Contamination-induced degradation of space-borne lidars

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ADM-Aeolus, with the Atmospheric Laser Doppler Instrument ALADIN, is the second of ESA's core Earth Explorer Missions. The launch of the satellite is planned for the end of 2008, and ESA and its contractors are currently performing tests to qualify the ALADIN laser for the three-year mission duration. One of the primary risks facing the laser is degradation or failure of the system as a result of contaminant deposition on the laser optics. To address this issue, a test bench has been set up at the European Space Technology and Research Centre, ESTEC, in Noordwijk to perform tests with polymer and silicone materials found in the laser cavity. This test bench is described in detail along with initial results.

Introduction

The ALADIN instrument, which will be launched on-board the ADM-mission is a complex instrument, containing a frequency-tripled high power Nd:YAG laser and both Rayleigh and Mie spectrometers. These spectrometers measure the amount of backscattered signal and their relative frequency shift with respect to the laser output. Since the time-of-flight of the backscattered signal is directly related to the atmospheric altitude, the instrument has the capability of measuring the wind speed in multiple atmospheric layers at once. The pulse duration is 15ns in the UV, and the oscillator is frequency stabilised with a seed laser. The aerosol back-scatter near the planet's surface (the lowest few kilometers) is measured by the Mie spectrometer, and the Rayleigh spectrometer measures the backscatter in the upper atmosphere (from 2km to 30km). To achieve a signal level that is sufficient to achieve the targeted accuracy of 1m/s for the Mie spectrometer and 2m/s for the Rayleigh spectrometer, the ALADIN emits as much as 120mJ in the at 355nm. To achieve this output energy, 460mJ of output power from a MOPA (Master Oscillator Power Amplifier) Nd:YAG laser is frequency tripled with the use of two LBO crystals.

Because of the high fluences in the laser, laser-induced damage is of particular concern to the project and a test campaign has therefore been set up at DLR (German Aerospace Centre) to qualify the optics with respect to their laser-induced damage threshold [1]. However, the ADM-Mission is planned to have a total duration of 39 months, with the ALADIN laser operating over the full mission duration, hence accumulating close to 3.5 billion laser pulses. Reports from experiments [2] and from NASA missions, e.g. [3] indicate that one of the most major risks the laser faces is contamination of the optics. One example of this is given by the LITE mission, which suffered power reduction on the order of 50% in it relatively short 10-day mission. More recently, it has been reported that the GLAS lasers on the ICESat satellite, launched in 2001, have either suffered degradation or failure that has been linked to the build-up of contamination on the optics. It is thought that vacuum operation make space-borne lasers particularly sensitive to contamination, possibly because of increased outgassing, but probably also because of the absence of oxygen, which is thought to mitigate contamination effects, e.g. [4]. In addition, experience from UV lithography shows that exposure of optics to very short wavelengths is particularly critical with respect to hydrocarbon contamination since the capability of breaking bonds increases [5].

Because of its compact design, the ALADIN optics is exposed to a relatively large fluence, and due to folding, there is a relatively large number of optics in the laser (more than 70 in total). While the wavelengths used in lithography are generally shorter than 355nm, it is very likely that the very high fluence of the ALADIN instruments makes it more sensitive to contamination. Tests are therefore being conducted both at DLR's facility in Stuttgart and at ESTEC to investigate the effect of contamination in Aladin. While contamination tests at 1064nm and 355nm are conducted at DLR[6], the ESTEC test facility concentrates on measurements at 355nm.

Test configuration

As with the tests at 1064nm, the initial tests at ESTEC are simple "go"-"no-go" test. That is, the silicone or hydrocarbon material under test was considered to be qualified for space operation, i.e. "go", if no deposit would form on a Fused Silica sample irradiated with a preset number of pulses of the laser beam. A Nomarski microscope with a magnification of up to 500 was used to determine if a deposit had formed during laser irradiation in contaminated vacuum.

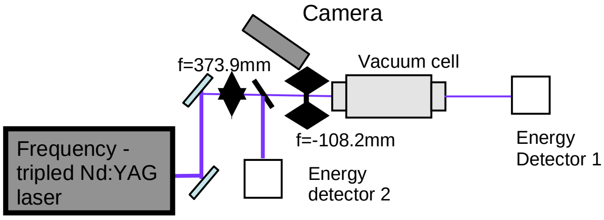

Figure 1 Experimental setup to investigate the contamination effect of space materials containing hydrocarbons and silicones.

The setup used for the contamination experiments at ESTEC is shown in Figure 1. The laser used for the experiment was a Continuum Powerlite II 9050 with internal frequency doubling and tripling crystals. The system operates at 50Hz and emits $1.0(2)\cdot10^{2}$mJ pulses at 355nm. The laser is injection seeded and has pulse duration of 4ns (specified) in the UV. The output of the beam propagates through a Galilean telescope with an objective focal length of 373.9mm and an ocular focal length of -108.2mm to give a collimated beam with a diameter of 1.5(5)mm and an estimated fluence of 2(1)J/cm^2 on both the input and output windows (Corning 7980) that double as test samples. During tests, a HDV camera was used to monitor and record the growth of deposits on the input window of the vacuum cell. Two energy detectors (see Figure 1) are used to monitor the laser transmission through the chamber. The gaseous contents of the chamber were monitored with a Prisma QMS-200 Faraday RGA with a mass range of 0-300a.m.u. and a Leybold ITR090 pressure sensor. The pump used to evacuate the chamber is a Leybold PT70-F oil-free turbo pump with a membrane fore-pump.

Irradiation at 355nm typically induces fluorescence in most hydrocarbons. Therefore, once a carbonaceous deposit is formed on the windows of the vacuum cell, this is picked up as a fluorescence signal visible by eye or by the camera. This method of detection is very sensitive, and in some cases, optics with clearly visible fluorescence show no sign of contamination under a Nomarski microscope.

To ensure the reproducibility and hence the validity of the test results, a measurement protocol was set up. This protocol is as follows

1. Bake-out of the chamber at 170ºC. The bellows and the pump are baked out at 110 ºC. The bake-out is conducted for a minimum of 12 hours to ensure a clean vacuum chamber.
2. The chamber temperature is then reduced to 40 ºC while the pump and bellows are set to room temperature. The chamber is then opened for 15minutes, closed again and re-evacuated.
3. During evacuation, the amount of volatile hydrocarbon materials is monitored with the RGA and $t_{re\text{-}evac}$, the time required to empty the chamber of any volatiles introduced upon opening is recorded. The chamber pressure is below 10^{-4}mbar.
4. The blank test is commenced and the test site is irradiated with the number of pulses (typically 3 million) planned for the ensuing contamination test (step 6). The blank test is considered successful if no fluorescence is observed during irradiation and if a visual inspection under a bright light source shows no sign of contamination. After a successful blank test, the material under test is placed in the test chamber and the chamber is closed after 15minutes.
5. The chamber is re-evacuated over the same time, $t_{re\text{-}evac}$, used for the blank test. Again the pressure must drop below 10^{-4}mbar.
6. The contamination test is commenced.

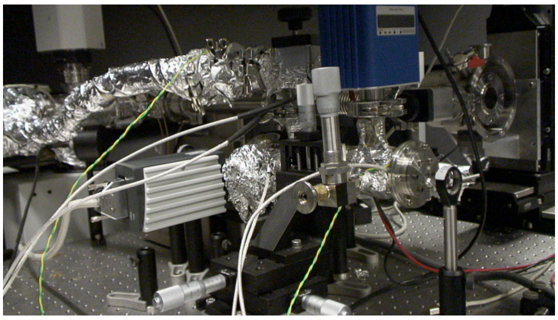

Figure 2 Vacuum chamber used for contamination experiments. The picture is taken during bake-out, with the fused silica windows replaced by aluminium blanks.

As an aside, since the contamination test is very sensitive to any form of contamination at 355nm, the bakeout must be conducted with outmost care and with every part being heated if the system is to pass the blank test. The chamber is shown during bake-out in Figure 2.

Early results

At current, two material samples have been tested. The first is a thin 8cm·8cm aluminium sheet coated with A12 (see Figure 3), a common structural epoxy used in space applications. This material, which was tested at a somewhat higher pressure (10^{-1}mbar), showed very strong fluorescence upon irradiation. A thick deposit visible by the naked eye was observed. The shape of the deposit was a typical ring shape around the irradiating beam. Similar tests by DLR at 355nm have given similar results[7], although the behaviour may be dependent on the sample itself.

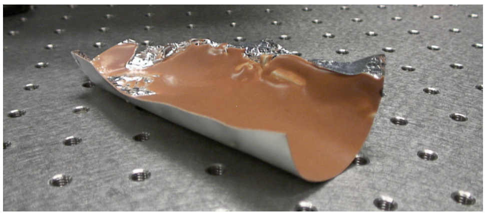

Figure 3 Sample used for contamination testing. The above image shows A12 deposited on a 3mm-thick aluminium sheet.

The first test with A12 was conducted with a relatively large sample, in particular considering the amount of material expected in the ALADIN laser. The second test was designed a bit differently. Here we used Solithane, a poly-urethane based potting material in very small amounts and with correspondingly low vapour pressures. Following the measurement protocol with the chamber reaching $3(1)\cdot 10^{-5}$mbar, we observed very faint fluorescence. A reduction in transmission was not observed. After exposing the sample to 10million laser pulses, we investigated the fused silica window under a Zygo NewView 100 white light interference microscope. Using this microscope, we measured a very thin deposit that was not thicker than 4nm.

In a second experiment with the same Solithane 113 sample but with a different spot being irradiated on the sample, we produced a second fluorescing ring. After half a million pulses, we increased the chamber pressure by bleeding laboratory air into the chamber. At an air pressure of 10mbar, the fluorescence spot disappears, indicating that air either quenches fluorescence by its presence or possibly removes or transforms the fluorescent material to a state that does not fluoresce. The presence of air has also been observed to suppress fluorescence for several materials. Thus there are indications that oxygen may inhibit deposit growth in the presence of high power 355nm radiation similar to that reported by Bates et al.[8] at 157nm light at comparatively low fluences.

In conclusion, a setup has been built at ESTEC to investigate the effect of outgassing from common space materials on optics. Initial experiments show that contaminants show surface fluorescence when irradiated even when the contamination layer remains very thin. In the near future we will investigate the growth rate of this layer and how air affects the contamination layer thickness when irradiated with 355nm light.

Acknowledgements
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