5 Photonic Propagation Technologies

5-1 Artificial Star Generation by Stratospheric Rayleigh Scattering

Shin YOSHIKADO, Shin OYA, Shuwing LI, and Tadashi ARUGA

The first domestic experiment of artificial star generation by stratospheric Rayleigh scattering was conducted successfully. The artificial star generation system utilizes a 1.5 m-diameter telescope of CRL for transmitting a laser beam to illuminate the atmosphere and for receiving back-scattered light. The light source of transmission used is the second harmonics of a pulse-oscillating Nd:YAG laser. Images of back-scattered light from various distances (altitudes) acquired in this experiment are analyzed from the viewpoint of their structures of image intensity distribution. Results of the analyses show that images of back-scattered light from distances over about 12 km have characteristic structures due to speckles similar to those of Polaris as a reference, and proved to be applicable as artificial stars.

Keywords
Artificial star, Laser guide-star, Rayleigh scattering, Atmospheric turbulence, Image compensation

1 Introduction

Artificial stars are sometimes referred to as “laser guide-stars.” This is based on the fact that an artificial star is produced by back-scattered light from the near-point source of a laser beam emitted into the upper atmosphere. Such a starlike shining spot is expected to be used as a reference light source to compensate for the inevitable effects when a telescope is used to observe a body in space through the atmosphere. One example of such effects is the blurring of an image caused by atmospheric fluctuations.

In a vacuum, the angular resolution of a telescope is expressed as the ratio of the observed wavelength λ to the aperture (D, the diameter of the primary mirror): $\Delta\theta \approx \lambda / D$. This is a well-known formula for the resolution of the diffraction limit. For example, when visible light of a wavelength of approximately 500 nm is observed using a 1.5-meter-aperture telescope, the value of $\Delta\theta$ is approximately 0.07 arcsecond. In the air, the resolution is controlled by atmospheric fluctuations for large apertures. Such a resolution, referred to as the “seeing,” depends on the geographic environment and air conditions, and is normally several arcseconds for the observation of visible light on level ground in Japan. When an image pickup device is used to record a point light source in astronomical observation, speckles (unevenly distributed spot images caused by atmospheric fluctuations) appear with a short exposure time. With a long exposure time, speckles are integrated, producing a blurred image.

A large-aperture telescope features a diffraction limit with superior resolution, compared with the seeing. Some measures must be taken for such a telescope to optimize its intrinsic performance, however. The most simple and fundamental measure is observation outside the atmosphere from a satellite in orbit, as with the Hubble Space Telescope, though such observation is costly. A much less expensive method of achieving improved resolution beyond the seeing limit is use of the above reference light source. There are several methods of compensating for the influences of atmospheric fluctuations on the results of observation[1]~[6]. One is to repeat the consecutive recording of a short-term exposure image and then produce an image intensity distribution, obtainable without atmospheric fluctuations, through image processing. Another is the application of adaptive optics, which allows real-time compensation for atmospheric-fluctuation-induced wave-front distortions measured by a wave-front sensor. This type of compensation is made possible through the use of a deformable mirror. A method of compensation of image processing without the need of reference light has already been proposed.[7] In adaptive optics, however, a reference light source is indispensable.

Ideal reference light is a light beam of adequate brightness under the effects of atmospheric fluctuations that can be considered to those affecting the light waves from an observation object. In other words, an ideal reference light source should be a point light source of adequate brightness that is oriented as close to the object as possible in the infinite distance. If a fixed star of adequate brightness lies near the object, it may be an ideal reference light source, but such cases are rare. An artificial star can be a useful reference light source when there is no fixed star available, although it differs slightly from an ideal reference light source since it lies in finite distance.

Various studies have advanced the technology to the point that artificial stars will be put to practical use in the near future[7]~[18]. For example, Philips Laboratory USA, a leading institute, has completed the world's most advanced system, an adaptive-optics demonstration system using an artificial star generated using a copper vapor laser with an average output in the 200-W class[5]. In Japan, the National Astronomical Observatory is working to develop an artificial-star generation system using a continuous-oscillation dye laser. The Communications Research Laboratory (CRL) has conducted studies on artificial-star generation and adaptive optics. At the core of our studies at this laboratory lies research work on the generation of artificial stars by using a 1.5-meter-aperture telescope to send and receive light[18].

The first stage of the work demonstrated that upper tropospheric and stratospheric Rayleigh scattering of a laser beam is useful in the generation of an artificial star. In this stage, we applied the second harmonics of a pulse-oscillating Nd:YAG laser to illuminate the upper troposphere and the stratosphere. Back-scattered light produced by Rayleigh scattering was received as image data by a CCD (ICCD) camera with an image-intensifier. The data obtained from a range of distances between 12 and 15 kilometers showed characteristic structure of image intensity distributions of speckles similar to those seen on an image of the polestar (Polaris). This was the first such experiment conducted in Japan. This report outlines the above experiment.

2 Atmospheric Fluctuations and the Artificial Star

As described above, atmospheric fluctuations affect the angular resolution of an astronomical telescope. The seeing is normally several arcseconds, and is as low as one arcsecond only under the most favorable conditions. The seeing lowers due to a temperature change and turbulence-induced change in the atmospheric refractive index. Light waves from a light source in outer space move through the atmosphere and reach two points separated by distance r on the aperture, resulting in a phase difference. The mean square of the difference is defined as structure function $D_p(r)$, as follows:[19]

$$D_p(r) = 6.88(r/r_0)^{5/3} \tag{1}$$

where

$$r_0 \propto \lambda^{6/5} \quad (2)$$

This value is referred to as the “Fried parameter,” and represents the coherence length of atmospheric fluctuations, or their spatial size.

A fixed star near the object to be observed can serve as a reference light source to compensate for the effect of atmospheric fluctuations if it has sufficient brightness between the 6th and 12th magnitudes, with a wavelength depending on the conditions of the seeing and the like. If such a star is not present nearby, an artificial star may be a reliable alternative as a reference light source and can be generated as back-scattered light by illuminating the upper atmosphere using a laser beam. In the latter case, two mechanisms can be used to produce back-scattered light[1][4]. One is Rayleigh scattering by atmospheric molecules in the stratosphere (10–20 km). The other is resonance scattering caused by the illumination of Na atoms in the Na layer (90–100 km) of the mesosphere using a laser beam having a D-ray-tuned wavelength. The Na-layer resonance scattering is closer to that of the ideal reference light source, as it occurs at a higher level than the Rayleigh scattering. When the aperture of the telescope is smaller than 3 meters, however, the Rayleigh scattering is said to be satisfactory in practical use.

The higher an artificial star, the more the effects of the atmosphere can be compensated for due to the greater distance from the ground to the star. The major part of the atmosphere that affects fluctuations lies below the troposphere or up to approximately 10 km above the surface. Above the troposphere the density rapidly decreases and, as a result, for observation using a telescope with a 1.5-meter aperture, back-scattering in the stratosphere is acceptable in the case of an artificial star. This was proven, as described later, by the scatter-position-dependent characteristic changes in structure of image intensity distribution that were found through the analysis of image data in an artificial-star experiment. In this case, no tuning of the laser-beam wavelength is necessary, unlike in the case of resonance scattering, making it possible to use various types of lasers.

Fig.1 is a schematic diagram of an artificial star generated by Rayleigh scattering in the stratosphere. Such an artificial star having favorable brightness is generated in the orientation close to a heavenly body to be observed. If this artificial star is in the same field of view of the telescope as the body, the two objects should produce nearly identical patterns of speckles. Thus, even if the heavenly body is not a point light source or does not have sufficient brightness, the artificial star is still useable as a reference light source to compensate for the effects of atmospheric fluctuations on the image.

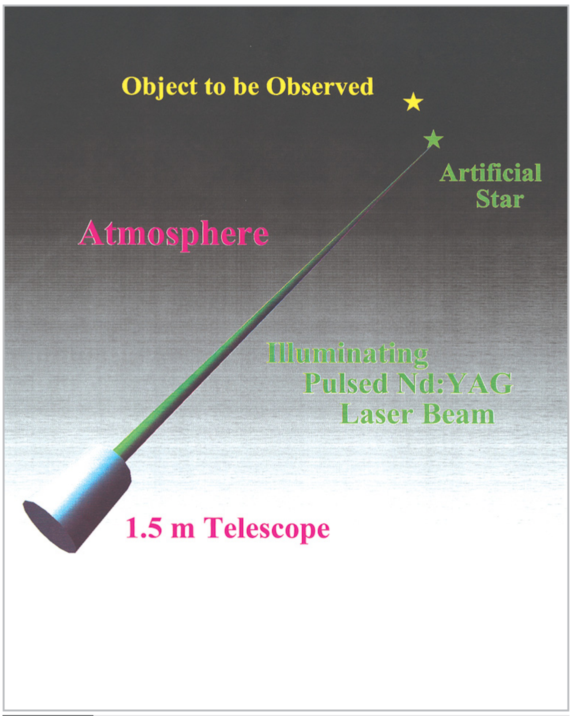

Fig.1 *Schematic diagram of an artificial star by Rayleigh scattering in the stratosphere (single column)*

3 Artificial-Star Generation System

3.1 Optical system

When one mirror is in common use for sending a laser beam and receiving scattered light, it is normal to use a beam splitter, which gives rise to a total loss of 6 dB. In the present system, on the other hand, an interface mirror is bored in the center, a laser beam is projected through the bore, and back-scattered light is received on the entire surface of the mirror. This mechanism eliminates the above loss. Fig.2 shows the 1.5-meter telescope and the optical system located in the Coude telescope room. Only the optical bench and light-source laser are shown in the figure. Fig.3 shows the center-bored mirror that connects the light-sending and -receiving systems.

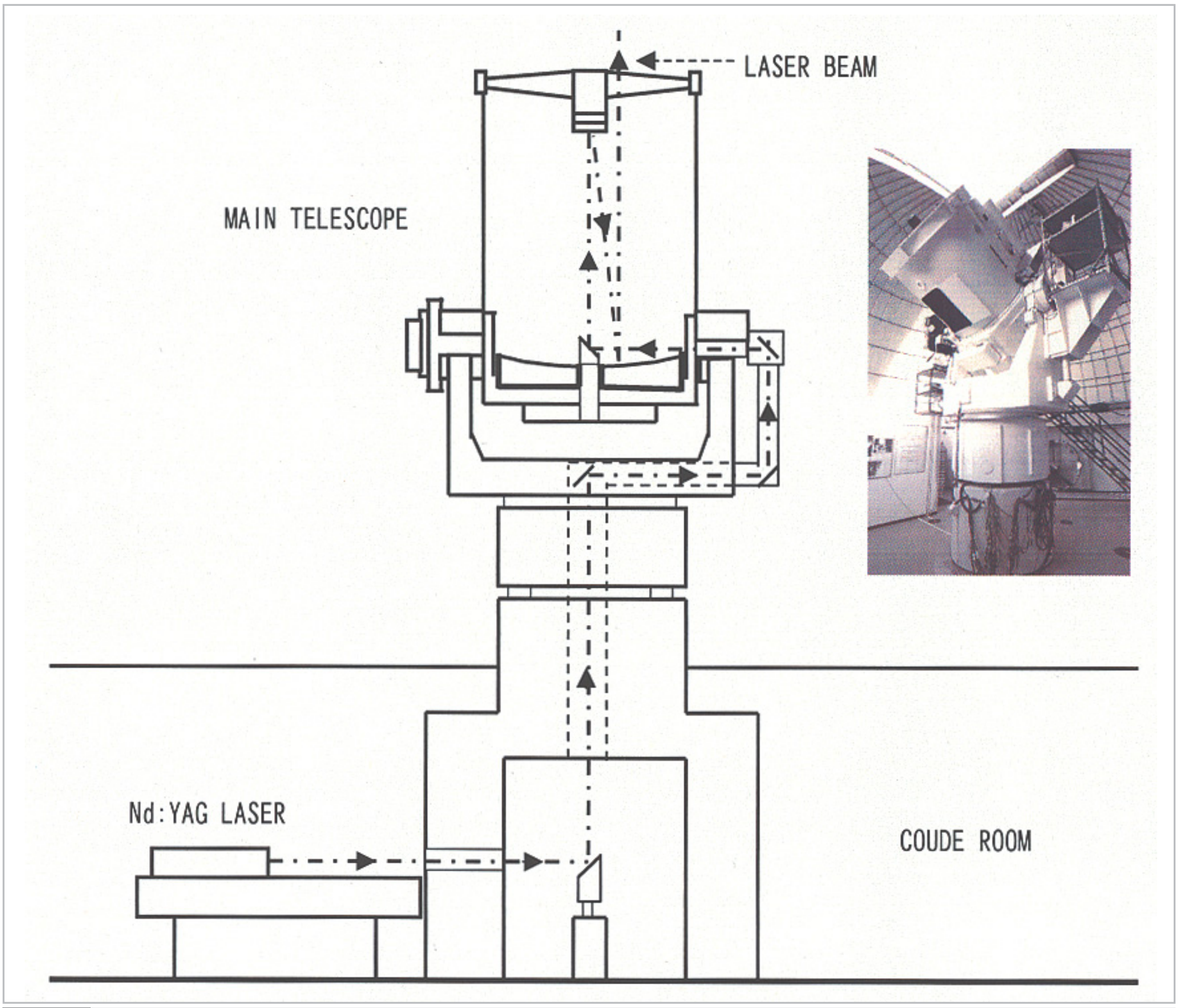

Fig.2 1.5-meter telescope and optical system located in the coude telescope room (both columns)

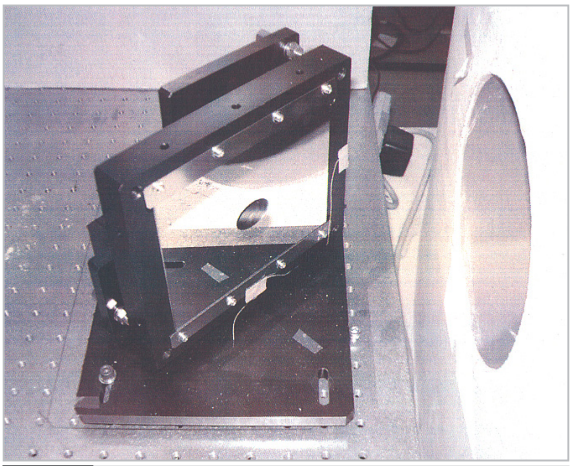

Fig.3 Center-bored mirror that connects the light-sending and -receiving systems (single column)

A beam emitted from the light-source laser passes through the bore of the mirror shown in Fig.3 and reflects off the switching mirror located directly under the azimuthal axis of the 1.5-meter telescope in the Coude telescope room. The beam is then guided through the Coude pass to the 1.5-meter telescope. As shown in Fig.2, the laser beam (with a diameter of 15 cm) is emitted through the central part of the primary mirror toward the sky.

Collimation of the beam is confirmed through the use of a guide telescope attached to the primary mirror. Back-scattered light from a high altitude travels back through the Coude pass to the bored mirror, and reflects off the entire surface of the mirror toward the light-receiving system. Fig.4 shows two combinations of a focusing stage and an ICCD camera. One is used to obtain an image of back-scattered light, while the other is used to obtain an image of the targeted heavenly body. Prior to these combinations, a filter is used to separate the received light.

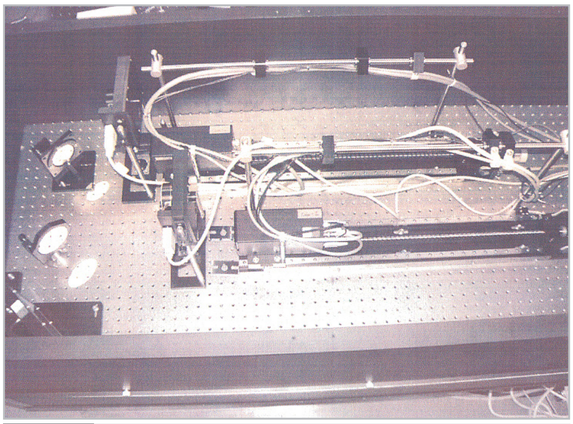

Fig.4 Light-receiving system: two combinations of a focusing stage and an ICCD camera

3.2 Light-source laser and image pickup system

3.2.1 Light-source laser

Table 1 shows major specifications for the pulsed Nd:YAG laser that was used as a light source. The pulse energy required to generate an artificial star by Rayleigh scattering at an altitude of 15 km in the stratosphere has been calculated to be 30 mJ or more[4]. This calculation is based on some general assumptions, such as that the quantum efficiency of the sensor = 50%, the Fried parameter r_0 (described in Section 2) = 15 cm, and the wavelength λ = 500 nm, among others. In this study, the energy per pulse was controlled at a level of 170 mJ to obtain an image.

Table 1 Major specifications for the pulsed Nd:YAG laser used as a light source (single column)

Model	Quantel YG781C-20
Type	Q-Switched Nd: YAG Laser
Wavelength	532nm (2nd harmonics)
Pulse Energy	500mJ max.
Repection Rate	5/10/20 Hz
Pulse Duration	～5－7ns

3.2.2 Image pickup system

Table 2 shows the major specifications for the ICCD cameras used to obtain images. As shown in Fig.4, these cameras are positioned on a pulse-control linear stage used for focusing. It is capable of adjusting the focus position of any object with good reproducibility, whether it is a relatively near artificial star or a very distant heavenly body. As previously described, the camera for the artificial star has a filter that allows selective filtration of a narrow band of light, including the oscillation line of a light-source laser beam. The camera for heavenly bodies has a filter that allows the selective filtration of light having wavelengths excluding the above narrow band. The composite focal distance of the entire image pickup system including the primary mirror is 45 meters.

Table 2 Major specifications for the ICCD cameras

Intensifierl TT Ultra Blue	
Gain (Typical)	40,000 (46.0dB)
CCD Camera	**Philips FTT1010**
Pixel size	9 × 9 μm
Pixel format	648 × 484 pixels
Field of view	33.6 arc seconds (diagonal)
Pixels / are sec	24.1

The ICCD cameras are operated by setting the delay time τ until the start of an exposure and the exposure time in reference to a trigger signal synchronized with an output pulse from the laser. These settings are made through a control computer using parameters for the intensifier gain, filter selection, a single exposure or consecutive exposures, and others.

The present system features a single telescope that receives back-scattered light in a high-altitude atmosphere as a transmitted pulse is consecutively traveled, in the same way that laser radar receives signals. As signals received before the delay time τ until the start of exposure are cut off, scattered light from beyond the distance, $R = c\tau/2$, in which the pulse travels at time τ, is picked up. In this equation, c is the speed of light. As back-scattered light rapidly attenuates with an increase in distance, even a long-term-exposure image can be thought to represent back-scattered light from the distance R.

4 Generation of an artificial star by Rayleigh scattering

In an early experiment using Rayleigh scattering of stratospheric air molecules to generate artificial stars, one of the two ICCD cameras was not properly prepared, so it was impossible to achieve simultaneous camera observation of an artificial star and heavenly body in a single field of view. Therefore, we first transmitted a laser beam in such a direction that the polestar was slightly out of the vision field. After obtaining an image of back-scattered light, we adjusted the telescope so that the polestar was within the field, and obtained an image of it.

When an image of back-scattered light is obtained, the delay time τ from the transmission of a laser pulse to the exposure start was set from 30 μsec (equivalent to R = 4.5 km) to 100 μsec (equivalent to R = 15 km), with an interval of 10 μsec. There were therefore 8 different durations of the delay time. The exposure time was set at 1 msec. For each value of the delay time, we obtained 16 consecutive images with an interval of 0.25 seconds. This interval was obtained by applying a trigger signal from the light-source laser oscillated at 4 pulses per second.

4.1 Structure of image intensity distribution on a back-scattered light image

Fig.5 and 6 show typical intensity distributions of back-scattered light from a distance of 6 km and 15 km, respectively. Fig.7 is a reference photograph showing the image intensity distribution on an image of the polestar. These distributions were obtained by the same image pickup system. This data was obtained by cutting a 10×10-pixel size square of major sections out of an entire 648×484-pixel image, as shown in Table 2. The field-of-view angle was 0.588 arcsecond (along a diagonal). Fig.5 indicates that back-scattering from a distance of several kilometers produced a collection of bright spots (or pixels of high luminance), and that no speckles were observed as a result of atmospheric fluctuations. Fig.6

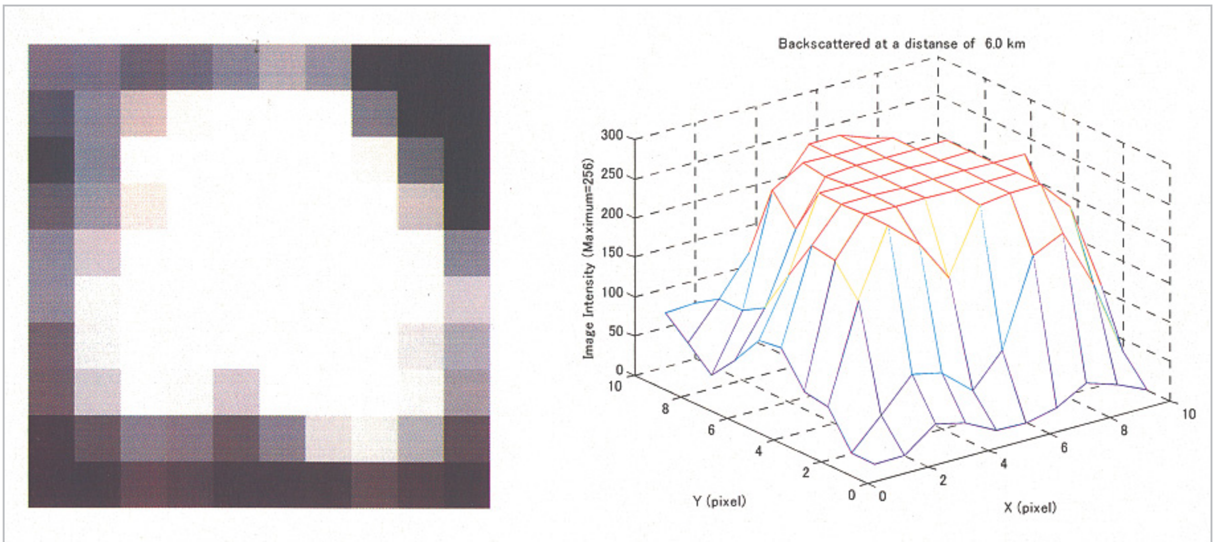

Fig.5 *Typical structure of image intensity distribution of back-scattered light from a distance of 6 km*

indicates that back-scattering from a distance of 15 kilometers produced clear speckles, like those in the image of the polestar shown in Fig.7, and that the image intensity distribution was complex, with ridges and valleys.

4.2 Histogram of image intensities

The image intensity data shown in Fig.5, 6, and 7 can be rearranged into the histograms shown in Fig.8. Thus, they are correlated. A simple structure such as that shown in Fig.5 produces a histogram having large numbers of pixels (corresponding to the highest intensities in the center of Fig.5) at the leftmost and rightmost ends of the intensities. Complex structures due to speckles, such as those shown in Fig.6 and 7, produce a relatively large number of pixels in portions of intermediate intensities. Fig.8 shows eight histograms of back-scattering at distances between 4.5 km and 15 km, along with one for the polestar.

Fig.9 shows the relationship between the percentage of intermediate-intensity pixels and the distance at which back-scattering occurred. The percentage tends to increase with the distance, eventually reaching values close to that of the polestar, at above 13 km. Thus, the percentage of intermediate-intensity

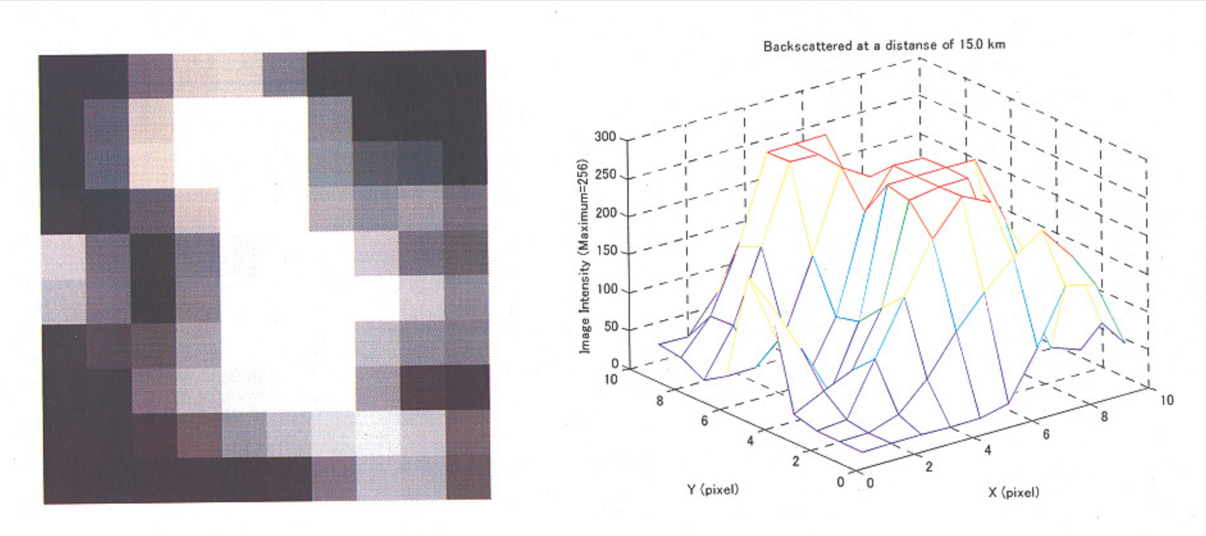

Fig.6 *Typical structure of image intensity distribution of back-scattered light from a distance of 15 km*

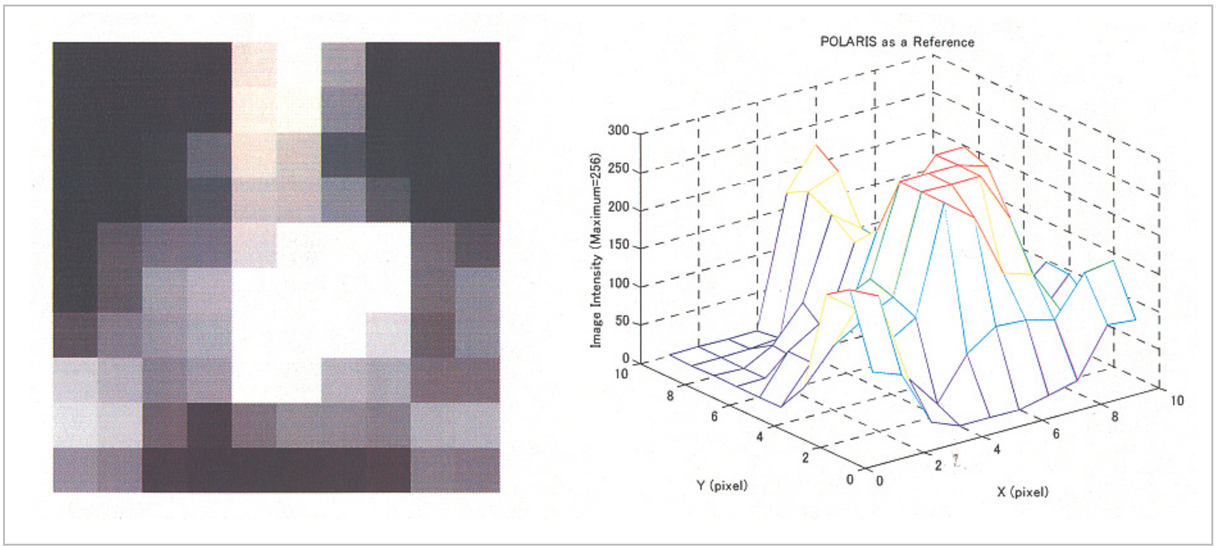

Fig.7 *Typical structure of image intensity distribution on an image of the polestar obtained using the same image pickup device as those for Figs. 5 and 6*

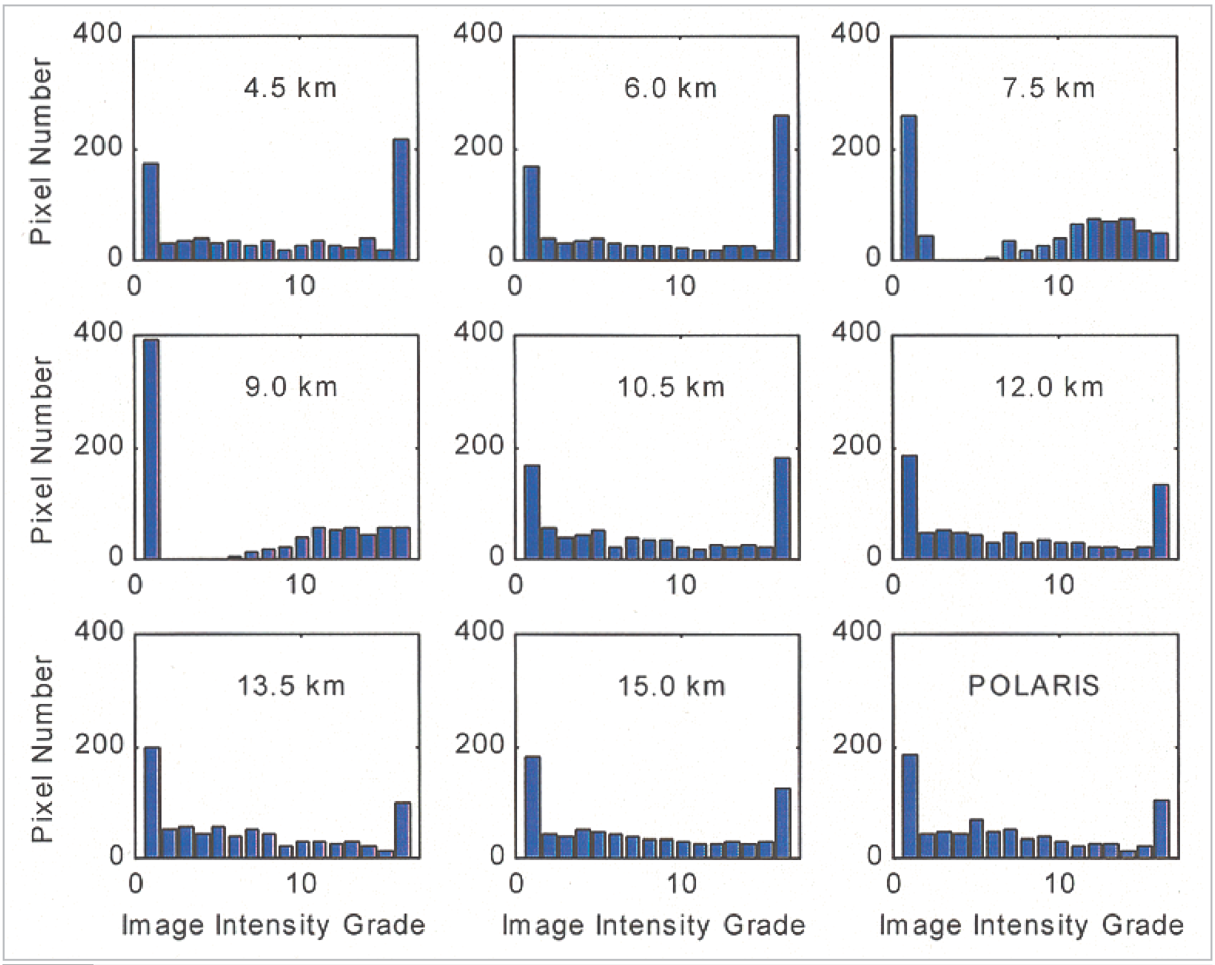

Fig.8 *Histograms of image intensities for back-scattering in a high-altitude atmosphere and for the polestar*

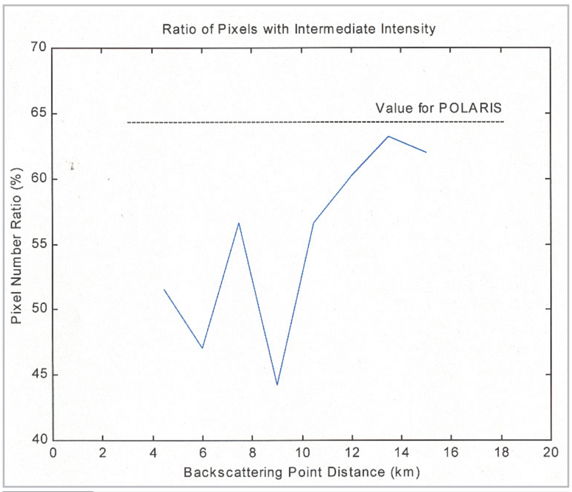

Fig.9 *Relationship between the percentage of intermediate-intensity pixels in a back-scattered-light image and the distance at which back-scattering occurred (single column)*

pixels may be an index for the structure of speckles caused by atmospheric fluctuations affecting back-scattered light. In particular, back-scattered light generated by Rayleigh scattering in the stratosphere may be from an artificial star for use as a reference light source, in terms of the structure of speckles.

5 Conclusions

We developed an artificial-star generation system using a 1.5-meter-aperture telescope to send a laser beam and receive back-scattered light. The laser beam was generated as the second harmonics of a pulsed Nd:YAG laser, and was transmitted into the upper troposphere and the stratosphere, where Rayleigh scattering took place. ICCD cameras were used to obtain image data on back-scattered light. The experimental results showed that the greater the distance from the telescope at which back-scattering took place, the more speckles formed on the image of back-scattered light. Back-scattering generated at a distance of between 12 km and 15 km may be from an artificial star, as the image showed a pattern of speckles similar to that of the polestar. Such an artificial star generated by 170-mJ/pulse at a distance of 15 km was approximately equivalent to a star of the 9th magnitude, having brightness approximately one-thousandth of that of the polestar, a star of the second magnitude.

If the artificial star is to be used as a reference light source to compensate for the effects of atmospheric fluctuations, the artificial star and the heavenly body to be observed should lie in a single field of view. They should therefore be separated by filters to allow their images to be obtained simultaneously on separate ICCD cameras. The two light sources have almost identical patterns of speckles due to atmospheric fluctuations. Therefore, by using an adequate algorithm to reproduce point images from the entire image of the artificial star that can be considered a point source of light, the image of a heavenly body that is generally not a point source can be corrected. This may make observation possible with a resolution beyond the limit of the seeing.

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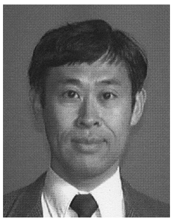


Shin YOSHIKADO*, Dr. Eng.*

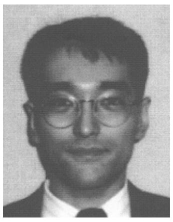
Senior Researcher, Advanced Optical Technology Research Center, Basic and Advanced Research Division

Laser sensing, Image processing, etc.

Shuwing LI*, Ph. D.*

Formerly, Advanced Optical Technology Research Center

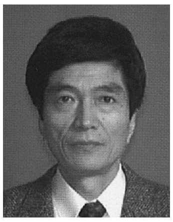
Laser sensing, Light propagation, etc.



Shin OYA*, Dr. Sci.*

Research Fellow, Advanced Optical Technology Research Center, Basic and Advanced Research Division

Light propagation, High spatial resolution imaging



Tadashi ARUGA*, Dr. Sci.*

Distinguished Researcher

Free Space Light Transmission/Propagation