D^{op}T^{rack}: Ground-station for Doppler Satellite Tracking of LEO satellites

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1 Introduction

The D^{op}T^{rack}is an initiative that proposes to acquire and operate radio equipment for the purpose of tracking Low-Earth Orbit (LEO) satellites by the means of the Doppler-shift observed in the carrier frequency of their telemetry signals. The radio equipment is to be installed along side the Space Systems Engineering (SSE) ground station located on the last floor of the Elektrotechniek, Wiskunde en Informatica (EWI) building and comprises of a radio receiver, a Software Defined Radio (SDR), a Global Positioning System (GPS) disciplined clock and a computer.

The D^{op}T^{rack}project intends to determine the orbit of over-passing LEO satellites by measuring the frequency shift associated with the Doppler effect of the carrier frequency of the telemetry signals that are continuously emitted by those satellites. It is possible to related the shift in frequency as the satellite approximates and distances himself from the ground station with its relative velocity or the *range-rate*. The measured range-rates are used to correct an initial guess of the orbit, usually given in the form of Two-Line Elementss (TLEs).

The main objective of the D^{op}T^{rack}is to provide the students of the TU Delft with a hands-on learning tool in the subjects of signal propagation, data processing, error analysis, orbital mechanics and Precise Orbit Determination (POD), to name a few. The secondary objectives are related to the continuous and autonomous tracking of LEO satellites and the establishment of cooperative network of Doppler-shift tracking ground stations between interested partners, such as other universities and amateur radio operators. The purpose of the additional objectives is the improvement of the orbits of LEO satellites relatively to the TLEs.

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2 Objectives

The objectives of the ground station are split into pedagogical, scientific and cooperative. The pedagogical objectives are related to the possibility of using the ground station as a teaching tool for the students of the TU Delft. The scientific objectives are the expected gained knowledge that is worthy of publication in a scientific journal or conference. The cooperative objectives aim at exploiting the complementary expertise of the Astrodynamics and Space Missions (ASM) and SSE groups and, at a later stage, strengthening the connecting with other universities.

2.1 Pedagogical objectives

The teaching activities envisioned within the $\mathrm{D^{op}T^{rack}}$ project take the form of practical student assignments. The students attend one session at the ground station premises where they take the necessary steps to gather the data for later analysis. The innovative part of the practical assignment is that the students analyse real data that they gathered themselves and are able to estimate actual quantities, through procedures and algorithms that they implement.

THe following practical projects are proposed:

- Orbit determination of LEO satellites, preferably TU Delft-built;
- Measurement of the Earth-Moon distance with radio signals;
- Orbit determination of Moon-orbiting probes.

2.2 Scientific objectives

The first objective of the $\mathrm{D^{op}T^{rack}}$is to perform the early post-launch orbit acquisition of Delfi-n3Xt (and all additional TU Delft-built satellites), prior to the availability of the (accurate) TLE data. On a routine basis, the $\mathrm{D^{op}T^{rack}}$will conduct the persistent and automatic acquisition of Doppler-shift profiles of over-passing LEO satellites and process the resulting measurements into improved TLE or position time series. With the accumulation of data, it is proposed to fine-tune the processing methods to improve the accuracy of the TLEs of LEO satellites.

2.3 Cooperative objectives

The $\mathrm{D^{op}T^{rack}}$proposes to improve the communication and interaction between the ASM and SSE groups. To that effect, the hardware built by the SSE group is used to gather data to be processed by the ASM group, synergistically bringing together the competences of the two groups for a common goal. As feedback, the lessons learned by processing the gathered data serve to provide suggestions for further hardware development at the SSE group.

On a wider scale, the cooperative objectives of the DopTrack are to implement of a world-wide network of Doppler-shift tracking ground stations, in cooperation with other universities, institutes or radio amateurs. The collected data is shared among all intervening partners. The world-wide distribution of the measurements poses a better constraint to the orbit determination problem, leading to larger improvements of the disseminated TLEs.

3 Methodology

The carrier frequency of the telemetry of satellites can be used to observe the relative velocity of the satellite with respect to a ground station. By measuring the frequency shift of the transmitted signal over a complete pass, a Doppler shift can be observed. This Doppler shift can be used to construct range-rate observables that further can be used in orbit determination.

The complete system of on-board transmitter, signal, antenna, radio equipment, data storage, post-processing and orbit determination can give students a better knowledge of satellite technology, telemetry and orbit determination. To let the student be involved in the complete process of scheduling, observation, pre-processing, post-processing and orbit determination it will motivate and enhance learning objectives.

A small pilot was performed in the second year project AE2-2222, during the 3rd and 4th quarters of 2013. Students stated that the project is interesting and motivating. They commented that the process is demanding, but they were willing to do this kind of work. Other comments can be found in Appendix A. They felt that they were learning and could grasp what they were doing, despite the complexity of the assignment. Their end result can be found in Appendix B. Their project was about extracting range-rate observables from the raw data (2 channel Windows Wave (WAV) file) and compare these observables with TLE data.

For orbit determination the TU Delft Astrodynamics Toolbox (TUDAT) software package, developed in the ASM group can be used to construct a tool for orbit determination. This hands on approach by students can give in depth knowledge of aspects in the orbit determination field.

This section will report on the different processes the students could work on. The sections are about signal analyses, data processing, Doppler shift theory, orbit determination and error investigation. All elements that are important in space technology.

3.1 Signal recording

The carrier frequency of the telemetry of LEO satellites needs to be recorded in digital form in order to be processed and the range-rates derived. The following steps are needed to accomplish this:

- The antenna receives the electromagnetic radiation associated with the satellite radio signal, i.e. the telemetry's carrier frequency;
- Located at the base of the antenna is the Low-Noise Amplifier (LNA), which amplifies the received signal;
- The radio receiver performs band-selection and filtering, forwarding a certain portion of the Radio Frequency (RF) spectrum to the SDR, after shifting the signal's high-frequency to the radio's Intermediate Frequency (IF), i.e. acting as a tunable frequency down-converter with adaptive filtering;
- The Analogue-to-Digital Converter (ADC) in the SDR digitalizes the signal in the form of In-phase/Quadrature (I/Q) components and feeds it to the computer via the Local Area Network (LAN) interface.
- The computer saves the I/Q data to the hard disk for later processing.

The large volume of data and the frequency of satellite overpasses dictates that the hardware is required to be fully automated and to be remotely operated for maintenance, monitoring and extraordinary operations.

3.2 Processing Chain

In brief terms, the data processing occurs in the following steps:

- The D$^{\mathrm{op}}$T$^{\mathrm{rack}}$ hardware records the telemetry signals in the form of the I/Q components, according to a pre-defined schedule[1];
- After the satellite disappears over the horizon, the Doppler-shift profile is extracted from the recorded I/Q data[2];
- The initial guess of the satellite's orbit, usually given by TLEs, is corrected so as to fit the Doppler-shift profile[2];
- The orbit, in the for of updated TLE data, is published on the D$^{\mathrm{op}}$T$^{\mathrm{rack}}$ website[2].

3.3 Data acquisition

The observed signal is stored in the WAV file format[3]. The file will have 2 channel, c_1 and c_2, because the recorded signal around the centre frequency is converted to an imaginary number, s:

$$s = c_1 + i * c_2, \quad i = \sqrt{-1} \tag{1}$$

The values in each channel are amplitudes with a pre-defined time step. For example:

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[1] The recording schedule is manually inserted and updated. At a later stage, it will be parsed from satellite tracking website, such as `www.heavens-above.com`.

[2] Generally without user intervention

[3] It is possible that other formats are supported by the SDR; further testing will determine if they are more suitable.

- 50 kHz will result in 300 MB files;
- 500 kHz will result in 2 GB files.

Students should be able to extract the data from these files in order to manipulate them.

3.4 Doppler-shift profile extraction

Doppler shift is visible in the frequency domain after performing a Fourier transform on the recorded signal, defined in the time domain. When a “waterfall plot” (amateur radio definition) is constructed, the characteristic Doppler curve can be seen and the frequency shift measured as function of time. The Fourier main signal associate with the carrier frequency the telemetry must be separated from noise and other irrelevant signals polluting the RF spectrum. Several numerical filters can be designed and implemented to accomplish this in a robust way.

The Doppler theory makes it possible to converted the frequency shifts to range-rate observables. These can be compared with other observations, such as TLE, GPS and alternative POD methods, or can be used to determine the actual orbit using the estimation software build in TUDAT.

3.5 Errors

The following error source are predicted, in decreasing order of expected magnitude:

- Tropospheric and ionospheric delays;
- Emitter frequency stability;
- Data digitalization;
- Receiver frequency stability.

The tropospheric and ionospheric delays result from deviations of the path of the radio signal between the satellite and the ground station due to refraction, as it goes through the two atmospheric layers. Use will be made of models to minimize the effect of these errors. In addition, the existing hardware of the SSE group, whenever available, will be used to eliminate the tropospheric and ionospheric delays of LEO satellites that emit in two frequencies.

The emitter frequency stability results from deviation in the reference frequency on-board the satellite, which is important to set the radio frequency in which the signal is emitted. It is not a factor that can be controlled and is a property of the radio emitter of each satellite. It is expected that temperature effects can be modelled and corrected to some extent, possibly increasing the accuracy of the measured Doppler-shift profiles.

The data digitalization error results from the transformation of the analogue radio signal into discrete digital data. The data sampling rate (how often the signal is measured) and the data resolution (the difference between two consecutive measurable values) of the ADC in the SDR are the most important factor to the digitalization error. For the measurement of Doppler-shift profiles, the data resolution is not dominant as long as the signal reaching the SDR is strong enough. The data sampling rate, on the other hand, is extremely important to increase the number of measurements in time and frequency.

The receiver frequency stability error is assumed to be very low since the GPS disciplined clock provides a very accurate reference frequency to the SDR and radio receiver. In the absence of GPS disciplined clock, the receiver frequency stability will decrease and possibly dominate the data digitalization error.

4 Hardware

The hardware of the $\mathrm{D^{op}T^{rack}}$ is dedicated to the reception of satellite radio signals and has the following components:

- Antennas and LNA;
- Radio receiver;
- SDR;
- GPS-disciplined clock;
- Computer.

4.1 Antenna

The current existing hardware in the SSE ground station includes two antennas: one omni-directional antenna for the 2 m band (or Very High Frequency (VHF) band, at around 146 MHz) and another 3 m-dish for the S-band (around 2.4 GHz). There is a third omni-directional 70 cm band antenna (or Ultra High Frequency (UHF) band, at around 430 MHz) which is not in use. The $\mathrm{D^{op}T^{rack}}$ project proposes to use this antenna to expand the number of satellites emitting in two frequencies so that a larger number of satellites can be tracked without errors associated with tropospheric and ionospheric delays.

The use of the antennas can be done simultaneously with the routine operation of the SSE ground station, since the antenna feeds are physically split to both radio receivers. Notably, both SSE and $\mathrm{D^{op}T^{rack}}$ hardware can receive different satellite signals at the same time from the same antenna, therefore not limiting the operations of either hardware streams. The exception concerns the S-band directional antenna and the occasional transmission of signals to the TU Delft-built satellites in the VHF and UHF bands.

There is the need to acquire one LNA to connect to the 70 cm antenna, since this equipment is not currently available. Figure 1 shows a typical LNA.

Figure 1: SP-7000 LNA

4.2 Radio

The radio receiver is important for the proper reception of the satellite signals since it contains a number of filters that eliminate strong terrestrial signals (and their harmonics) from radio sources located at the vicinity of the $\mathrm{D}^{\mathrm{op}}\mathrm{T}^{\mathrm{rack}}$ antennas. The location of the EWI building exposes it to a large number of such signal sources, making this issue a point of concern. It is possible to connect the antennas directly to the SDR but the neighbouring terrestrial signals may overload the input of the SDR, causing intermodulations and a strongly decreased sensitivity. In that case, the weak signals from satellites may be impossible to receive.

The requirements for the radio receiver are:

- Reception of satellite's main telemetry downlink frequency bands (2 m, 70 cm and S-band);
- Analogue IF output to connect to the SDR;
- external reference frequency input;
- Remote controllable.

Using the radio receiver as a down-converter also opens the possibility of other listening to other frequency bands of interest. Should that prove to be advantageous in the future, there is only the need to acquire the corresponding antenna and LNA.

The radio receiver of the $\mathrm{D}^{\mathrm{op}}\mathrm{T}^{\mathrm{rack}}$ is chosen to be the AOR AR5001D[4], see Figure 2, with the following relevant characteristics:

- Frequency range: 40 kHz to 3.15 GHz;
- 10 MHz reference input (SMA-J connector) for 0.01 ppm frequency accuracy for the 10 MHz internal master oscillator is obtained when synchronized to a GPS signal;

[4] Further details: wsplc.com

- 45.05 MHz Analogue IF output with 15 MHz bandwidth (BNC-J connector);
- Universal Serial Bus (USB) 1.1/2.0 connector for Personal Computer (PC) control;
- remote antenna switching, requires AOR AS-5001DX[5].

Figure 2: AOR AR5001D Radio receiver

4.3 SDR

The SDR is the key component of the $\mathrm{D^{op}T^{rack}}$ hardware, since it digitalizes the satellite signal to be properly processed. The requirements for the SDR are:

- High data sampling rate;
- Open-source Hardware Driver;
- External reference frequency input;
- External pulse per second (pps) input;
- Remote controllable.

The SDR of the $\mathrm{D^{op}T^{rack}}$ is chosen to be the USRP N210[6], see Figure 3, with the following relevant characteristics:

- 50 MS/s streaming rate (upgradable to 100 MS/s);
- Gigabit LAN Interface to PC;
- 10 MHz reference frequency input;
- Dual 100 MS/s, 14 bit ADC;
- based on open-source GNU Radio software;
- USRP BasicRX Daughterboardfor 1 − 250 MHz reception.

[5]Further details: shop.boger.de
[6]Further details: ettus.com

Figure 3: USRP N210 Software Defined Radio

4.4 GPS disciplined clock

The clock is responsible for feeding the radio receiver and SDR with a 10 MHz reference frequency, so that the incoming signal's frequency can be measured accurately. Failing to do so means that the radio and SDR will have to resort to the internal (usually Quartz) oscillator to determine the incoming signal's frequency. It is expected at least two orders of magnitude decrease in the frequency stability if the oscillators of the SDR and radio receiver are not externally stabilized.

Additionally, double-frequency tropospheric and ionospheric delay correction can only be accomplished if the two hardware streams are synchronized. The clock provides 1 pps signals that allow for the synchronization of all relevant hardware components, namely the two computers. Additionally, the pps signals provides a timing reference to the SDR for accurate triggering of the recording session and time-tagging of the measurements.

The requirements for the GPS disciplined clock are:

- High frequency stability, better than 0.01 ppm
- Multiple reference frequency outputs;
- Multiple pps outputs;
- Remote controllable.

The GPS disciplined clock of the D$^{\mathrm{op}}$T$^{\mathrm{rack}}$ is chosen to be the Spectracom Epsilon Clock EC20S[7], see Figure 4, with the following relevant characteristics:

[7] Further details: spectracomcorp.com

- GPS 12 channel reception on 1575.42 mHz GPS carrier (L1) Coarse/Acquisition code (C/A-code);
- pps accuracy to Coordinated Universal Time (UTC): 25 ns (1σ);
- 10 MHz accuracy < 2e-12 (one day average);
- Temperature Stability (peak to peak): 1e-9 (from 0 − 60 °C);
- 7×10 MHz sine wave outputs;
- 7×1 pps outputs;
- Remote management through Ethernet port;
- Network Time Protocol (NTP) server;
- Full remote control by serial port RS-232C.

Figure 4: Spectracom Epsilon Clock EC20S GPS disciplined clock

4.5 Computer

The PC for the $\mathrm{D^{op}T^{rack}}$ does not have particularly strong requirements, since the heavy processing is done in the SDR:

- Gigabit LAN Interface;
- Able to run Ubuntu Operating System (OS);
- 200 − 500 Gb hard disk.

All these requirements are easily met with an old computer that is not longer in use, which is advantageous to reduce costs.

4.6 Budget

The budget of the $\mathrm{D^{op}T^{rack}}$ hardware is summarized in Table 1

Component	Model	Cost (€)	Rerence
LNA	SP-7000 LNA	313.45	ssb.de
radio receiver	AOR AR5001D	2,689.55	shop.boger.de
antenna switch	AOR AS-5001DX	83.19	shop.boger.de
SDR	USRP N210	1,490.00	ettus.com
SDR daughter-board	USRP BasicRX Daughterboard	66.00	ettus.com
SDR Rack Mount	USRP U3 Rack Mount Kits	220.00	ettus.com
disciplined clock	Spectracom Epsilon Clock EC20S	2,790.32	cnrood.com
UHF omni-directional	EB-432 M^2	198.00 (!)	stecker-shop.net
bias-T (×3)	DCC 12/N	207.87	ssb.de
lightning protection (×2)	N-FF-J01028B0045	99.16	ssb.de
VHF/UHF splitter (×2)	ZFSC-3-1WB-N+	131.29	minicircuits.com
S-band splitter	ZB3PD-63-N+	99.90	minicircuits.com
computer	HP Compaq dc7800 Minitower	0	hp.com
cables, connectors, etc		500	ssb.de
taxes		1,747.98 (!)	
shipping costs		136 (!)	
assembly costs		300 (?)	
total		10000 (!)	
maintenance costs		1000/year	
teaching assistant		600(?)/year	

Table 1: Budget for the D^{op}T^{rack}hardware.

5 Software

The following software is going to be used in order to accomplish the objectives.

- Ubuntu[8] OS;
- Bourne-again shell (BASH) shell and Ruby[9] for automation;
- MATrix LABoratory (MATLAB) or Python[10] for the extraction of the Doppler-shift profiles from the I/Q data;
- TUDAT and C++ for the orbit estimation.

[8] www.ubuntu.com
[9] www.ruby-lang.org
[10] www.python.org

Acronyms

ADC	Analogue-to-Digital Converter
ASM	Astrodynamics and Space Missions, Faculty of Aerospace Engineering, T.U. Delft
BASH	Bourne-again shell (`www.gnu.org/software/bash`)
C/A-code	Coarse/Acquisition code
EWI	Elektrotechniek, Wiskunde en Informatica faculteit (Faculty of Electrical Engineering, Mathematics and Computer Science), TU Delft
GB	Giga Bytes, i.e. $1024 \times 1024 \times 1024$ bytes
GPS	Global Positioning System
LAN	Local Area Network
IF	Intermediate Frequency
I/Q	In-phase/Quadrature
L1	1575.42 mHz GPS carrier frequency
LAN	Local Area Network
LEO	Low-Earth Orbit
LNA	Low-Noise Amplifier
MB	Mega Bytes, i.e. 1024×1024 bytes
MATLAB	MATrix LABoratory (`www.mathworks.com`)
NTP	Network Time Protocol (`www.ntp.org`)
OS	Operating System
PC	Personal Computer
POD	Precise Orbit Determination
ppm	parts per million
pps	pulse per second
RF	Radio Frequency
SDR	Software Defined Radio

SSE	Space Systems Engineering group of the Faculty of Aerospace Engineering, TU Delft
TLE	Two-Line Elements (`www.space-track.org`)
TUDAT	TU Delft Astrodynamics Toolbox (`tudat.tudelft.nl`)
UHF	Ultra High Frequency band of the RF spectrum
UTC	Coordinated Universal Time
USB	Universal Serial Bus
VHF	Very High Frequency band of the RF spectrum
WAV	Windows Wave file format

A AE2-2222 student feedback

A.1 Questions

1 : What did you think of the project?
2 : How was the workload distributed over the project?
3 : Did you have sufficient knowledge to do the project?
4 : Can you recommend this project to other students?
5 : What did you learn during this project?

A.2 Answers

A.2.1 Student A

Question 1 : This was probably the best project I've done so far; I found the subject to be incredibly interesting and challenging. I especially liked how this was a real project, and not something that has been done countless of times before.

Question 2 : The workload was distributed properly.

Question 3 : At the start of the project: not really. This problem was solved by the literature research. Subjects that were still unclear, were clarified by you (which I really liked)

Question 4 : I would recommend this project to any student who even slightly interested in space.

Question 5 : Non-content related: looking at your own work with criticism. Content related: how to filter a very noisy signal, what range-rate is and the different reference frames and how they can be transformed into each other.

A.2.2 Student B

Question 1 : I found it very satisfying. Maintaining an overview of what we were actually doing was difficult at times, it was easy to forget that we're dealing with something physical when we were busy handling or discussing data. I am happy with our end result, and I think the idea that we, as students, actually managed to determine the range-rate of an object in space is very empowering.

Question 2 : I would say we all put roughly the same amount of effort in. The coding work was concentrated on by only a few people, which was unfortunate but unavoidable. I think most of us contributed to the conceptual work, figuring where to go next, what our data means, etc.

Question 3 : Not at the start, I had to learning more about Latex for the report writing, and a lot about signal analysis to understand what we were doing and to write a report on it. TLE data was a completely new topic I had to learn, however the Doppler shift concept I could handle and could use.

Question 4 : I highly recommend it to other students, I felt like I really accomplished something and didn't just "passively" go through the project. What seemed challenging at first was surprisingly achievable, and I think that is rewarding and shows that it is important to always put effort in.

Question 5 : I learned about side-lobes, sources of attenuation and noise, and many other signal analysis related topics. I discovered the value of a data set and how it can be used in not-so-obvious ways, for example attempting to determine the satellite's tumbling rate based on the periodic change in the frequency's amplitude (was not included in the report). Besides knowledge of the topic, I also learned how to criticize scientific conclusions (our own work) and data, and how to write a scientific report.

A.2.3 Student C

Question 1 : I think that this project was really fun working on. I really liked the idea that we got real data from a real satellite orbiting the earth. It was also very interesting to determine orbital parameters (even if it was only range rate) from only the signal in a relatively simple method. I found it nice that our method came relatively close to the official NASA method. And because we used real data we saw some interesting things which we would never see in college and stuff. It was also nice to have a totally space project for a change. All the other projects so far were really focussed on aircrafts. Sometimes space is stuffed in the project somewhere, but this was totally different. And compared to other groups we had the most interesting subject. It was also nice to bring the theory to practise, I really enjoyed it

Question 2 : The workload was quite high compared to other groups. But it was not too much in my opinion. Other groups were 3done with the project some weeks before the project officially ended. we were on the other hand busy with calculations until the last moment. But this was not bad at all, in my opinion it is how a project should be. The workload was quite evenly distributed over the project. Ad the end of the project we had more work because we had to write the article, but this is normal, at the end the work is always more.

Question 3 : At the start of the project not yet, but this is normal. During the project I learned a lot, which is the purpose of a project in my opinion. We had enough knowledge to start and develop our skills to the required level.

Question 4 : Simply yes. It was fun and I learned a lot

Question 5 : I learned a lot about MATrix LABoratory (MATLAB). Before this project I could do some simple work, make a basic plot and so on, but during this project I learned additional skills in for example plotting. Further I learned some things about the current orbit determination methods. But the most important thing is in my opinion the way of thinking. Programming in MATLAB requires a special way of thinking and in the projects before this one we didn't really practise this. It was also nice to learn some stuff about the Doppler effect.

B AE2-2222 student results