LASER BASED OBSERVATION OF SPACE DEBRIS: TAKING BENEFITS FROM THE FUNDAMENTAL WAVE

Uwe Voelker(1), Fabian Friederich(1), Ivo Buske(1), Daniel Hampf(1), Wolfgang, Riede(1), Adolf Giesen(1)

(1) German Aerospace Center (DLR), Institute of Technical Physics, Pfaffenwaldring 38-40, 70569 Stuttgart, Germany, Email: uwe.voelker@dlr.de

ABSTRACT

After the successful experimental demonstration of the prior published concept on laser-based monitoring of space debris in early 2012, we will present further technological and conceptual advancements of this position sensing scheme. The laser based measurement of LEO space debris positions in general offers the potential of a very high accuracy on the order of 10 meters in 3D, which in turn is the input for orbit processing of objects which are seemingly on collisional course.

We argue that it is beneficial for the photon budget to make use of the so called fundamental wave, which is present in frequency doubled laser systems anyway. Thus, the here proposed move to near infrared wavelength is technologically easy to achieve and promising towards an operational laser-based debris ranging and tracking system.

1 Introduction

As the space debris problem is a growing concern to operators of satellites as well as to users of satellite based data products, solutions towards high accuracy position sensing are sought after. Besides Radar approaches for LEO debris tracking (e.g. the German TIRA [1]), laser-based systems are discussed. The latter approach offers the potential of a very high accuracy on the order of meters [2, 3]. Within the laser-based approach, two different implementations have been followed so far: (*i*) a low pulse repetition rate (f_{rep}), high pulse energy (E_{pulse}) scheme, and just recently experimentally validated [4] (*ii*) a high f_{rep}, low E_{pulse} setup. Setup (*i*) (low f_{rep}, high E_{pulse}) has the advantage of a strong signal level but the drawback that the chances to hit the target with the laser are limited due to the low number of laser pulses. Setup (*ii*), however, is complementary to the afore mentioned: the high amount of laser pulses increases the chances to illuminate the debris object, but the weak laser pulses reduce the signal strengths.

Obviously, it is desirable to combine the advantages of both approaches. This would, of course, require a laser system offering a high pulse repetition rate *and* a high pulse energy. In [2], a system pulsing at a frequency of $f_{rep} = 1$ kHz with a pulse energy of $E_{pulse} = 1$ J is proposed for the observation of 10 cm LEO debris. As such a laser system is not available to date - and as a future system should be optimised towards best possible results as well - we assess in this paper the influence of the laser wavelength on the achievable results. Since laser development for space debris laser ranging (SDLR) is ongoing at the DLR Institute of Technical Physics, we will use the emitted wavelength of the chosen material system (i.e. Ytterbium YAG (Yb:YAG), $\lambda = 1030$ nm) for the discussion conducted below.

2 Wavelength of the laser system

Since the above mentioned experiments of SDLR have been performed at satellite laser ranging (SLR) stations, we will discuss briefly the dedication and the technical layout of such stations. SLR is performed (for instance by the members of the International Laser Ranging Service, ILRS [5]) in order to support geodetic analyses. Hence, best possible range-resolution and accuracy is necessary. Driven by this needs, and due to the early availability of single photon counting detectors in the green spectral region, the historical evolution of SLR systems led to silicon-based detectors as tool of choice.

As a consequence, the wavelength of the pulse laser had to be adjusted to the central wavelength of the detector. Because lasers directly emitting in the green spectral range are not available with sufficiently high pulse energy, the well-known nonlinear optical process *second harmonic generation* (SHG) is employed to transform the wavelength of a near infrared laser (fundamental wave) to the green (second harmonic wave). The wavelength of a Yb:YAG laser (i.e. 1030 nm) can in such way be frequency-doubled to 515 nm.

This approach requires a nonlinear optical host material. Usually crystals like Potassium Titanyl Phosphate (KTP) are used for this purpose. Whereas momentum conservation has to be adjusted by phase matching, energy conservation is fulfilled automatically: it needs two photons from the near infrared to excite the nonlinear oscillation process in the material which emits one green photon. The latter photon possesses twice the energy compared to one photon at the near infrared wavelength.

Proc. '6th European Conference on Space Debris'
Darmstadt, Germany, 22–25 April 2013 (ESA SP-723, August 2013)

The SHG process is usually conducted at an efficiency of approximately 50%. Hence, if it is desired to generate a particular pulse energy in the green, it is necessary to offer the doubled energy in the near infrared and thus four times the number of photons. This means, by moving from the due to historical reasons (c.f. above) widely used green wavelength towards the fundamental wave, there are four times more photons available. We want to point out that this basically just requires the removal of the frequency doubling crystal from the laser system.

3 Photon budged considerations

3.1. Transmission aspects

After the above conclusion that the fundamental wave at λ = 1030 nm offers inherently an almost quadrupled photon number compared to the second harmonic wave at λ = 515 nm, we will compare the atmospheric transmission of these two wavelengths.

The spectral properties of light scattering and absorption of the atmosphere are well described by the Air Force Phillips Laboratory's FASCOD3P model [6]. Ontar commercialized this model within the software PCLnWin [7], which can be used to simulate atmospheric transmission properties. The advantage of PcLnWin is that properties of the transmitted beam can be analysed with high spectral resolution for certain visibilities, site altitudes, aerosol densities, and elevation angles.

Results show that the single pass transmittance τ_{fund} for the fundamental wavelength is about 86%, whereas the transmittance at 515 nm is about $\tau_{sh} = 61\%$ [2]. Both values are generated for vertical propagation from sea level in cloud-less conditions and visibility of 23 km. By applying a planar atmospheric assumption, the transmission as a function of elevation angle evolves as follows [8]:

$$\tau(\lambda, \Theta) = \tau(\lambda)_{90°}{}^{sec(\pi/2-\Theta)}, \tag{1}$$

where τ denotes the transmission and Θ the elevation angle versus horizon. In order to get access to the double-path transmission, the value τ(λ,Θ) has to be squared.

Figure 1 shows the ratio of the double-path transmissions of the fundamental and the second harmonic wave. It can be observed that the gain from working at λ = 1030 nm is approximately a factor of two at high elevation angles. However, decreasing the elevation angle, the gain dramatically increases towards a value of 10 at 20° elevation angle thanks to the longer path through the atmosphere.

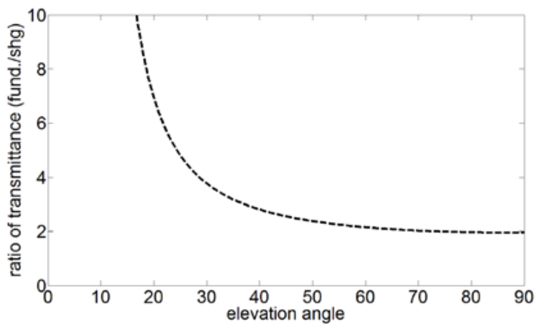

Figure 1. Ratio of double-path transmittance for λ =1030 nm and λ = 515 nm as a function of elevation angle.

3.2. Reflection features

The spectral reflection features of space debris is not conclusively clarified in literature. While there are some hints that the reflection coefficients in the visible and the near infrared spectral range are close to identical, there are as well reflection spectra which reveal a different behaviour. For instance, Africano et al. show spectra where the reflectance at 900 nm is more than two times higher than at 500 nm [9]. Kapton is reported to show comparable behaviour, both pre-flight and post-flight [10]. Jorgensen et al. are reporting about a "reddening seen in many space objects" [11], meaning a higher reflectance at wavelength above the visible.

Concluding from this literature data, we expect more reflected near-IR photons than reflected green photons. However, as this positive effect can't be quantified, we do not assign any numbers to this aspect of the photon propagation chain.

3.3. Consequences for the photon budget

The above claimed impacts of the lasing process (including second harmonic generation) and the spectral transmission can simply be multiplied to get an impression how the number of photons at λ = 1030 nm ($\#Ph_{1030nm}$) exceeds those when the SHG process is used to work at a wavelength of λ = 515 nm ($\#Ph_{515nm}$). Hence, the following relation for the number of returning photon is valid:

$$\#Ph_{1030nm} \approx 10 \cdot \#Ph_{515nm}. \tag{2}$$

This ratio of 10 holds for vertical laser illumination; for elevation angles unequal to 90° the situation gets even more positive with a functional dependency as described in Figure 1. Thus, the advantage of factor 10 at vertical emission increases to a factor of 50 at an elevation angle of approximately 20°.

Referring to the above given comparison of the fundamental wave to the second harmonic wave regarding the number of returning photons, we can obviously expect well beyond magnitude more photons at λ = 1030 nm depending on the particular elevation angle.

4 Detector for the near infrared

The requirements on the detector for SLR and SDLR are similar, but not identical. While it is - driven by the geodetic background - necessary for SLR to have ~100 picosecond timing accuracies, this is certainly not the case for debris observations. For this application, the timing jitter should be smaller than the laser pulse duration, which is intended to be on the order of 10 ns. This relaxes the requirements towards this aspect of the detector and the supporting electronics.

The requirement of high detection efficiency and single photon counting capability is the same for both applications. Thus, it makes sense to rely for the debris application on the same detection concepts as used for SLR. For the latter, a lot of stations make use of "single photon avalanche diodes" (SPADs). Briefly described, these devices are photodiodes which are used such that the high gain voltage induces one detection event to completely saturate the detector. Thus, one photon is able to saturate the detector. The advantage of this is an increased photon detection efficiency (PDE), which is the product of the quantum efficiency (QE) of the detector material and the trigger probability. The latter depends on the gain voltage.

In order to maximize the QE, it is a reasonable strategy to match the bandwidth of the (semi conducting) material of the detector with the energy of the impinging wave. This leads typically to Silicon-based detectors for visible wavelength, whereas Indium-Gallium-Arsenide (InGaAs) is the material of choice for near infrared waves.

A typical value of the photon detection efficiency of Si-SPADs is 0.6 [12], meaning that there is a chance of 60% to detect a single incoming photon. InGaAs-SPADs with a PDE of 0.3 at λ = 1030 nm are commercially available [13].

5 Benefits

The results of section 3 revealed, that the number of returning photons is more than a magnitude higher when the fundamental wave at 1030 nm is used compared to the second harmonic wave at 515 nm. Furthermore, in section 4 we showed that a suitable material system for near-infrared detection exists and is commercialized. Here, we will assess how the above discussed factors influence the detectability of space debris using pulsed lasers. For this purpose, we employ an approach similar to the one described in [2] for both wavelength of interest.

In Figure 2 the system performance for a 10 cm sized debris object is shown. Here, the elevation angle under which such an object is expected to be detectable is shown as a function of the laser pulse energy for both, λ = 515 nm (green curve) and λ = 1030 nm (red curve). The space debris (1000 km orbital height) is considered as "detectable", if a detection rate of 10% is achieved at minimum (the Poisson distribution is used to account for the photon statistics). The divergence angle of the emitted laser is in both cases set to 10 µrad, the receiver telescope had an aperture 0.5 m and a transmittance of 60%. The PDEs of the detectors are 0.6 and 0.3, as stated in section 4. The black star and the black square denote one possible pair of values for the E_{pulse} of the fundamental and second harmonic wave, respectively. It can be seen that the utilization of the fundamental wave with E_{pulse} = 1 J leads to a detection possibility of the 10 cm- object down to elevation angles of 20° (black star), whereas the same object could be laser ranged using the second harmonic wave (at 0.5 J) only just down to 50° elevation angle (black square).

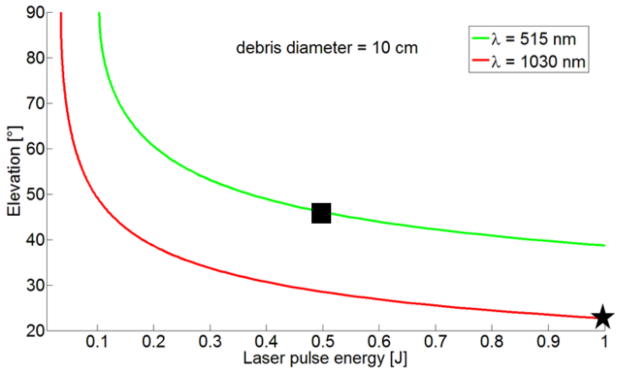

Figure 2. Assessment of the system performance for a 10 cm debris object in terms of elevation angle of a detectable object vs. necessary pulse energy. Green curve: λ = 515 nm, red curve: λ = 1030 nm. For further explanation, please see text.

In Figure 3, the detectable debris size at a fixed elevation angle of 45° is shown as a function of the pulse energy. Again, the red and the green curve indicate the fundamental (1030 nm) and the second harmonic wave (515 nm), respectively. Apparently, smaller objects can be observed at the near infrared wavelength. We want to point out, though, that at lower elevation angles than 45° the discrepancy between the detectable objects spreads even more than shown here.

Since future SSA networks should include SDLR stations, it is highly aspired that these station are usable on an operational level. This means, that they need to be reliably working for small objects observable under low elevation angles with sufficiently high return rates. As can be seen in Figure 2, at a wavelength of 1030 nm it is possible to use the SDLR system at dramatically lower elevation angles compared to the green wavelength. Besides this, using the fundamental wave facilitates the measurement of smaller debris objects compared to the second harmonic wave (c.f. Figure 3).

As shown above, in such an operational scenario it makes highly sense to not use the frequency doubled wave (at green wavelength), but instead make use of the fundamental wave (at near infrared wavelength), especially as this wave with the above deduced performance advantages is existing anyways in laser systems typically used.

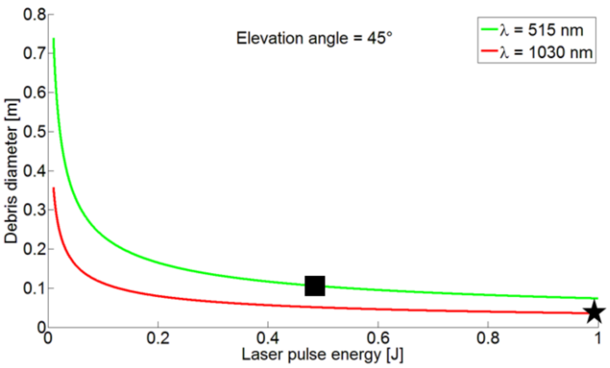

Figure 3. Detectable debris sizes using both wavelength as a function of pulse energy. The elevation angle is set to 45°. For further explanation, please see text.

6 Summary and Conclusions

Space debris laser ranging has proven itself as promising method for debris position sensing. Since we foresee both a high pulse energy and a high pulse repetition rate as necessary for future SDLR systems, we explored further ways to improve the system performance. This includes (besides ongoing laser development) the utilization of the fundamental wave instead of frequency doubled laser systems. This leads inherently to a quadrupled number of photons, an atmospheric transmittance better by a factor of 2 to 10 and to an increased reflectivity of the debris. As furthermore suitable detectors are available, we assessed that the system performance dramatically benefits from using $\lambda = 1030$ nm in favour of the frequency double wave at 515 nm.

For existing laser ranging stations, it would thus make sense to remove the frequency doubling crystal from the laser and to adopt the optics of the optical path. Of course, this does only affect the debris related activities and not necessarily the original dedication, i.e. highly accurate satellite laser ranging.

For debris laser ranging stations to be build, we articulate the advice to design the system without a frequency doubling stage in order to take benefits from the fundamental wave.

7 REFERENCES

1. Radar – a key technology, www.fhr.fraunhofer.de/en.html, visited on April 17th, 2013.

2. Voelker, U, Buske, I., Hall, Th., Hüttner, B., Riede, W. (2011). *Laser-Based Space Debris Monitoring*, Cambridge AIP Conf. Proc.,**1402**,354-363.

3. Buske, I., Voelker, U., Riede, W., Speiser, J., Giesen, A. (2011). *Laser-Based Ranging and Tracking of Space Debris*, Conf. Proc. CD 6th Future Security, Berlin, Germany.

4. Kirchner, G., Koidl, F., Friederich, F., Buske, I., Voelker, U., Riede, W. (2013) Laser measurements to space debris from Graz SLR station, Adv. in Space Research **51**(1) 21-24.

5. International Laser Ranging Service, http://ilrs.gsfc.nasa.gov, visited on April 17th, 2013.

6. Clough, S.A., Kneizys, F.X., Rotman, L.A., Smith, H.J.P., Dube, D.J., Gardner, M.E. (1978) *Fast Atmospheric Transmittance And Radiance Algorithm – FASCODE*. J. Opt. Soc. Am. **68**(10), 1424-1425.

7. Ontar Corporation, www.ontar.com/Software/ProductDetails.aspx?item=PcLnWin, visited on April 17th, 2013.

8. Shell, J.R. (2010) *Optimizing Orbital Debris Monitoring With Optical Telescopes*, 2010 Advanced Maui Optical and Space Surveillance Conference Technical Papers.

9. Africano, J.L., Stansbery, E.G., Kervin, P.W. (2004) *The Optical Debris Measurement Program at NASA and AMOS,* Adv. in Space Research **34**, 892-900.

10. NASA Space Environments and Technology Archive System (SETAS), Final Report "Evaluation of Space Environment and Effects on Materials", http://setas-www.larc.nasa.gov/esem/final_report_append_e.html, visited on April 17th, 2013.

11. Jorgensen, K., Jarvis, K., Hamada, K., Parr-Thumm, T., Africano, J.L., Stansbery, E.G. (2003) *Comparison of Photometric and Spectral Data from NASA's CCD Debris Telescope (CDT) and NASA AMOS Spectral Study (NASS) Observations*, Proc. of the 54th International Astronautical Congress, Bremen, Germany.

12. Stipcevic, M., Skenderovic, H., Gracin, D. (2010) Characterization of a novel avalanche photodiode for single photon detection in VIS-NIR range, Optics Express **18**(16), 17448.

13. *Single-photon detection with InGaAs/InP avalance photodiodes*. Application Note, http://www.idquantique.com/, visited on April 19th, 2013.