Transportable optical ground station for high-speed free-space laser communication

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ABSTRACT

Near real-time data downlinks from aircrafts, satellites and high altitude platforms via high-speed laser communication links is an important research topic at the Institute of Communications and Navigation of the German Aerospace Center (DLR). Ground stations for such scenarios are usually fixed at a certain location. With a motivation to provide a ground station that is quickly and easily deployed anywhere in the world, a transportable optical ground station (TOGS) has been developed. TOGS features a pneumatically deployable Cassegrain-type telescope with main mirror diameter of 60 cm, including optical tracking and receiving system. For calibration of position and attitude, multiple sensors like dual-antenna GPS and inclination sensors have been installed. In order to realize these systems, robust software that operates and controls them is essential. The software is platform independent and is aimed to be used on both mobile and ground terminals. It includes implementation of accurate pointing, acquisition and tracking algorithms, hardware drivers, and user interfaces. Important modules of the software are GPS tracking, optical tracking, star- and satellite tracking, and calibration of the TOGS itself. Recently, a first successful data-downlink from an aircraft to TOGS using GPS tracking has been performed. To streamline the software development and testing process, some simulation environments like mount simulator, aircraft path simulator, tracking camera simulator and tracking error analysis tool have also been developed. This paper presents the overall hardware/software structure of the TOGS, and gives results of the tracking accuracy improvement techniques like GPS extrapolation and optical tracking.

Keywords: TOGS, Simulator, optical communication, aircraft downlink, pointing, acquisition and tracking, tracking error, GPS extrapolation, free-space optical communication.

1. INTRODUCTION

Laser communication is gaining a lot of attention in the scientific world because of its benefits like high data rates, small terminal sizes, low transmit power, high data-security and no bandwidth regulation issues.[1] Currently, Institute of Communications and Navigation of DLR is highly involved in the research and demonstration of variety of optical communication applications. This includes experiments like downlinks from Japanese LEO-satellite OICETS,[2] downlinks from TerraSAR-X satellite,[1] downlinks from stratospheric balloon payload[3] and downlinks from DLR experimental aircraft (Dornier-228).[4] Two terminals used for laser communication are ground station, and mobile terminal installed in aircraft, satellite or other high altitude platforms. Main motivation for doing high-speed optical downlink is to receive near real-time data from earth-observation (EO) sensor installed in both space-based and atmospheric platforms.[1] One of the typical application scenario would be to aid crisis- and traffic management during large-scale events like olympics and disasters like earthquakes, flooding.[4] This could be done by installing earth-observation sensors in an aircraft and flying it over the incident area and sending sensor-data to the ground station as fast as possible.[4] In such scenarios, a fixed ground station would not be feasible because it is almost impossible to keep line of sight between two geographically widely separated terminals.[5] This situation drew interest within DLR for developing the transportable optical ground station (TOGS) that could be quickly and easily transported and deployed anywhere in the world.

DLR's TOGS features a pneumatically deployable telescope with the main mirror spanning a diameter of 60 cm. The telescope is working to a height of 3 m. The transportation and supply unit is supported by four manually mounted supports, that provide leveling of the station and compensation for ground roughness. In

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Figure 1. TOGS ready for downlink.

Figure 2. TOGS folded inside the truck for transportation.

order to achieve short installation time and setup time, the supply unit contains the necessary control units for calibration and operation. For calibration of position and attitude, TOGS contains multiple sensors. A dual-antenna GPS device provides position and heading information, and an inclination sensor measures roll and pitch angles. In addition, a special truck is also manufactured which can be used for transporting the TOGS. Moreover, the truck also has an operation room which contains all necessary components like computers to control and operate the TOGS. The TOGS can be operated on both AC and DC power networks supporting common line voltages and frequencies. The whole setup can also be powered using a generator.

2. TOGS HARDWARE

2.1 Optical System

The optical system consists of the telescope, and a tracking- and receiver unit which is located behind the telescope as shown in the Figure 3. Optical signal received by the telescope is divided by a beam splitter cube and focused on the tracking and data receiver. If the free-space optical receiver front-end is optimized, the spot with diameter of approximately 80 μm can be achieved which is sufficient for receiving signal at the receiver front-end using photodiodes.

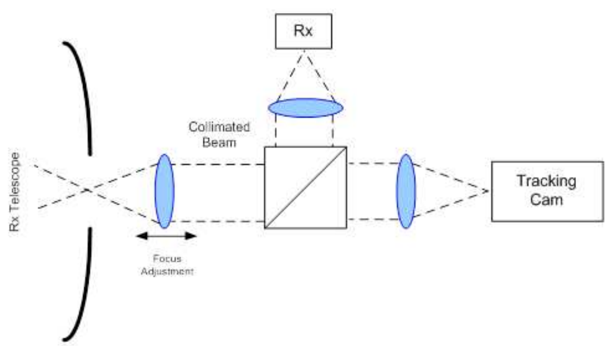

Figure 3. Optical systems of TOGS telescope

2.2 Telescope

The telescope used in TOGS is a Ritchie-Chrétien-Cassegrain-Telescope, which provides a very small structure in proportion to the main mirror diameter. Main and secondary mirrors are manufactured from aluminium. The telescope mount is manufactured of carbon fiber that makes it light-weight and strong. Some important parameters of telescope are stated in Table 1 and detail specifications of telescope mount are listed in Table 2. The telescope also contains drive motors and a slip ring for supplying power supply to the drive and receiver electronics, and for data transmission.

Table 1. Specification of the telescope.

Telescope type	Cassegrain (Ritchie-Chrétien)
Main mirror diameter	600 mm
Secondary mirror diameter	158 mm
Focal length	1500 mm
Design wavelength	1550 nm
Focus spot diameter	$< 80\ \mu$m
Field-of-View(FoV) of tracking camera	4.8 mrad with 50 mm lens
Field-of-View(FoV) of receiver front-end	167 μrad with 30 mm lens

Table 2. Specification of the telescope mount.

Type	Fork mount (Azimuth-Elevation)
Material	Carbon fiber
Drive train	Torque-motors
Encoder accuracy	$< 8\ \mu$rad
Angular velocity	max. $20°/s$
Angle range elevation	$-15...\ 95°$
Angle range azimuth	Unlimited

3. CONTROL SOFTWARE FOR TOGS

In order to control the TOGS, control software has been developed in C++. The software is designed in such a way that same software which is used in the TOGS can also be configured for controlling mobile terminals. Moreover, the software is made platform independent, meaning it would run in Windows or Linux operating systems without additional modifications. The structure of the software is divided in three layers namely, user-interface layer, system layer and device layer. User-interface layer includes implementation of graphical user interface (GUI) letting user to control the software, system layer includes implementation of core part of the software including control algorithms, and finally the device layer consists of driver implementation of devices used like cameras, joystick, Global Positioning System (GPS) and Inertial Measurement Unit (IMU). User-interface layer sends user's instruction to the system layer via network. This feature enables the user also to control unmanned mobile terminals remotely like those installed in Unmanned Aerial Vehicles (UAVs).

3.1 Pointing, Acquisition and Tracking (PAT)

The key to free-space optical communication is continuous line-of-sight lock between two terminals. For this, a beacon laser is installed co-aligned with the communication laser, in both terminals to illuminate each other. Based upon the prior knowledge of whereabout of its counter terminal, both terminals points towards each other and scans unless line of sight is acquired and laser beam coming from partner terminal is seen in the narrow field-of-view (FoV) tracking camera. Finally, after acquiring the partner terminal, TOGS continuously tracks the moving target. This process all together is called *pointing, acquisition and tracking*.[6] The whole process can be explained with the help of Figure 6.

For initial pointing, TOGS receives or calculates the instantaneous position of the mobile terminal. For aircraft tracking, TOGS receives GPS position of the aircraft via bidirectional TeleMetry and TeleControl (TMTC) RF-link.[4] For satellite tracking, the TOGS software calculates the instantaneous position of the selected satellite using publicly available two line elements (TLE).[3] A GPS device is also installed in the TOGS to receive its own position. Knowing the target and own GPS position, the core software calculates the pointing angle that the mount needs to move in azimuth and elevation direction. It then commands the mount driver to move the mount towards the target. On the other hand, it also continuously receives the position where the mount is actually pointing at. Using this information and basic control loops, the mount tracks the mobile terminal. This process is called *open-loop tracking*. However, open-loop tracking has some errors up to few milliradians because GPS devices cannot provide very accurate real-time position and there are also delays of few milliseconds in TMTC link. This error (position offset) is seen in narrow-FoV infra-red tracking camera. If the camera is perfectly aligned with the telescope and the receiver front-end, the laser beam coming from the mobile terminal will be seen as a bright spot at the center of the camera or to the known spot target position in the camera frame (as shown in Figure 4). The spot target position is the position of the spot in the camera image where the receiver front-end receives the signal. This position is measured by performing alignment tests with test lasers. In case of pointing/tracking error, the spot will not lie exactly at the target position in the tracking camera frame but will be a few pixels away. There is a separate software module called *Visual Tracker* which detects the spot in the tracking camera frames and corrects the error. At first, images are thresholded to separate the bright laser spot by subtracting the background. Hence, the spot is detected by calculating the center of gravity of the resulting image (see Equations 1 and 2).

$$CoG_X = \frac{\sum_{x,y} I_{x,y} \cdot x}{\sum_{x,y} I_{x,y}}, \tag{1}$$

$$CoG_Y = \frac{\sum_{x,y} I_{x,y} \cdot y}{\sum_{x,y} I_{x,y}}, \tag{2}$$

where CoG_X, CoG_Y are the center of gravity coordinates and I_{xy} is the pixel value at point (x, y) of the image frame. Finally, the tracking error is calculated using Equations 3 and 4.

$$dx = atan\left((CoG_X - target_X)\frac{a}{f}\right) \times \frac{180}{\pi}, \tag{3}$$

$$dy = atan\left((CoG_Y - target_Y)\frac{a}{f}\right) \times \frac{180}{\pi}, \tag{4}$$

where dx, dy is the tracking error in azimuth and elevation respectively. $target_X$, $target_Y$ are the spot target position in the camera, a is multiplication factor and f is the focal length of the optical system.

This process is repeated continuously for each image frame and calculated error information is sent by visual tracker to the core program to compensate for the error. This improves the overall tracking accuracy and the process is called *optical tracking* or *closed-loop tracking*. Figure 4 shows the laser spot position in open-loop tracking mode, and optical tracking mode. It can be seen that when optical tracking was enabled, the mount moved such that the spot coincides the target position in the camera, thereby reducing tracking error of the whole system. Open-loop tracking is done in the beginning for pointing and acquiring signal from the mobile terminal. Once the terminal's laser spot is seen in the tracking camera, optical tracking is switched on and locked. This mode is named as *camera-only mode*. In this mode tracking is not influenced by inaccurate GPS information of the target. It only considers offsets observed in the tracking camera, which is more accurate.

3.2 Calibration of the TOGS

TOGS consists of both mechanical structure and optical elements which might not be aligned perfectly and might introduce some errors. These errors could be small offsets in azimuth and elevation, non-perpendicularity of azimuth and elevation axes, non-perpendicularity of optical axis and elevation axis, tilt of azimuth axis towards North, tilt of azimuth axis towards East, telescope flexure etc. A set of such angular errors is called *pointing model* (PM) of the mount. These errors will lead to significant tracking errors. Therefore, it is very important

Figure 4. Tracking camera simulated image frame showing the effect of optical tracking. Left: open-loop tracking mode, Right: closed-loop/optical tracking mode. Red cross in the picture shows the spot target position and white spot is the simulated laser spot seen in the tracking camera.

to compensate them by calibrating the mount before real operation. Simple errors like azimuth and elevation offsets can be calculated by pointing the mount to some known GPS locations and using the joystick to move the mount until the target is seen at the known target position of the tracking camera.

However, a more complex pointing model of the mount is calculated by following the calibration process similar to that of astronomical telescopes. Like astronomical telescopes, TOGS is calibrated by calculating its pointing model parameters. This is done by tracking various bright stars. Instantaneous position of stars are calculated with respect to geographical location of the TOGS using publicly available star catalogs.[7] Firstly, a bright star is selected and the mount is commanded to track the star. As explained in Section 3.1, if there are no errors, stars should be seen at the known target position of the tracking camera. However, if there are some errors (smaller than field-of-view of the camera), the star will be seen away from the known target position. In order to eliminate the error, small azimuth and elevation offsets are entered manually that compensates for error and brings the star to coincide with the target position in the tracking camera. Now, the measurements like original position of the mount and the position after manual correction are saved for PM calculation. Same procedure is repeated for a number of bright stars around the sky. Finally, the PM parameters is calculated by fitting the PM to the adjusted positions using the saved measurements. The pointing angle calculated before the correction is called *horizontal coordinate* and the error-compensated pointing angle is called *instrumental (mount axes) coordinate*. The block diagram presented in Figure 5 explains the procedure how calibration of the TOGS is performed.

Once the calibration of the mount is done and the pointing model is calculated, it will be used to transform the calculated pointing angle in horizontal coordinate to instrumental coordinate. This enables the mount to correctly point and continuously track its counter terminal as shown in Figure 6.

4. SIMULATION ENVIRONMENT

It is not always feasible to have optical downlink scenario to test every feature of the software. Therefore, a simulation environment has been developed for testing the software and making it more robust before using it in the real hardware. Various simulators have been developed within DLR, namely flight-path simulator, tracking camera simulator and mount simulator. Figure 7 shows how simulators are used for testing the software.

4.1 Flight-path simulator

The flight-path simulator is developed for testing and improving the pointing, acquisition and tracking of the TOGS especially for aircraft downlink scenarios.[8] As the name suggests, flight-path simulator simulates the possible paths of the aircraft during downlink. The main advantage of this simulator is that varieties of paths can

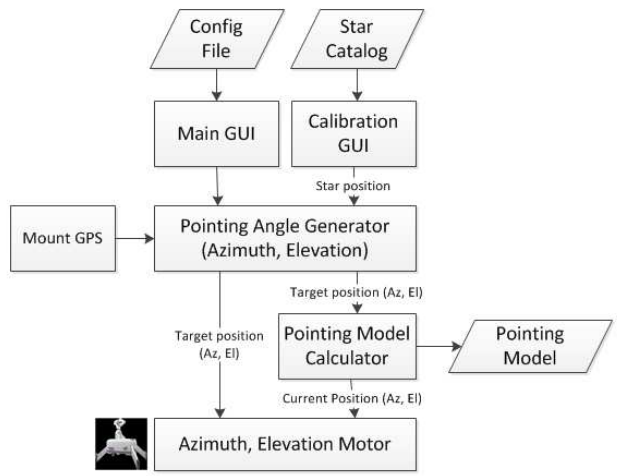

Figure 5. Calibration of the TOGS using star tracking. Target position is the target azimuth and elevation angle that mount should move. Current position is the azimuth and elevation angle where the mount is currently looking at.

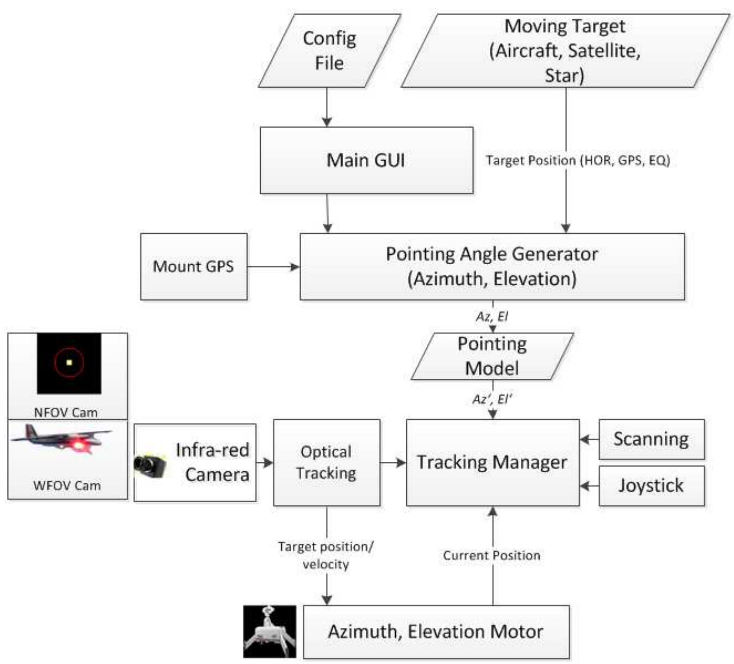

Figure 6. Operation of the TOGS. Az, El is the target position in horizontal coordinate system that is transformed to the target position in instrumental coordinate system (Az', El') using pointing model.

be tested repeatedly. The log files containing instantaneous position of the aircraft during previous downlinks can be loaded, or new paths can also be created. It also simulates the TMTC link which sends GPS information of the aircraft in NMEA format to the ground at a certain rate. In addition, various possible problems like interruption or delay in the TMTC links, receiving invalid NMEA strings, are also simulated to test the robustness of the software.

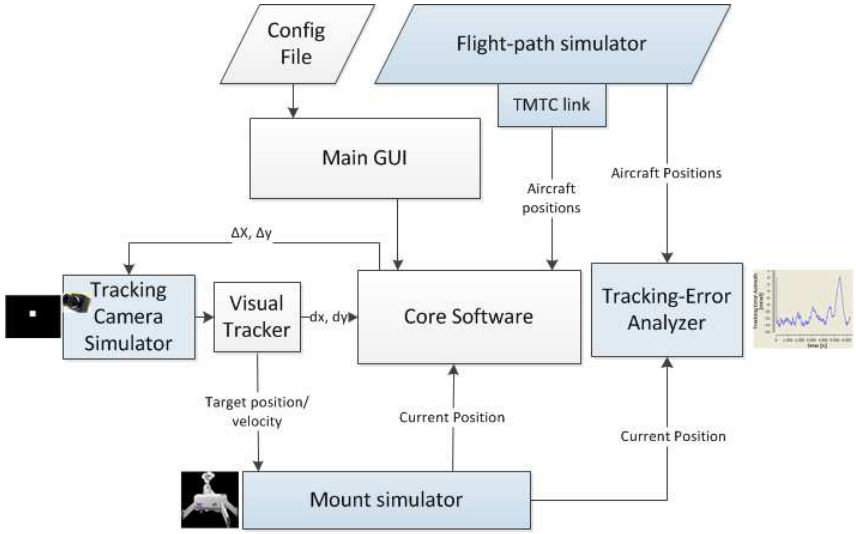

Figure 7. Control software and simulators. $\triangle X, \triangle Y$ is the difference between target and current position of the mount. dx, dy is the optical offset calculated by visual tracker. All blue blocks are simulators.

4.2 Tracking error Analyzer

Tracking error analyzer is a very important tool developed to evaluate overall tracking performance of the system in real time. It receives the instantaneous GPS position of the aircraft from flight-path simulator and current position of the mount from the real mount or the mount simulator, and calculates the tracking error. Tracking error is defined as the difference between the current position (where the mount is currently looking at) and the target position (position of the aircraft). The tracking error analyzer calculates the tracking error and plots it in real-time. This tool has been very useful for measuring overall performance of the system and testing different algorithms without using real hardware.

4.3 Mount Simulator

Mount simulator is a module that mimics the behavior of the real mount. In particular, the simulator is able to receive commands sent by higher software layer and calculate the motion of a real mount considering all physical conditions as realistically as possible. It considers two axes of a mount i.e. azimuth and elevation, similar to the real mount. Positional, velocity and acceleration limit in each axis can be configured like the one in the real mount. In addition, different pointing models (error) can also be inserted in the mount which enables the possibility to test the calibration module of the software too. Mount simulator also contains a GUI which displays the motion of the mount graphically and displays various useful parameters used in the software.

4.4 Tracking camera simulator

Optical tracking is one of the most essential part of the software and it is very important to extensively test the algorithm. However, it is inconvenient to have a moving laser source which would emulate the moving target. Therefore, tracking camera simulator has been developed that produces the image with laser spot of the moving terminal, like images produced by the tracking camera. The position of the spot in the image frame and size of the spot can be changed manually from GUI. When this tracking camera simulator is connected to the core software, it receives offset information i.e. the difference between real target position and current mount position from the core software. It them creates images with laser spot of certain diameter and few millimeter (offset) away from the spot target position. Similar to the tracking camera input, this image can be sent to the visual tracker which will then detect the spot and sends offset information to the core software as explained in Section 3.1.

5. GPS EXTRAPOLATION

For tracking aircraft, its instantaneous GPS position is very important and it is received by the TOGS via TMTC link. Normally the link is not fast enough and it has some additional delays. By the time GPS information of the aircraft reaches the ground station and mount moves to the position, aircraft is already in a new position. Therefore, there is always small lag between the target and current position of the mount. This leads to additional tracking error. In order to avoid this, GPS extrapolation module is implemented, which predicts the real-time position of the aircraft by doing linear extrapolation using two previous real positions.

A GPS tracking test is performed using flight-path simulator to produce a linear path as shown in Figure 8. The core software receives 5 positions per second via network (simulating TMTC link). The core software then controls the mount to track the aircraft. Tracking error analyzer is used to measure instantaneous pointing/tracking error of the mount. The aforementioned test is performed once without GPS extrapolation, and the test is repeated with GPS extrapolation. The result as shown in Figure 9 confirms that the GPS extrapolation decreases the tracking error. In this test, the tracking accuracy is improved approximately by 0.3 milliradian. It is expected that the tracking error can be further improved by doing higher order extrapolation and optimizing the GPS extrapolation algorithm.

Moreover, sometimes the TMTC link might not work perfectly, and consequently there might be interruptions or delays. In such cases if the mount keeps tracking the old position, it would cause mis-pointing, and line-of-sight contact would thereby be lost. GPS extrapolation is also expected to improve the tracking error significantly in such scenarios.

Figure 8. Aircraft path used for testing.

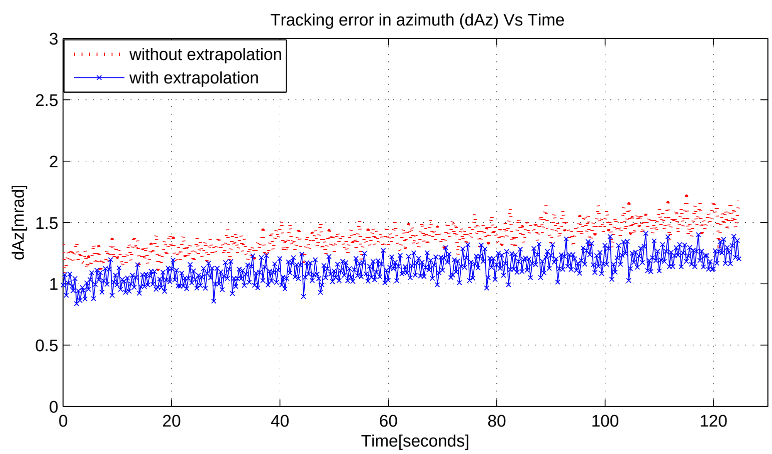

Figure 9. Tracking error measured using mount simulator for the aircraft path shown in Figure 8.

6. CONCLUSION

Both hardware and software of the TOGS is ready for various optical downlink scenarios like those with aircrafts, satellites and other high-altitude platforms. The control software has been extensively tested using simulator as well as real hardware. Recently, first successful data downlink was performed from DLR aircraft, which was flying in half circular paths around the TOGS. Various tests were performed by flying the aircraft at a distance of 20 km, then 10 km and finally 5 km away from the TOGS. During all the tests, open-loop GPS tracking performed well enough, such that the beacon laser spot from the aircraft was visible on the tracking camera. When spot was detected in the tracking camera, optical tracking was enabled. It is expected that with further optimization in optical tracking and using GPS extrapolation in future downlinks, tracking accuracy can be significantly improved.

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