Demonstration of Athermal and Light-weight Optical Telescopes For Airborne LIDAR System

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Abstract: In airborne LIDAR system, optical telescope is required to be small, lightweight, and insensitive to temperature and pressure change in flight. In this paper, we designed athermal light-weight optical telescopes with CFRP (Carbon Fiber Reinforced Plastic) barrel and frame structures. We also evaluated optical performance with Shack-Hartmann wavefront Sensor under flight environment.

Keywords: Airborne LIDAR System, Optical System, Wavefront Sensor

1. Introduction

Development of the system which can foresee outbreak of the turbulence by measuring the wind velocity in front of an aircraft is desired for many years, because primary cause of aircraft accident is the unexpected turbulence. On this subject, we are developing airborne LIDAR (Laser Imaging Detection And Ranging) system, which can detect CAT (Clear Air Turbulence) [1-3]. This system enables us to measure wind velocity in fine weather, compared to radar detection system that are already installed in aircraft. However, in this airborne LIDAR system, the optical telescope, which has the function of transmitting laser beam into the atmosphere and receiving aerosol backscattered beam, is required to be small, light-weight, and to be robust against environmental conditions in flight. In particular, it is necessary to maintain optical performance against environmental temperature changes, that is, to minimize the change in focal length of the optical telescope against environmental temperature changes. This is because, the change in focal length of the optical telescope causes the reception efficiency of the backscattered beam to be lowered, and also causes deterioration of the wind speed measurement accuracy and measurement distance. It is also important to maintain optical performance against high loads caused by acceleration and deceleration of the airplane.

In this paper, we designed athermal optical telescope with CFRP (Carbon Fiber Reinforced Plastic) structures taking into consideration of CTE of CFRP as shown in Figure 1. Furthermore, we evaluated optical performance with Shack-Hartmann wavefront Sensor under flight environment.

Figure 1 The outside view of optical telescopes (φ162 mm)
2. Design Concept of Athermal Optical Telescope

As shown in Chapter 1, in designing optical telescope of airborne LIDAR, it is required that the optical antenna is required to be small, robustness, light-weight, and insensitive to temperature and pressure change in flight. In this study, we adopted CFRP (Carbon Fiber Reinforced Plastic), which has low density, high rigidity ratio and low thermal expansion, for the optical telescope lens barrel. Furthermore, we adopted a passive athermal design method that realizes temperature compensation by appropriately setting the optical and mechanism design parameters based on aberration theory. In this method, as shown in Equation 1, under the condition that the lens barrel of the telescope constructed with CFRP, we designed lens barrel, lens material, and lens shape to compensate the thermal aberration in each lens with the aberration which caused by changing of the distance between lenses by the linear expansion of the CFRP lens barrel under the environment temperature change.

$$\Delta f = f \left( \alpha_g - \frac{1}{n-\frac{dn}{dT}} - \alpha_n \right) \Delta T = 0$$

f: Focal-length, $\alpha_g$: Coefficient of thermal expansion of the lens, $\alpha_n$: Coefficient of Linear expansion of CFRP lens barrel, n: Refractive index of the glass material constituting the lens, T: Temperature

3. Result of system design for telescope

(i) Optical system design

Figure 2 shows the result of optical system design. We also evaluated wavefront aberration of optical telescope with simulation, based on optical system design as shown Fig 2. Figure 3 shows temperature dependence of wavefront error with (a) CFRP lens barrel and (b) Aluminum lens barrel. In this study, the optical telescope with Aluminum barrel should not show athermal performance, because we applied the passive athermal design method for CFRP lens barrel. As Fig. 3 shows, for the case of telescopes with CFRP lens barrel, the wavefront error doesn’t change from 15°C to 25°C. On the other hand, in optical system with Aluminum lens barrel, large thermal aberration occurs at 15°C and 25°C. The nominal wavefront error is 0.0086 λ, RMS at 20°C. The wavefront error with Aluminum lens barrel is over 0.05 λ, RMS at 25°C, and it shows significant dependence of the temperature. On the other hand, in the case of CFRP, the wavefront error is suppressed under 0.01 λ, RMS in this temperature range.

Figure 2 Result of optical system design for telescope

(a) CFRP  (b) Aluminium

Figure 3 Temperature dependence of wavefront error of the our telescope
(ii) Mechanical system design

Figure 4-(a) shows appearance of the optical telescope. In this study, the telescope includes three tolerance compensators in order to compensate the wavefront aberration which caused by manufacturing tolerances of lens, lens barrel, and alignment errors during assembly of these components. The Compensator C1 is a part for adjusting the distance L3-L4, the Compensator C2 is a part for adjusting the eccentricity of L1, the compensator C3 is a part for adjusting the distance L2-L3. Figure 4-(b) shows the effect of tolerance compensators on wavefront aberration. From this result, it can be seen that wavefront aberration due to manufacturing tolerance and alignment errors can be effectively reduced by mounting all the compensators C1 to C3. It was expected that the wavefront aberration 0.07 \( \lambda \), RMS could be achieved with a probability of 90\% or more by simulation. This wavefront aberration result of 0.07 \( \lambda \) RMS corresponds to the reception efficiency loss of backscattered beam of 1.0 dB on wind measurement.

![Figure 4](image_url)

Figure 4 Result of mechanical system design

4. Results of optical performance evaluation of telescope

As shown in Fig. 1, we prototyped optical telescope based on result of optical and mechanical system design. As a result of applying CFRP to the lens barrel and optimizing the structure, the weight of the telescope become 2.54 kg, 70 \% lighter than the conventional one which weight is 7.1kg.

Furthermore, we evaluated its optical performance by a Shack-Hartmann wavefront sensor [4]. The sensor is a wavefront measuring method using Hartmangram image, which consists of multiple focusing beam spot spatially divided by the micro lens array. The tilt of wavefront in front of each lens of microlens causes displacement of focusing beam spot. In other words, we can get tilt of each place of light flux so that of the wavefront of measurement object can be calculated by differential value of wavefront which is equal to tilt.

In this study, we evaluated the change of the wavefront aberration under the situation where the static load was applied to the prototype telescope. The wavefront aberrations with the static load of 1 G to 6 G are shown in Figure 6. From this result, compared to the wavefront aberration without the load, the wavefront aberration fluctuation is about 0.002 \( \lambda \), RMS with the static load of 1 G to 6 G is applied. This result indicates that the structure of the optical telescope designed in this report has appropriate robustness. Furthermore, the transmitted wavefront shape of optical telescope shown in Figure 7, where the wavefront shape was maintained against application of static load. In conclusion, we confirmed that the optical telescope designed in this report was expected to be applicable to airborne LIDAR.
5. **Summary**

In airborne LIDAR system, the optical telescope is required to be small, light-weight, and to be robust against environmental conditions in flight. We developed an engineering model of lightweight athermal telescope with aperture diameter of 162 mm, length of 368 mm and weight of 2.54 kg. Performance of athermal properties was experimentally verified as variation of wavefront error of less than 0.01 \( \lambda \) under environmental temperature at 15°C to 25°C. Furthermore, wavefront errors were also evaluated as their variation of 0.002 \( \lambda \) under static load was externally applied from 1G to 6G. In conclusion these results showed that the present athermal telescope has the primary performances for airborne LIDAR.

6. **References**


