CONICAL-BEAM LASER RADAR FOR SPACE DEBRIS MEASUREMENT

Makoto Tanaka[1], Susumu Sasaki[2], Tadashi Takano[2], Toshiaki Yokota[3], Fumio Tohyama[1], Masahiro Ota[4]

1. Tokai University, 1117, Kitakaname, Hiratsuka, Kanagawa, 259-12 Japan
2. The Institute of Space and Astronautical Science, 3-1-1, Yoshinodai, Sagamihara, Kanagawa, 229 Japan
3. Ehime University, 3, Bunkyo, Matsuyama, Ehime, 790 Japan
4. Tokyo Metropolitan University, 1-1, Minamiosawa, Hachioji, Tokyo, 192-03 Japan

ABSTRACT

The purpose of this study is to develop a test model of a conical-beam laser radar and to evaluate its performance for space debris measurement. A 1.5 MW class laser and associated optics and detectors have been assembled for the experiment. The capability of target imaging, ranging, and measurement of target size has been evaluated using a target of 1 - 20 cm size located up to 17 m ahead of the laser radar. The results suggest that this laser radar system can be a potential technology for active measurement of the small particles in space.

1. INTRODUCTION

During the last 39 years human activities in space have resulted in man-made space debris as artificial dusts. At the present day, there are mixed particles including natural meteoroids and space debris in the near earth space environment. Space debris larger than 10 cm in diameter have been detected by ground-based RF radars and optical observations. On the other hand, the population of the smaller particles has been investigated by impact analysis of the retrieved spacecraft. The Long Duration Exposure Facility (Ref.1) is a well known example of retrieved spacecraft after nearly six years in space. Another way to measure the small particles in space is to use the dust detector of impact plasma detection type. The dust detectors installed on the Galileo and Ulysses spacecraft were capable of measuring both mass and velocity of the small particles(Ref.2). Since the aperture of the dust detector of this type is usually several hundreds of square centimeter, the detectability is extremely limited. Retrieved spacecraft and dust detectors provided a significant information on debris and meteoroid population of the near earth orbit. But the data are still far insufficient to establish a reliable population model. In recent years, the feasibility studies on space based laser radar for small debris detection, have been done by several authors(Refs.3-6). In particular, Sasaki et al.(Ref.7) showed that the conical-beam laser radar system is one of the potential technologies for active measurement of small debris and its detection capability is much superior to that of the dust detector with a small detectable area. Technologies of a laser radar, called lidar(light detection and ranging) or ladar(laser detection and ranging), have been widely studied already for atmospheric research, satellite tracking, and space science(Refs.8-12). However, as for the laser radar for detection of space debris and meteoroids, very few experimental efforts have been made so far.

In order to evaluate the capability of the laser radar for small debris measurement, experimental studies(Refs.13-18) are required as well as theoretical studies(Refs.7,17). We have developed a conical-beam laser radar for detection of moving small particles for space application. This paper describes the laser radar system currently developed for this study and its theoretical background. Experimental results on the basic performance are also shown for evaluation.

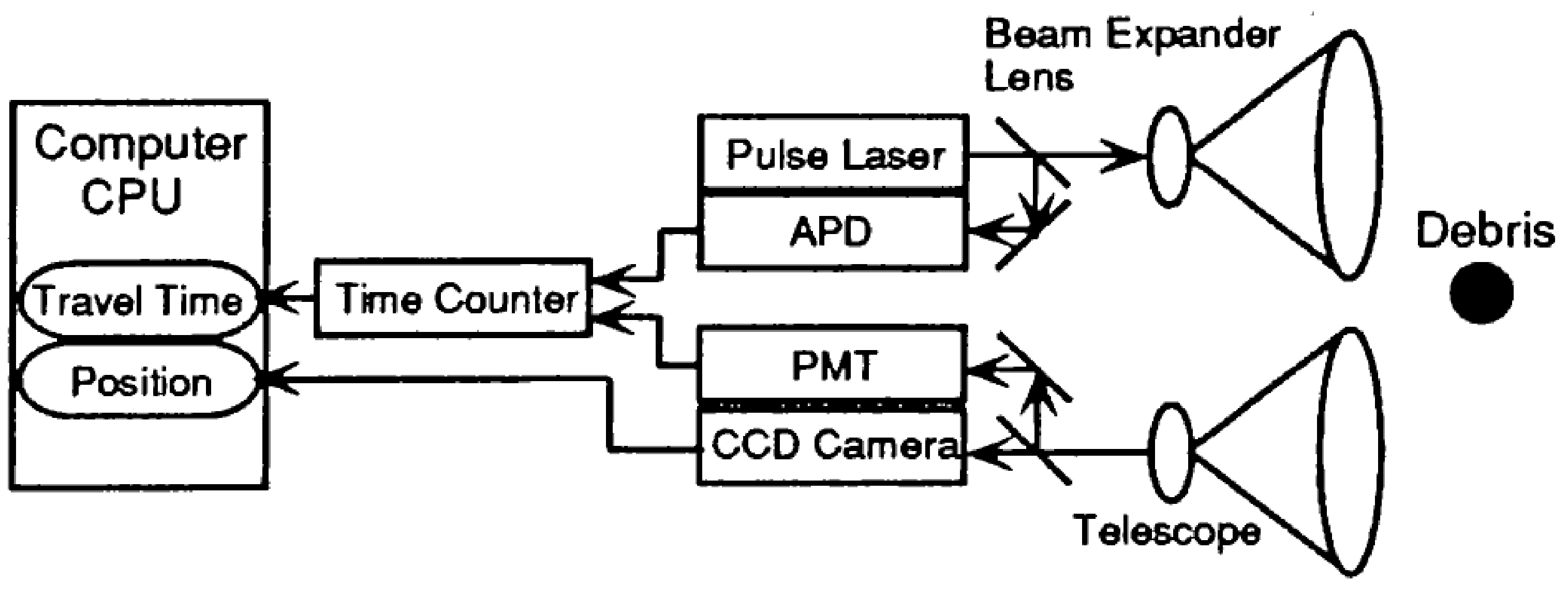

Figure 1. System block diagram of the laser radar.

Proceedings of the Second European Conference on Space Debris, ESOC, Darmstadt, Germany, 17-19 March 1997, (ESA SP-393, May 1997)

2. LASER RADAR SYSTEM

2.1 Concept

Fig. 1 displays the system block diagram of the laser radar. The laser radar is composed of a giant pulse laser, a beam expander lens, a telescope, a CCD camera, a photomultiplier tube (PMT), an avalanche photo diode (APD), a time counter, and a CPU. This system is based on the optical scattering and the incoherent detection system without modulation and photomixing techniques. The differences of this laser radar from the existing lidars are; 1) a conical laser beam expanded by a lens is used for detecting debris in a large volume, 2) consideration is given to measure the distance, position angle, velocity vector, and size or radar cross section (RCS) of debris, and 3) the system is designed to be simple and light in weight for space use.

2.2 Theory of measurement

Distance of debris is derived from the travel time of the laser light. The position angle is determined by the image on a CCD sensor. The displacement of the image gives a radial velocity component and a tangential velocity component. The radial velocity is evaluated by the change of the distance. The velocity vector of debris is calculated using two sets of the distance and the image(Refs.14,16).

The laser radar system can determine the size of debris by the use of a laser radar equation. When the size of the target is sufficiently smaller than the size of the laser beam at the target, the following laser radar equation is applicable(Ref.19),

$$P_R = \frac{P_T \eta_T}{4\pi R^2} \times \frac{4\pi}{\Omega_{Tbeam}} \times \rho A_{target} \times \frac{1}{4\pi R^2} \times \frac{4\pi}{\Omega_{Rbeam}} \times A_R \eta_R \quad (1)$$

where,

P_R: received signal power (watt),
P_T:transmitter power (watt),
η_T: transmission factor of the transmitter,
R: distance to debris (m),
Ω_{Tbeam}: transmit solid angle (steradian),
ρ: target reflectance,
A_{target}: backscatter cross section (m^2),
Ω_{Rbeam}: scattered solid angle of debris(steradian),
A_R: receiver aperture area (m^2), and
η_R: transmission factor of the receiver.

If the optical characteristics of the target, ρ and Ω_{Rbeam}, are reasonably assumed, the size of the target is estimated by A_{target} in Eq. 1.

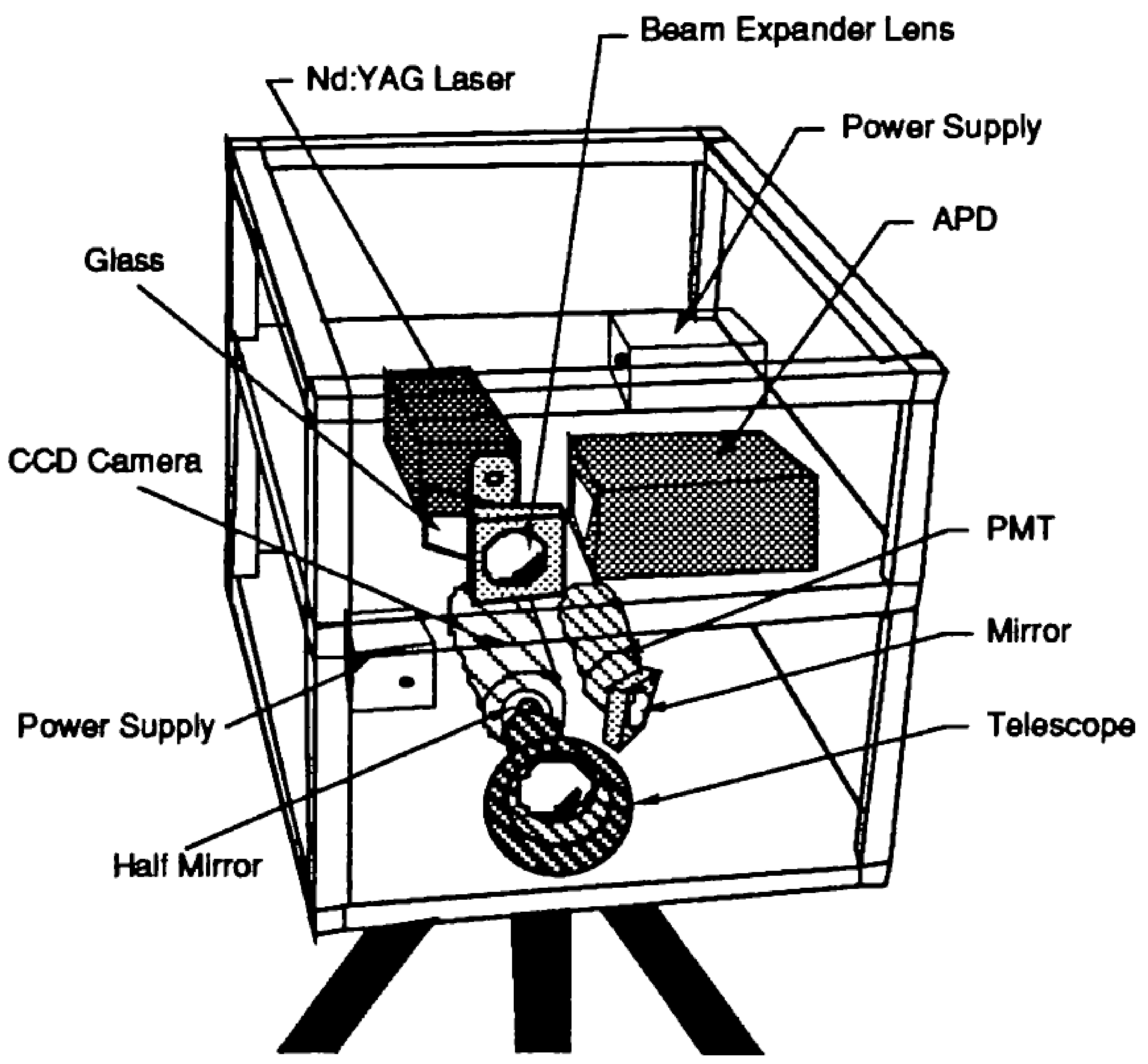

Figure 2. Configuration of the optics and sensor assembly.

3. INSTRUMENT

Fig. 2 illustrates a schematic configuration of the optics and sensor assembly of the laser radar. The weight and size are 20 kg and 300H×300V×400D mm, respectively. The optics and sensor assembly is composed of a Nd:YAG laser (model LEXY/P-G, LEONIX), a beam expander lens, an APD (model C5331-01, Hamamatsu Photonics), a telescope (Nikon), a CCD camera (model XX1560N, DHT), and a PMT (model R1398, Hamamatsu Photonics). This assembly is connected to a control and data analysis system consisting of a storage oscilloscope (model TDS310, Sony/Tektronix) and a desktop computer (model Macintosh IIci, Apple).

The laser head emits a double-pulse beam of 3 mm diameter at the wavelength 532 nm. Using a Q-switch film, a double-pulse of 12 mJ/pulse is generated. The pulse width and time interval of the double pulse are 8 ns and 0.1 sec, respectively. The average power of light is 1.5 MW per pulse. The Nd:YAG laser is operated at 1 Hz or in a single shot mode which generates one set of the double-pulse by manual switching. The beam is expanded by the beam expander lens which has a 30 mm aperture and 31.7 mm focal length. The spreading angle of the conical beam is 6.36 deg with a lens, and 3.18 deg without a lens.

The scattered light from a target is gathered by the telescope with a 58 mm aperture and 9.2 mm focal length. A compact refracting telescope of 1 kg is used for focusing the faint scattered light from small debris in a wide detectable volume. The field of view is 90 deg. The half mirror reflects 50 % of the focusing light to the CCD camera, and the other 50 % passes through towards the PMT. The camera is combined of the hybrid image intensifier using a microchannel plate (MCP) and a CCD area sensor. It has a wide aperture area with 18 mm diameter. In the optical path of the MCP, the image circle with 18 mm diameter is converted into a standard 2/3 inches(11 mm diameter) which is same size as the CCD array. The pixel format is 768(H)×493(V) and the pixel size is 11(H)×13(V) microns. The typical detection limit is 2.6×10^{-6} watt/pixel. The CCD camera with an 8 bit analog/digital converter outputs the NTSC signal at a maximum frame rate of 30 Hz. The another split faint light is detected by the PMT. The typical detection limit of the PMT with a 28 mm aperture is 1.0×10^{-13} watt.

The data obtained by the APD, the PMT, and the CCD camera are analyzed by the desktop computer.

4. LABORATORY EXPERIMENT AND RESULTS

In order to evaluate the performance of the conical-beam laser radar, several tests were performed in a radio wave un-echoic chamber of the Institute of Space and Astronautical Science (ISAS). The purpose of this experiment is to investigate the basic functions of the laser radar including, 1) acquisition of image, 2) distance(range) measurement, 3) the $1/R^4$ law in Eq. 1, and 4) size measurement. In the test, styrofoam spheres with 1, 5, 10, 20 cm diameter were used as the target.

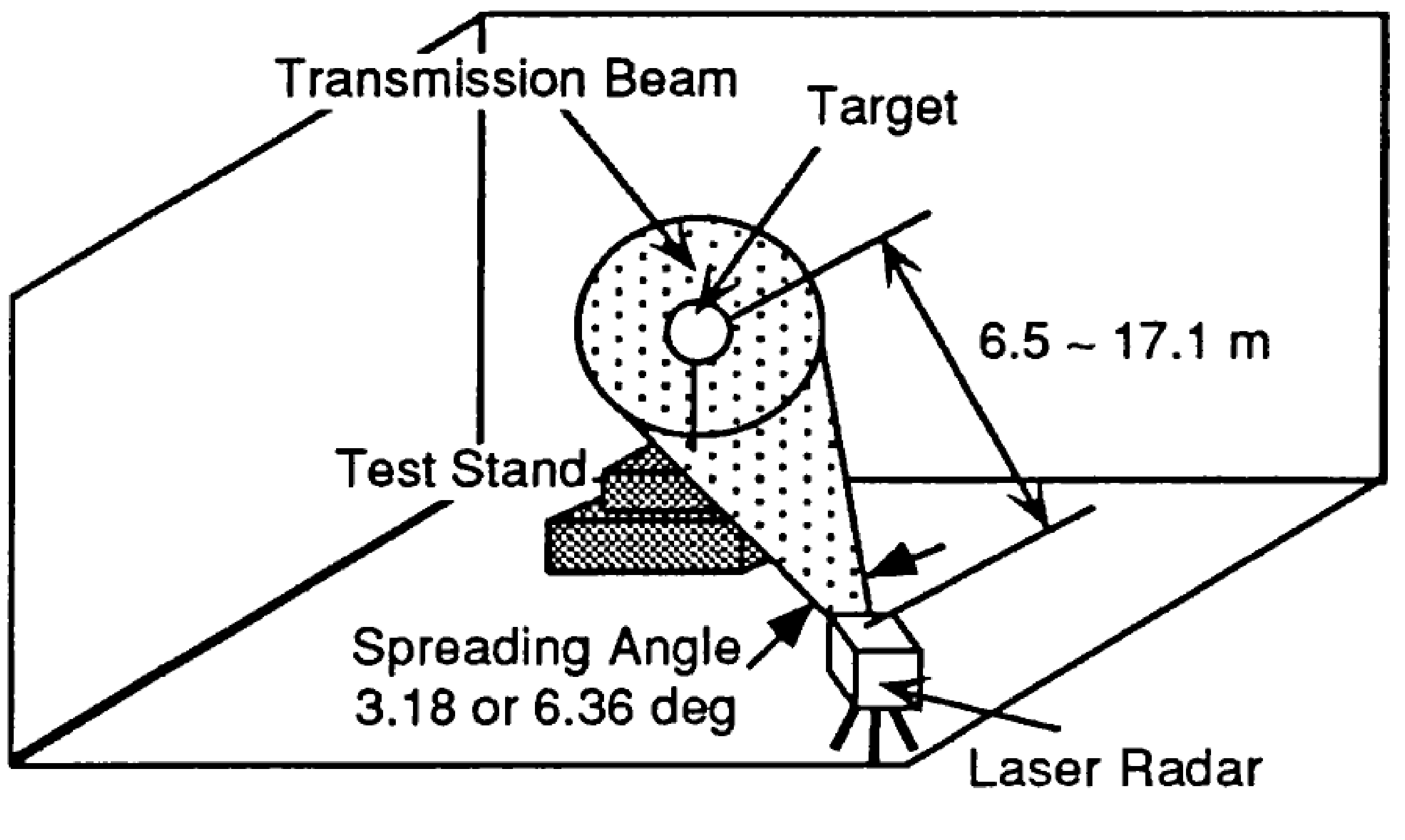

Figure 3. Experimental configuration for laboratory experiment.

Fig. 3 displays the test configuration in the chamber. The optics and sensor assembly was configured at the corner of the chamber, and the control and data analysis system was set separately in another room. The target made of styrofoam was put on the top of an aluminum pole of 1 cm diameter on the test stand. The aluminum pole was covered with a black tape to prevent light scattering. The test stand was also covered with a black cloth. The distance between the laser radar and the target was changed from 6.5 to 17.1 m. The test was carried out with two spreading angles of the conical beam, 6.36 deg and 3.18 deg.

The results in the range measurement show the dispersion was within the range error, 0.15 m, resulting from the time resolution of the time counter. The range accuracy of the laser radar is higher than that of general incoherent laser radar, typically ±2 m(Ref.19). The received power of the PMT is in inverse proportion to R^4. This result proves that the laser radar system is controlled by the laser radar equation, Eq. 1.

Size measurement was conducted using several sizes of the target. Fig. 4 shows the measured diameter at 17.1 m on condition that the spreading angle of the conical beam was 3.18 deg or 6.36 deg. The diameter D of the target was obtained from $A_{target} = \pi D^2/4$ in Eq. 1. The parameters ρ and Ω_{Rbeam} were measured through calibration test. The size of the target was determined with an accuracy of 20 %.

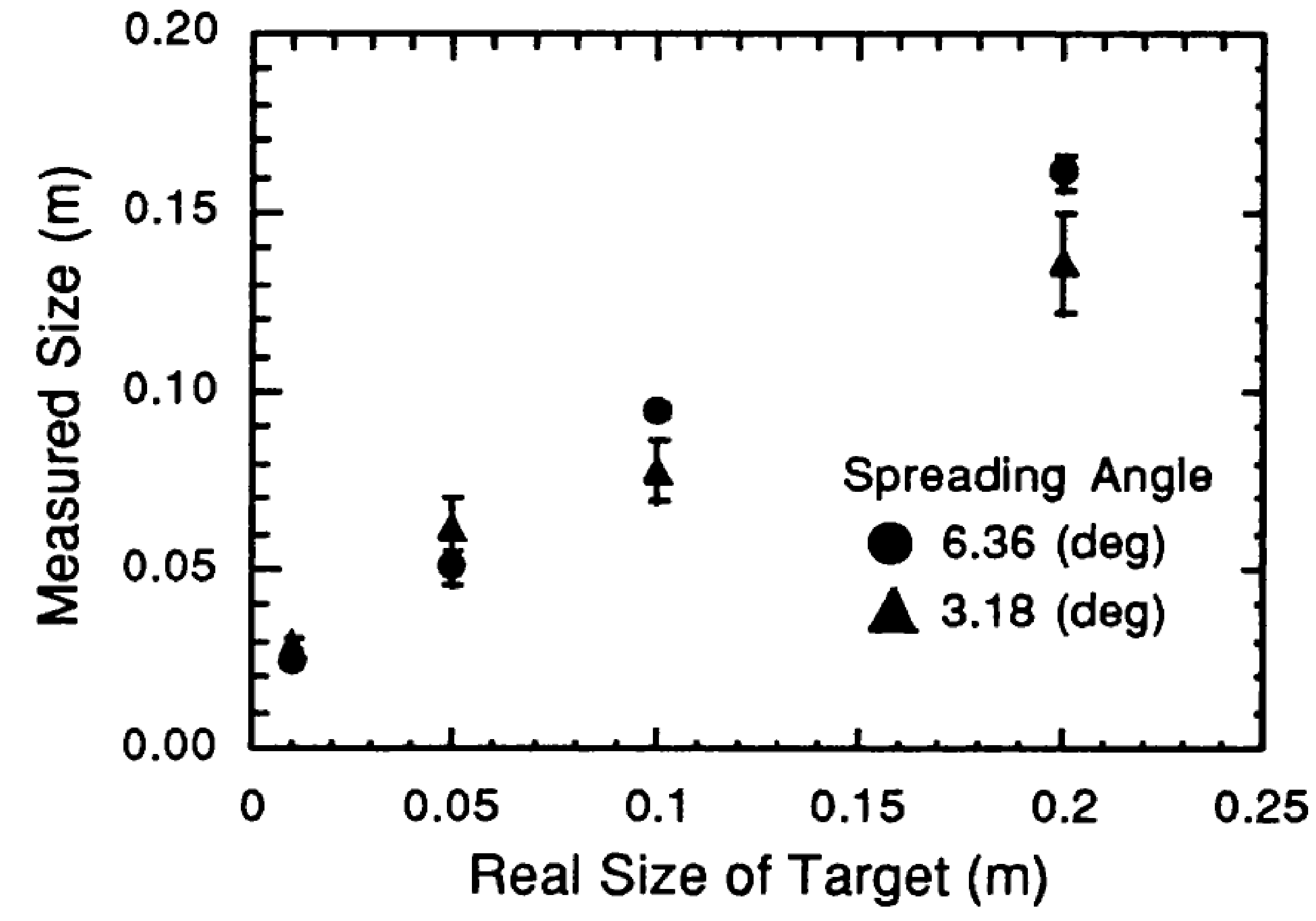

Figure 4. Diameter measured by the laser radar.

5. CONCLUSION

This research is aimed to evaluate the laser radar as an active measurement system for a small particle by laboratory experiment. For this, a laser radar consisting of a giant-pulse laser, and associated optics and sensors has been developed and tested. The laboratory model has the capability of size and velocity measurement of a target, as well as the ranging capability. The major results obtained in the laboratory experiment are; 1) the ranging capability with an expected accuracy was achieved, 2) the system performance was found to follow the laser radar equation, and 3) the size of the target was correctly estimated based on the laser radar equation. These results demonstrate that the laser radar system is a feasible technology for detection of small particles in space. Further study will be required to apply this system for detection of a moving particle.

6. ACKNOWLEDGMENTS

This work was supported by the fund for basic experiments oriented to space station utilization of ISAS. The authors are grateful to Mr. Y. Kamata and Mr. Y. Watanabe of ISAS, Mr. Y. Kanai and Mr. T. Tsunoda of LEONIX Corp., Mr. K. Kanai and Mr. T. Fujita of Tokai University for laboratory experiment.

7. REFERENCES

1. Michael Zolensky et al., Meteoroid and Orbital Debris Record of the Long Duration Exposure Facility's Frame, *Journal of Spacecraft and Rockets*, Vol.28, No.2, 204-209, 1991.
2. E. Grun et al., Reduction of Galileo and Ulysses Dust Data, Planetary and Space Science, Vol.43, No.8, 941-951, 1995.
3. Sherman L. Neste, In Situ Orbital Debris Experiment Concepts, *NASA Conference Publication 2360*, 134-149, 1982.
4. J. Bendisch et al., Detection of Space Debris by the Use of Space Based Optical Sensors, *Proc. of the First European Conference on Space Debris*, Darmstadt, Germany, ESA-SD-01, 91-97, April 5-7, 1993.
5. G. D. Arndt et al., Signal Processing Requirements for a Space-borne Radar for Detecting Orbital Debris, *Space Instrumentation and Dual-Use Technologies, Proc. of SPIE*, Vol.2214, 102-110, 1994.
6. David A. Freiwald and Joyce Freiwald, Range-gated Laser and ICCD Camera System for On-orbit Detection of Small Space Debris, *Space Instrumentation and Dual-Use Technologies, Proc. of SPIE*, Vol.2214, 116-123, 1994.
7. Susumu Sasaki et al., Particulates Measurement by Laser Radar in Space, *Advances in the Astronautical Sciences*, AAS 91-635, Vol.77, 263-271, 1992.
8. C. A. Northend et al., Laser Radar(Lidar) for Meteorological Observations, *Review of Scientific Instruments*, Vol.37, No.4, 393-400, 1966.
9. P. H. Anderson et al., 2A10-Laser Experiments for Determining Satellite Orbits, *IEEE Journal of Quantum Electronics*, Vol.QE-2, No.8, 215-219, 1966.
10. R. T. H. Collis et al., Lidar in Space, *Optical Engineering*, Vol.17, No.1, 23-29, 1978.
11. Robert J. Curran, NASA's Plans to Observe the Earth's Atmosphere with Lidar, *IEEE Transactions on Geoscience and Remote Sensing*, Vol.27, No.2, 154-163, 1989.
12. Lt. Col. P. L. Rustan, Clementine:Mining New Uses for SDI Technology, *Aerospace America*, 38-41, January, 1994.
13. Toshiaki Yokota et al., Laser Radar System for Space Debris Measurement, *Proc. of 18th International Symposium on Space Technology and Science*, Kagoshima, Japan, 2377-2382, 1992.
14. Toshiaki Yokota et al., Consideration of Laser Radar System for Space Debris Measurement, *19th International Symposium on Space Technology and Science*, ISTS 94-n-08, Yokohama, Japan, 1994.
15. Makoto Tanaka et al., Study of Laser Radar for Space Debris Measurement, *19th International Symposium on Space Technology and Science*, ISTS 94-n-30p, Yokohama, Japan, 1994.
16. Makoto Tanaka et al., Laser Radar for Space-Debris Measurement, *46th Congress of IAF*, IAA-95-IAA.6.3.07, Oslo, Norway, 1995.
17. Tadashi Takano et al., System Investigation of a Laser Radar for Space-Debris Detection, *Advances in the Astronautical Sciences*, AAS 95-651, Vol.91, 1045-1052, 1995.
18. Toshiaki Yokota et al., Result of Engineering Model of Laser Radar System for Detection of Space Debris, *Proc. of 20th International Symposium on Space Technology and Science*, ISTS 96-m-22p, Gifu, Japan, 1996.
19. Albert V. Jelalian, *Laser Radar Systems*, 1st ed., Artech House, Norwood, 1992.