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論文内容の要旨

The study on orbital motion and the interior structure of the Moon and planets is one of the methods to approach for the revolution as a dynamical system and the origin of the solar system. It is a powerful method to measure the gravity fields obtained by the orbital motion of a spacecraft in order to estimate the inner layer and the density structure of the Moon and the planets. Orbits or positions of a lunar or planetary spacecraft have mainly been determined by range and Doppler measurements. These measurements provide only one-dimensional information about the position along the line of sight. On the other hand, differential VLBI (Very Long Baseline Interferometry) has the sensitivity of positioning in direction perpendicular to the line of sight, so that combining both range and Doppler measurements with differential VLBI enables us to measure three-dimensional position of a spacecraft. The research in this thesis is to develop a new three-dimensional positioning technique to determine the position and the motion of a spacecraft and to estimate the gravity fields and interior of the Moon or planets. In order to attain this purpose, a new differential VLBI, "Multi-frequency VLBI" is proposed, and the developments of its system and software for the estimation of phase delay are described. In addition to the VLBI method, effects caused by an antenna phase pattern and a spin on Doppler measurements are also described, and the correction method of this effect is proposed to improve the Doppler measurement accuracy.

VLBI methods have been used for positioning of spacecrafts since 1960's. In these methods, carrier waves were transmitted from a spacecraft because of saving its transmitting power and obtaining high SNR. Unfortunately, the phase delay of a carrier wave, however, has cycle ambiguities, therefore only phase delay rate has been mainly used so far. If plural carrier waves at different frequencies are transmitted from a spacecraft, the group delay among the plural carrier waves enables us to resolve the cycle ambiguity of the phase delay. There is one example which used two carrier waves 6.5MHz apart transmitted from the spacecraft of the Venus. A group delay between the two frequencies was successfully determined without the ambiguity, in other words, bandwidth synthesis of only two frequencies was first conducted in this experiment. The accuracy of positioning reached 10 km for about 1 AU distance. In addition, the ionospheric effect could not be corrected because the two carrier waves were in the same frequency band.

We propose a new VLBI method, "Multi-frequency VLBI". The system transmits three frequency signals in S-band and one signal in X-band. These frequencies are set to resolve the cycle ambiguity from a lot of group delays and to correct the ionospheric effect. In this system, the phase delay of RF signals at S and

X-band can be estimated, so that the accuracy of positioning can be drastically improved by a factor of 1300 (8.4GHz/6.5 MHz). In order to realize this VLBI method, we developed a ground VLBI system, software to estimate phase delays and an interface with the software of gravity fields and orbits estimation. This software has the distinctive features as follows. It can estimate the current frequency from the predicted orbital motion and calculates the phase delay from the phase difference at the frequency. This performance allows us to utilize the oscillator for general use, such as a crystal oscillator, as a frequency reference onboard a spacecraft.

We carried out VLBI experiments of NASA's spacecraft, Lunar Prospector (LP), as a preliminary test of the whole system. Unfortunately, LP transmitted only one frequency signal, so that we could not correct the phase variations with period longer than several tens seconds due to the ionosphere, troposphere, discrepancy of the lunar gravity model and so on. As a result of this experiment, residual phases from predicted ones are within $\pm 2\pi$, and the Root-Mean-Square (RMS) of the residual for the period of several seconds is about 4 degrees. The RMS residual for the several seconds, however, means that we can determine the position of LP within the accuracy of 1.5m around the Moon if we can correct the variations with long period by using the Multi-frequency VLBI.

In the study of the Doppler measurements, we pointed out seven error sources that are the ionosphere, the troposphere, spin of the spacecraft, a phase pattern of an antenna, attitude of spacecraft, instability of a transponder and instability of a frequency standard. In particular, the effects caused by spin of a spacecraft and phase pattern of an antenna have not been discussed so far. We pointed out that the spin and the phase pattern of the antenna considerably affect the Doppler measurements and these effects must be removed from observed Doppler frequency data for a precise gravity determination. For this research, we analyzed a Doppler data of spin stabilized satellite, ″Nozomi″ and detected their effects of the spin and the phase pattern of the antenna for the first time. Furthermore, we developed a new method to remove this effect, and confirmed the validity of the method by applying the method to Doppler data of ″Nozomi″.

All the Multi-frequency VLBI and corrected Doppler frequency data can be combined as observables in the orbit and the lunar gravity estimation software of ″GEODYN-II″, and analyzed for three-dimensional positioning of a spacecraft. Because the VLBI system uses narrow bandwidth signals and the amount of the data is much less than those in conventional one, the system has a potential of real time VLBI through the INTERNET. This means that the system can be widely used in real time positioning of various spacecrafts, for instance a module landing on the Moon and the ″Nozomi″ in a transfer orbit to the Mars.

論文の審査結果の要旨

これまで宇宙飛翔体の位置決定は主にドプラ周波数による視線方向の１次元観測のみによって行われてきた。ドプラ周波数の観測に加え、視線に垂直な方向の偏位に感度を持つVLBI観測で電波伝搬の遅延を測定できると、３次元で飛翔体位置の決定が可能になり、画期的に位置推定精度が改善されるのであるが､VLBI観測で遅延を観測量とするためには、広帯域信号発生器が必要になり、消費電力と搭載ミッション重量が厳しく制限された宇宙飛翔体に搭載することは困難である。一方、宇宙飛翔体が狭い帯域の搬送波のみを送信した場合、VLBIの観測量としては２πの不確定性を持った位相情報のみになり、遅延が推定できなくなる。このため、この２πの位相不確定性がVLBIによる高精度飛翔体位置決定への応用を阻んできた。

申請者は国立天文台が現在参加しているSELENE計画で採用されている全く新しい高精度遅延決定手法を実現するために、電離層や中性大気など地球をとりまく宇宙環境や衛星搭載アンテナのスピン変調で発生する大きな位相変動などの誤差要因を研究し、誤差低減に必要な観測条件を明らかにした。さらに、SELENE計画において最終的に期待できる計測精度についても検討し、実験的に検証した。

論文は６章から構成されているが、研究内容は大きく２つに大別できる。１つはスピン変調を取り除いて高精度なドプラ計測を可能にする全く新しいデータ解析手法について論じた部分とVLBI位相計測で期待できる最終観測精度について論じた部分である。前者は、申請者独自のオリジナルなアイデアであり、この手法の有用性を実証するために宇宙科学研究所の火星探査衛星「のぞみ」が発する電波を観測した。観測データを解析した結果、高精度のドプラ計測のためには、スピン周期およびデータのサンプリング周期との間に特定の必要条件が存在することを明らかにした。この必要条件の存在を明示したのは本論文が初めてであり、この研究成果は実際のSELENE計画に反映されると共に、情報通信学会の論文誌にも掲載されている。

ドプラ計測を高精度化する前者の研究に加えてVLBI位相観測による飛翔体位置決定精度の改善についても定式化し、最終的に期待できる究極の精度について実験的な検証も行った。このVLBI実験は、米国の打ち上げた月探査衛星「Lunar Prospector」を水沢、鹿島基線で観測することでなされた。残念ながら「Lunar Prospector」が単一周波数の搬送波送信機しか搭載していなかったために、SELENEでは可能な多数搬送波による電離層の影響除去が行えず、その軌道を精密に決定するまでには至らなかったが、最終的には４°の誤差で干渉位相が決定可能であることを示した。これは、月周回軌道で 1.5mの位置決定精度に相当し、視線方向のドプラ計測のみを観測量とする従来の方法と比較して３桁もの驚異的な位置精度改善が実現できることを意味している。この計測精度を実験的に検証した意義は高い。申請者はまた、この研究結果を2005年打ち上げ予定の月探査機SELENEに適用し、これまで最も高精度であるとされている月の重力場モデルを更に 1.5桁改善できること、その結果から月の中心核の密度を推定して、月の成因に迫ることができることを示した。また本研究の実証実験の過程で申請者が開発したデータ処理・解析ソフトウエア及び観測装置はSELENE計画を遂行するに当たり十分な機能・性能を持つことも実証された。

申請者によって得られたこれらの成果は宇宙飛翔体の精密追尾技術に新しい道を切り

開いただけでなく、今後の月・惑星科学に貢献でき、高く評価できる。