GOCE High Level Processing Facility

Optimization of Gradient Prediction

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Abbreviations and Acronyms

AD	Applicable Document
ADD	Architectural Design Document
ADIR	Architectural Design and Interface Review
ADP	Auxiliary Data Provider
AIT	Acceptance, Integration, Test
AO	Announcement of Opportunity
AR	Acceptance Review
AS	Anti-Spoofing
ATP	Authorisation To Proceed
ATR	Algorithm Test Review
CAB	Change Appeal Board
CBCP	Current Baseline Cost Plan
CCN	Contract Change Notice
CDAF	Command and Data Acquisition Facility
CDP	Configuration and Documentation management Plan
CDR	Critical Design Review
CFI	Customer Furnished Item
CHAMP	CHAllenging Minisatellite Payload for geophysical research and application
CMF	Calibration and Monitoring Facility
CNL	Contract change Notices status List
COP	Commissioning Operations Phase
COS	Consortium Organisation Structure
CPF	Central Processing Facility
CPR	Cycle Per Revolution
CPS	Company Project Structure
CR	Change Request
CRB	Change Review Board
DCN	Document Change Notice
DDP	Design and Development Plan
DFACS	Drag-Free and Attitude Control System
DPA	Data Processing Archive
DPM	Detailed Processing Model
DSAT	Development Site Acceptance Test
DTL	Documentation Tree and status List
E2E	End-to-End Simulator
ECMWF	European Centre for Medium-range Weather Forecast
ECP	External Calibration Products
ECSS	European Cooperation for Space Standardization
EFRF	Earth Fixed Reference Frame
EGG	Electrostatic Gravity Gradiometer
EGG-C	European GOCE Gravity Consortium
EGM	Earth Gravity Model
EGM96	EGM 1996
EM	Engineering Model
EME2000	Equinox and Mean Equator of J2000.0
EO	Earth Observation
EOEP	Earth Observation Envelope Programme
EPAR	Extended mission Product Acceptance Review
ESA	European Space Agency
FM	Flight Model
FOCC	Flight Operations Control Centre
FOS	Flight Operations Segment
GLONASS	GLObal NAvigation Satellite System
GOCE	Gravity field and steady-state Ocean Circulation Explorer
GPS	Global Positioning System
GRACE	Gravity Recovery And Climate Experiment
GRF	Gradiometer Reference Frame
GS	Ground Segment
GSOV	Ground Segment Overall Validation
GSRR	Ground Segment Readiness Review
HK	House-Keeping
HOP	Hibernation Operations Phase
HPF	High level Processing Facility
HW	Hardware
IAG	International Association of Geodesy
ICD	Interface Control Document
IGS	International GPS Service
ILRS	International Laser Ranging Service
IPF1	Instrument Processing Facility level 1
ISP	Instrument Source Packet
ITT	Invitation To Tender
L	Level, L-band frequency
LAN	Local Area Network
LEOP	Launch and Early Orbit Phase
LORF	Local Orbital Reference Frame
LRR	Laser Retro-Reflector
LSC	Least Squares Collocation
LTA	Long-Term Archive
MBW	Measurement BandWidth
MOP	Measurement Operational Phase
MPS	Mission Planning System
NA	Not Applicable

NRT	Near-Real Time
OBCP	On-Board Control Procedures
OBT	On-Board Time
ORR	Operational Readiness Review
OSAT	On-Site Acceptance Test
PAR	Product Acceptance Review
PCD	Product Confidence Data
PDD	Product Definition Document
PDS	Payload Data Segment
PF	Processing Facility
PI	Principal Investigator
POD	Precise Orbit Determination
PSD	Packet Structure Definition; Power Spectral Density
QL	Quick-Look
QLP	Quick-Look Products
RD	Reference Document
RERF	Radial Earth-pointing Reference Frame
RFQ	Request For Quotation
RMS	Root-Mean Square
RPF	Reference Planning Facility
RSS	Root-Sum Square
S/C	Space-Craft
SCP	Secure Copy (remote file copy program)
SDE	Software Development Environment
SFTP	Secure File Transfer Program
SGG	Satellite Gravity Gradiometer
SLR	Satellite Laser Ranging
SMF	Software Maintenance Facility
SOW	Statement Of Work
SPC	Satellite Prime Contractor
SPF	Sub-Processing Facility
SPR	Software Problem Report
SPRL	Software PRoblems status List
SRD	System Requirements Document
SRR	System Requirements Review
SST	Satellite-to-Satellite Tracking
SSTI	Satellite-to-Satellite Tracking Instrument
SSTR	Sub-System Test Review
STP	Software Test Plan
SVT	System Validation Test
SW	SoftWare
SWRD	SoftWare Requirements Document
TBC	To Be Confirmed
TBD	To Be Defined
TC	TeleCommand
TM	TeleMetry
TP	Test Plan
TR	Test Report
USF	User Services Facility
UTC	Universal Time Coordinated
V0/1/2	Version 0/1/2
VC	Virtual Channel
WAN	Wide Area Network
WBS	Work Breakdown Structure
WP	Work Package
XML	eXtensible Markup Language

Table of Contents

1. INTRODUCTION

1.1 PURPOSE AND SUMMARY

The purpose of this document is to describe the tests that have been performed in the context of HPF BP1420. Improvements and the effects of the improvements which have made in the program GEOCOL for the prediction of gravity gradients are described.

1.2 APPLICABILITY

This document is part of V3 of the HPF and was requested during the AR-3 review process.

2. APPLICABLE AND REFERENCE DOCUMENTS

2.1 APPLICABLE DOCUMENTS

[AD-1] GO-ID-HPF-GS-0041; Product Specification for Level-2 Products and Auxiliary Data Products; Issue 5.2, 26.2.2007.
[AD-2] GO-TN-IAPG-GS-0001; Detailed Processing Model for EGG; Issue 4.2, 31.10.2006.
[AD-3] GO-TN-HPF-GS-0111; GOCE Standards; Issue 2.1, 27.11.2006.
[AD-4] GO-RS-ESA-GS-0158; HPF Bridging Phase (HPF-BP) Statement of Work; Issue 1.0, 27.9.2006.
[AD-5] GO-RS-ESA-GS-0080, HPF Management Requirements, Issue 2.0, 4.5.2004.
[AD-6] GO-PL-HPF-GS-0003, HPF Project Management Plan, Issue 2.0, 9.9.2004.
[AD-7] GO-RS-ESA-GS-0082, HPF Technical Requirements Specification, issue 2.0, 4.5.2004.
[AD-8] GO-LI-ESA-GS-0081, Deliverable Items List, Issue 2.0, 17.5.2004.
[AD-9] GO-CN-HPF-GS-0174, Financial, Management and Administrative Proposal for GOCE HPF Bridging Phase, issue 1.0, 9. 10.2006.
[AD-10] GO-CN-HPF-GS-0173, Technical proposal for GOCE HPF Bridging Phase, issue 1.0, 9.10.2006
[AD-11] GO-MA-HPF-GS-0110, GOCE Level 2 Product Data Handbook, Issue 3.2, 26.2.2007.
[AD-12] GO-TN-HPF-GS-0191, Bridging Phase Study Mid-Term report, Issue 1.0, 14.5.2007.

2.2 REFERENCE DOCUMENTS

[RD-1] ESA-SP-1233(1): Gravity Field and Steady-State Ocean Circulation Mission
[RD-2] GO-RS-ESA-SY-0001: GOCE Mission requirements Document
[RD-3] GO-TN-ESA-GS-0017: GOCE Ground Segment Concept and Architecture
[RD-4] GO-SP-AI-0004: GPS Receiver Ground Processing Algorithms Specification
[RD-5] GO-SP-AI-0003: Gradiometer Ground Processing Algorithms Specification
[RD-6] GO-TN-AI-0067: Gradiometer Ground Processing Algorithms Documentation
[RD-7] GO-TN-AI-0068: Gradiometer Ground processing Analysis
[RD-8] GO-PL-AI-0039: Gradiometer Calibration Plan
[RD-9] GO-TN-AI-0069: Gradiometer On-Orbit Calibration Procedure Analysis
[RD-10] GO-RP-AI-0014: Mission Analysis Report
[RD-11] CS-MA-DMS-GS-0001: Earth Explorer Mission Conventions Document
[RD-12] GO-MA-AI-0002: GOCE User's Manual
[RD-13] GO-TN-AI-0027: Performance Requirements and Budgets for the Gradiometric Mission
[RD-14] GO-TN-IAPG-0001: Detailed Processing Model for EGG
[RD-15] GO-TN-IAPG-0002: Detailed Processing Model for SSTI

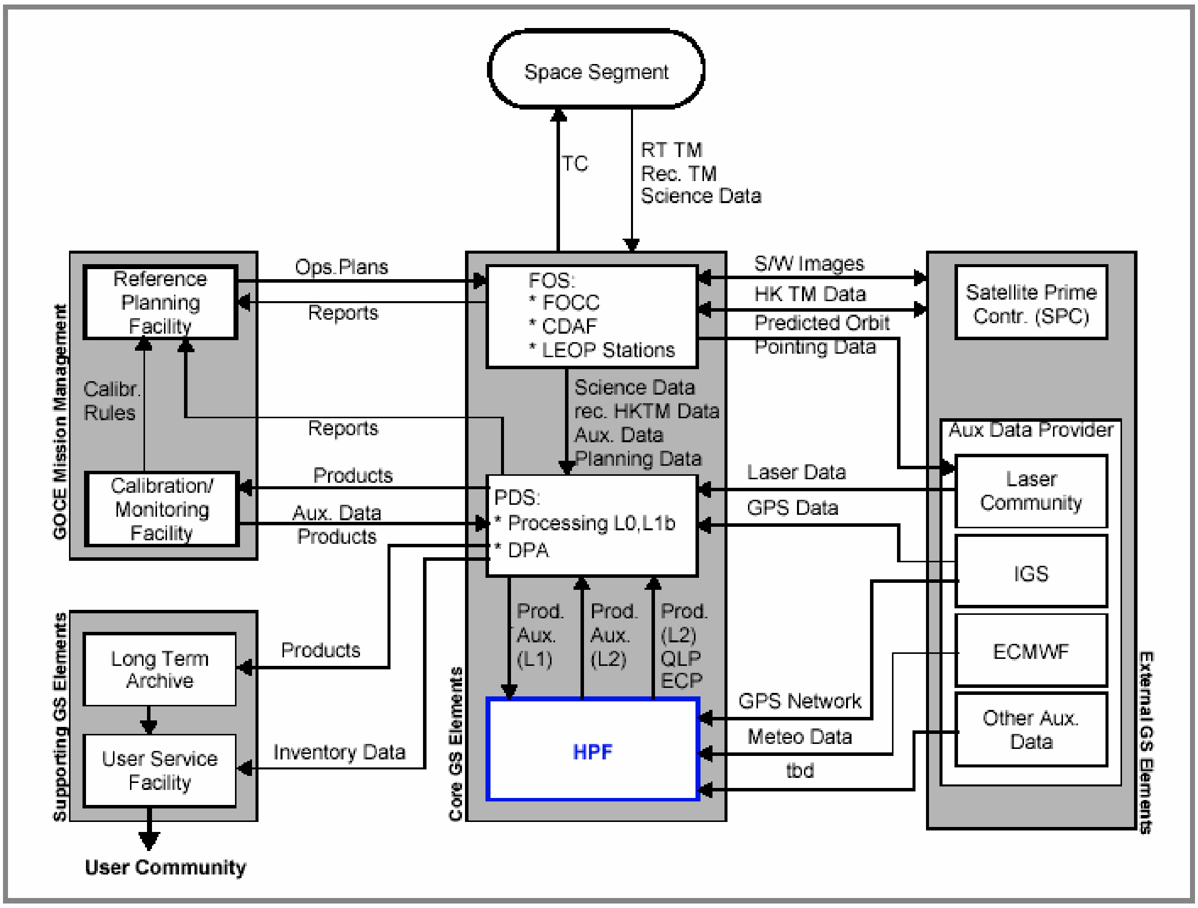
[RD-16] GO-ID-ESC-FS-5070: FOS/PDS – PDS/SLR: Predicted Orbit File
[RD-17] GO-RS-ESA-GS-0052: Product Requirement Document
[RD-18] ECSS-M-00A: Policy Principles
[RD-19] ECSS-M-10A: Project Breakdown and Structures
[RD-20] ECSS-M-20A: Project Organization
[RD-21] ECSS-M-30A: Project Phasing and Planning
[RD-22] ECSS-M-40A: Configuration Management
[RD-23] ECSS-M-50A: Information / Documentation Management
[RD-24] ECSS-M-60A : Cost Schedule Management
[RD-25] ECSS-M-70A: Integrated Logistics Support
[RD-26] GO-MI-ESA-0101: Minutes of the HPF Negotiation Meeting
[RD-27] GO-AI-HPF-GS-0008: Action Item Reply of HPF Negotiation Meeting
[RD-28] GO-AI-HPF-GS-0013: Action Item Reply of HPF Negotiation Meeting
[RD-29] Arabelos, D. and C.C. Tscherning, 1998, Calibration of satellite gradiometer data aided by ground gravity data. JoG, 72, 617-625
[RD-30] Bouman, J., R. Koop, C.C.Tscherning and P.Visser (2004): Calibration of GOCE SGG Data Using High-Low SST, Terrestrial Gravity data, and Global Gravity Field Models. Journal of Geodesy, 78, no. 1 -2. DOI 10.1007/s00190-004-383-5
[RD-31] Moritz, H.: Advanced Physical Geodesy, 1980
[RD-33] Torge, W.: Geodesy, 3. ed., 2001
[RD-34] Tscherning, C.C.: Testing frame transformation, gridding and filtering of GOCE gradiometer data by Least-Squares Collocation using simulated data. Proceedings IAG General Assembly, Sapporo July 2003, pp. 277-282, 2004.
[RD-35] Tscherning, C.C., R.Forsberg and P.Knudsen: The GRAVSOFT package for geoid determination. Proc. 1. Continental Workshop on the Geoid in Europe, Prague, May 1992, pp. 327-334, Research Institute of Geodesy, Topography and Cartography, Prague, 1992.
[RD-36] Tscherning, C.C.: A FORTRAN IV Program for the Determination of the Anomalous Potential Using Stepwise Least Squares Collocation. Reports of the Department of Geodetic Science No. 212, The Ohio State University, Columbus, Ohio, 1974.
[RD-37] Tscherning, C.C.: The role of High Degree Spherical Harmonic Expansions in Solving Geodetic Problems. Proceedings of the International Association of Geodesy (IAG) Symposia, Vol. 1, pp. 431-441, 1983.
[RD-38] Tscherning, C.C.: On the Chain-Rule Method for Computing Potential Derivatives. Manuscripta Geodaetica, Vol. 1, pp. 125-141, 1976.
[RD-39] Arabelos, D. and C.C.Tscherning: External calibration of GOCE SGG data with terrestrial gravity data. GO-TN-HPF-GS-0070, GOCE HPF Report, 2005.
[RD-40] Tscherning, C.C. and M.Veicherts: Calibration of GOCE gradiometer data in the MWB using ground data. GO-TN-HPF-GS-0175, 2006.
[RD-41] Arabelos, D. and C.C.Tscherning: On a strategy for the use of GOCE gradiometer data for the development of a geopotential model by LSC. 3rd Int. GOCE user workshop, ESA-ESRIN, 6-8 2006, ESA-SP-627, pp. 69-75, 2007.

3. GOCE GROUND SEGMENT

3.1 OVERVIEW GOCE GROUND SEGMENT

The GOCE ground segment concept and architecture is described in [RD-3]. The following gives a brief summary of all ground segment elements, depicted in Figure 3-1.

Figure 3-1: GOCE Ground System



3.2 HIGH-LEVEL PROCESSING FACILITY

Within the GOCE GS the HPF is one of the Core GS Elements (ESA-controlled), and it is charged with the generation of L2 products and acquisition of the external (auxiliary) data needed to generate these products, the delivery of these products (auxiliary, intermediate and final) to the PDS/DPA and/or the LTA and the generation of QLP and ECP for the purpose of the activities of the CMF.

4. OVERVIEW

In the GOCE HPF WP3000 and WP7000 gravity gradients are predicted. In WP3000 gravity gradients in the gradiometer reference frame are predicted from ground gravity (Bouman et al. 2004) and in WP7000 the gradients are predicted in equi-angular grids from gradient values observed by GOCE, i.e. also in the gradiometer reference frame, (Tscherning, 2004).

The predictions are executed by the FORTRAN Program GEOCOL (Tscherning, 1974) using Least-Squares Collocation (Moritz, 1980) and the remove-restore principle (Tscherning, 1983). Basically all computations are carried out in a spherical reference frame, East, North, Radially-Up and then transformed to any other reference frame by rotations (Tscherning, 1979, 2004). In order to execute the transformations reference model values and covariances of all derivatives of the same degree must be available simultaneously.

One may take advantage of this both when establishing the normal-equations and when predicting all components of the gravity gradient and calculating their error-estimates. Here only improvements related to the prediction of gravity gradients have been made and will be described in Chapter 5.

Many computers are today equipped with several processors. For gravity gradient prediction we may take advantage of this when (a) establishing the normal equations, (b) executing Cholesky-reduction of the equations (c) predicting gravity gradients and (d) calculating error-estimates and error-correlations. Only improvements related to (b) and (d) have been implemented because the implementation in (a) and (c) requires very complicated changes of the GEOCOL program. The changes and the effect of the changes are reported in Chapter 6.

5.SIMULTANEOUS PREDICTION OF ALL GRAVITY GRADIENTS.

The prediction of all gradient components in a point requires the computation of several quantities which all sum up to the predicted quantity:

Function	Subroutine	Interface through
Reference system change	TRANS	COMMON Block
Contribution from EGM	GPOTDR	Same
LSC contribution from data	COPRED, PRED	Same
Error-estimation	NES, NES_MP	File on Disk
Output of result	COUT	COMMON Block

Table 1. Functionalities and subroutines changed to enable prediction of all gravity gradients

The usual prediction equation is based on that the anomalous potential is split into 3 parts

$$L_P T = L_P(T_{TRANS}) + L_P(T_{GPOTDR}) + L_P(T_{LSC})$$

where L_P is the linear functional associated with the predicted quantity,
e.g. a second order along track derivative.

The calculation will for gravity gradients involve a rotation to or from an East/North/Up local system, i.e. all components of the gradient will have to be computed in order to make the rotation.

The LSC contribution is computed as the product sum of the covariances between the observations and the individual gravity gradients:

$$L_P(T_{LSC}) = \sum_{i=1}^{N} b_i \operatorname{cov}(L_P, L_i), \text{ where}$$

b_i are the solutions to the normal - equations
N the numner of observations and
L_i the observation functionals.

The computational saving is due to that all covariances between the gradient components and the observation are available simultaneously. Obviously, the product sum between observations and predicted quantities has to be calculated in all cases.

The saving may be illustrated by the number from a typical WP3000 funcionality (Arabelos and Tscherning, 2005, Tscherning and Veicherts, 2006), where gravity gradients in the Scandinavian area are predicted from 14728 surface gravity anomalies. The computation time for one predicted component was 1.36 s while it for all 6 components was 1.41 s. I.e. as expected a six-fold gain in computational speed.

There are also computational savings when calculating error-estimates. These estimates are calculated as the Cholesky-reduced of the N-vector or the Nx6 matrix containing the covariances between the predicted quantities and the observations. The savings are again not in the formation of the product sums used when calculating the Cholesky-reduced, but in the reduction of disk-transports between the central memory of the computer and the disk where the reduced normal-equations are stored.

6.MULTIPROCESSING.

Multiprocessing has been implemented in order to speed-up the two most heavy tasks, namely the Cholesky factorisation of the normal equations and the computation of error-estimates and error-correlations.

The GEOCOL program has in its earlier versions exclusively been using Fortran77, but the use of multiprocessing requires the use of Fortran90. Three compilers have been available for the creation of executables: Portland Group pgf90, Intel and Power FORTRAN compilors.

The key to the parallelisation is that when a diagonal element in column *j* has been reduced may each element in the *j*'th row be reduced separately

$$L_{ij} \cdot L_{jj} = (C_{ij} - \sum_{m=1}^{j-1} L_{im} L_{jm}),$$

since it involves only row - elements in same column j.
Hence each processor may take care of one column at a time.

Now the question is

- Should one row be reduced at a time ?
- Or should we make the factorisation of blocks of elements ?
- Out-of-core factorisation needed for large matrices, so let the processors work on blocked matrices.

The last option has been selected in order to handle very large systems of equations or matrices added to the reduced normal-equation system, and is illustrated in Fig. 6.1.

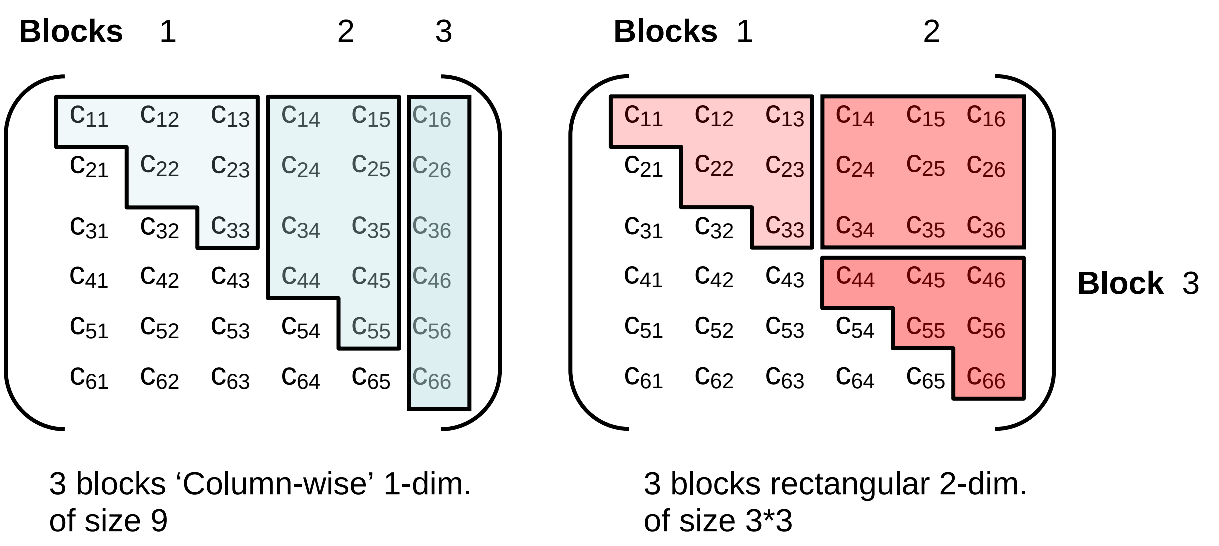


Fig. 6.1 Old and new blocking system used for the normal-equations.

The effect of the selected block-size was tested on systems of equations with 10000 and 20000 unknowns. A clear dependency on the block-size is seen in Fig. 6.2. It is probably related to the use of the cache when transferring data in and out of core.

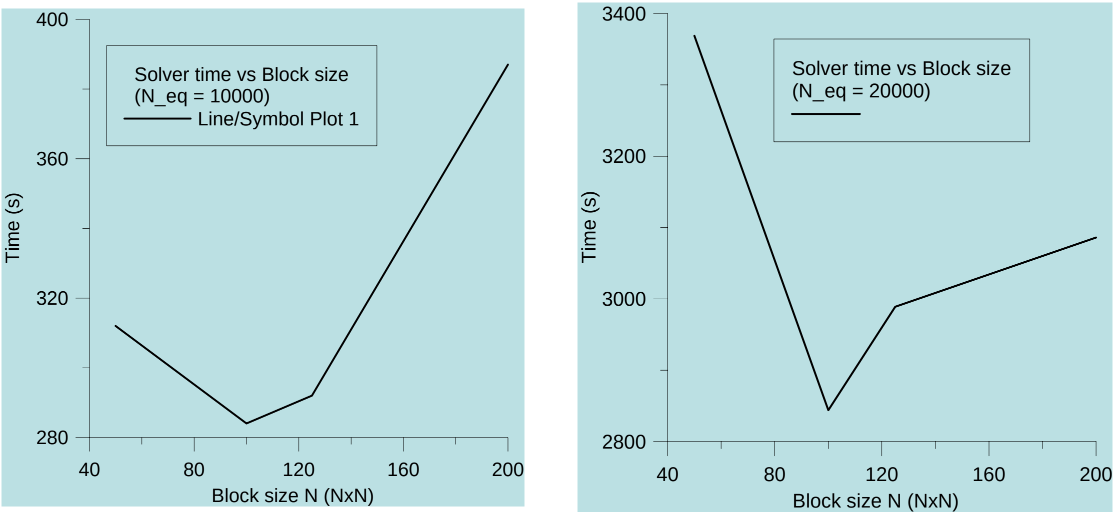


Fig. 6-2 Dependency of the execution time of the Cholesky factorisation of the normal-equations as a function of block-size.

The flow of the GEOCOL program segment which executes the Cholesky-factorisation is illustrated in Fig. 6-3. In the old versions of GEOCOL (17 and below) everything was executed by one subroutine "NES". In the new version 18, a subroutine NES_MP is used to execute the factorisation, aided by a number of subroutines which executes the reduction or factorization.

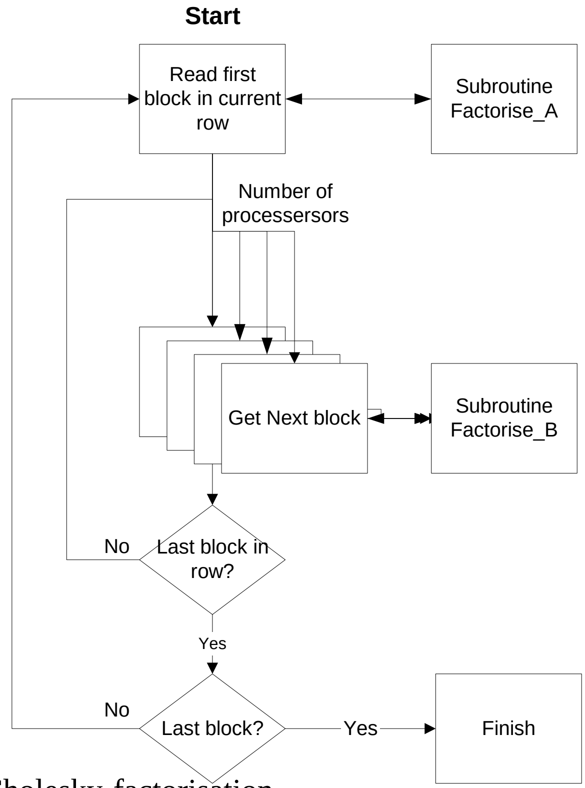


Fig. 6-3. Flow-chart of Cholesky-factorisation.

The performance of the subroutines have been tested on two computers of the Niels Bohr Institute, called “GOCE” and “IKOS”. In Table 6-1. results from using 1, 2 and 4 processors are shown.

		GOCE (4x3GHz, 2GB)		IKOS (4x2.66GHz, 4GB)	
PROC	NEQ.	NES	NES_MP	NES	NES_MP
1	6400	775	177		
2	6400		130	136	71
4	6400		87		
1	8100	1570	347		
2	8100		228		
4	8100		177		
1	10000	2966	650	586	290
2	10000		446		159
4	10000		369		

Table 6-1. Execution time for old and new subroutines NES and NES_MP in seconds as a function of number of equations (column headed NEQ) and number of processors shown for two different computers (Servers).

The saving in execution time is always somewhat below 50 % when 4 processors are used. It is however quite dependent on which optimization options have been used when compiling the program. Other typical processing times for the Cholesky-factorisation are shown in Table 6-2.

Server	NEQ	Geocol17	Geocol18 Processors		
			1	2	4
GOCE	5000	370	80	46	24
	10000	2971	851	630	354
	20000	9464	4249	2844	2081
IKOS	5000		23		
	10000		330		

Table 6-2. Execution times using old (GEOCOL17) and new version (GEOCOL18) with respect to Cholesky factorisation.

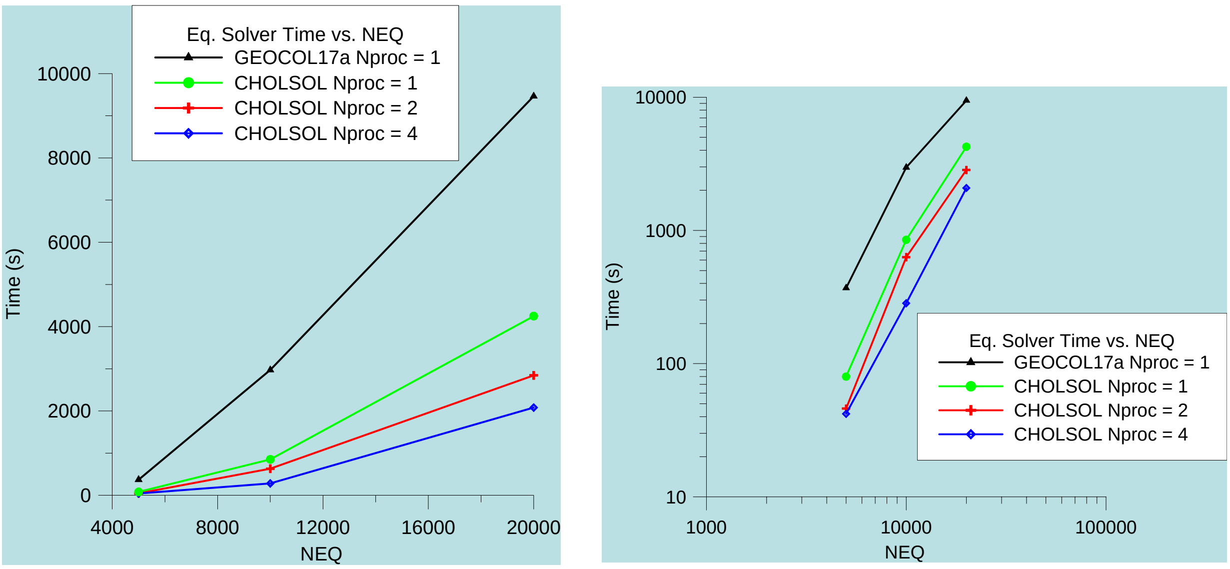


Fig. 6-4. Examples of execution times for the Cholesky-factorisation.

7.CONCLUSION.

The optimization has been successfully implemented with substantial savings in processing time for gravity gradient prediction. The application of the “analytic” property that all quantities related to the 6 independent gravity gradient components resulted in a factor 6 in saving when predicting all components.

The implementation and use of multiprocessing gives substantial savings in computational time for the Cholesky factorisation. Factorisation is computational time inversely proportional to the number of available processors are found in a number of tests. The reduction is slightly less than 50 % when 4 processors are used. It could in theory be 25 %, but it is not possible to use all processors all the time.

But let us mention a final result from a processing example where 39606 equations were solved. The execution time was 30360 seconds = 56 minutes. This opens up for a number of large computational experiments using GOCE data, see e.g. Arabelos and Tscherning, 2007.

8.APPENDIX. LSC AND CHOLESKY-FACTORISATION.

The basic observation equation for LSC is

$y_i = L_i(T_{LSC}) + e_i + A_i^T X$, where
X are contingent parameters, A_i is a vector connecting parameters and the observations,
e_i is the error contribution.

Here the contribution from a contingent datum-transformation and a EGM must have been subtracted.

The estimate of T_{LSC} is obtained by
$\tilde{T}_{LSC}(P) = \{C_{Pi}\}^T \overline{C}^{-1}\{y - A^T X\}$, where $\overline{C} = \{C_{ij} + \sigma_{ij}\}$, and
σ_{ij} is the variance - covariances of the errors.
The estimate of the (M) parameters are obtained by

$$\tilde{X} = (A^T \overline{C}^{-1} A + W)^{-1}(A^T \overline{C}^{-1} y)$$

The error-estimates and error-covariances, ec_{kl} are found with:

$$H = \{COV(L_k, L_i)\}^T \overline{C}^{-1}, \text{ MxN matrix}$$

$$m_X^2 = (A^T \overline{C}^{-1} A + W)^{-1}$$

$$\{ec_{kl}\} = \{\sigma_{kl}\} - H\{\mathrm{cov}(L_j, L_l)\} + HAM_X(HA)^T$$

W is the matrix of contributions from observations only related to parameters such as differences between geodetic coordinates in a geocentric and non-geocentric datum.

Despite the occurrence of the mathematical sign for inverse (-1) as a superscript, it is not necessary to compute the inverse. Only the solution is needed. This may be obtained by Cholesky factorisation. With *L* being a lower-triangular matrix we have

$$\overline{C}x = LL^T x = y$$

$$L^{-1}(LL^T)x = L^{-1}y$$

$$L^T x = L^{-1}y, \text{ now upper - triangular system.}$$

$$L_{ij} = (C_{ij} - \sum_{m=1}^{j-1} L_{im}L_{jm}) / L_{jj}$$

$$L_{jj} = (C_{jj} - \sum_{m=1}^{j-1} L_{jm}^2)^{1/2}$$

The procedure may be generalized to include also the parameter-estimates by regarding an extended matrix equation.

$$\begin{Bmatrix} \{\overline{C}_{ij}\}_{nn} & \{A_{jl}\}_{mn} \\ \{A_{ik}\}^T_{nm} & \{W_{kl}\}_{mm} \end{Bmatrix} \begin{Bmatrix} x \\ X \end{Bmatrix} = \begin{Bmatrix} y \\ p \end{Bmatrix},$$

This system may be Cholesky factorized using negative accumulation when subscript are $\geq$ n.

It may be even further generalized, by extending the system with the matrices which contain the covariances between observations and quantities to be predicted.

$$\begin{Bmatrix} \{\overline{C}_{ij}\}_{pp} & \{A_{jl}\}_{pq} & \{C_{jm}\}_{pr} \\ \{A_{ik}\}^T_{qp} & \{W_{kl}\}_{qq} & \{A_{jk}\}_{qr} \\ \{C_{in}\}^T_{rp} & \{A_{ni}\}^T_{rq} & \{\sigma_{nm}\}_{rr} \end{Bmatrix}$$

when factorized with negative accumulation for subscript larger than p and no accumulation for subscript large than $p+q$ returns error - covariances.