DEVELOPMENT OF A LASER RANGE FINDER FOR THE ANTARCTIC PLATEAU

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ABSTRACT

The development of sensing subsystems is crucial to the operation of highly autonomous robots in harsh environments. This paper will describe the methodologies used and the preliminary measurement campaigns, with the relevant results obtained, which were carried out for the realisation of a high performance laser range finder. The sensor will be installed on an autonomous rover (RAS), lodged on a specially conditioned housing in front of the vehicle allowing for the greatest visibility and optimum protection. The RAS will be used for scientific campaigns and logistic support operations specifically in Antarctica and possibly in other snowy environments. Preliminary tests have been already carried out in Glaciers and Snow fields campaigns. A problem is the very poor S/N ratio in sunlight conditions, caused by the total backscattering of clean snow surface. Additional difficulties come from the behaviour of icy surfaces and from the poor transparency of the atmosphere caused by wind-driven ice microcrystals. The technological solutions chosen to overcome these aspects will be analysed.

INTRODUCTION

The exploration of harsh environments, especially for wide area operations and measurement campaigns, is a reference field for highly autonomous robotics. The requirements of these applications lead to the development of a wide spectrum of technologies with special emphasis on the sensing subsystems, crucial point for a reliable world representation and thus for correct operation planning by the robot intelligence subsystem.

In harsh environments the availability of a sensor (intended as the total time of reliable operation) can be low and then the best solution is to achieve a good redundancy for each needed sense. Range finding is one of the crucial points for the robot operation, giving the distance and other information between the mobile platform and the other objects of the scenario and has been achieved in the RAS (Robot for Antarctica Surface) project with three separate systems: stereo vision, millimetric wave radar, laser radar. The research project, funded by the Italian Ministry of Research in the frame of the PNRA (National Program for Researches in Antarctica) is well positioned from the point of view of national and international co-operation. The activity is conducted in conjunction with CNES (Centre National d'Etudes Spatiales) and LAAS (Laboratory for Analysis and Architecture of Systems) in the frame of the CONCORDIA initiative, the Italian and French Joint venture for the realisation of an international scientific base for the development of research activities in the interior of the Antarctica continent (in the site named DOME C). In particular CNES is interested in the development of autonomous or semiautonomous vehicles for planetary exploration, similar to the recent experience of JPL (Jet Propulsion Laboratory, Pasadena) with the Rover Sojourner on Mars, and in this respect the Antarctica site offers a number of significant conditions for testing the most critical technologies. Again for space applications, ENEA (Italian National Committee for New Technology, Energy and Environment) is also exploring the possibility to coordinate a common experiment with the Italian Space Agency (ASI) and other high technology operators like Tecnomare to test on the RAS remote control techniques when long and very long communication delays occur.

RAS is a large robotics platform, built on a snowcat (Kässbohrer PB 260A, shown in picture 1) which is intended to support human operations in the Antarctic environment, ranging from the automation of measurement campaigns to carrying out potentially dangerous tasks in logistics operations, for instance reconnaissance during traverses with man-driven vehicles. An autonomous vehicle has been recognised as a great safety improvement when travelling over crevassed surfaces in order to identify the best path for other vehicles. The project is therefore aimed at the study and development of the autonomy aspects and at the capability to make decisions relevant to the specific tasks assigned to the robot (typically navigation).

To achieve these aims the robot needs to operate on a robust world representation based on complete metrology information, reliable sensing of its own dynamic and kinematic data, semantic interpretation of the detected objects surrounding the vehicle, knowledge of meteorological conditions (the latter allowing to adequately weight the reliability of data coming from the different sensors), and to have an easy and stable communications subsystem. Starting from this information, a high level, rule based control system can be realised.

Picture 1: Antarctica traverse operation of Kässbohrer - RAS motion platform

This paper aims to present the problems encountered in icy environments with a laser sensor. ENEA worked for several years on the various techniques centred on the use of laser for range measuring. The most important problem to be faced within this experience is to cope with the extreme light intensity of the Antarctic environment, partially, but not to the same extent, met also in glaciers at higher latitudes. This requirement, coupled with the need to ensure eye-safe operation, since these machines are also to operate in the presence of men, and a long-range operation (some tens of metres) represents a significant challenge for the realisation of the sensor itself. The final testing of the fully functional device is planned for the 2000-2001 winter campaign in the Arctic circle. The campaign in the final target environment, the Antarctic plateau, will be conducted one year later.

METHODS

The topological radar upon which the range finder is based is described briefly in this section together with the relevant basic theory and the environmental characteristics peculiar to its use.

Topological radar: description and theory

Here a brief description of the demonstration unit, designed and developed in our laboratory, is given. The instrument consists of an incoherent diode laser sensor, suitable to be equipped with a mechanical scanning camera. A modulated beam sounding technique is used for applications at medium or low target distances, since the heterodyne technique employing a frequency down-conversion allows an indirect measurement of the round trip time delay of the sounding beam through a measurement of the phase delay of the signal photocurrent.

The transceiving component of the unit is shown in Figure 1. The telescope and the laser semiconductor are used in a monostatic configuration. The absolute range measurement is performed by using a beam modulation technique carried out at 10 MHz frequency, so that unambiguous measurements can be obtained up to 15 m. Since the sensor should be able to operate in a wide range of environmental conditions, a minimisation of the intense background light, expected during daylight operation, is required on the receiving optics before reaching the detector. This has been obtained by introducing a very narrow bandwidth interference filter (10 Å), combined with an iris which restricts the instantaneous field of view approximately to the dimensions of the beam spot on the remote target. A portion of the modulated laser beam is reflected by a beamsplitter and two prisms on a photodiode generating a sinusoidal signal with constant amplitude and phase. This acts as a reference for the instantaneous phase measurement of the current signal coming from the detector. The sinusoidal signal generated by the beating of the reference and the signal beam, which is detected by the avalanche photodiode, has an amplitude depending on the reflectivity of the scene and a phase depending on the distance of the target (1). The sensor can be operated in combination with a mechanical scanning camera, which sounds the scene with a raster of collimated and focused modulated beam synchronised with an analogue to digital converter and acquisition system.

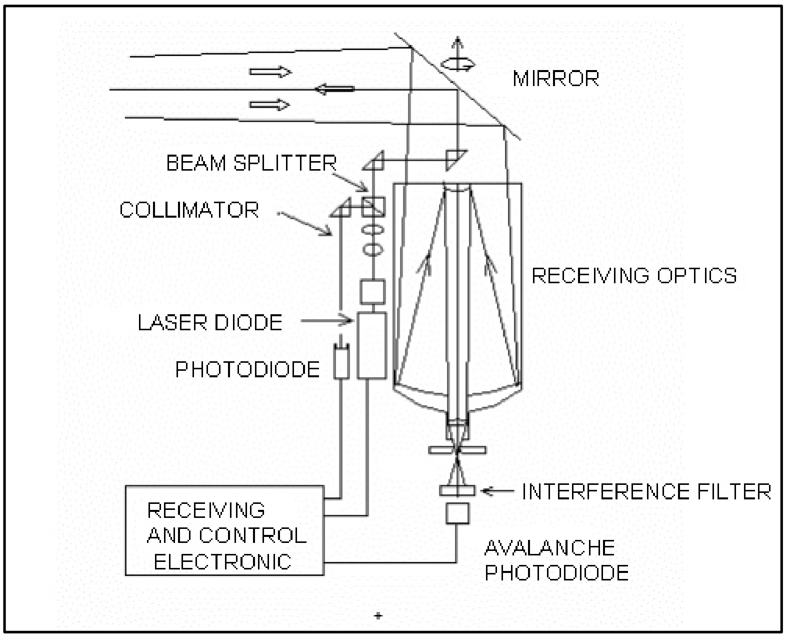


Figure 1: The laser range finder layout

An evaluation of the optical level available on the avalanche photodiode of the described transceiver can be carried out as follows: let P_L be the power of the transmitted laser beam, R the distance of the target, ρ the overall target reflectance. Neglecting the power reflected in the mirror-like mode, we obtain (refer to Table 1 below for a full parameters definition) for the optical power on the detector:

$$P_s = P_L\ r\ e\ T\,D^2\,F(q)\ e^{-2aR} / 8R^2 \qquad (1)$$

where

$$F(\,q\,) = \ g \cos q \ + j\ S\,(\,q\,) \qquad (2)$$

is the angular distribution of the backscattered signal, which adds to the cosine Lambertian distribution a retroreflective component $j\,S(q)$ weakly dependent on q when j is near to the unity. Typical practical values valid for a large variety of target surfaces are listed in Table 1.

Table 1: Typical parameters for operation of a laser range finder

Optical wavelength	λ = 670 nm

Transmitted laser power	P_L = 2 mW
Carrier modulation depth	M = 0.8
Beam modulation frequency (Hz)	$f = \omega/2\pi = 10^7$
Distance from the target	R = 1-15 m
Atmospheric absorption coefficient	α = 0.89 / km
Incidence angle of the sounding beam	$\theta = 0°$
Target average reflectivity	ρ = 35 %
Lambertian fractional power	γ = 85 %
Retroreflective fractional power	S (θ) = 15 %
Aperture of the receiving optics	D = 0.05 m
Collection efficiency of the receiver	ε = 50 %
Transmission of the interference filter	T = 60 %
Quantum efficiency of the detector	η = 80 %
Detector noise factor	Γ = 1.5
Pixel sampling time	τ =10 ms

In order to determine the spatial resolution of a modulated laser sensor, the "phase noise" of the measurement process must be accounted for. This consists of the uncertainty in the phase that originates from a temporal jitter of the signal and can be evaluated as the inverse of the product of the modulation frequency, depth of modulation m and the current signal-to-noise ratio $\mathrm{SNR_i}$ of the generated current. The phase noise Δ_R is then represented by the formula

$$D_R = c/(2mw\mathrm{SNR_i}) \tag{3}$$

Assuming the arrival of the photons on the photocathode as a Poisson random process, and taking into account only the shot noise of the signal, the current signal-to-noise ratio has the following expression:

$$\mathrm{SNR_i} = (P_s h\ t\ /hn\ G\ )^{1/2} \tag{4}$$

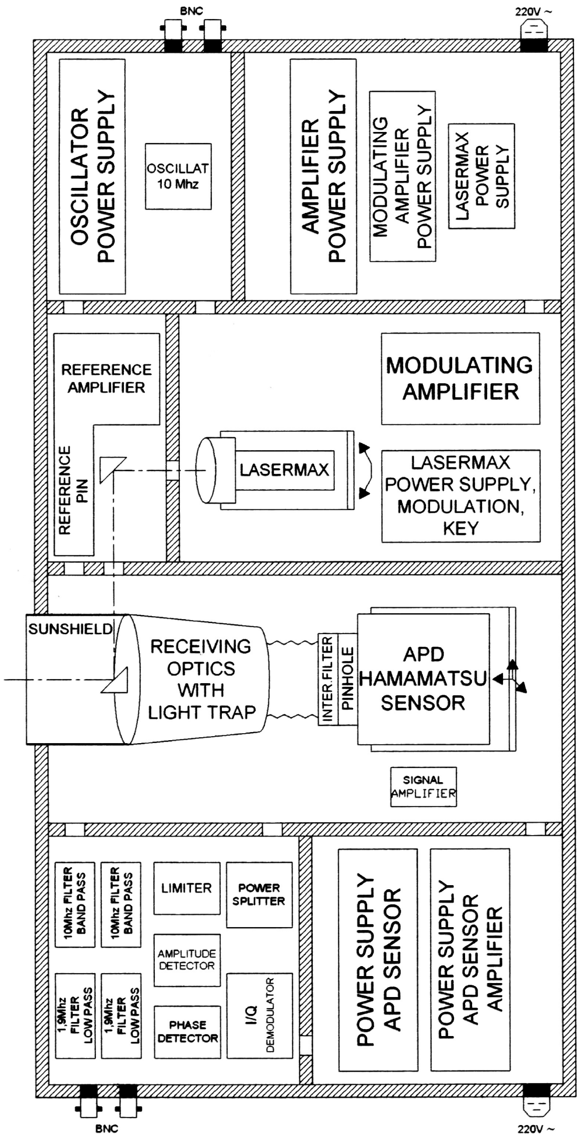
where h is Planck's constant and n is the optical frequency, $t = 1/2B$ and B is the bandwidth of the detecting electronics; h represents the quantum efficiency and G is the noise factor associated with the avalanche amplification process in the detector.

The scene background

Daylight operation of the designed scanning transceiver requires the use of several optical elements to reduce as much as possible the level of stray light reaching the detector from the scene background through the receiving optics. This is due to the scattered sunlight in the field of view (FOV) of the transceiver. The amount of spurious light can be estimated by evaluating the ratio of the sunlight transmitted by an interference filter with a wavelength bandwidth $\Delta\lambda$ and the total sunlight irradiance. Approximating the sun with a 6000°K blackbody radiator, this ratio is

$$r = F\ Dl \tag{5}$$

where F is a form factor, which can be shown equal to F= 1.16 e^{-3} at the wavelength of 6328 Å. If a multilayer interference filter with $\Delta\lambda$=10 Å is considered, and estimating in 0.13 W/cm^2 the value of the total solar irradiance on the earth (2), the expected background level in the FOV of the receiving optics is about 1.5 e^{-4} W/cm^2 during daylight experiments.



In order to avoid excessive photon noise on the received signal, the contribution of the scene background should be minimised by reducing the FOV of the receiving optics to values comparable with the spot size of the transmitted beam on the target. In this case adaptive optics (3) can be inserted to adjust the position and the diameter of the iris on the lens focus on the whole depth of field. These elements can be crucial to operate in severe stray light conditions; their proper design and test will be the object of next laboratory investigations.

The compact arrangement designed for assembling the laser range finder inside the RAS is reported in Figure 2. Two sensors will be hosted on the sides of a thermo-isolated compartment, together with a millimetric radar. For this purpose a large box was built on the front of the vehicle in place of the snowbucket (approx. 1.5 m x 0.4 m x 0.3 m) and equipped with optical benches on anti-vibrating holdings.

Figure 2: Executive schematic of a single laser range finder module for RAS

EXPERIMENTAL RESULTS

In order to match the sensor specifications for its optimised utilisation on RAS in an Antarctic environment, a series of measurements was carried out with the available modulated laser radar prototype (4), adapted to work in an external scenario under different daylight conditions. Results were compared to similar sets of laboratory measurements.

Hereafter the dc outdoor measurements (taken without any laser modulation) are reported, as they were extremely useful to understand variations of the snow reflection coefficient during whole day, with different snow density and compactness. Furthermore ac indoor measurements (taken with the laser modulation) were performed. During the laboratory experiment a strong light background was simulated by means of an external 3400°K 1000 W lamp. From ac measurements, the received power, the signal to noise ratio and the resolution in distance were estimated.

Outdoor reflectivity measurements were taken in the last year during test campaigns held at different sites characterised by the presence of snow and ice coupled to different meteorological conditions (sun irradiance, wind). Results reported here refer to Tonale glacier (Alps, June 1999), Campo Felice Snow field (Appennines, January 2000), the Arctic Base (Svalbard, March 2000) of CNR (Italian National Research Centre). Data taken on mountain places at intermediate latitudes correspond to high sun irradiance and strong variability of meteorological conditions with the sudden passage of clouds, while in the polar region a constant sun illumination was met, with dominant grazing incidence, and stable meteorological conditions. The latter situation might be quite similar to what characterises the Antarctic Plateau during the Austral summer.

In these measurements a semiconductor laser, with 2 mW power on the target and 670nm wavelength, was used in a monostatic configuration. The reflected power was collected by a BK7 lens (50 mm diameter and 200 mm focal length) and detected by an avalanche photodiode (Hamamatsu 5460, DC-10MHz); one interference filter (10 Å bandwidth) was inserted to reduce the sunlight background.

In all the field experiments the signal reflected by a white paper placed at 5 meters from the sensor was also measured, and its value was compared with signals coming from the different targets. A significant summary of data is reported in Table 2.

Field experiments led to valuable considerations relevant to the design of the final sensor for RAS, which are mostly related to background problems. Major findings can be summarised as follows:

- a cylindrical darkened tube was necessary as a sunshade screen to avoid direct sunlight,
- in most cases at intermediate latitudes it was essential to introduce two interference filters in order to reduce the strong background and avoid the detector saturation,
- the sunshine background dramatically depends on atmospheric conditions; its variations affect dramatically the measurements,
- a Lambertian behaviour of the snow was dominant for powdery and fresh snow,
- old snow, developing a compact crust, may exhibit marked specular properties.(5,6)

Table 2: Reflectance data measured with the laser range finder operated without modulation. For each signal the background is given in parenthesis.

Environmental Conditions	Sun	Clouds	Clouds
Measurement Tool	Voltmeter	Voltmeter	Voltmeter
Measurement Unit	mV	mV	mV
Measurement Ref.	Target (vs. Laser Off)	Target (vs. Laser Off)	Target (vs. Laser Off)
Target Distance	5 m	5 m	13 m
Laser Wavelength	670 nm	670 nm	670 nm
Interferential Filter	670 nm	670 nm	670 nm
White Paper	1410 (1360)	133 (81)	38 (27)
Iced Snow	817 (800)	97 (83)	36 (30)
Perpendicular Ice			37 (30)
45° Slanted Ice			34 (30)
Grazing Ice			34 (30)

In the laboratory, outdoor conditions were simulated by using a halogen lamp, and the physical parameters of the modulated laser radar could be estimated. The laser beam has been modulated up to 10 MHz by changing the bias current, with a mean power on the target equal to 2mW (as in the field experiments). The light reflected by a white paper at about 5 meters was collected by a single lens and focused on an avalanche photodiode (Hamamatsu C5460) whose characteristics were described above. The background was also measured in the laboratory configuration by using a radiometer. It was possible to adjust the operative conditions to have about 1 mW/cm^2 of background irradiance. We calculated a background value of about 9 mW in the field of view defined from the optics receiver, which corresponds to a 1.1 V to the detector output. This is a value comparable with the operative condition obtained in the outdoor measurements.

In Figs. 3-5 the theoretical values of received power, signal-to-noise ratio and resolution are shown as full blue lines for an integration time equal to 10ms. The corresponding experimental results obtained in the laboratory are reported as red diamonds on Figs. 4 and 5. Signals have been detected by using white paper targets at several distances. Data are in good agreement with calculations, showing a maximum deviation of about 15% from the theoretical curves.

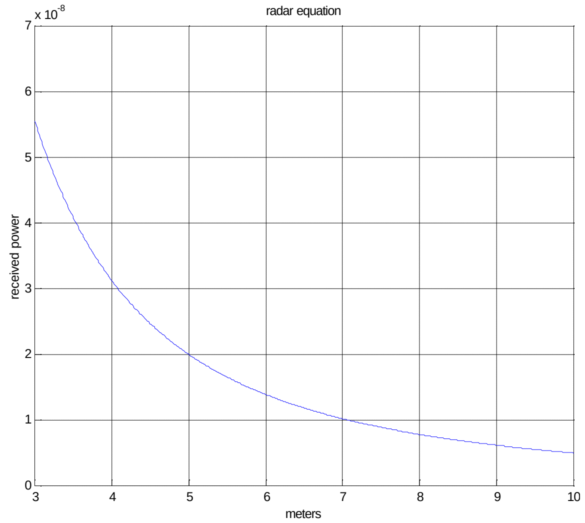


Figure 3: Values From radar equation

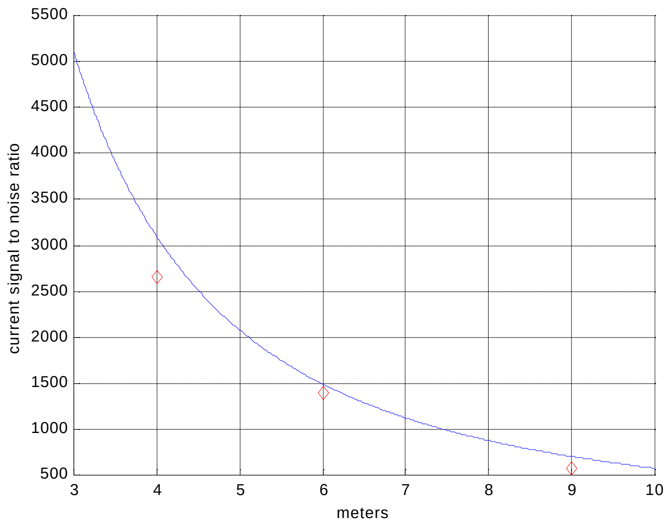


Figure 4: Current signal-to-noise-ratio

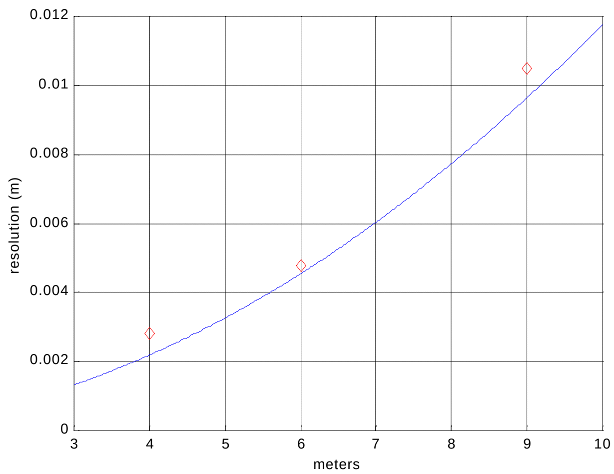
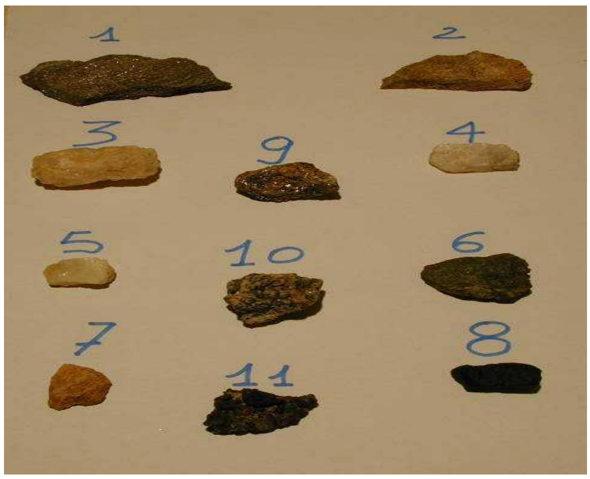


Figure 5: Resolution



Picture 2: Antarctic stones collected near BTN

In order to complete the series of tests needed for the definition of the expected sensor performance in the final real environment (Antarctic Plateau), laboratory measurements were performed on some typical Antarctic stones collected near the Italian Base of Baia Terra Nova (BTN), in an area where it is known that very old (440 - 460 million year) rocks of granitoid composition dominate. A preliminary petrographical analysis of the samples, which are shown in Picture 2, revealed the metamorphic origin of most of them. Overall information on the rock composition is given in Table 3; data relevant to sample number 1 and 10 have been confirmed by X-ray diffraction. The measured reflection coefficients for all the samples are reported in Table 4. These values, obtained at 4 m distance from the sensor for normal and 45° incidence, are compared to the reference signal from white paper. The target average reflectivity's estimated r change from 0.5 (sample number 3) to 0.075

(sample number 8). Average values obtained for all samples, except the last one which is probably a more recent lavic fragment (about 10 million year old), are rather high for granite-like rocks. This fact is related to their richness in quartz, almost pure quartz crystals (sample n. 3,4,5) showing the highest values, and to the presence of two high reflecting micas, the muscovite and the biotite, which appear as lighter and darker bright components respectively.

Table 3: Main constituents of different Antarctic stones collected nearby BTN station (January 1998).

Rock sample no.	Assignment	Average composition (remarks)
1	metamorphic metasediment	Quartz, feldspar, biotite.
2	granitoid	Muscovite, quartz, rose feldspar.
3,4,5	quartz	Pure crystals (white and rose colours).
6,9	two-micas metasediment	Biotite, muscovite (probably different contents in Iron and Calcium).
7,10	pink granite	Quarz, biotite, different feldspars, rutile (the pink colour is due to K-feldspar).
8	Black lavic stone	(porous, low specific weight).

Table 4: Reflection coefficients of samples listed in Table 3. Values refer to 90°/45° incidence. Measured background is 30 in all cases.

Target no.	reference white paper	1	2	3	4	5	6	7	8	9	10
Detector voltage (mV)	170/ 135	80/ 30	60/ 35	100/ 80	85/ 55	95/ 65	40/ 20	70/ 50	15/ 10	55/ 40	50/ 35

CONCLUSIONS

Remotely Operated Vehicles like the Antarctic RAS (Robot for Antarctic Surface) robot ask for a robust, multi-equipment sensing system. These vehicles must be able to operate in environmental conditions where one or more sensors cannot measure reliable data but some information still **must** be granted to the Supervisor to avoid the loss of the vehicle and/or the halting of the current operation, sometimes crucial.

The multisensorial equipment of RAS includes stereo camera Artificial Vision, Laser radar, millimetre waves radar, GPS (Geoplanetary Positioning System), GPR (Ground Penetrating Radar) and a suitable inertial system. Each one of these systems has been selected to be reliable in the reference environment without high costs. This research aims to demonstrate the feasibility of the laser radar in environments where the noise generated by the extremely high intensity of the reflected sunlight could heavily affect the reliability of measurements made.

The results up to now attained confirm the exploitability of this technique, the most precise available in the whole equipment, together with the mm radar device, not yet fully tested. The current obtained precision, that can be derived by Figure 5, is already satisfactory for the present application. This feature is expected to be substantially improved in the final device after optimising the optical arrangement, the signal processing electronics and algorithms. At least a resolution of 1 cm at 30 m is expected following current laboratory tests.

Aspects that need further investigations refer to the scanning speed under different light conditions. Despite the presence of the stereo cameras, in some operative conditions, a scanning system is requested also for the laser sensing equipment and the corresponding precision vs. the scanning speed in the snowy Antarctic plateau under all the different light conditions (different orientations of sensor vs. sunlight direction, foggy atmosphere, ice micro crystals under windy conditions) is important. The final equipment will be ready by the end of 2000 and the first tests on the Arctic field will be carried out at the beginning of 2001.

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