PARTICULATES MEASUREMENT BY LASER RADAR IN SPACE

Susumu Sasaki*, Tosiaki Yokota† and Masahiro Ohta‡

Laser radar is considered to be one of the potential technologies for active probing of the particulates in space. A compact laser radar to measure the particulate environment surrounding a spacecraft is studied. A solid state laser is operated in pulse mode, generating an expanded beam in a cone angle of 90 degrees. The photons reflected from a particulate in the laser beam are detected by a photomultiplier and a high-sensitivity solid state area sensor. The reflection is due to either Rayleigh(λ>D), Mie($\lambda \approx$D), or Optical scattering (λ<D), where λ and D are the wavelength of the laser and the diameter of the particulate, respectively. The distance of the particulate from the laser radar is measured by time delay. The location is determined by the position of the array element which detects the reflected photons. The size of the particulate can be estimated from the intensity of the reflected light, by assuming the surface reflectivity and shape of the particulate. With a 10 mJ, 10 ns laser (1 MW), particulates of 1 mm size at 240 m from the laser radar will be detectable by the photomultiplier. The total weight of this system is estimated as 100 kg. The required electric power will be 200 Watts on average.

* The Institute of Space and Astronautical Science, 3-1-1 Yoshinodai, Sagamihara 229, Japan.

† Ehime University, 3 Bunkyou-cho, Matsuyama 790, Japan.

‡ Tokyo Metropolitan University, 1-1 Minami-ohsawa, Hachiouji 192-03, Japan.

INTRODUCTION

Space environment components, such as gas, plasma, electromagnetism, and radiation, have been extensively measured and are more or less modeled today. These models are taken into consideration in designing spacecraft and onboard instruments. They are also used to evaluate the effects on human activities in space. However, the space environment of particulates, including meteoroids and space debris, has not been measured in a systematic manner. Space scientists do not have a well-established model for space particulates.

Knowledge of the particulates in orbit is important to evaluate the degradation of spacecraft surfaces and onboard instruments exposed in space. The existence of the particulates may also endanger human activities in space. The number density of space particulates inevitably increases with human space activities. On the other hand, space activities will be hampered if the population of particulates exceeds a critical value[1].

Many space researchers have been pointing out the potential hazard of space particulates to all human activities in space. They wish to take early measures to reduce the growth of the particulate population, by regulating human space activities. However, their warning has not seriously been considered by the international space societies nor major space agencies. One of the reasons for that is a high degree of uncertainty existing in the knowledge of the actual environment of space particulates. Evolution analysis and risk evaluation are not possible without a reliable particulate model. The immediate need is to get reliable data on what is the exact particulate population now and what are the on-going trends in the short and long term.

In the future, artificial removal of space particulates could eventually be necessary. Collection of particulates and change of their orbits to lower altitudes are examples of artificial removal. Any method of removing space particulates will require their detection as the first technology.

PARTICULATE DETECTION

It is impossible to detect an object of less than 10 mm in LEO from the ground radar or optical observations using existing technologies. The population of particulates less than 10mm has been estimated by investigating the surface of retrieved spacecraft. SOLAR MAX and LDEF[2] provided valuable information on space particulates. However, inspection of the retrieved spacecraft is a passive measurement of the integrated number of particulate impacts. Several assumptions must be made in order to estimate the particulate population from such inspection, and as a result, the derived model inevitably includes a high degree of uncertainty.

In-situ measurement of particulates will provide much more reliable information on the particulate environment. There are several means of in-situ measurement proposed to detect the space particulates, such as an RF radar, an elecrostatic dust detector, and a laser radar. Among them, the laser rader is most promising from a stand point of its fine detectability. The RF radar cannot detect objects much smaller than the RF wavelength. The elecrostatic dust detector sensing the impact to a target can detect only the particulates coming into the instrument. On the other hand, the laser radar is able to detect particulates with a size comparable to the laser wavelength in a wide region, depending upon the laser power.

LASER RADAR

A laser radar consists of a laser and a photon detector. Some of the photons ejected in a pulse from the laser are reflected by a particulate back to the photon detector. The number of reflected photons is dependent on the size, reflectivity, and distance of the particulate. The propagation time of the reflected photons is directly related to the distance between the laser radar and the particulate. The technologies associated with laser radar are well established today in the field of atmospheric research on the ground.

There are three types of laser emission; a pencil beam, a fan beam and a conical beam. The pencil beam with the least expansion can detect particulates at the longest range; the reflected laser intensity is proportional to $(\text{range})^{-2}$. The fan beam can detect the particulates in the widest area; the reflected laser intensity is dependent on $(\text{range})^{-3}$. The conical beam detects the particulates in the largest volume near the spacecraft; the reflected intensity rapidly decreases with the range, proportional to $(\text{range})^{-4}$. The conical beam, although the range capability is shortest, is most effective to measure the population of particulates in a volume.

The system block diagram of the laser rader considered here is shown in Fig.1. A pulsed Nd:YAG laser pumped by laser diodes is selected judging from its high pulse intensity, power efficiency, compactness, and life. The same type of laser is to be used in the LITE(Lidar In-space Technology Experiment) on the Space Shuttle. A 10 mJ and 10ns laser with 0.53μm wavelengths(second harmonic) operated at 10 pps will be available for the space use. It injects

2.7×10^{16} photons per pulse. The laser beam is expanded to a conical beam with a cone angle of 90 deg(full angle). The power density in space is 1.5×10^{15} watt/rad with 90% transmission laser optics. The detector will consist of a light collector using ultra low expansion glass, 50 cm diameter optics, with a filter, a photomultiplier and a high-sensitivity solid state area sensor. The photomultiplier detects even faint reflection from a small or distant particulate, while the area sensor provides the direction of the particulate if a sufficient number of photons are received. The detection limit of a conventional photomultiplier is 10^{-13}watt. Both sensors will be refrigerated by electric cooling to decrease the dark current. The S/N ratio is increased by the optical filter and a pulse correlation process.

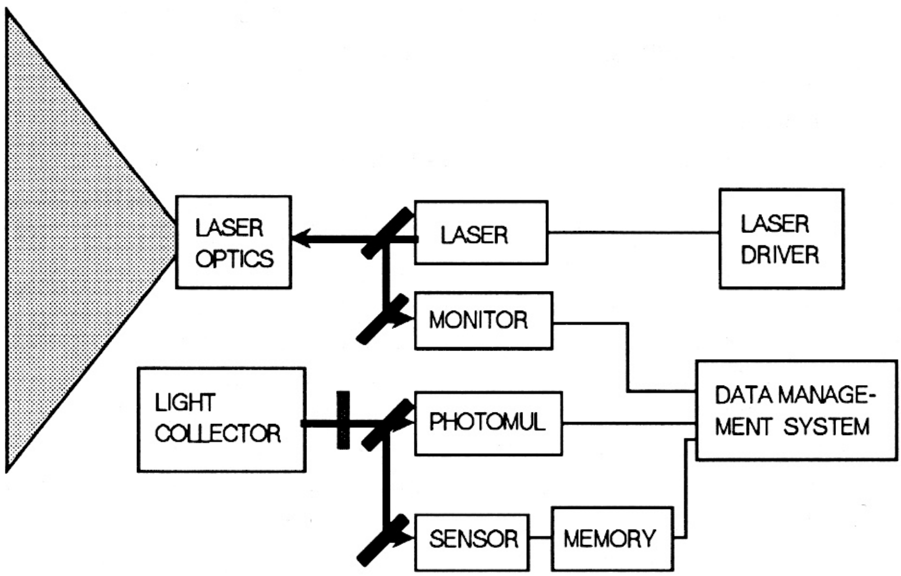

Fig.1 System Block Diagram of Laser Radar

The detectability of the particulates is determined by the laser power, the laser optics, the cone angle of the laser beam, the size of the light collector, the receiver optics, the sensitivity of the detector, and the light intensity of the background star field. The limit of the range is expressed as:

$$Zc=3.54\times10^{-5}\left(\frac{TiTrPopd^2D^2}{Pc(1-\cos(\theta/2))}\right)^{0.25}$$

where Zc: maximum range(m)
Po: laser power(watt)
Ti: transmission of laser optics
Tr: transmission of receiver
ρ: reflectivity of particulate
d: diameter of particulate(μm)
D: diameter of light collector(cm)
Pc: sensitivity limit of detector(watt)
θ: cone angle of laser light(deg)

The calculated limiting range versus the diameter of particulate is shown in Fig.2, in which ρ, Ti, and Tr are assumed to be 0.1, 0.9, and 0.27, respectively. In the calculation, the background field noise is neglected.

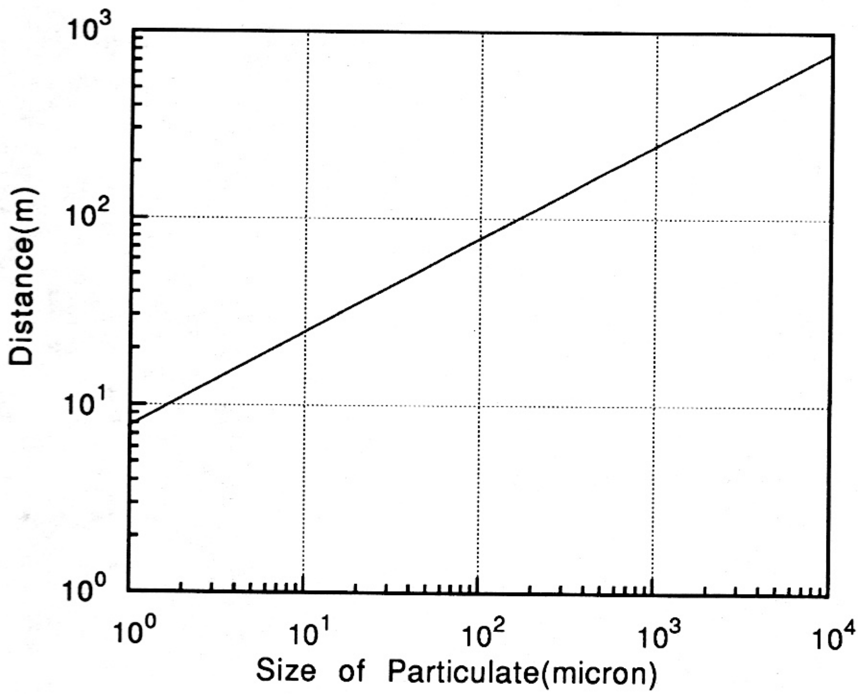

Fig.2 Detectable Range versus Diameter of Particulate

The detectable volume per shot V(m^3) is:

$$V=\frac{2\pi Zc^3(1-\cos(\theta/2))}{3}$$

Then, the number of the particulates to be detected per day is:

C(counts/day) = 8.64×10^4VNF
where N:density of particulates(/m^3)
F:laser pulse repetition rate(Hz)

The frequency of particulate detection in LEO per day is shown in Fig.3, estimated from the existing particulate model[3]. In the calculation, a relative velocity of 10 km/sec is assumed for the particulates. About 750 events on average will be detected per day for the particulates larger than 1μm. This means 1 event is recorded every 2 minutes on average.

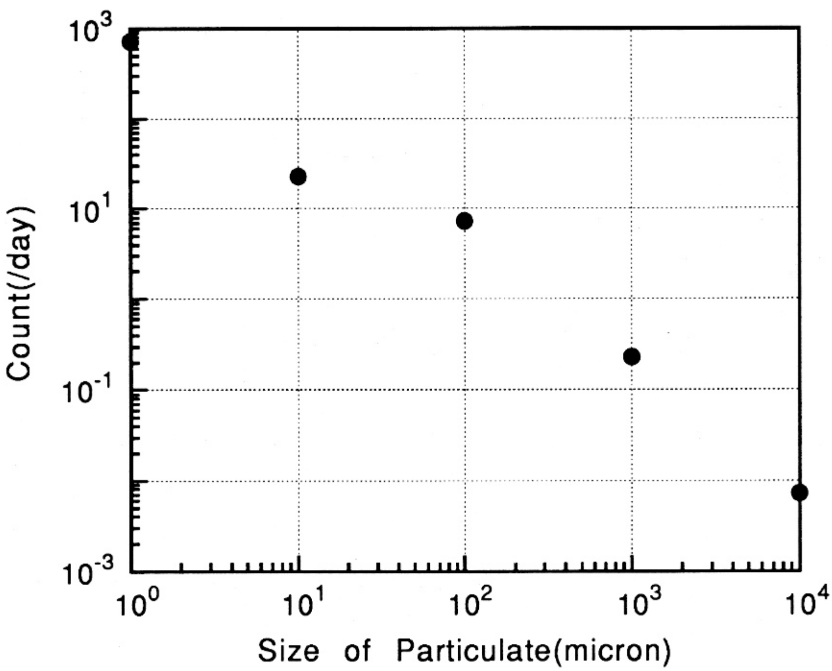

Fig.3 Frequency of Particulate Detection

Table 1 shows the detection capability of the laser radar, compared with the equivalent area of a witness plate. The detection capability of the laser radar is much superior to the witness plate, especially for the larger particulates.

Table 1
DETECTION CAPABILITY OF LASER RADAR

Diameter of Particulates	Equivalent Witness Plate Area
1μm	$0.3m^2$
10μm	$8m^2$
100μm	$260m^2$
1,000μm	$8,400m^2$
10,000μm	$260,000m^2$

The area sensor will have a sensitivity of 10^{-8} watt at 10^8 Hz. The detection range is 14 m for 1 mm diameter particulate. With the information of the direction of the particulate from the area sensor, the position of the particulate can be determined. This system will detect particulates released from the spacecraft surface, caused by an impact of a space particulate on the surface, or by spacecraft activities. The particulates generated at the surface of the spacecraft will have a low relative velocity, less than 1000 m/sec. The location of the particulate detected in the subsequent images every 100 msec enable us to determine the velocity vector of the particulate and to identify their source on the spacecraft.

The data management system will have a high-speed transient recorder and a data analysis processor. The signals from the photomultiplier are filtered and recorded by the transient recorder, and then transferred to the analysis processor. The processor outputs the pulse height and delay time for each event.

The area sensor integrates incident photons during 1 ms after each laser pulse and transfers the image data to a frame memory. The image data is compared with that obtained just before the laser shot in the processor and the difference is detected. The processor outputs the address number of the sensor element which receives the photons beyond a threshold level after the laser pulse.

The weight breakdown of the laser radar system is shown in Table 2. The total weight is 100 kg.

Table 2
WEIGHT OF LASER RADAR SUBSYSTEM

Subsystem	Weight(kg)
Laser, Laser Optics, and Driver	70
Light Collecting Mirror	10
Receiver Optics and Detector	15
Control and Data Management	5
Total	100

The dimension of the instrument is typically 500 x 500 x 500 mm. The power required for the system is 200 Watts. The data rate will be 10kbps. The life is estimated as 2 years, and is limited by the laser pumping system. The system specification of this laser radar is summarized in Table 3. Since this system requires moderate resources, it could be installed on many large satellites which have their own missions. It would be most effective if we could put 5 small satellites dedicated to particulate observation into orbits at 500, 1,000, 5,000, 10,000 and 50,000 km. This scheme will provide a complete data set of the space particulate environment.

Table 3
SPECIFICATION OF LASER RADAR

Laser	Nd:YAG Pumped by Laser Diodes, 0.53μm
Laser Power	10mJ/10ns, 10Hz
Laser Beam	Conical Beam with a 90 Degree Cone Angle
Light Collecting Mirror	ULE Glass, 500mm Diameter
Detector	Photomultiplier, Area Sensor
Total Weight	100 kg
Volume	500 x 500 x 500 mm
Power	200 Watts
Data Rate	10 kbps

CONCLUSION

A compact laser radar for space use is proposed to measure the particulate environment. The system consists of a solid state laser and photon detectors, both of which technologies are now well-established on the ground. Based on the current model for the particulate environment in low earth orbit, the system will record approximately 500,000 particulates larger than 1 μm during the 2-year mission period. If we can place several satellites carrying laser radar distributed at different altitudes from low earth orbit to geosynchronous orbit, a complete data set for the particulate environment will be obtained. Based on the in-situ measurements, we could establish a model for the space particulates, and conclude what we have to do for our future in space.

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