Graduate School of Pure and Applied Sciences

Title of Doctor Thesis: Analytical and Numerical Study of a Radio Point-Diffraction Interferometer as a Novel Reflector Surface Measurement Method for the Antarctic Terahertz Telescope

(南極テラヘルツ望遠鏡に向けた新しい鏡面測定法としての
電波点回折干渉計の解析的及び数値的研究)

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Abstract

In this thesis, we discuss Radio Point-Diffraction Interferometer as a novel reflector surface measurement method for Antarctica Terahertz Telescope. The Antarctic plateau is one of the best place for submillimeter observations and the only place for terahertz observations on the planet. In a project of the Antarctica Terahertz Telescope, a 10-m terahertz telescope is planed to be constructed on the Antarctic plateau in order to make scanning survey for the submillimeter galaxies.

The reflector surface accuracy of the primary reflector must be kept high to keep high optical performance of the telescope. Deformation of the primary reflector distorts the reflected wavefront. The deformation of the optical system including the primary reflector is evaluated using Strehl ratio. When the Strehl ratio is 0.8 or more, we can make efficient observations. When the wavefront accuracy achieves $< \lambda/42$, the Strehl ratio can be > 0.8. To satisfy this requirement for the Antarctica Terahertz Telescope, the wavefornt accuracy of 4.7 μm or less is required.

In order to satisfy this requirement, we propose a measurement method of the reflector surface using a Point-Diffraction Interferometer (PDI). PDI generates a reference wave as a reference by using a small diffraction object or pinhole and passes a test wave which includes the distorted wavefront. Interferograms are made from the test and reference waves. One of PDI using a Polarizing Point-Diffraction Beam Splitter (PPBS) is proposed in the previous studies. PPBS has two regions, namely, one is a pinhole and another is an outer region. Each of them is passed through as orthogonal polarized waves by the wire grid. The wave passing through the pinhole is the reference wave, and the wave passing through the outer is the test wave. The wavefront can be estimated from the obtained interferograms made from these waves.

In this thesis, a Radio Point-Diffraction Interferometer (RPDI) is proposed as PDI in the radio field for the Antarctic Terahertz Telescope. RPDI has a configuration in

which PPBS is installed on the pupil plane and the interferograms are obtained on the focal plane. When an incident wave which is distorted by deformation of a reflector surface and having a wavefront error passes through PPBS, the reference and test waves independently propagate as orthogonally polarized waves and reach the focal plane. The two waves are independently guided on the transmission lines inside the receiver placed on the focal plane, and each of the waves is branched into four. Using delay circuits, the reference waves are made four kinds of phase-modulation of 0, $\pi/2$, π, and $-\pi/2$. Couplers make the interferograms from the reference and test waves. And four detectors simultaneously obtain four types of the interferograms.

We confirm that RPDI can be used to measure the wavefront on the reflector surface using the interferograms by analytical calculations. Five types of methods are shown to estimate the complex electric field distribution on the focal plane from the interferograms. The electric field on the pupil plane can be calculated from the electric field on the focal plane using the Fourier transform. By using the Fresnel diffraction formula for the electric field on the pupil plane, the electric field on the reflector surface can be estimated.

In order to confirm whether RPDI can estimate the wavefront on the reflector surface, we verify the principle of RPDI by numerical calculations. First, we discuss the systematic error by the analytical calculation of RPDI. As the systematic error, there are two errors which are a difference between the analytic calculations and the numerical calculations and an error due to the approximation used in the analytic calculations. As a result, the sum of these errors is $\lambda/43$ and is comparable to the targeted estimation accuracy of $\lambda/42$. When we measure the deformation on the reflector surface, it is necessary to subtract this systematic error. Therefore, we need to measure or calculate the systematic error of the optical system in advance.

Next, we confirm whether the deformation on the reflector surface can be estimated with the target accuracy. The deformation is calculated in two case of deformation. One is made by two-dimensional Gaussian function, and another is made by displacement by a fun shape panel. These results show the estimation error of the wavefront increases with the magnitude of the deformation and the displacement. When the estimation and correction of the deformation on the reflector surface are repeated, we think that the estimation accuracy is decreased. In the case of the Gaussian function, the worst RMS of the wavefront error is $\sim \lambda/88$ except for one of the estimation methods. In the case of the panel displacement, the worst RMS of the wavefront error is $\sim \lambda/59$ except for one of the estimation methods when the displacement of the panel is -0.05 to $+0.10$ mm and is not on the edge of the reflector. These results show that RPDI can estimate the deformation on the reflector surface with the target accuracy of $\lambda/42$.

We consider effects of calibration errors in the polarization properties of PPBS on the estimation accuracy of the wavefront. The tolerance analysis is performed for each of the errors, which are the deviations from true values of amplitude transmittances δ_{T_1} and δ_{T_2}, and the deviation from true value of phase-modulation δ_{ϕ_T}. For each of the errors, the estimation accuracy of the wavefront is aimed at achieving $\lambda/100$. As a result, the required calibration accuracy in the amplitude transmittances of PPBS are

$\delta_{T_1} \leq 10^{-4}$ and $\delta_{T_2} \leq 3 \times 10^{-6}$ to achieve the target accuracy. And when the calibration accuracies of the phase-modulation by PPBS is $\delta_{\phi_T} \leq 0.01$ deg, we can estimate the wavefront with accuracy of $\lambda/100$. It is necessary to develop PPBS which has these calibration accuracies.

Finally, we discuss change of the estimation accuracy of the wavefront due to the system noise. The noise is defined as the signal-to-noise ratio (SNR) which is given as a ratio of the peak of the intensity on the focal plane of the reference wave to RMS of the noise. If SNR is ≥ 10 dB, the estimation accuracy of wavefront achieve $\lambda/100$. In order to satisfy this SNR, it is necessary to use an artificial radio source as a signal source for reflector surface measurements.