Miniaturized laser range-finder for the volumetric characterization of underground cavities

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ABSTRACT

Laser remote sensing has proved to be a mature technique in many scientific, military, and civilian fields. In particular, laser range-finders are widely applied in non-contact measurements of distances. In the framework of the project ARCHEO, funded by the Italian Ministry for Universities and Scientific and Technological Research, we have developed GEOLIDAR, a miniaturized laser range-finder that provides useful information for archaeological excavations. More precisely, GEOLIDAR performs volumetric characterizations of underground cavities, such as buried tanks, temples, and tombs. A coring machine bores a small-diameter hole up to the cavity where GEOLIDAR is let down and executes a motor-driven three-dimensional scan. Operation and acquisition are fully controlled by a user-friendly computer interface.

Keywords: subsurface prospecting, laser range-finding, electro-optical sensors.

1. INTRODUCTION

In the framework of the development of new techniques for archaeological prospecting, MURST (Italian Ministry for Universities and Scientific and Technological Research) entrusted CORISTA (Consortium for Research on Advanced Remote Sensing Systems) with the three-year project ARCHEO (Advanced Devices and Techniques for Detection and Recovery of Archaeological Zones)[1]. ARCHEO is subdivided in three research lines:

1. development of airborne and ground GPRs (ground penetrating radars) for archaeological surveys;
2. realization of a Mobile Unit equipped with hardware and software tools for data acquisition and recording before, during and after excavations;
3. development of a knowledge-based system to assist design, execution, and maintenance of excavations in difficult conditions (e.g. urban areas).

The Mobile Unit includes five subsystems. OMERO is a software able to guide the archaeologist in the choice of the more appropriate technique in the search for buried remains. SIRIA is a system conceived for the positioning and the photographic recording of finds. GEOSCOPE consists of a coring machine and a probe: the coring machine bores the soil while recording the drilling parameters, the probe performs visual inspections and data acquisitions in the hole. GEOLIDAR – object of this paper – is a laser range-finder conceived for the volumetric characterization of buried cavities by motor driven three-dimensional scan. SIAI is a database for the cataloguing of the information acquired and processed by the other subsystems.

Various kinds of underground cavities (homes, temples, tombs, ovens, wells, tanks, and aqueducts) can be found among the buried remains. A precise determination of the dimensions of such buildings should be useful to guide possible excavations. GEOSCOPE allows one to get images and to measure the vertical dimensions with an accuracy of 0.01 m. As regards the horizontal dimensions, the ground GPR will reach an accuracy of 0.3 – 0.5 m. Consequently, an improvement in the evaluation of the horizontal dimensions should be desirable. For this reason, an optical radar[2] has been developed. This extension of GEOSCOPE has been named GEOLIDAR because the optical radar is commonly known as lidar (acronym of "light detection and ranging"). The lidar technique, being based on the time measurement of the light pulse round trip, allows one to realize a compact instrument and a low divergence radiation beam. Thanks to these characteristics, it is possible to insert the system in the drilling instead of the probe and to reference the distance measurement to a given direction: rotating the beam, a three-dimensional scan of the cavity can be obtained.

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2. OPTICAL RADAR

The optical radar is essentially composed of a transmitter and a receiver. The transmitter emits a light pulse toward the target at the distance R and the receiver observes the backscattered fraction of it. The analysis of the detected signal as a function of t, time interval between emission and detection, allows one to determine R, since the relation between t and R is given by:

$$R = \frac{c\,t}{2}, \tag{1}$$

where c is the speed of light.

If the target is Lambertian[3], contains the laser footprint and the transmitter divergence is smaller than the receiver field of view, the received power P is given by[4]:

$$P = P_0 \frac{A\,\eta_t\,\eta_r\,\rho}{\pi\,R^2} \exp(-2\,\alpha\,R), \tag{2}$$

where P_0 is the transmitted power, A is the receiver area, η_t and η_r are the transmitter and receiver efficiency, respectively, ρ is the target reflectivity, and α is the air attenuation coefficient.

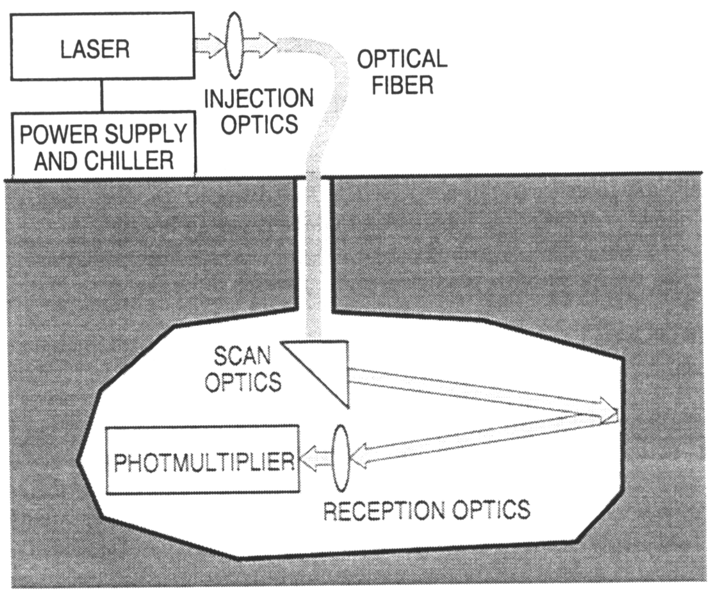

Fig. 1. Optical scheme of GEOLIDAR.

3. GEOLIDAR

3.1. DESCRIPTION

The optical scheme of GEOLIDAR is outlined in fig. 1. The laser provides the light pulse emitted by the transmitter. The radiation is conducted in the cavity through the optical fiber. This is accomplished thanks to a special optics that injects part of the light in the fiber. The transferred beam is then collimated and aimed in a well-defined direction by the scan optics. Part of the radiation backscattered by the cavity wall, after having been collected and filtered by the reception optics (interference filter), reaches the photomultiplier (PM) where it is transformed in an electronic signal. A Nd:YAG laser with frequency tripling[5] has been chosen as source emitting short pulses of ultraviolet radiation. The heart of the scan optics consists of two prisms able to rotate independently around perpendicular axes: in this way, the laser beam can be aimed in nearly all the solid angle. The rotations are performed by two stepper motors.

The electronic scheme of GEOLIDAR is shown in fig. 2. The system is computer driven through two RS232 and a GPIB interfaces: the first RS232 is for the laser and the second for the controller of the stepper motors, the GPIB is for the oscilloscope. The trigger is provided to the oscilloscope by a PM that observes a very small part of the laser pulse reflected by two uncoated optical surfaces, transferred thanks to an optical fiber and transmitted through an interference filter. The trigger and receiver PMs are identical, in order to avoid any bias in the distance measurement that could arise from a difference in rise time. The operator can adjust their responsivities through potentiometers that control the voltage of the power supplies. If necessary, a preamplifier and an amplifier can be inserted after each PM. Then, the signal undergoes analog-to-digital conversion in the oscilloscope and is transferred to the computer where it is stored. Finally, the GEOLIDAR software measures the distance and controls laser, stepper motors and oscilloscope.

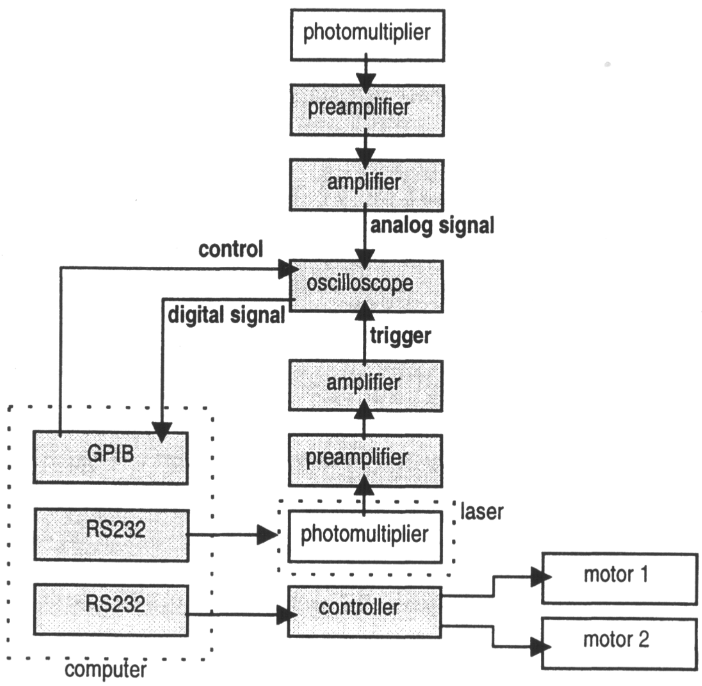

Fig. 2. Electronic scheme of GEOLIDAR. Preamplifiers and amplifiers are optional.

3.2. DESIGN CHOICES

In this section we justify briefly the design choices made during the development of GEOLIDAR.

LASER – A low power optical radar could be realized with a flash lamp. Nevertheless, due to the duration of the pulse emitted by such source (generally greater than 1 μs) the resolution of the instrument should be of the order of 100 m, undoubtedly inadequate to our purposes.

ND:YAG – The Nd:YAG laser is extremely reliable and sturdy. It provides pulses characterized by high energy (hundreds of mJ), short duration (few ns) and reasonable cost (tens of thousands dollars). Although it normally operates in the near infrared, taking advantage of nonlinear phenomena in special crystals, it can emit visible or ultraviolet radiation.

ULTRAVIOLET – The ultraviolet radiation has been chosen mostly for eye safety reasons[6]. Unlike the very dangerous infrared and visible, ultraviolet constitutes a risk to the human eye only at very high energies. GEOLIDAR, being addressed also to users not experts in laser operation, has been conceived so that its emission is lower than the maximum permissible exposure for intrabeam viewing. Two further reasons that convinced us to choose the ultraviolet radiation are the nearly absolute absence of solar background and the outstanding efficiency of PMs in this spectral region.

OPTICAL FIBER – The optical fiber has some inconveniences (problem of injecting a high-energy pulse, attenuation, and necessity of collimating the beam at its output) but offers the irreplaceable advantage of conducting the radiation in zones otherwise hardly accessible.

PRISMS – The prisms have a slightly inferior efficiency with respect to the mirrors, but allow one to make more compact and sturdy the scan optics. Such advantages have been considered decisive, bearing in mind the underground use of GEOLIDAR.

PM – The PM has been chosen because, notwithstanding the remarkable development of solid state devices, it remains the more sensitive detector of light radiation. Moreover, the chosen model is fast, sturdy, compact and user-friendly (it contains a built-in high voltage supply remotely controlled by a potentiometer).

INTERFERENCE FILTER – In case only one wavelength is used, the interference filter is the more practical, compact and inexpensive device for the selection of a spectral band.

DIGITAL OSCILLOSCOPE – It would have been possible to use an analog-to-digital conversion board with slightly lower cost but definitely worse time resolution. The board has been discarded because, as we will see, the time resolution is the dominant error source. Moreover, the oscilloscope has been very useful during the realization and test of GEOLIDAR.

3.3. ACCURACY CALCULATION

If the laser pulse is Gaussian, the accuracy in the measurement of R, distance between optical radar and target, is given by[7]:

$$\sigma_R^2 = \left(\frac{c\,\tau}{2} \frac{1.2}{SNR} \right)^2 + \left(\frac{c\,\Delta t}{2} \right)^2 , \tag{3}$$

where c is the speed of light, τ the pulse duration, SNR the signal-to-noise ratio and Δt the resolution of the device measuring t, time interval between emission and detection.

Equation (3) is obtained under the assumption that any bias in the measurement of t has been avoided (as an example of source of bias, let us consider a threshold discriminator: such device measures the occurrence of a higher pulse before that of a lower one).

As regards SNR, we can write[3]:

$$SNR = \frac{i_s}{\sqrt{i_{sn}^2 + i_{bn}^2 + i_{dn}^2 + i_{an}^2}} , \tag{4}$$

where i_s is the signal current (root mean squared) and i_{sn}, i_{bn}, i_{dn} and i_{an} are the noise currents (root mean squared) due to, respectively, signal fluctuation (shot noise), environmental radiation (background noise), dark current (PM noise) and preamplifier (amplification noise). More explicitly[4]:

$$SNR = \frac{Q\,G\,P}{\sqrt{2\,e\,B\,G^2\,(Q\,P + Q\,P_b + i_d) + B\,i_a^2}} , \tag{5}$$

$$Q = \frac{e\,\lambda\,\eta}{h\,c} , \tag{6}$$

$$P_b = A\,\eta_t\,\Delta\lambda\,H\,\Omega \left\{ \rho \exp(-\alpha\,R) + \frac{1}{4} [1 - \exp(-\alpha\,R)] \right\} \frac{1}{\pi} , \tag{7}$$

where G is the PM gain, P is the received power, e is the electron charge, B is the receiver bandwidth, i_d is the PM dark current, i_a is the preamplifier current, λ is the transmitted wavelength, η is the PM quantum efficiency, h is the Planck's constant, A is the receiver area, η_t is the transmitter efficiency, Δλ is the interference filter passband, H is the solar irradiance, Ω is the receiver solid angle, ρ is the target reflectivity, and α is the air attenuation coefficient.

parameter	value	unit
P_0	1.3×10^7	W
A	5×10^{-5}	m^2
η_t	1.6×10^{-2}	
η_r	0.4	
ρ	0.05	
α	1.2×10^{-3}	m^{-1}
R	10	m
c	3×10^8	$m\ s^{-1}$
τ	6×10^{-9}	s
Δt	10^{-9}	s
G	9×10^5	
e	1.6×10^{-19}	C
B	5×10^8	Hz
i_d	5×10^{-10}	A
i_a	8×10^{-7}	A
λ	3.6×10^{-7}	m
η	0.06	
h	6.6×10^{-34}	J s
$\Delta\lambda$	1	nm
H	0.4	$W\ m^{-2}\ nm^{-1}\ sr^{-1}$
Ω	0.3	sr
N	100	

Table 1. Values of the parameters used in the calculation of the GEOLIDAR accuracy.

Usually, the distance between optical radar and target is obtained measuring <R>, mean of R calculated averaging on N laser pulses. The corresponding accuracy is:

$$\sigma_{<R>} = \frac{\sigma_R}{\sqrt{N}}. \qquad (8)$$

Substituting in equations (2), (3), (5), (6), (7), and (8) the fundamental constants, the characteristics of the GEOLIDAR components and the typical values of other parameters, we obtain (table 1) an accuracy of 0.015 m. This value is extremely encouraging if compared with the ground GPR accuracy for the horizontal dimensions of underground cavities (0.3 – 0.5 m) and taking into account that the laser emits 100 pulses in only 10 s. The dominant source of error is the resolution of the device measuring t (digital oscilloscope). The noise comes from the signal fluctuation (about 2/3) and the optional preamplifier (about 1/3). The noise due to background and dark current is negligible.

3.4. ACCURACY MEASUREMENT

The accuracy has been measured in laboratory mounting GEOLIDAR on an optical bench (fig. 3) and aiming the beam at a target (paper sheet) at known distance (measured with a ruler having precision of 1.3 mm). After acquisition and analog-to-digital conversion, the output signals of the trigger and receiver PMs are transferred to the computer where an algorithm calculates the distance between GEOLIDAR and target.

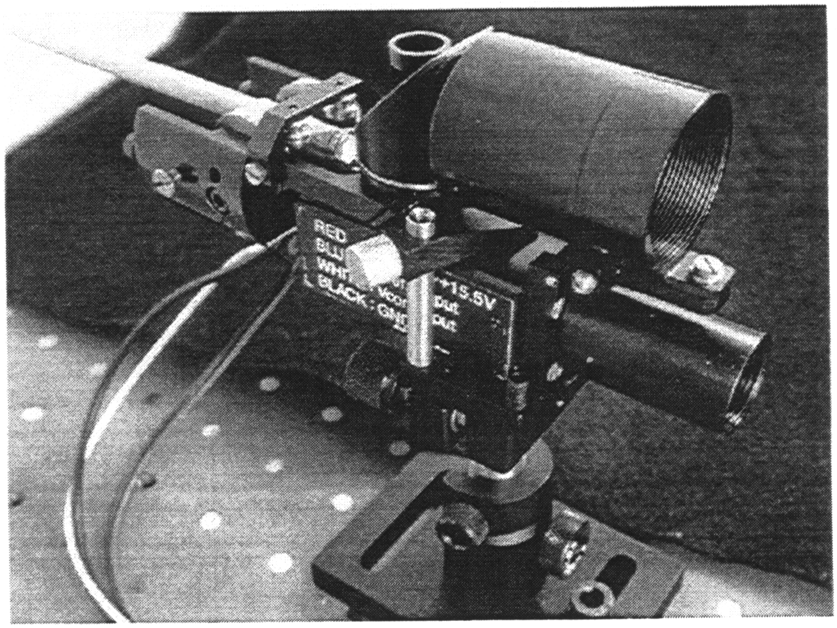

Fig. 3. Particular of GEOLIDAR. The transmitter ends with the optical fiber (grey cable on the top left), the prisms (the first under and the second in the 45°-cutted vertical cylinder) and the lens (in the big horizontal cylinder). The receiver consists of the interference filter (in the small horizontal cylinder) and of the PM (the box with inscriptions). The diameters of the big and small cylinders are 27 mm and 18 mm, respectively.

Observing the output signal of the trigger and receiver PMs, one notes that their shapes are similar for a given pulse (fig. 4), even if the pulse shape changes slightly in time. Consequently, it is necessary to find an algorithm able to determine the relative delay of the two signals from their comparison. The more refined method is the calculation of their correlation as a function of their relative delay. Unfortunately, such method is quite slow and can hardly suit a system that should take many measurements in real time. Finally, after some trials, an excellent compromise between accuracy and speed has been found. Such procedure can be schematized as follows:

1. the two signals are inverted (the output of the PMs is negative);
2. the maximum of both signals is determined;
3. the instants where each signal reaches half of its maximum are measured (the signal between two consecutive sampling points is obtained by linear interpolation);
4. the time interval between the aforementioned instants is calculated;

steps 1 – 4 are repeated for N (100, in our case) laser pulses and, at last, the computer provides the mean value.

Of course, we should subtract to such value the offset due to the dissimilar paths of the trigger and receiver signals caused by the different length of optical fibers and electronic cables. In order to solve elegantly this problem, we can determine the calibration curve of GEOLIDAR. From equation (2), we expect such curve to be a straight line with slope c/2 and intercept the aforementioned offset. Calculating the linear fit of the data[8], one obtains a result like:

$$d = mt + n \,, \tag{9}$$

where d is the correct distance and t is the measured time. The intercept is -1.860 m and the slope is, as expected, 1.500×10^8 m/s. The experimental points and the calibration curve are shown in fig. 5. As it can be noticed, the difference between points and curve is small, more precisely it is comprised between 0.02 m and 0.03 m. Such values are greater of a factor 1.5 – 2 with respect to the theoretical accuracy. This result is not surprising: the calculation did not take into account the uncertainty in the trigger instant determination that, in our case, is performed in a way similar to that of the reception instant. Anyway, the improvement of the accuracy for the horizontal dimensions of underground cavities is adequate to our purposes (more than one order of magnitude with respect to the ground GPR).

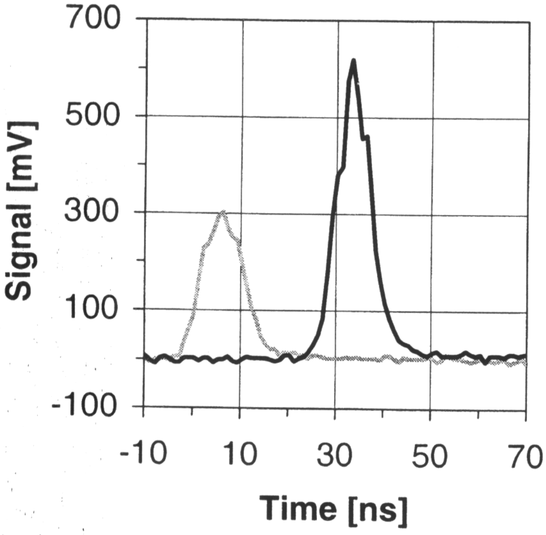

Fig. 4. Output signals of trigger (grey line) and receiver (black line) PMs afterwards the transmission of a laser pulse. Note the similitude of the two graphs.

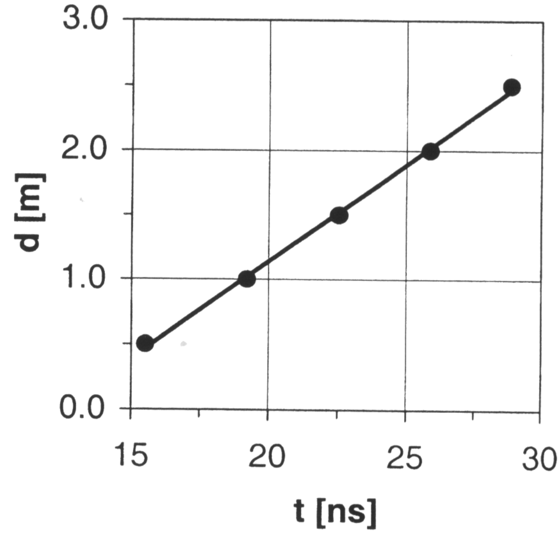

Fig. 5. Experimental points and calibration curve of GEOLIDAR.

4. CONCLUSIONS

This paper has described GEOLIDAR, an innovative range-finder developed in the framework of the research project ARCHEO, funded by MURST for the development of new techniques for archaeological prospecting. After a description of the system and of the design choices, its first measurements have been discussed. In particular, its theoretical and experimental accuracy has been carefully examined. In conclusion, GEOLIDAR provides the archaeologist with precise determinations of the size of underground cavities, particularly valuable before excavations.

In the near future, GEOLIDAR will be used in an artificial site at CIRA (Italian Aerospace Research Center), specially designed for ARCHEO, and in an important archaeological area (the ancient Roman town of Cales). In our opinion, the usefulness of GEOLIDAR is not limited to archaeology because it could find interesting applications in many other fields such as geology (territory assessment), civil engineering (structural inspection), and remote sensing in hazardous area (nuclear power plants).

5. ACKNOWLEDGEMENTS

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6. REFERENCES

1. Contratto di Ricerca 179201-1325/458, Ministero dell'Università e della Ricerca Scientifica e Tecnologica, Roma, Italy, 1996.
2. T. Bosch and M. Lescure, eds., *Selected Papers on Laser Distance Measurements*, SPIE, Bellingham, WA, 1995.
3. A. V. Jelalian, *Laser Radar Systems*, Artech House, Norwood, MA, 1992.
4. G. Mamon, D. G. Youmans, Z. G. Sztankay and C. E. Mongan, "Pulsed GaAs Laser Terrain Profiler," *Applied Optics*, Vol. 17, March 1978, pp. 205-221.
5. F. L. Pedrotti and L. S. Pedrotti, *Introduction to Optics*, Prentice Hall, Englewood Cliffs, NJ, 1993.
6. *American National Standard for the Safe Use of Lasers - ANSI Z-136.1*, ANSI, New York, NY, 1993.
7. D. C. Carmer and L. M. Peterson, "Laser Radar in Robotics," *Proceedings of the IEEE*, Vol. 84, February 1996, pp. 299-320.
8. W. H. Press, S. A. Teukolsky, W. T. Vetterling and B. P. Flannery, *Numerical Recipes in C*, Cambridge University Press, Cambridge, UK, 1994.