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論　　文　　名	「Calibration and Evaluation of Submillimeter- Wave Radiometers for Atmospheric Observation （大気観測のためのサブミリ波ラジオメータの評価と較正法に間する研究）」
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論文要旨

Calibration of submillimeter-wave radiometers is a principal part in the discussions of this thesis. The Superconducting Submillimeter-Wave Limb-Emission Sounder (SMILES) is a submillimeter-wave radiometer of which the calibration is discussed here. SMILES is the first sensor to observe the Earth's atmosphere with a highly-sensitive submillimeter-wave radiometer that was developed by applying superconducting technology in space. SMILES was developed jointly by the National Institute of Information and Communications Technology (NICT) and the Japan Aerospace Exploration Agency (JAXA), and successfully operated on the International Space Station from October 2009 to April 2010. The author has been extensively involved in the design, development, and data-analysis of SMILES in NICT. This thesis covers a part of those works relating to SMILES. In particular, the calibration and evaluation of the submillimeter-wave radiometer of SMILES are discussed here.

Calibration plays an important part in a data-processing chain that converts sensor-output raw data to scientifically usable quantities. Atmospheric measurement by remote sensing often uses an indirect measuring method. SMILES measures an atmospheric emission spectrum, which itself may not be meaningful for most of atmospheric scientist. Through spectral analysis, we can retrieve, for example, the abundances of atmospheric molecules, such as ozone and chlorine monoxide. The data-processing chain usually comprises the level 1, level 2, and level 3 processings. The product of the level 1 processing consists of engineering values, which are quantities with unit that can be directly mapped from the output values of the sensor. This mapping or tuning of the mapping is called calibration. The atmospheric emission spectra are the level 1 product in the SMILES case. The level 2 product is the quantities relating to the observation target, such as atmospheric molecular abundances. The level 3 product is further processed values according to scientific demands. In such a processing chain, the discussion in this thesis is mainly relevant to the level 1 processing. Most of the discussions on the levels 2 and 3 processings are out of the scope of this thesis. Even though the data discussed here deeply relates to the stratospheric ozone-depletion-related molecules, the atmospheric chemistry and physics are not the themes of the thesis.

Besides the calibration, the descriptions of the performance, characteristics, and operational conditions of the submillimeter-wave radiometer is another important part of this thesis. These evaluation study of the sensor relates to the discussion of the calibration. Conversely, it can be said that an accurate calibration is possible only when the responses of the sensor to the input signal and the environment are known enough for the required accuracy in the calibration. The characteristics of the sensor can be measured before, during, or after the observation. The discussion in this thesis includes the analyses of the performance measurements of SMILES before the launch, as well as the analyses of the in-orbit data.

The calibrations of a ground-based millimeter-wave radiometer and a balloon-borne submillimeter-wave radiometer are also included in the discussion of this thesis. The removal of the variations in the attenuation of and emission from the surrounded thick atmosphere is the main subject of the calibrations of the ground-based and balloon-borne radiometers. In spaceborne radiometer, such as SMILES, the calibration in this sense is easy because substantially no surrounded atmosphere exists. Moreover spaceborne instruments for remote sensing often show relatively stable performance compared with ground-based or balloon-borne instruments. By discussing three configurations of atmospheric soundings, a wide range of calibrations is comprehensively studied in this thesis.

The above-mentioned scope of this thesis is described in four chapters. Chapter 1 introduces microwave radiometry, which includes the studies with submillimeter-wave radiometers, and the position of SMILES in the history of the microwave radiometry. Chapter 2 discusses the evaluation of the submillimeter-wave radiometer, by focusing on the discussion of the measurements of the SMILES receiver. Chapter 3 discusses the calibration of the submillimeter-wave radiometer. The calibrations of the ground-based, balloon-borne, and spaceborne radiometers are discussed in this chapter. Chapter 4 concludes the thesis. From the next paragraph, main conclusions of each chapter are summarized.

Chapter 1 emphasizes the importance of the calibration to bring out the best result from the SMILES measured spectra, which are the most precise one in the atmospheric spectra ever measured by submillimeter radiometers. For this purpose, Chapter 1 documents the historical background of the atmospheric measurement by microwave radiometry, general concept of microwave passive observation systems, and the position of this study. Chapter 1 presents two major expected outcomes from this study; first is to provide better calibrated data based on the measurements and data analysis and contribute to the users who retrieve atmospheric properties from the SMILES limb spectra; second is to make clear the principles of radiometer calibration by showing the case of SMILES as an example and contribute to those who are planning, designing, and developing future microwave sensors.

Chapter 2 introduces the SMILES instrument and discusses the results of its performance evaluations. The remarkable characteristics of the SMILES instrument are the extremely low noise performance in the submillimeter-wave receiver and the spectral baseline flatness of the measured emission spectrum. Because the spectral baseline ripple of SMILES is practically ignorable, most of discussions in Chapter 2 are devoted to the noise performance evaluation. The noise performance of the SMILES receiver were measured before the launch and in orbit. The consistency between the noise measurements are found. Furthermore, the root-mean-square of the random components of receiver-output fluctuation is compared with the calculation of the noise from the filter bandwidth, which is also measured in orbit, and also found to be consistent with it. This consistency shows the reliability of the measurements and the interpretation of them. This demonstration is important for two reasons. One of the reasons is the necessity of the exact performance measurement for the first superconducting receiver for the atmospheric observation in space. Another reason is that the receiver functions used in the interpretation of the measurements are needed to be verified in order to be also used in the calibration of the observation data. In the discussions of the noise performance of SMILES in this chapter, it is unique in the spectroscopic atmospheric sounders that the random and drift noises are clearly separated and evaluated. The separative noise evaluation is helpful to both measurement noise estimations in two kinds of retrievals. One of retrievals solves atmospheric quantities from spectral contrast, in which the drift noise can be ignored. Another retrieval solved lower atmospheric quantities from absolute intensity of continuum emission. The SMILES data are used for both retrievals so that the random and drift noises are needed to be separately quantified.

Chapter 3 discusses the calibration. In the first section of Chapter 3, the range that the calibration study covers is defined by contrast with the higher level processing of observed data. The section discusses that the calibration has the unique optimum result, which differs that the solution in the higher level processing may not be unique but depends on the scientific objectives.

The second section of Chapter 3 is the discussion on the ground-based millimeter-wave radiometer. In the ground-based radiometer for the stratospheric observation, the main concern is the removal of the tropospheric variation and suppression of the spectral baseline undulation by tuning the observation method. Because the ground-based observation suffers with the most severe spectral baseline distortion, its suppression technique can provide useful information for other geometrical configurations of radiometric observation. The ground-based radiometer installed in Alaska was developed and operated by the author, and successfully observed the stratospheric ozone and chlorine monoxide, which are the key molecules in the stratospheric ozone chemistry.

A balloon-borne submillimeter-wave limb sounder is discussed in the third section of Chapter 3. The data analysis of the balloon experiment that launched in 2003 is a good example of the calibration of antenna beam efficiency. From limited information of the antenna beam efficiency measured on the ground, the efficiency during the flight is estimated. The agreement of the measured ozone profile with that measured by other instrument proves the successful calibration.

The latter half of sessions in Chapter 3 discusses the calibration of SMILES. The discussion of the calibration of SMILES is divided into 3 parts. Section 3.4 is the radiometric calibration of SMILES. The radiometric calibration accuracy of SMILES is sometimes requested to be comparable to the noise in the averaged observation data. The dependence of the calibrated intensity on the physical temperature variation needs to be minimized so that the observation of the seasonal or local-time-dependent variation of the atmospheric quantities becomes usable data. The gain nonlinearity correction is an important part of the radiometric calibration. The gain nonlinearity is the error due to a small deviation from a proportional relation between the receiver output and the input emission intensity. The gain nonlinearity of SMILES receiver was measured before the launch. The responses of a nonlinear amplifier to continuous (sine) wave and to broadband noise are theoretically shown in the section. On the basis of this result, a black-body emission was used as an input to the receiver in the gain-nonlinearity measurements. The method of the gain-nonlinearity measurement is an original one. The receiver nonlinear components can be divided into two sections by the bandwidth of the component. In SMILES case, the bandwidth of the broadband section is about 1.3 GHz, while that of the narrow-band section is about 1.1 MHz. With the newly developed measurement method, we can know the gain nonlinearities separately in the broadband and narrow-band sections. By applying the measured nonlinear parameters to in-orbit observation data, it is found that the corrected data has a good internal consistency. The drift reduction is another important part of the radiometric calibration. In retrievals from continuum emission, it is preferable to reduce the error due to the drift. Using the results of the measured receiver noise discussed in Chapter 2, the optimum interpolation method, which minimizes the error due to the drift, is derived. It is revealed that the optimum interpolation is a weighted linear interpolation, which gives better result than a quadratic interpolation in case of a 1-by-f noise.

Frequency calibration is important in the data processing. This study contributes to an improvement in the frequency registration method of spectrometer with a reference-frequency signal. With a developed method, the center frequency of the spectrometer channel can be determined to a relative precision of a hundredth of the resolution of the channel.

Spatial location of the observation is essential information in remote sensing. In limb observation, an atmospheric emission propagating to the tangential direction of the spherical atmospheric layer is observed on a satellite located at thousands kilometer away. The altitude of the tangential point, tangent height, needs to be determined to an accuracy of 100 m in the SMILES limb observation. The attitude of the sensor is necessary information to know the tangent height. A ring laser gyroscope is used to measure the attitude. To convert the angular data of the ring laser gyroscope into the attitude in an inertial coordinate system, the initial attitude of the gyroscope is necessary. By using the star sensor data, the attitude is determined. An algorithm is developed to determine the attitude, which has lower error during the SMILES limb scanning period.

In this thesis, millimeter- and submillimeter-wave radiometer for atmospheric research and their calibrations were discussed in detail. The first objective of this study, that is to provide better calibrated data based on the measurements and data analysis and contribute to the SMILES users, was achieved. I hope the study can contribute to achieving the second objective, that is to make clear the principles of radiometer calibration by showing the case of SMILES as an example and contribute to those who are planning, designing, and developing future microwave sensors.

審査結果の要旨

本論文は，成層圏の化学組成など地球大気の諸量を，ミリ波やサブミリ波の電磁波を用いたラジオメータで観測する観測装置とデータ処理に関するものである．特に，ラジオメータの性能評価，及び較正法について研究し，それらを，国際宇宙ステーション (ISS) 上で，世界で初めて宇宙で超伝導技術を利用して高感度に地球大気を観測したラジオメータ (SMILES) に適用した結果を述べたものである．成層圏，中間圏の塩素量観測，化学組成の日変化観測による光化学反応の理解，成層圏風速の観測等の，SMILES に期待される大気科学上の知見を得るには，中間圏高度に対しても較正精度が良く，分光データの周波数較正精度も良い観測データが必要だが，従来のサブミリ波ラジオメータでは感度不足で観測が困難であり，上記目的のデータを得るための較正法も十分なものでない問題があった．本研究で，観測データの精度を改善する較正法を提案し実装することで上記問題を解決した．特に本論文では以下の研究成果を得ている．

(1) 観測データの雑音を，ランダム成分とドリフト成分とを分けて評価し，ドリフト成分雑音による誤差を最小とする較正法を示した．この結果を用いることにより，観測装置の較正の時間間隔を適切に設計することも可能となった．

(2) 地上から，また，高高度気球からの大気観測データを検討し，SMILES では影響の少ない，アンテナの主ビーム以外の方向から入射する信号を見積り較正する方法等を示した．

(3) 観測装置の入力と出力の信号強度の線形関係からの外れを較正法として，大気の分光観測に用いるのに適切な測定法と較正法を提案した．これにより SMILES 観測で中間圏等の高度域の観測値の較正精度を改善した．

(4) 分光計で測定される信号の周波数較正精度を改善する較正アルゴリズムを提案することにより，SMILES による成層圏風速観測の精度が改善された．

(5) ISS からのリム観測における観測高度を，姿勢データから精度良く，ISS の姿勢変動や振動にかかわらず，求める方法を示した．

以上の研究成果は，SMILES の観測データ精度向上により科学成果の創出に貢献するとともに，将来のラジオメータを設計するのにも有益な情報を提供しており，受動的リモートセンシングにおける大気観測の発展に貢献するところ大である．また，申請者が自立して研究活動を行うに必要な能力と学識を有することを証したものである．学位論文審査委員会は，本論文の審査ならびに最終試験の結果から，博士（工学）の学位を授与することを適当と認める．