DELFT UNIVERSITY OF TECHNOLOGY

LASER SWARM

SIMULATOR REPORT

DESIGN SYNTHESIS EXERCISE

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Abstract

As part of a laser swarm feasibility study, this document preliminarily describes the design and workings of a simulator. This simulator simulates a satellite swarm with a single emitter and multiple receivers flying in formation for the purpose of mapping the Earth's surface. The how and why of the simulator is discussed in this document.

Contents

List of Acronyms

ASTER Advanced Spaceborne Thermal Emission and Reflection Radiometer

BRDF Bidirectional Reflection Density Function

DEM Digital Elevation Model

ECEF Earth-Centered, Earth-Fixed

GDEM Global Digital Elevation Model

JAT Java Astrodynamics Toolkit

laser Light Amplification by Stimulated Emission of Radiation

TOD True Of Date

WGS84 World Geodetic System 1984

Chapter 1

Introduction

This report preliminarily discusses the design and workings of a software tool developed with the purpose of guiding and validating the results of the tradeoff done in the main laser swarm project, as well as demonstrating the feasibility of the concept of the laser swarm.

Generally speaking, the simulator program is divided into two parts. The first part is the simulation of the physical path of the photons in the laser pulse up to the point were they are received by the receiving satellites. This part has been documented in chapter 2, page 4.

The second part is the analysis of the received photon data, to determine terrain height and Bidirectional Reflection Density Function (BRDF). Obtaining this data is what the software and in general this feasibility study is about. This part is described in chapter 3, page 8.

Chapter 2

Simulation

In this chapter the simulation of the satellites moving through space and sending and receiving laser pulses is discussed. In section 2.1 the emitter and receiver satellite orbits are considered. In section 2.2 the way the Earth's surface was modeled is explained. In section 2.3 the path of the signal is examined, whereas in section 2.4 the introduction of noise into the signal is disclosed.

2.1 Orbit

The orbit of each satellite in the constellation is defined by means of six Keplerian elements. These define the shape of the orbit, the orientation of the orbit with respect to the center of the Earth and the position of the satellite on the orbit.

As there are a number of rotating bodies, three reference frames are used in order to facilitate the process of locating the satellites in space. Three reference frames employed.

The first is True Of Date (TOD). Its x-axis points towards the direction of the vernal equinox and its z-axis coincides with the axis of rotation of the earth. TOD takes into account nutation and precession of the earth. For practical reasons, it does not rotate with respect to the sun.

In the second place we have Earth-Centered, Earth-Fixed (ECEF). Its x-axis points towards $0°$ latitude and $0°$ longitude. The XY plane lies in the plane of the equator. Its origin is in the center of mass of the Earth.

Thirdly there is the PQW. The P-axis points towards the perigee of the orbit, the PQ plane lies in the plane of the orbit and the W-axis is perpendicular to the plain of the orbit. The origin of the frame is at the focal point.

The program converts between the before-mentioned reference frames for the user's convenience.

The position of the satellite is defined with respect to the TOD reference frame. The position for a certain time is determined by means of solving Kepler's equations. The orbit is determined for every satellite in the constellation. The orbit is assumed to be perfect, meaning that its orientation and shape do not change: perturbations are not considered.

The Earth's rotation about its own axis and around the Sun is simulated in order to provide a more realistic simulation environment. From the rotation of the Earth around the Sun, the sun vector is deduced;

this is used in noise calculations.

Most of the functions are adapted to the simulator from the Java Java Astrodynamics Toolkit (JAT) library.

2.2 Earth Model

The Earth model is the digital representation of the Earth surface. It stores a Digital Elevation Model (DEM), and the scattering characteristics of the local terrain. In section 2.2.1, the DEM implementation will be elaborated and section 2.2.2 describes the way incoming radiation is scattered.

2.2.1 Digital Elevation Model

A Digital Elevation Model is a digital representation of a topographic surface. For the ground representation in the simulator a few tiles of the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) were used. This DEM was created using the complete history of the ASTER instrument launched on the Terra satellite. This DEM has a spatial resolution of one arc-second and a vertical accuracy of $7 \sim 14$ meters. The elevations of the intermediate points were obtained using nearest-neighbor interpolation.

The ASTER GDEM elevations are expressed with respect to the World Geodetic System 1984 (WGS84) ellipsoid. To simplify the internal simulator, the DEM tiles were projected to the EPSG:3857 spheroid. The projection is done using the GeoTools Java toolkit [geo(2010)].

The digital elevation is used to compute the total distance (and thus the time) that the laser pulse travels. Because scattering is dependent on the terrain normal, this normal is derived form the DEM. This normal is derived from the two perpendicular surface gradients that can be extracted from the DEM.

2.2.2 Scattering Model

Scatter is the physical process where incident radiation is absorbed and reflected back into the atmosphere. To this end a scattering model is used. This scattering model is a way to construct a BRDF. A BRDF is a distribution of the incident light over the hemisphere [Rees(2001), pages 47-49]. An example is shown in figure 2.2.2, page 6.

The most basic example of a BRDF is the Lambertian model [Rees(2001), pages 49-50]. This model assumes a homogeneous perfectly rough surface, causing a homogeneous scattering distribution. Apart from the index of refraction of the air, the incident radiation vector and the exittant radiation vector (which are all known) use of Snell's law is needed to find Fresnel's coefficients, thereby requiring the index of refraction of the ground.

A modification that can be made to take into account the tendency of surfaces to scatter more in the direction of the surface normal, is called the Minnaert model [Rees(2001), page 50]. It causes a more elliptical BRDF. It depends on the Minnaert parameter κ.

Another important modification is the Henyey-Greenstein term. It accounts for the tendency of surfaces to back- or forwardscatter [Rees(2001), page 51]. This rotates and deforms the elliptical BRDF obtained from the Minnaert model. The Henyey-Greenstein term is parameterized by Θ. The final result is shown in figure 2.2.2, page 6.

This is the scattering model used in the program. Because there is no data from which all three parameters can be accurately determined, a coefficient map was made up. It does not matter much what the precise form of the BRDF used in the simulation is, so long as it can be retrieved.

With the help of the formulae from [Rees(2001), pages 43-51], the incidence vector can be taken and the number of photons radiated in a specific direction can be calculated. Note that the program does not integrate over part of the sphere: because the angle of the cone is very small, the BRDF is assumed to be constant over the cone. The error induced here is worth avoiding the computationally expensive integration.

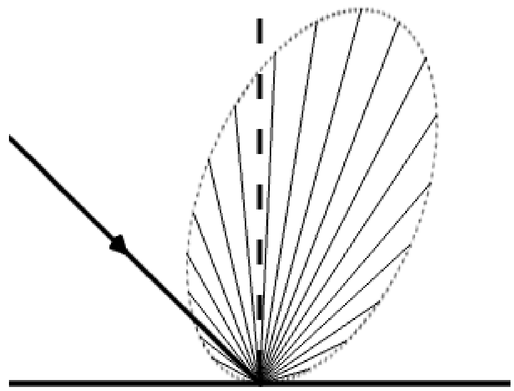

Figure 2.1: Example of a BRDF

2.3 Signal Path

The simulated path that the Light Amplification by Stimulated Emission of Radiation (laser) signal follows is visualized in figure 2.3 on page 6. There are three distinct phases. The first one is the travel of the signal down through the atmosphere. This is followed by the scattering on the Earth's surface. Finally the pulse has to travel back up through the atmosphere. This sequence is elaborated on in more detail below.

The signal originates from the emitter. For each pulse, the emitter position is determined from a set of Kepler elements. The energy in the pulse is found by distributing the emitter power over a constant number of pulses of a given duration.

The signal then starts to propagate through the atmosphere. The atmosphere affects the signal in several manners, but the most important one is the attenuation of the signal. Attenuation is the only disturbance by the atmosphere taken into account. The pulse energy exponentially decays with travel distance through the atmosphere. Furthermore also the optical thickness of the atmosphere is taken into account.

Then the intersection of the pulse with the DEM is computed. As a simplification in this process, the intersection of the pulse (i.e., the ray) with a sphere is computed. The sphere has a radius of the average terrain height of the DEM tile plus the Earth radius. Then the ray-sphere intersection point coordinates are converted into latitude and longitude. These are then used to find the actual terrain elevation from the DEM and the three-dimensional position.

Then the scattering characteristics are constructed. For this, the terrain normal and the inbound laser pulse vector are used. The power of the emitted pulse is now distributed over the entire footprint area of the emitter and then scattered back using the scattering technique described in section 2.2.2. The backscattered energy is computed separately for every receiver satellite.

The reflected pulse now travels back through the atmosphere. More attenuation takes place along this path. The energy received by the receivers now depends on the receiver aperture. The received energy can then be converted into photons by dividing the energy received by the energy per photon.

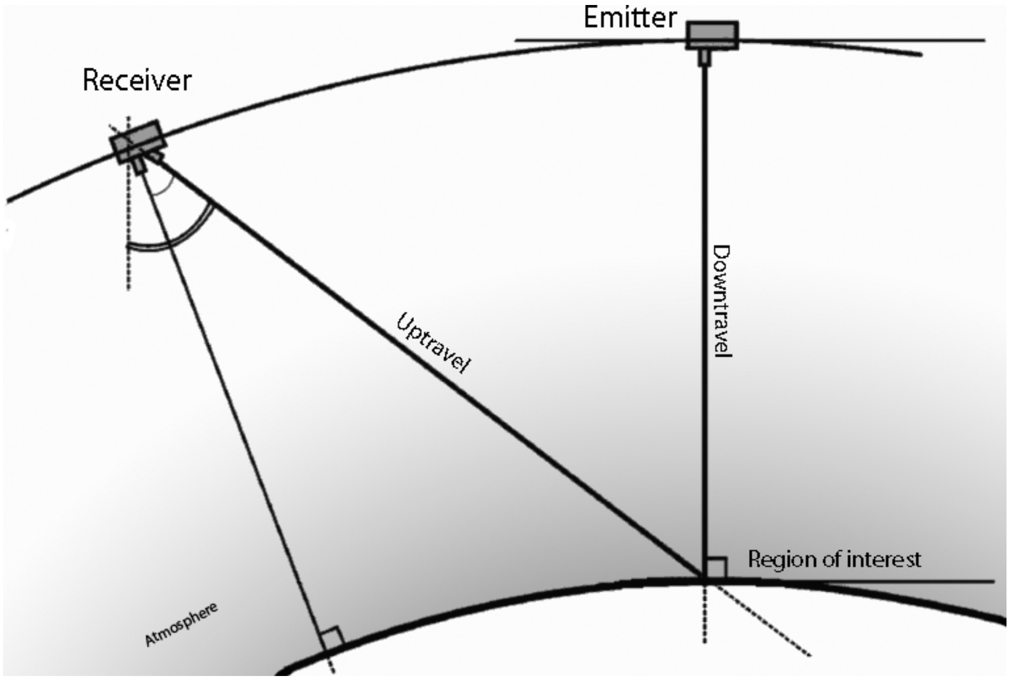

Figure 2.2: Signal path representation

2.4 Noise Introduction

The main source of noise in the system comes from the Earth's surface. This includes sources on the Earth such as lights along highways and reflected radiation, i.e. the Earth's albedo. The amount of radiation that is received by the receivers depends on the footprint of the receivers. This is an ellipse created by the intersection of the cone originating from the receiver with the terrain. A simplification is made in that the DEM is assumed to be a flat area with the elevation of the center point.

The amount of power emitted per square meter is dependent on the illumination of the Earth by the Sun. If the Sun illuminates the footprint, the emitted power is the scattered power of the Sun in the receiver detection wavelength bandwidth. This power can be found by integrating Planck's law over the detection spectrum and the solid angle the Sun subtends to the receiver footprint on Earth. If the Sun does not illuminate the receiver footprint, it is night on Earth at the footprint, and the exitant radiation in the visible spectrum is assumed to be zero[1].

While noise propagates trough the atmosphere it is also attenuated. This attenuation is computed in the same way the signal attenuation is; see section 2.3.

[1]Contributions from civilized light sources can be neglected when compared to the Sun's power output.

Chapter 3

Data Analysis

In this chapter the analysis of the received photon data taken care of in the software tool is elaborated on. The analysis consists of two parts: the terrain altitude determination and the BRDF determination. The first is expounded in section 3.1, the second in 3.2.

3.1 Altitude Determination

In order to tackle the problem of decrypting the raw data and converting it into a coherent terrain model, various statistical techniques need to be employed. The basic principle behind the altitude determination of the terrain is as following. First the time difference between generation and reception of the pulse is registered. As the position of the emitter at the time when the pulse was sent is known, just like the position of the receiver at the time the pulse was received is, the distance to ground can be determined. In theory only one emitter and one receiver are necessary to determine the altitude, but due to various uncertainties in position and noise characteristics of the received data, more receiving satellites are necessary to obtain a reliable and complete terrain representation.

In the simulator the emitter is modeled such that it records the time when the pulse was sent. The receivers are modeled such that they register the time and intensity (in photons) of the received pulse. The problem is that not all emitted pulses are registered, and sometimes noise, which does not correspond to any emitted pulse, is registered.

One of the ways to solve this problem is to use multiple receivers. The noise could be identified and removed by means of looking for a spike in the received photons for the whole swarm within a certain time range (usually twice the time it takes for a light beam to travel the orbit altitude). This data could be filtered by means of correlating the distance of the receiver to the Earth center and the time of the received pulse. Usually, the larger the distance, the larger the time difference. This method helps to eliminate outliers. Since the footprints overlap, the measured altitudes could be further smoothed out by means of a running average.

3.2 Bidirectional Reflection Density Function Determination

The BRDF returns the ratio of the radiance to irradiance for a given angle perpendicular to the surface. In theory, it is possible to measure it by means of the received photons of all of the receivers for a given pulse, where each received photon indicates the relative intensity. From the position of the receivers the direction of the irradiance vector can be calculated. Having the direction and intensity of the reflected radiation a segment of the BRDF for a specific incident angle could be reconstructed. By making a multiple passes over the same region, a partial BRDF for different incidence angles can be recorded. If the data is interpolated, a complete BRDF can be determined.

Bibliography

[geo(2010)] Geotools, May 2010. URL `http://www.geotools.org/`.

[Rees(2001)] W. G. Rees. *Physical Principles of Remote Sensing*. Cambridge University Press, Cambridge, second edition, sixth printing edition, 2001. ISBN 9780521669481.