國 立 交 通 大 學

土 木 工 程 學 系

博 士 論 文

以低軌衛星追蹤資料推求地球重力場及其時變：CHAMP 及 GRACE 衛星任務個案研究

研 究 生 ： 王 成 機

指導教授 ： 黃 金 維　陳 春 盛

中華民國九十四年六月

以低軌衛星追蹤資料推求地球重力場及其時變：

CHAMP 及 GRACE 衛星任務個案研究

Determinations of the Earth’s gravity field and its temporal variation from satellite tracking data: case studies for CHAMP and GRACE missions

研　究　生：王成機	Student : Cheng-Gi Wang
指導教授：黃金維　博士	Advisor : Dr. Cheinway Hwang
：陳春盛　博士	Advisor : Dr. Chun-Sung Chen

國 立 交 通 大 學
土 木 工 程 學 系

博 士 論 文

A Dissertation
Submitted to Department of Civil Engineering
College of Engineering
National Chiao Tung University
in partial Fulfillment of the Requirements
for the Degree of
Doctor of Philosophy
in
Civil Engineering
June 2005
Hsinchu, Taiwan, Republic of China

中華民國九十四年六月

以低軌衛星追蹤資料推求地球重力場及其時變：CHAMP 及 GRACE 衛星任務個案研究

研究生：王成機　　　指導教授：黃金維 博士

：陳春盛 博士

國立交通大學土木工程學系

摘　要

衛星重力測量之蓬勃發展，使得衛星追蹤衛星（SST）技術趨近成熟，而低軌衛星 CHAMP、GRACE 重力衛星任務之成功升空，更是開創了衛星重力測量邁向高精度高解析度的新紀元。這兩個衛星任務各自扮演高-低（HL-SST）和低-低衛星追蹤衛星（LL-SST）技術之角色，也都酬載直接量測非引力引起之擾動力的加速度儀及測定衛星姿態資料的星載敏感器。尤其 GRACE 之雙星計畫更裝載 K 波段測距系統(KBR)，量測與重力場高度敏感之雙星間距離及距離變化率(RR)，其精度分別可達 10 μm 及 1 μm/s，因而可得高精度距離變化率速度(RRR)。CHAMP 及 GRACE 衛星追蹤資料之獨特性及空前的精度引發本文研究之動機，本文主要重點在提出有效率之方法來反演地球重力場，進而探討重力場之時變。

首先利用低軌衛星上 GPS 接收之 SST 資料開發一個相位法，以相位計算低軌衛星與 GPS 衛星之視線加速度，再配合 GPS 精密星曆求解低軌衛星加速度，由於低軌衛星加速度是地位係數之線性函數，因此可用最小二乘法以非常簡單且高效率來反演地球重力場，所得之全球重力趨勢與 EGM96 相似。

其次，依 GRACE 衛星之特性，以線性解析擾動理論構建 RR 或 RRR 與地位係數之嚴密線性表達式，這些表達式是基於 RR 是兩顆衛星重力位差的函數，本文利用 EGM96 及 OSU91A 地位係數模擬 GRACE 雙星之距離變化率，開發程式軟體測試解析擾動理論解算地球重力場之方法。

再以直接加速度法探求重力場時變，本法是將低軌衛星軌道直接以數值微分得加速度，扣除各種保守攝動力，而非保守攝動力則以加速度儀觀測量替代，並以經驗參數吸收模式未完善之誤差。本文利用一年之 CHAMP 軌道及四個月之 GRACE 軌道分析 J_2 變化，經與 NASA 利用 SLR 同期觀測之 J_2 變化比較，發現二者皆有季節性之變化且趨勢相同，在夏天 J_2 變大，而冬天變小。最後累加每 7 天一弧段之法方程式，計算平均地球重力場模型，發現大地起伏精度在空間解析度 1000 公里時為 5 mm，精度比 EIGEN-1S 及 EGM96 佳。

Determinations of the Earth's gravity field and its temporal variation from satellite tracking data: case studies for CHAMP and GRACE missions

Student : Cheng-Gi Wang
Advisor : Dr. Cheinway Hwang
Advisor : Dr. Chun-Sung Chen

Department of Civil Engineering
National Chiao Tung University

Abstract

With the advent of the CHAMP and GRACE satellite missions, satellite gravimetry has opened a new era featuring high spatial resolution and accuracy. These two missions provide continuous satellite tracking data in a high-low（HL-SST） and a low-low satellite-to-satellite tracking（LL-SST） scenario. They are both equipped with accelerometers for determining non-gravitational forces and star-cameras for determining attitudes. For each mission a laser retro-reflector is also mounted to provide additional tracking data. The GRACE mission uses a K-band ranging system to determine ranges and range rates (RR) between the two GRACE satellites at an accuracy of 10 μm and 1 μm/s, respectively. Precise range-rate rates (RRR) can be derived from RR. The uniqueness and the unprecedented accuracy of CHAMP and GRACE's tracking data have motivated this study, which mainly focuses on methods for efficiently recovering the Earth's gravity field and its temporal variation.

A phase method is developed. In this method, GPS phase observations of a low earth orbiter (LEO) are used to compute line-of-sight accelerations between GPS and LEO, which are then used to determine the 3-dimensional accelerations of LEO using precise GPS ephemeris. Accelerations are linear functions of gravity coefficients, which make the least-squares estimation of gravity coefficients very simple in terms of computational effort. This method is efficient and does not require modeling GPS integer ambiguities. However, accelerations other than the Earth's gravity-induced acceleration must be modeled and removed from the phase-determined accelerations. The gravity coefficients recovered from CHAMP by this method agree well with the

EGM96 gravity coefficients.

Closed, linear expressions between RR or RRR and gravity coefficients are established using a linear orbit perturbation theory. These expressions are based on the concepts that RR is a function of the potential difference between two satellites and RRR is the line-of-sight acceleration. These expressions are used in a least-squares estimation of gravity coefficients from GRACE's RR or RRR. Seven days of simulated data using EGM96 and OSU91A have been used to test the theories and computer programs based on these expressions.

A direct acceleration method is employed to determine the time variation of the Earth's gravity field. In this method, the accelerations of LEO are determined by numerical differentiations of the positions of LEO. After removing accelerations other than the Earth's gravity-induced accelerations, linear relations between LEO accelerations and gravity coefficients can be established, as in the phase method. Empirical parameters can be used to model the residual non-Earth-gravity accelerations. The time series of J_2 derived from one year of CHAMP data and four months of GRACE data by this method closely resemble the SLR-derived time series of J_2. Moreover, one set of normal equations is computed from a 7-day orbit arc. A total of 42 such normal equations from CHAMP data and 33 normal equations from GRACE data are computed. These normal equations are considered uncorrelated and are combined to determine an averaged gravity field. This gravity field yields a geoid model with an accuracy of better 5 mm at a spatial resolution of 1000 km half-wavelength, which is better than those derived from the recent satellite-only EIGEN-1S and EGM96 gravity fields.