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論文内容の要旨

The continuous gravity observation with a superconducting gravimeter (SG) #016 was started on March 22, 1993 at Syowa Station, Antarctica (69.0 N, 39.5 E). Since then, the observation is continued by Japanese Antarctica Research Expedition (JARE). This thesis mainly describes the analysis results for tidal gravity changes using the Syowa SG data and discusses the various oceanic effects on its observation. The tides treated here are those for the 12 hours to 1 year in the period. In connection with the analysis for long-period tides, the gravity effects at Syowa Station due to the polar motion were reanalyzed and compared with other two SG sites in the mid latitude (i.e. Esashi, Japan and Canberra, Australia). The effect of Sea Surface Height (SSH) variations are also discussed mainly focusing into the annual gravity changes.

The thesis consists of nine chapters. In Chapter 1 (Introduction), first, the importance of gravity observation made at high latitude is described. The remaining part of Chapter 1 explains the outline of contents of this thesis. Chapter 2 reviews the tidal phenomena and the definition of several quantities appeared in the thesis. Chapter 3 describes the method to estimate the ocean effects and the computer program used in this thesis. The characteristics of SG is described in the first part of Chapter 4 in connection with the observation results shown in the later Chapters. The locality of Syowa Station, the procedures for setting up of the SG and the data acquisition system used in the observation are also introduced in Chapter 4. We used the computer program called BAYTAP-G and -L for the tidal analysis. The method and some problems on the actual analysis used this analysis method are mentioned in Chapter 5. The observed results are discussed in Chapters 6, 7 and 8 for the short-period tides, the long-period tides and the polar motion effect especially focusing into the annual

component, respectively. Finally, the concluding remarks are given in Chapter 9.

In Chapter 6, we reexamined the gravity tidal factor (δ-factor) of the diurnal and semi-diurnal tides at Syowa Station. The 2-year SG data obtained in the period from March 1993 to March 1995 were used in the analysis. The ocean tide effects (the effects of the attraction and loading due to the ocean mass) were estimated using a new global ocean tide model by Matsumoto et al. (1995). As the δ-factors corrected for the ocean tide effects, we obtained the values of 1.144, 1.127, 1.157 and 1.111 for O_1, K_1, M_2, and S_2 waves, respectively. We compared the observed mean δ-factors with the two theoretical values inferred from Wahr's (1980) theory and the Dehant's (1987) theory. The discrepancies between our values and the Wahr's theory are at about 0.2 % for both the diurnal and semi-diurnal tides and those with the Dehant's are at about 0.6 % and 2 % for the diurnal and semi-diurnal tides, respectively. The Syowa SG data indicate that the Wahr's theory is much consistent with the observation than the Dehant's theory. Judging from the consistency among the three observation results obtained by the three different gravimeters (Ogawa et al., 1991; Kanao and Sato, 1995; this study), and from the results for the computations of the ocean tide effects, it is highly probable that the large discrepancy exceeding 10 % in the δ-factors for the semi-diurnal tides at Syowa Station, which has been pointed out by Ogawa et al. (1991), is mainly caused by their inaccurate estimation of the ocean tide effects.

In Chapter 7, we examined the long-period tides (M_f and M_m waves) based on the 2 years SG data which are the same data as those used in the analysis for the short period tides (Chapter 6). The obtained amplitudes, phase lags and amplitude factors (δ- factors) are 11.642 ± 0.035 μGal, $-0.12° \pm 0.17°$ and 1.1218 ± 0.0034 for the M_f wave, and 6.143 ± 0.058 μGal, $0.33° \pm 0.54°$ and 1.1205 ± 0.0106 for the M_m wave, respectively ($1\ \mu\text{Gal} = 10^{-8}\ \text{m s}^{-2}$). The ocean tide effects at the observation site were estimated using the five global ocean tide models: equilibrium ocean tide model, Schwiderski (1980) model, Dickman (1989) model, CSR model (Eanes, 1995), and Desai & Wahr (1995) model. The averages of the five estimates are 0.433 μGal and 0.243 μGal in amplitude and 192.9° and 179.5° in phase for the M_f and M_m waves, respectively. The five estimates differ by a maximum of 0.057 μGal in amplitude and 18.7° in phase for the M_f wave, and by 0.033 μGal and 6.4° for the M_m wave. The estimated M_m phases are nearly 180° for the five models, and the variation of their values among the models is relatively small compared with that of the M_f phases. These indicate that the M_m wave is much close to an equilibrium tide than the M_f wave. Due to the variation of the ocean tide corrections, the corrected δ-factors were scattered within the ranges of 1.157 to 1.169 for the M_f wave and of 1.161 to 1.169 for the M_m wave. However, it is noted that the mean δ-factors of the five ocean models, i.e. 1.162 ± 0.023 for the M_f wave and 1.165 ± 0.014 for the M_m wave, prefer slightly larger value rather than those estimated from the theory of the elastic tide.

In Chapter 8, the results for the polar motion effect are described. First, the previous analysis results and the problems on the analysis for this effect, which were obtained from the analysis by Sato et al. (1997) using the two years Syowa SG data, are summarized. They discussed the two problems, i.e. on an interference problem between the annual and Chandler components and on an effect of the inaccurate estimation of step-like changes including the observed data. Based on their experiences, a revised analysis model is applied here and the analysis is carried out using the Syowa SG data much longer than those used in the previous analysis. Thus, it is revised so that (1) the annual component of the polar motion data was excluded from the IERS EOP (International Earth Rotation Service Earth Orientation Parameter) data before fitting and (2) the term to estimate the step-like changes using the Heviside's function was added to the previous model. It was shown that, by using the revised model, the analysis error for the annual component is improved by about 15 % in the case of Esashi, for example. The reliability of the analysis results is also affected by the stability of the period of Chandler component in time. We, therefore, examined this using the 22 years IERS EOP data, and we recognized that the period of Chandler component is stable within ±1.3 days during the observation period of the 17 years from 1983 to 1999. We obtained a value of 435.4 as the mean Chandler period averaged over the 17 years. This value was used for the fitting though this study.

In Chapter 8, we discussed also the results for the estimation of annual gravity changes by calculating the four effects of the solid tide, ocean tide, polar motion and SSH variations. In order to pull out the effect of mass changes in the SSH variations, it is needed to estimate the thermal steric changes in SSH variations, and to correct its effect. We evaluated the steric coefficient based on mainly the POCM (Parallel Ocean Climate Model, Stammer, 1996) SSH (Sea Surface Height) data and the SST (Sea Surface Temperature) data, and we obtained a value of 0.60×10^{-2} m/°C. The predicted annual effect at the three observation sites (i.e. Esashi in Japan, Canberra in Australia and Syowa in Antarctica) were compared with the actual data obtained from the superconducting gravimeters respectively installed at these three sites. The results of the comparison indicate that the predictions agree with the observations within 20 % in amplitude (i.e. within 0.2 μGals, where 1 μGal $=1\times10^{-8}$ ms^{-2}) and 10° in phase at each observation site, when we use the above steric coefficient. We have also tested other values for the steric coefficient, i.e. 0.0×10^{-2} m/°C and 1.0×10^{-2} m/°C, but find that the fit to observations is clearly better at 0.60×10^{-2} m/°C. For comparison, we have also evaluated the SSH effect using TOPEX/POSEIDON data (T/P data). The results from the T/P data indicate a very similar dependence on magnitude of the steric coefficients with that obtained from POCM data, although there exist some systematic differences in amplitude and phase between the two SSH data of the POCM and T/P. It is worth noting that the gravity observations favor a steric coefficient of 0.60×10^{-2} m/°C. This means that the gravity observations support the steric coefficient which was independently estimated from the SSH and SST data. This may be important on future applications of the gravity observation as a data to monitor the mass changes in the oceans which could not be detected from the precise satellite altimetry such as the T/P altimeter. We consider that the agreement between the observation and prediction shown here gives us a base to study the Earth's response to the Chandler motion and/or the excitation problem on it.

論文の審査結果の要旨

現在、日本の超伝導重力計（Superconducting Gravimeter,SG)観測グループは、北は北極・ニーオルスン(北緯79度)、南は南極・昭和基地（南緯69度）まで、地球を南北に縦断する7箇所で構成される「GGP-Japan観測網」と呼ばれる国際観測網を展開し、地球重力の時間変化の観測を行っている。SGは、従来の重力計になかった高性能（高感度，広帯域，高い長期安定性）をもち、観測が困難とされた微小な重力変化、長周期の重力変化、また未知の重力変化の観測ができると期待されている。この国際観測網の展開は、1993年3月の南極・昭和基地での観測立ち上げに始まる。

本申請者は、江刺（日本)、昭和基地（南極)、キャンベラ（オーストラリア)、ニーオルスン（北極)、の４箇所の観測の立ち上げに直接関係し、地球潮汐に関係した多くの論文を書いている。本論文は，それらのうちから、南極・昭和基地での観測結果を中心に、短周期重力潮汐（半日-1日周期)、長周期重力潮汐（14日-1月周期)、さらに極運動による重力変化（1年-14カ月周期）についての解析結果、また各周期帯での海洋変動の影響についての研究結果をまとめたものである。

海洋の影響の正確な評価は，重力観測から地球内部起因の重力変化を検出する上で重要である。本研究で特に注目されるのは、重力の年周変化について、極運動による年周成分と太陽による年周潮汐の他に、海洋固有の年周変動の物理モデルを構築したことで、海洋変動の効果を数値的に評価できたことである。すなわちSG観測により、極運動の年周変動と年周潮汐に加えて海洋の質量分布の変化の影響を明確に捕らえることができた。これは世界で初めての成果であり、海洋固有の変動のみならず地球回転における海洋の効果等の研究に新しい知見をもたらすものである。本論文で示される主な研究成果は以下の通りである。

（１）南極・昭和基地での短周期重力潮汐について

約２年分（1993年3月-1995年3月）のSGデータを使い、昭和基地における半日潮汐と日周潮汐の重力潮汐ファクター（δ-ファクター）について議論し、観測値と理論値とは0.2%-0.6%の差で一致することを明らかにした。この結果は、重力潮汐ファクターの緯度依存性や地球内部構造の影響、また日周潮汐における流体核共鳴の影響等を調べる上での基礎になるものである。

（２）南極・昭和基地での長周期重力潮汐について

高緯度で長周期潮汐の振幅が相対的に大きくなることに注目し、中緯度の観測ではできない長周期潮汐の研究をした点に特徴がある。（１）の短周期潮汐の解析に使った2年間のSGデータを基に、昭和基地における長周期潮汐（半月潮汐：Mfと1月潮汐：Mm）について解析している。また、５つの海洋潮汐モデルを使って計算した海洋潮汐の影響量と観測値とを比較し、重力観測からもMmがMfよりも平衡潮汐により近い振る舞いをしていることを示した。結果として、Mf、Mm分潮のそれぞれの重力潮汐ファクターの平均値として、1.162+/-0.023、1.165+/-0.014の値を得た。これらはいずれも弾性体地球の理論値より幾分大きな値になっており、潮汐から地球の非弾性効果の可能性を捉えた点が評価できる。

（３）年周重力変化について

極運動の年周成分、潮汐項及び全球海水位変動による年周重力変化の見積り、それを含めた地球物理モデルと観測値の比較から、観測値を0.1μGal（マイクロガル）の精度で再現できることを示したことは大いに評価できる。極運動の主要成分には年周成分（強制振動）のほかにチャンドラー成分（自由振動）があり、従来地球回転データと大気・海洋データを使った研究がほとんどであったが、重力観測から極運動の年周項を含めた解析がなされた点が独創的と言える。重力の観測は、人工衛星高度計データとは異なり、海洋変動の熱膨張による効果（これは重力変化をもたらさない）から質量分布を生じさせる変動とを区別して捕らえることが可能なことが示された。結果的に、観測精度、年周とチャンドラーとの分離等がまだ不十分という問題があり、重力から極運動の励起や減衰について議論できる段階ではないが、本研究は、観測期間を延ばすこと、また観測点をふやすことで、今後、重力観測からも極運動を十分に議論できる可能性を原理的に示している。重力データが地球の長周期での力学特性を解明する上で有効であることを示した意義は大きい。

以上を勘案して本審査委員会は、全員一致で、本論文が博士（理学）の学位を受けるにふさわしい内容をもつものと判定した。