A laser range finder and reflectivity meter for the MARS-96 international space project

G.P. Arumov[1], G. B. Al´tshuler[5], V. Heikkinen[4], V. J. Khramov[5], J. Kostamovaara[2], M. Lehto[3], R. Myllylä[4], K. Määttä[2], V. A. Nekhaenko[1], A. V. Turin[1], R. Verkasalo[4]

1 Space Research Institute, Russian Academy of Science, 84/32 Profsoyuznaya St., GSP-7, Moscow 117810, Russia.

2 Electronics Laboratory, University of Oulu, SF-90570 Oulu, Finland.

3 Noptel Ltd. Teknologiantie 1, SF-90570 Oulu, Finland.

4 Technical Research Centre of Finland, P. O. Box 202, SF-90571 Oulu, Finland.

5 Institute of Fine Mechanics and Optics, 14 Sablinskaya St., St Petersburg, Russia.

ABSTRACT

A laser altimeter based on the time of flight principle has been developed to be put on board a gondola of a balloon drifting in the atmosphere of Mars. The light source is a PGT:Nd solid state laser (λ = 1.067μm) which emits pulses about 10 ns wide at a repetition rate of 0.2 Hz, the energy of each pulse being about 7.5 mJ. Special attention was paid in the development work to minimising the size, weight and power consumption of the altimeter. Thus its weight is 450 g and the average power consumptions of the electronics and laser have been reduced to about 30 mW and 0.6 - 0.8 W, respectively, by switching on the power supply to the measurement and interface part only during the 50 ms measurement period. The time interval between the transmitted and received signal is measured digitally by counting clock pulses obtained from a 100 MHz oscillator. The measurement range and single shot resolution are about 6 km and +/-1.5 m, respectively. The laser altimeter contains two peak detectors to measure the amplitudes of the transmitted and received pulses for recording of the albedo on the surface of Mars. Test results show that the altimeter is capable of operating in a temperature range of -80°C - +60°C and at an air pressure of few torr. The minimum average reflection coefficient of the Martian surface is about 0.1 which enables the measurement range of 13 km if the minimum signal to noise ratio of the measurement is about 10.

1. INTRODUCTION

An unmanned spacecraft is intended to be launched to Mars in 1996 in an international "MARS-96" project, and an aerostactic gas-filled balloon will be launched in the atmosphere of Mars from this orbiting Mars probe to drift at an estimated height of 50 m - 5 km during the daytime on Mars and descend to the surface at night. Scientific instruments will be installed in a gondola and on guide ropes hanging below the balloon.

One of the scientific instruments to be placed in the gondola is a laser altimeter designed for remote sensing of the surface of the planet.[1] This will give information on the underlying surface relief and reflectivity properties of the surface. The horizontal and vertical resolutions of the measurements at the maximum designed drifting height of 5 km are 15 m and +/-1.5 m, respectively, and the typical sensing rate will be 0.2 Hz - 0.5 Hz. The designed operating time of the balloon is about two weeks, which means that the size, weight and power consumption of the altimeter should be as small as possible.

This article describes the construction of the laser altimeter and the properties of the solid state laser, receiver optics and electronics. Measurement results relative to a calibrated target obtained with the latest laboratory models in a temperature vacuum chamber and outdoors are given.

2. CONSTRUCTION OF THE LASER ALTIMETER

2.1. Description of the construction and operation of the laser altimeter

The laser altimeter consists of a laser device and its power unit, receiver optics and measurement and interface unit (MIU) as shown in Figure 1. Its operation is based on the pulsed time-of-flight (TOF) technique, with a PGT:Nd solid state laser as the light source. The MIU is connected to the laser power unit electrically and to the laser by means of an optical fibre. The laser power unit receives its +15 V operating power from the common service system of the gondola via the MIU. A CHARGE signal from the MIU starts generation of the discharge voltage to the laser in the power unit and a TRIGGER signal shoots the laser. After a light pulse has been emitted from the laser a part of it is fed to the MIU as an optical start pulse. An optical stop pulse is obtained from the receiver optics and is also fed to the MIU by means of an optical fibre. The measurement and interface unit is connected to the electrical interface of the common service system of the gondola. This interface enables the main processor of the gondola control the operation of the laser altimeter.

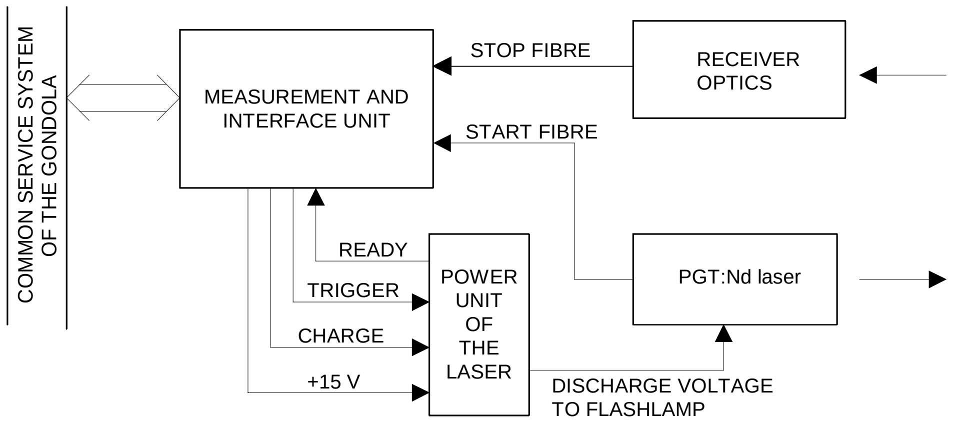

Figure 1. Block diagram of the laser altimeter

To achieve a low average power consumption, most of the power of the MIU is switched on only during the measurement period of about 50 ms. Since the total measured power consumption of the electronics is about 2.9 W, the maximum average power consumption of the altimeter is about 30 mW if the measurement rate is 0.2 Hz, as designed. Only the interface part of the electronics has its power switched on all the time. The amplitude of the start and stop signals can be measured, which gives information for calculation of the albedo on the surface of Mars.

A typical measurement sequence is shown in Figure 2. First the main processor of the gondola triggers the power unit of the laser transmitter on by means of the CHARGE pulse. The charging of the laser capacitor takes between two to five seconds, after which the laser power unit sends a READY signal to the MIU which switches on the power in the measurement unit. During the first 50 ms after power has been switched on the internal reset signal resets the time interval and amplitude measurement electronics in the MIU, after which the interface electronics generate a trigger pulse within about 2.5 s to shoot the laser. A start signal obtained from the laser activates the time interval measurement electronics and stop signal from the receiver optics stops it. A status byte is transmitted from the MIU to the main processor about 0.2 ms after the TRIGGER pulse, and this may be used to interrupt the program flow of the main processor. When the main processor of the gondola has read the measured time interval and the amplitudes of the start and stop signals, it switches off the power in the MIU. In the case of a missing stop signal an overflow signal is generated which also causes the main processor to switch off the power to the measurement part. To ensure that the power to the MIU is turned off, security hardware in the measurement unit will do this in any case 100 ms after the power has been switched on.

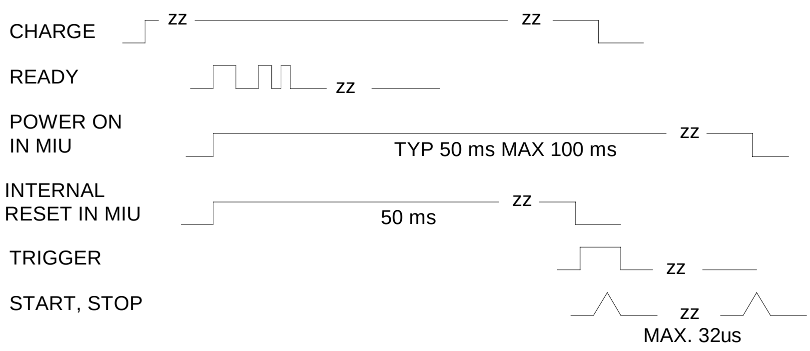

Figure 2. Measurement sequence of the laser altimeter

2.2. Construction of the laser transmitter and receiver optics

The laser of the altimeter is a solid state laser on a PGT crystal Q-switched by a dye-based saturable absorber with radiation wavelength 1.067 μm. The laser must operate under fairly severe atmosphere conditions of Mars, as the gas pressure is 2 to 3 torr and the temperature variation during a Martian day is between -100°C and +50°C. Also, the laser must be of minimal weight and its mean power consumption from the on-board source must be no more than 0.8 W with 75% efficiency of the laser power unit. The maximum pumping energy of the flashlamp at an operation frequency of 0.2 Hz is 3 J. To ensure stable operation at distances up to 5 km, the radiation energy of the laser must be about 8 - 10 mJ, its pulse width 6 - 10 ns and its divergence angle no more than 3 mrad.

To determine the operation efficiency of various laser media at low pumping levels, comparative tests were carried out on some laser emitter models with the following active media: YAG:Nd (size 3x50 mm), YSGG:Cr:Nd (size 3x50 mm), GSGG:Cr:Nd (3x50 mm) and PGT (potassium gadolinium tungstate) (3x32 and 3x50 mm). Film dye absorbers - LiF crystal-based absorbers with F2 dyeing centres and absorbers based on GSGG and YAG crystals activated by Cr and Fe - were used as saturable absorbers. The length of the resonator base was about 100 mm. The following conclusions were reached from the results of tests carried out on available specimens of active elements and saturable absorbers:

1. To obtain the generation energy needed for all active media given a saturable absorber with an initial transmission of 0.4 +/- 0.03 at the exit mirror, a reflectivity of 0.45 +/- 0.05 is required.

2. The lowest value of the threshold pumping energy was observed in the PGT:Nd-based active elements (size: 3x32 mm). The value for the other active media in our models varied within the range 2.9 to 4.2 J.

3. The width of the emitted pulse when applying GSGG and YAG-based saturable absorbers was 15 to 20 ns, and the pulse itself has a complicated structure in the time domain. Its width for dye and LiF-based saturable absorbers was observed to be 8 +/-2 ns. Since the mass and size of a dye-based saturable absorber is much smaller than that of a LiF-based one, former type was preferred.

Thus the comparative test results led to the choice of the active medium based on the PGT crystal together with a film dye-based saturable absorber.

The core element of the laser is a thin-walled quartz tube with an active element inside, as shown in Figure 3. A semitransparent mirror is attached to the quartz tube on one side and a special invar bracket on the other. The saturable absorber and a totally reflecting mirror are mounted inside the bracket. The laser is adjusted by removing material from three adjustment plates of a special supporting ring on the bracket. The quartz tube with its bracket is fixed to one part of a disconnectable dust-protecting case and the flashlamp is fixed to the other part. The diffuse reflecting coating is deposited on the inner surface of the dust-protecting case, around the flashlamp and active element. The dust-protecting case may be made of plastics or magnesium aluminium alloys to reduce the weight of the laser.

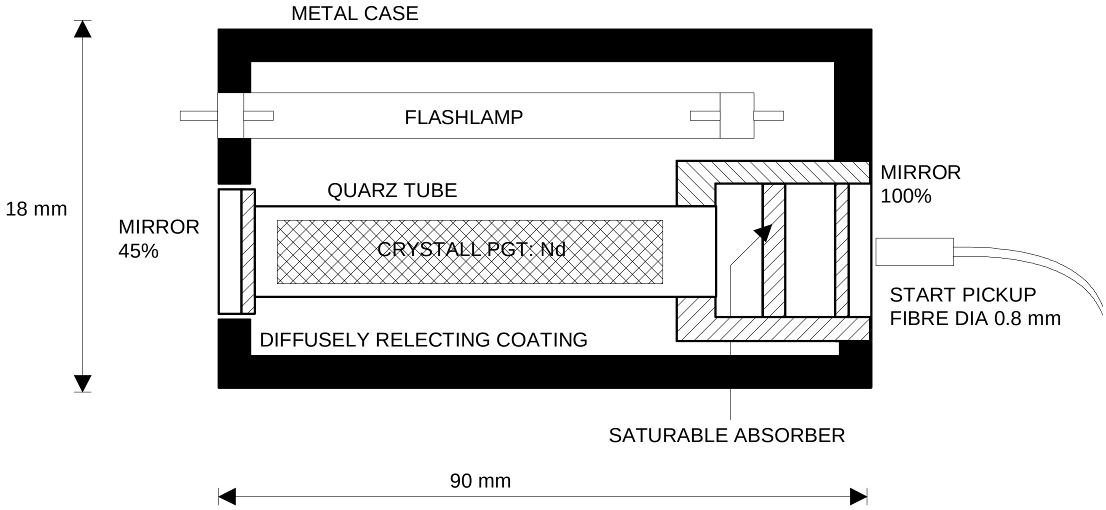

Figure 3 Schematic diagram of the PGT:Nd laser

The total masses of the prototype and its power unit are 45 g and 115 g, respectively, and the length of the laser resonator base is 80 mm. The shape of the emitted light pulse is shown in Figure 4, as measured with an optical probe and a fast digitising oscilloscope with a bandwidth of 350 MHz.

A schematic diagram of the receiver optics is presented in Figure 5. A fraction of the laser radiation reflected from the surface of Mars is collected by the optics, which are designed on the Cassegrain principle, with a spherical primary mirror and a plane secondary mirror. The filter block consists of three glass plates each having a clear aperture of 37.5 mm and a thickness of 2 mm. The first filter is made of infra-red glass and has a wide pass band, while the second and third glass plates form an interference filter which has a bandwidth of 12.8 nm (FWHM). The filter block has a total transmittance of 54.6 % at a wavelength of 1.067 µm.

Figure 4 Shape of the laser pulse in the time domain

The main mirror which reflects the incoming radiation to the back surface of the filter block, is spherical and has a radius of curvature of 160 mm and diameter of the clear aperture of 37.5 mm. The back surface has a dielectric reflective coating with a diameter of 13.5 mm. Finally the radiation is focused to the end of a polyimide-coated optical fibre with a pure fused silica core and doped fused silica cladding placed at the focal point of the optics. The core and cladding diameters of the fibre are 800 µm and 880 µm, respectively, and its numerical aperture is 0.22.

Calculations show the angular field of view of the optics to be 10 mrad, which is about three times larger than the divergence of the laser. This ensures that the receiver is able to see the laser spot on the surface of Mars even though there may be some misalignment between the optical axis of the laser and the receiver optics. The total effective area of the optics is 9.6 cm^2.

2.3. Construction of the measurement and interface unit

The measurement and interface unit of the laser altimeter consists of a power supply, interface part and measurement part. The power supply possesses current limiters, power switches and a -5 V voltage regulator. Input voltages are +5 V, -15 V to the measurement and interface unit and +15 V to the laser power unit, and output voltages +/-5 V and +/-15 V. The +5 V supply has a current limit of 200 mA, and the -15 V supply a current limit of about 150 mA. The +15 V power supply is protected with a fuse.

The interface part is based on an industry standard UART circuit which communicates with the main processor via a serial interface at bit rates up to 9600 bps. It decodes commands from the main processor of the gondola and executes them, controls the timing of the measurement cycle and reads the distance measurement results and status from the measurement part.

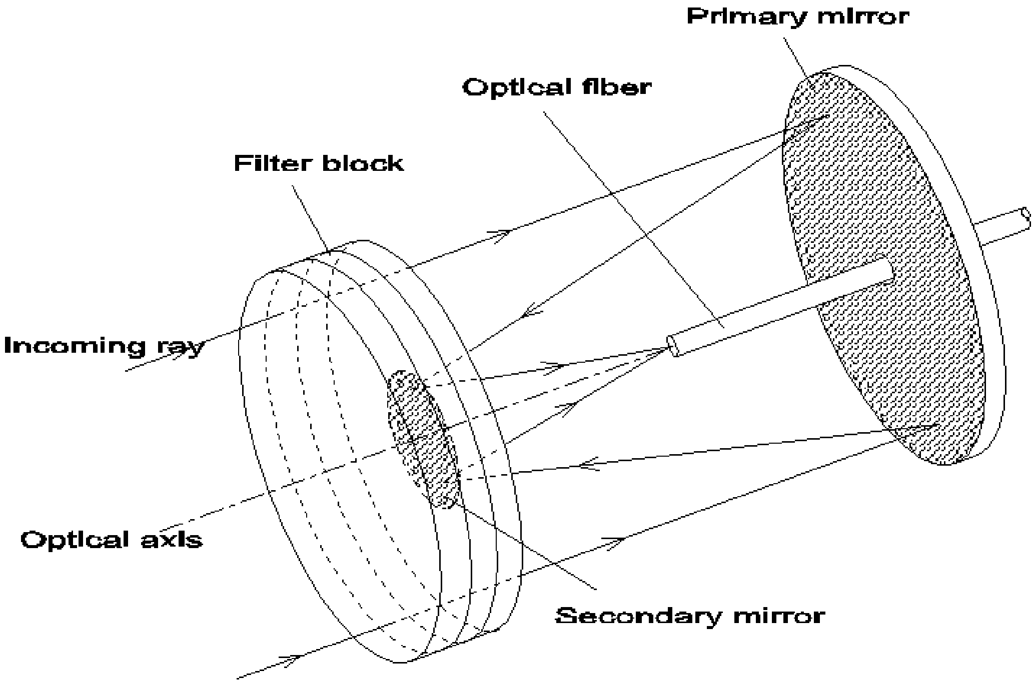

Figure. 5 Construction of the receiver optics of the laser altimeter

The measurement part, Figure 6, consists of separate start and stop channels for timing pulses, two peak detectors and time interval measurement electronics One of the main goals when designing and constructing the measurement unit was to minimise the power consumption.

The start channel consists of a pigtailed PIN photodiode and a fast comparator with a constant level threshold. The start fibre is a step index glass fibre about 20 cm long. The peak detector measures the amplitude of start signal. The stop channel consists of a pigtailed AP photodiode, a transimpedance preamplifier, three postamplifiers, a peak detector and a comparator. The bias voltage of the AP photodiode is controlled with respect to changes in ambient temperature so that the gain of the diode remains constant over the whole temperature range. The transimpedance of the preamplifier is 3 kΩ, the bandwidth about 30 MHz and the noise level of the electronics at the input of the preamplifier about $4\ \mathrm{pA}/\sqrt{\mathrm{Hz}}$. The amplification of each of the three postamplifiers can be set to two values. Minimum gain of the channel is 1.5 and the maximum about 90. The gain is controlled electrically by increasing the amplification of the stop channel with respect to time from the start pulse according to Table 1.

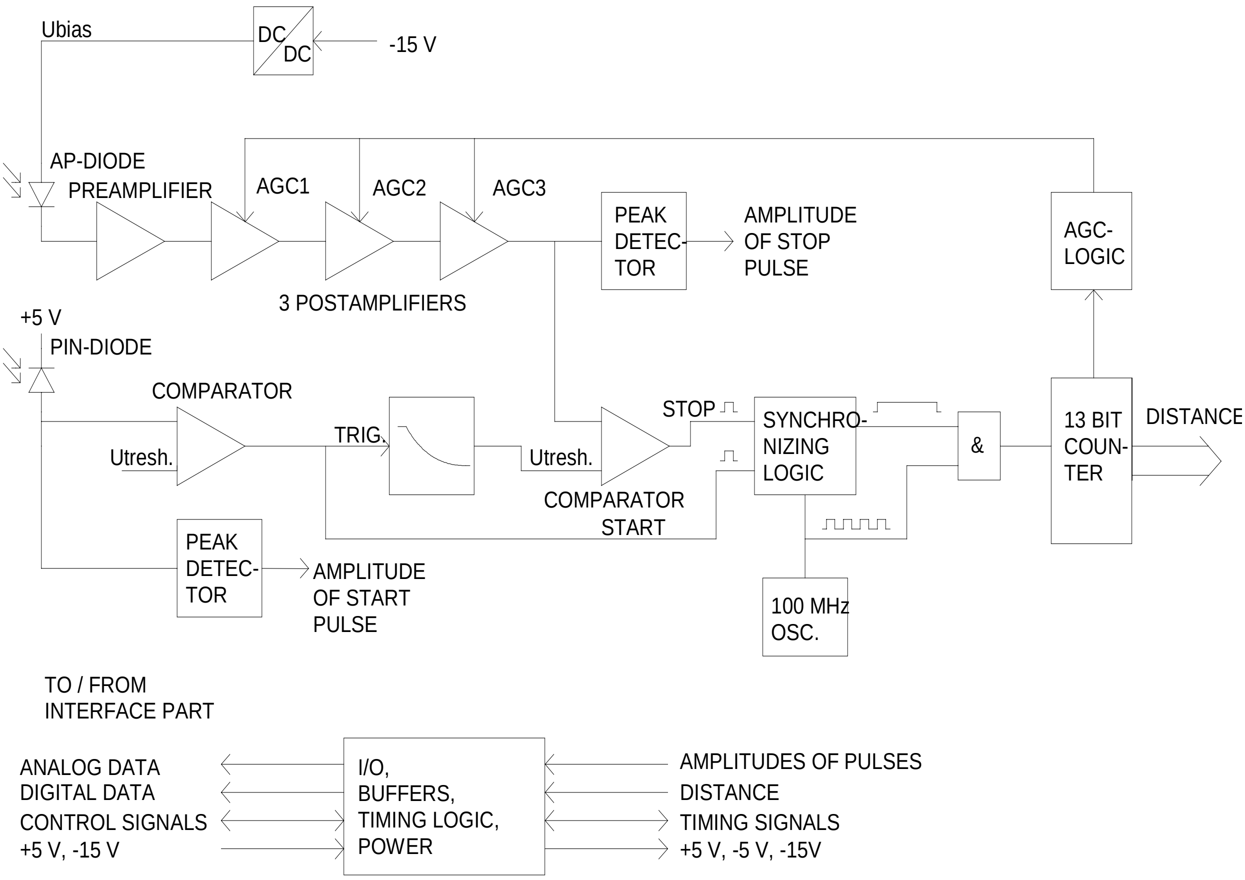

Figure 6. Block diagram of the measurement part of the laser altimeter

Timing discrimination is achieved by an adaptive threshold method in which the start signal triggers the stop threshold generator, upon which the threshold level changes from 1.4 V to 150 mV with a RC constant of 2.5 μs. The peak detector measures the amplitude of the stop pulses.

The peak detectors in the start and stop channels each consist of a fast bipolar front end stage which stretches the 10 ns wide stop pulse to about 500 ns and a slower additional hold stage which captures this stretched pulse. The dynamic range of each peak detector is from 200 mV to 2.2 V, its linearity being better than 10%. If the amplitude of the transmitted optical pulse, amplification of the receiver channel and AP diode and measurement distance are known, the albedo of the Martian surface can be calculated.

Table 1. Gain of the receiver channel

Time from start pulse	Gain
0 < t < 3 μs	1.5
3 μs < t < 6.5 μs	6
6.5 μs < t < 13 μs	20
t > 13 μs	90

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t > 13 μs	90

Time interval measurement is based on the digital method, counting the pulses of a free running oscillator between the start and stop pulses. The frequency of the oscillator is 100 MHz, giving a single shot resolution of +/- 10 ns or +/- 1.5 m. The time interval measurement electronics consist of a synchronised 13 bit counter, constructed by partly ACMOS and partly HCMOS technique, by which a measurement range of 80 µs can be achieved, corresponding to a distance of about 12 km. The physical dimensions of the electronics are 126 mm * 188 mm * 20 mm and their weight is about 200 g.

3. TEST RESULTS

Climatic tests have been performed at short (3 m - 50 m) and long distances (up to 6 km) within a temperature range of about -80°C to +60°C both at normal air pressure and in a vacuum of about 1 torr. The tests were carried out using the range simulator equipment and test arrangement shown in Figure 7.

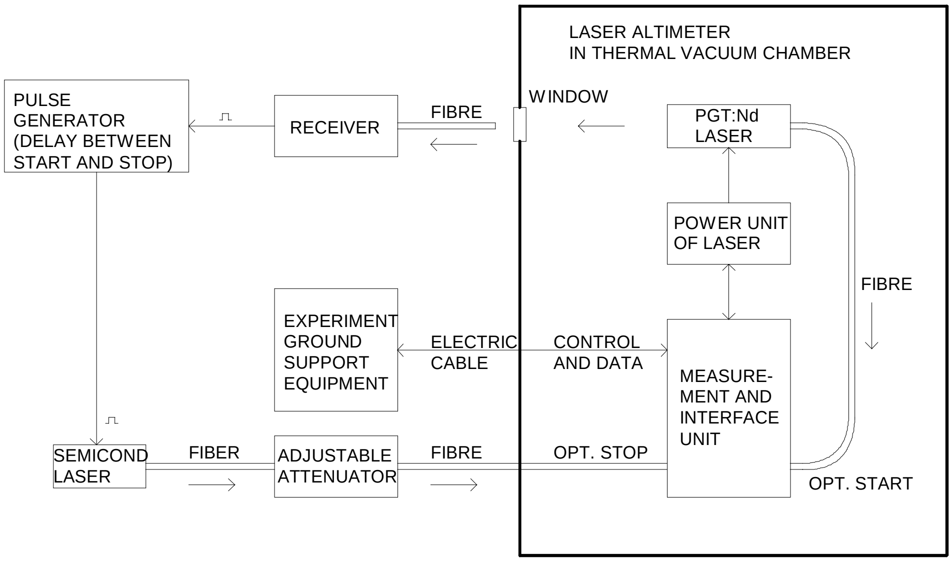

Figure 7 Measurement set-up for the thermal vacuum chamber tests

The optical part of the laser altimeter with the power unit of the laser, interface and measuring unit were installed in the chamber, the temperature and air pressure in which could be varied. The optical light pulse from the laser unit was detected by a photodiode located outside the chamber. A pulse from the diode triggered a delay pulse generator, which sent a trigger pulse to the semiconductor laser diode after the desired time delay. The optical pulse was guided to the AP diode of the stop channel by optical fibres through an optical attenuator. The electronics of the altimeter were monitored during the tests with an industry-standard PC running special control and measurement software and connected to the interface part of the altimeter through electrical ground support equipment (EGSE) which simulate the electrical interface of the gondola.

The tests show that the measurement and interface unit works properly over the designed temperature area. Time intervals corresponding to distances of up to 6 km were measured, and the drift in distance measurement remained within +/- 1.5 m, i.e. within the single shot resolution of the time interval electronics. The optical output power of the laser decreases with ambient temperature, as shown in Figure 8, where the amplitude of the start pulse is depicted as a function of the ambient temperature. The reason for this is a decrease in the pumping energy and a partial misadjustment of the resonator with temperature. At very low temperatures the laser pumping energy falls below the generation threshold and generation ceases.

The probability of detecting noise as a stop pulse is about 10^{-4} if the signal to noise ratio (SNR) is about 10.[2] To ascertain the achievable measurement range, measurements were made using passive, diffusely reflecting targets of known reflectivity between 0.09 and 0.62 at distances from a few tens of metres to 650 m. The maximum achievable distance (SNR = 10) was calculated to be about 13 km if the reflectivity of the target is 0.12, which approximately corresponds to the minimum average reflectivity of the surface of Mars.

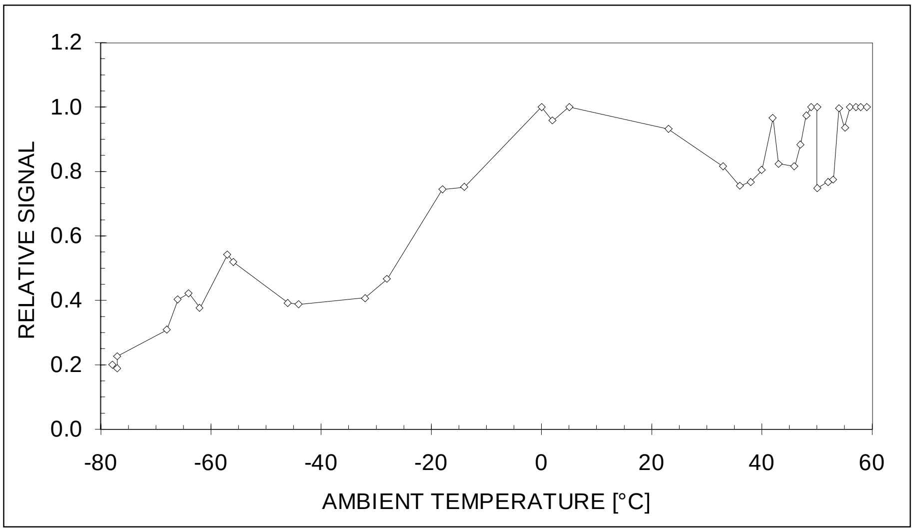

Figure 8 Output power of the laser as a function of ambient temperature

4. CONCLUSIONS

A laser altimeter developed for the international Mars-96 project is described here which is based on the time-of-flight techniques and measures the transit time of a laser pulse about 10 ns wide to the surface of the planet and back. The altimeter consists of a PGT:Nd solid state laser, receiver optics and a measurement and interface unit. Its typical measurement frequency is about 0.2 Hz. Special attention is paid in the design to minimising the size and power consumption of the electronics, and the average power consumption is reduced to about 30 mW, by switching the power on only during the measurement period of 40 ms in every 5 s. The average power consumption of the laser is about 0.8 W.

The measurement range of the altimeter is about 13 km if the reflectivity of the target is 0.1 and the single shot resolution is about +/- 1.5 m, which is limited by the 100 MHz oscillator clock rate. Temperature measurements in a vacuum chamber show that the electronics are capable of operating over the whole temperature range of -80°C - +60°C and the drift in the measured distance remains within +/- 1.5 m over this range. The output power of the laser decreases by a factor of 0.2 at lower temperatures because of a decrease in pumping energy. The measurement unit of the altimeter measures the amplitudes of the transmitted and received signals, enabling calculation of the albedo of the surface of Mars.

5. REFERENCES

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