的环月探测后, 先后开展了对日地系L2点探测的拓展试验和对4179号小行星探测的再拓展试验. 由于探测器在深空转移轨道飞行阶段所受的动力学约束减弱, 且地基测量精度随着地心距的增加而降低, 所以拓展任务中的探测器定轨精度降低并且对定轨弧长要求变高. 本文的定轨分析结果表明, VLBI数据可以大幅度提高定轨精度并缩短定轨所需弧长.

使用基于多项式逼近的动力学定轨法, 用多项式或其他函数形式替代动力学模型来描述探测器的运动方程, 对探月二期动力落月段的轨道确定方法进行研究. 采用此方法对CE-1探测器落月段的实测数据进行轨道确定, 定轨精度与常规动力学统计定轨法相当; 对CE-1探测器硬着陆的落月点进行计算, 计算结果与单点定位以及常规动力学定轨法相比较, 其值相差在千米量级以内.

使用运动学统计定位方法对探月二期月面固定目标进行定位, 并应用月球数字高程图提高极端条件下的定位精度. 对于只能使用单点定位方法的月面目标行走间定位, 本文提出通过积分时延率的方法以获得可以用于月面目标行走间定位的高精度时延数据. 仿真分析结果表明, 数据采样率对积分时延率方法的定位精度影响较大, 目前的VLBI数据采样率为5 秒/点, 单步积分(5 s)相对定位精度约为20 m, 与传统单点定位方法只能得到数千米的定位精度相比, 此方法将定位精度提高了2个数量级.

对于探月三期中的月球轨道交会对接任务, 本文利用同波束VLBI观测量同时对两颗飞行器进行轨道确定. 仿真分析结果表明, 同波束VLBI数据可以在量级上提高两颗探测器的绝对和相对定

†2013-07-07获得博士学位, 导师: 上海天文台胡小工研究员、黄勇研究员; pjli@shao.ac.cn

轨精度; 在只有单目标的测距观测数据时, 联合同波束VLBI数据可以同时对双目标进行定轨, 且定轨精度与使用双目标测距数据联合同波束VLBI数据的定轨精度量级相当. 使用上海天文台自编软件对SELELNE任务中的两颗小卫星Vstar和Rstar的实测数据进行轨道确定分析, 计算结果表明同波束VLBI数据可以显著提高两颗探测器的定轨精度. 尤其对测距数据较少的Vstar探测器, 同波束VLBI数据的加入使得其定轨精度相比较测距单独定轨提高了近1个量级, 与Rstar定轨精度相当.

Researches on the Orbit Determination and Positioning of the Chinese Lunar Exploration Program

LI Pei-jia

(*Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai 200030*)

This dissertation studies the precise orbit determination (POD) and positioning of the Chinese lunar exploration spacecraft, emphasizing the variety of VLBI (very long baseline interferometry) technologies applied for the deep-space exploration, and their contributions to the methods and accuracies of the precise orbit determination and positioning. In summary, the main contents are as following:

In this work, using the real-time data measured by the CE-2 (Chang'E-2) detector, the accuracy of orbit determination is analyzed for the domestic lunar probe under the present condition, and the role played by the VLBI tracking data is particularly reassessed through the precision orbit determination experiments for CE-2. The experiments of the short-arc orbit determination for the lunar probe show that the combination of the ranging and VLBI data with the arc of 15 minutes is able to improve the accuracy by 1-1.5 order of magnitude, compared to the cases for only using the ranging data with the arc of 3 hours. The orbital accuracy is assessed through the orbital overlapping analysis, and the results show that the VLBI data is able to contribute to the CE-2's long-arc POD especially in the along-track and orbital normal directions. For the CE-2's 100 km×100 km lunar orbit, the position errors are better than 30 meters, and for the CE-2's 15 km×100 km orbit, the position errors are better than 45 meters.

The observational data with the delta differential one-way ranging (ΔDOR) from the CE-2's X-band monitoring and control system experimental are analyzed. It is concluded that the accuracy of ΔDOR delay is dramatically improved with the noise level better than 0.1 ns, and the systematic errors are well calibrated.

Although it is unable to support the development of an independent lunar gravity model, the tracking data of CE-2 provided the evaluations of different lunar gravity models through POD, and the accuracies are examined in terms of orbit-to-orbit solution differences for several gravity models. It is found that for the 100 km×100 km lunar orbit, with a degree and order expansion up to 165, the JPL's gravity model LP165P does not show noticeable improvement over Japan's SGM series models (100×100), but for the 15 km×100 km lunar orbit, a higher degree-order model can significantly improve the orbit accuracy.

After accomplished its nominal mission, CE-2 launched its extended missions, which involving the L2 mission and the 4179 Toutatis mission. During the flight of the extended missions, the regime offers very little dynamics thus requires an extensive amount of time

and tracking data in order to attain a solution. The overlap errors are computed, and it is indicated that the use of VLBI measurements is able to increase the accuracy and reduce the total amount of tracking time.

An orbit determination method based on the polynomial fitting is proposed for the CE-3's planned lunar soft landing mission. In this method, spacecraft's dynamic modeling is not necessary, and its noise reduction is expected to be better than that of the point positioning method by making full use of all-arc observational data. The simulation experiments and real data processing showed that the optimal description of the CE-1's free-fall landing trajectory is a set of five-order polynomial functions for each of the position components as well as velocity components in J2000.0. The combination of the VLBI delay, the delay rate data, and the USB (united S-band) ranging data significantly improved the accuracy than the use of USB data alone.

In order to determine the position for the CE-3's Lunar Lander, a kinematic statistical method is proposed. This method uses both ranging and VLBI measurements to the lander for a continuous arc, combing with precise knowledge about the motion of the moon as provided by planetary ephemeris, to estimate the lander's position on the lunar surface with high accuracy. Application of the lunar digital elevation model (DEM) as constraints in the lander positioning is helpful. The positioning method for the traverse of lunar rover is also investigated. The integration of delay-rate method is able to achieve higher precise positioning results than the point positioning method. This method provides a wide application of the VLBI data.

In the automated sample return mission, the lunar orbit rendezvous and docking are involved. Precise orbit determination using the same-beam VLBI (SBI) measurement for two spacecraft at the same time is analyzed. The simulation results showed that the SBI data is able to improve the absolute and relative orbit accuracy for two targets by 1-2 orders of magnitude. In order to verify the simulation results and test the two-target POD software developed by SHAO (Shanghai Astronomical Observatory), the real SBI data of the SELENE (Selenological and Engineering Explorer) are processed. The POD results for the Rstar and the Vstar showed that the combination of SBI data could significantly improve the accuracy for the two spacecraft, especially for the Vstar with less ranging data, and the POD accuracy is improved by approximate one order of magnitude to the POD accuracy of the Rstar.