Design and commissioning of a transportable laser ranging station STAR-C

Leif Humbert, Thomas Hasenohr, Daniel Hampf, Wolfgang Riede

German Aerospace Center, Institute of Technical Physics, Pfaffenwaldring 38-40, 70569 Stuttgart, Germany

ABSTRACT

An increasing number of space debris and the rise of mega constellations as well as the deployment of small cost efficient satellites are a growing concern for space faring nations and their missions. Hence, a tight network of worldwide stations to support maintenance of catalogues for various tasks such as space surveillance tracking and space traffic management will significantly increase the reliability and availability of the collected data and therefore the safety of missions. A promising concept are transportable laser ranging stations in order to increase the number of observing stations and hence the coverage of the sky. Built and tested on a building test site they can be deployed to a desired site for operation. High energy laser with short pulses provide accurate ranging data to objects in space both cooperative and uncooperative, e.g. objects with a retroreflector and without one. This work introduces the progress of a transportable laser ranging station, of a Surveillance, Tracking and Ranging Container (STAR-C), built into a 20ft ISO container.

1. INTRODUCTION

Nowadays high energy laser with short pulse durations and sufficient beam quality are available and the method of laser ranging can be applied to residential space objects (RSO). Here, the simple method is to take the time of flight (TOF) for a laser pulses' round trip to a RSO and back to an observer [1]. In the simplest form the slant range R is given by $R = \frac{1}{2}\, c\, TOF$, where c is the speed of light. Taking corrections into account, in order to compensate for atmospheric effects, one can reach millimeter accuracy for particular targets [2]. Moreover, the dimension and the rotational state can be determined from TOF measurements with pulsed lasers [3]. STAR-C is a compact, cost efficient laser ranging station currently located at a test site in Stuttgart/ Germany for commissioning all hardware and verifying the performance of the tracking and ranging.

Most objects within the NORAD catalogue are space debris (95.6 %) such as dysfunctional satellites, upper stages, fuel tanks or fragments which are related to missions or break ups of satellites for instance. Blind tracking with optical methods of these objects with orbit predictions based on the two-line elements (TLE) within the NORAD catalogue is impossible, since the orbit predictions are too inaccurate. However, the predicted orbit is sufficiently accurate to capture the object's reflection of solar light within the field of view (FoV) of a wide field telescope during an overpass, compare Fig. 2. Taking the coarse prediction and a feedback control such that the objects appears at a specific position within the FoV makes it possible to track an object with an accuracy of 2 arcsec rms [4]. While the loop for tracking is closed, one can point a laser towards the object in order to determine the slant range R during the overpass for precision orbit determination (POD).

Inside the 10 t container (total weight) there is room for two air conditioned work places. In another separate room there is a 4 t heavy duty frame raising and lowering a platform with an alt-azimuth mount carrying two telescopes in a bi-static set-up. The heavy duty fame is mechanically decoupled from the rest of the container with four stilts which lift the frame off the bottom of the container but also level the heavy duty frame within a margin of ±0.3° with respect to the normal. A team operating STAR-C can communicate or exchange data with other sites via a fast Long Term Evolution (LTE) connection. A detailed description of the hardware can be found in [5].

Each axis of the alt-azimuth mount is driven with direct drive motors, where absolute encoders give a theoretical angular resolution of 1/50 arcsec. One telescope with an aperture of 10 cm is used for the transmit channel of a pulsed infrared laser including an active beam stabilization. The other telescope (Planewave CDK17), for the receive channel with an aperture of 43 cm collects the light both for tracking and ranging of a RSO. Both parts are separated on a cold mirror, where the infrared light transmits through the cold mirror and the visual reflects of the cold mirror, see Fig. 3.

Fig. 1. STAR-C at the test site with raised platform.

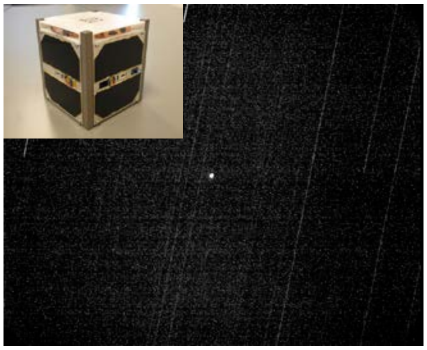

Fig. 2. A residential space object (for example Cubesat AAUSAT3, inlet upper left) appears stationary and bright during the closed loop tracking, while stars appear as tracklets.

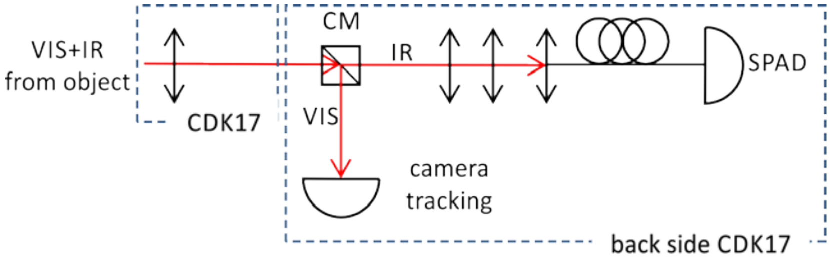

Fig. 3 Receive channel of STAR-C: From the receiving telescope the infrared and visual light are separated on a cold mirror. While the cold mirror transmits the infrared light, the visual is reflected.

The infrared light propagates through an optical system and is finally focused on a fiber-coupled single photon detector (SPD) for taking the TOF measurements. Any visual light is reflected onto the sensor of a low noise sCMOS camera that runs at a frame rate of up to 2Hz for tracking the RSO.

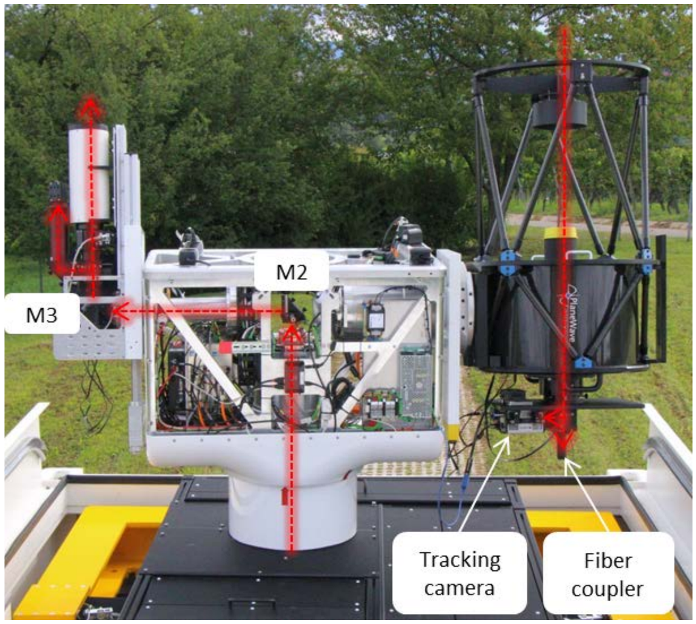

Fig. 4. The beam paths of the laser light from the source to the transmitting telescope and on the receiving channel. . On the left hand side of the mount is the transmitter telescope for the pulsed laser, whereas on the right hand side is the receiving telescope for tracking and collecting the returning photon of the transmitted pulse

A close up of the transmit and receive optics is shown in Fig. 4, which will be described in more detail in the following sections. A high energy laser is placed on the platform as well and its light is guided through the axis of the alt-azimuth mount, which is described in more detail in section 2. All hardware in STAR-C is controlled with a self-written software Orbital Objects Observation Software (OOOS) which is described in more detail elsewhere [6].

2. LASER BEAM STEERING

2.1 **Beam steering and ranging**

The Coude´ train in STAR-C, see Fig. 4 and a schematic overview in Fig. 5, guides the light of a laser source, see Fig. 8, to a transmitter telescope. Two mirrors, M1 and M2, guide the ranging laser through the azimuth and elevation axis of the mount onto the final mirror M3. This final mirror M3 is a remotely controlled and piezo driven mirror in order to steer the pointing of the ranging laser. A major challenge in laser raging RSOs is pointing and holding the ranging laser at a RSO. In order encounter this challenge a beam sampler picks a fraction of the light and is focused on a camera, see Fig. 5. Assuming a diameter of 10 mm of a laser beam at a wavelength of 1064 nm being focused by a 200 mm lens yields a spot size of 42.7 µm of a diffraction limited laser beam, covering 12 pixel of a CCD with a pixel size of 3.45 µm. However, fast fitting of the beam profile achieves sub-pixel accuracy and hence the desired pointing accuracy. Finally, the transmit telescope magnifies the laser beam by a factor of six and diffraction limited divergence is on the order of a few arcseconds.

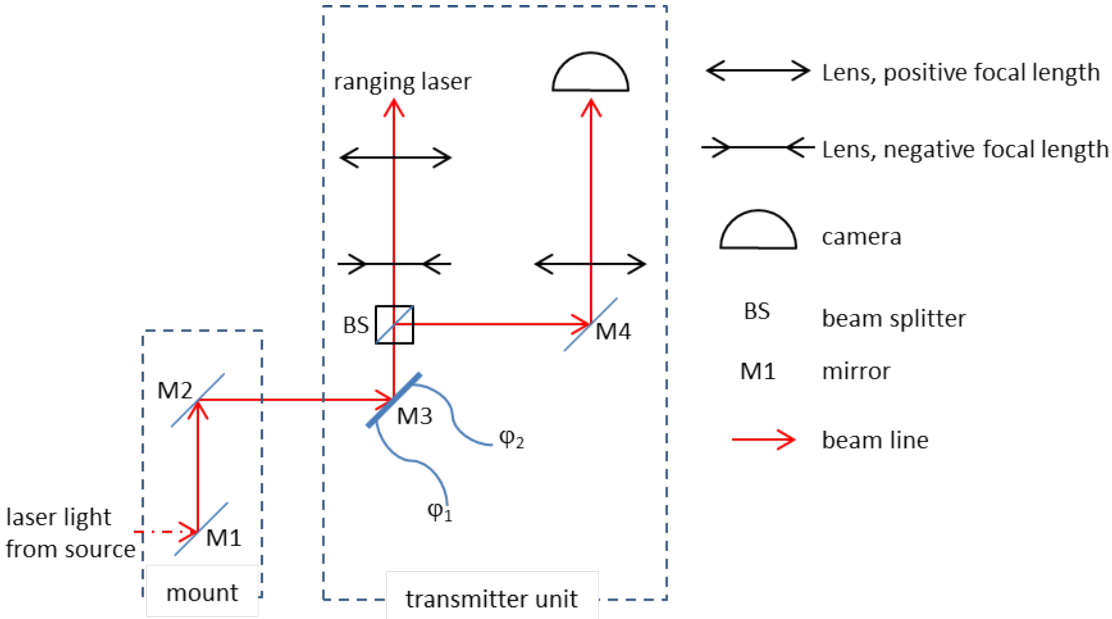

Fig. 5. Transmitter channel of STAR-C: The mirrors M1 and M2 guide a laser beam onto a remotely controlled piezo driven mirror M3. A fraction of the laser beam is picked by a beam ampler and focused onto a CCD for accurate pointing.

3. TESTING THE RANGING

First tests of the time tagging electronics are taken to a stationary retroreflector at a distance of 7 km. The separation of the two telescopes of 1.46 cm the divergence of the retroreflector and the short distance are disadvantageous for testing the electronics. As the ranging laser illuminates the retroreflector with a beam diameter, see Equation 1, which is much greater than the diameter of the retroreflector, 12.7 mm, only a fraction of the initial energy is reflected. Now the reflected light propagates back towards the source and the beam diameter grows as well according to Equation 1.

$$w(z) = w_0 \sqrt{1 + \left(\frac{z}{z_R}\right)^2} \sim \frac{\lambda}{\pi\, w_0} z \;\; for \; z >> z_R$$

Equation 1 The beam radius *w(z)* of a Gaussian laser varies with *z* along the propagation axes, where w_0 is the the waist at the focus and z_R the Rayleigh length.

Only a fraction of this light is collected by the receiving optics which is off center with respect to the center of propagation of the reflected beam, see Fig. 6. However, one can calculate the amount of collected energy as a function of the beam diameter, seen by the receiving optics. The results of such a calculation are shown in Fig. 7. For smaller diameters no light enters the telescope. As the diameter grows more light is collected and reaches a maximum. Beyond this maximum the energy density decreases as the beam diameter increases and the amount of collected energy is reduced. The slope reaches a maximum for a beam diameter of 2.05 m, which corresponds to an ideal aperture of the retroreflector of 2.4 mm, when solving Equation 1 for w_0.

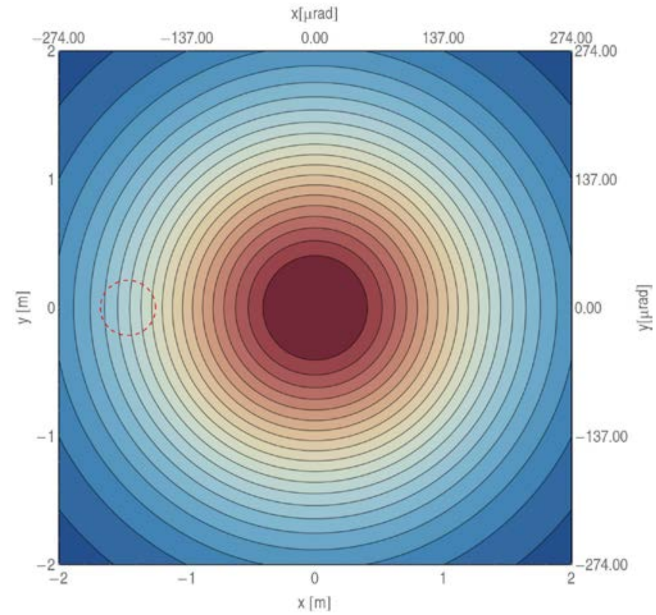

Fig. 6. The receiving optics (red, dashed circle) collects only a fraction of the reflected intensity.

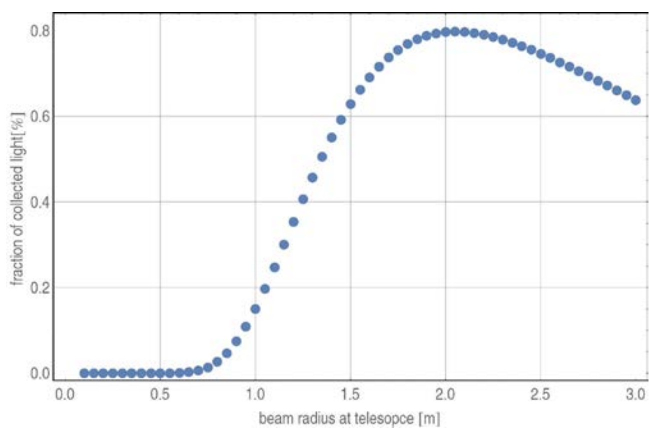

Fig. 7. The collected fraction of light as a function of the beam diameter in front of the receiving optics reach a maximum for a beam diameter of 2.05 m.

4. HIGH ENERGY LASER

Currently a high energy laser source is under construction by neoLase GmbH, which will be built into the setup by the end of the year. The laser head will be placed directly onto the platform while the electronics will be mounted underneath the platform, see Fig. 8. This laser source will require no additional cooling and provide infrared laser pulses at a wavelength of 1064 nm with an energy of more than 50 mJ per pulse, a pulse duration of less than 6 ns at a repetition rate of a few hundred Hertz. Space debris in low Earth orbits (LEO), such as fragments, rocket bodies or fuel tanks for example, are uncooperative objects that can be ranged with this laser and tracking method as described above.

Monitoring the air space is essential to ensure the safety of air crafts during the operation of the ranging laser. Therefore various safety features will be implemented to ensure the safety. An ADS-B receiver (Modebeast Radarcape), which is joined with other receivers, will alert a user, if a space craft flies within the vicinity of the ranging laser. Using an All Sky camera, eye safe laser range finder or even RADAR are other possibilities for air craft detection.

5. OUTLOOK

Subject of the ongoing research is, despite precise orbit determination with laser based TOF measurements the exploitation of TOF measurements, which contain much more information than just the slant range [3]. From the TOF measurements one can derive the rotational state as well as the dimension of the object. In addition, the link budget gives rise to the reflectivity of an object [2]. In future such measurements will provide essential information for the success of missions intended to remove space debris from endangered orbits. STAR-C can easily be shipped to a site close to a radar station. Joint observations will enhance the accuracy of orbit determinations, but also increase the quality and quantity of the knowledge of RSOs.

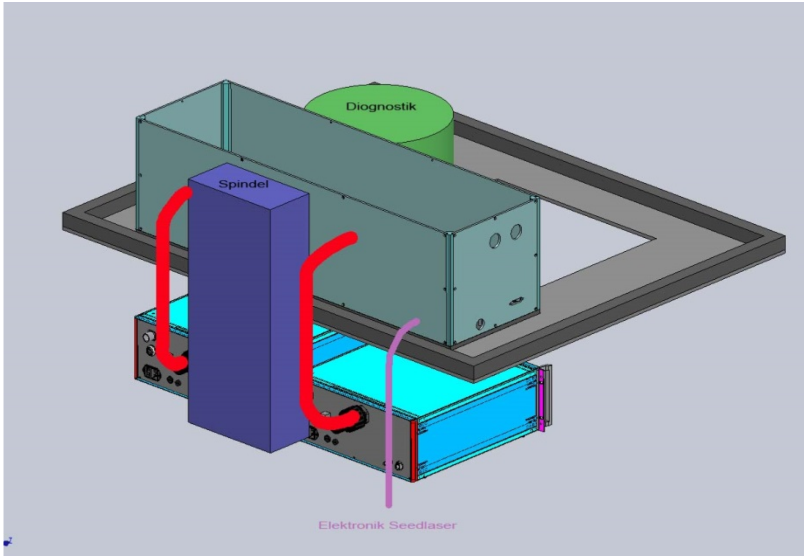

Fig. 8. The high energy laser (gray box) will be placed on the platform (black frame). The control units (blue/turquoise boxes) for the seed laser and amplifier will be placed underneath the platform.

6. REFERENCES

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