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Data transfer from satellite to ground station emulator

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Abstract. "Data transfer from satellite to ground station emulator" application has been developed for modelling data transfer between a small spacecraft at low-earth orbit and a control center on Earth. The application takes into account multiple parameters allowing to replace a number of experiments. Additionally, the SGP4 model and models such of parameters such as bit error rate and rain rate attenuation are studied and used in development of the application. Finally, the use cases for the application in education and introduction of school and university students to space-themed projects are considered.

1. Introduction

On March 22, 2021 the satellite of the National research university "Higher school of economics", CubeSX-HSE was launched, targeted at remote sensing of the Earth. So as to provide the high school and university students and opportunity to study the process of interaction with the satellite from Earth, a decision was made to develop the "Data transfer from satellite to ground station emulator".

With the growth of public interest in space research, astrophysics and celestial mechanics, including satellite technologies, demand for specialists and educational resources in these fields also increases and a complex solution is required.

Conducting certain experiments requires large investments, and software for modelling and visualising the processes involved is used to decrease them.

Nowadays, a significant portion of software is built using the client-server model as base, since it allows remote usage and expands the potential audience.

The developed product is targeted to visualise the communication between a spacecraft and a ground station, thus helping the user to form intuition regarding the parameters of a radiocommunication channel and the effect they have on the information being transmitted.

1.1. Two-line elements

Two-line element sets (TLE) [1] is a format of satellite telemetry used as an input in some orbital state vector determination models. TLE format allows to describe the orbital state with sufficient precision over a short period of time since its epoch (the time when the data that formed the TLE has been measured), but the precision decreases the larger the interval of time since epoch till the moment for which the prediction is computed. Due to that, TLE are generally considered valid for a week since the corresponding epoch.

TLE are generally provided as a set of two lines, each line being 69 symbols. TLE contain general metadata of the satellite as well as telemetry parameters.

1.2. SGP model
Simplified Perturbations Models [2] are a range of five mathematical models for computation of satellites orbital state vectors in earth-centered inertial coordinates. The models include: SGP, SGP4, SDP4, SGP8 и SDP8, with SGP4 with TLE as input along with its derivatives being the most widespread model in operation since the 1970s.

1.3. Client-server architecture
Client-server architecture is a model where the service requester (client) passes data to a service provider (server) which processes it and returns the result back to the requester. Such architecture allows to lessen the computational load on the client system.

1.4. Remote procedure calls; gRPC
gRPC is an open-source remote procedure calls (RPC) framework [3]. For transport it takes HTTP/2. Among its features is the following functionality: authentication, bidirectional streaming, flow control, bindings, cancellations and timeouts.

Alike many other RPC frameworks, gRPC takes the idea of defining the interface as a set of methods as its base, providing a way to execute the methods remotely with specified argument and return value types. The default interface and data type definition language used by gRPC is Google Protocol Buffers.

1.5. Data transfer channel mathematical model
The application described in this work models the change of data sent from a satellite at a low-earth orbit to a ground station due to noise. In order to take into account, the effect that the external factors have on the quality of data transfer, a model of bit error rate (BER) is used. The model is analogous to the one described in [4]. The simulation there is based on using sequences of parameter measurements taken over time. In addition, the model allows to gather, display and store statistics of the received results.

1.6. Mathematical model of signal attenuation due to rain
One of the major parameters used in computation of BER is the received signal strength. In addition to the free path loss, rain attenuation has to be taken into consideration for a more precise computation. The model for determining the loss due to this kind of attenuation is described in detail in ITU-R P.838-3 [5], using the parameters of the received signal, the position of the satellite relative to the ground station and rain rate.

2. Overview of existing solutions
In the MATLAB environment [7] there is a ConSat system [8], built on the basis of Simulink, which was used in the PoSAT-1 microsatellite project. ConSat is an open-source system [9].
The package can be used to simulate the dynamics of the translational and rotational motion of a satellite; all basic environmental conditions affecting a satellite in orbit; simulates the operation of sensors of the orientation determination system: magnetometer, solar sensor, Earth horizon sensor. Magnetic coils and flywheels are modelled as actuators. The package allows the user to embed their own algorithms and has a developed user interface.

2.1. Simulink environment, based on MATLAB
The Simulink environment [6] can be considered a similar solution, implemented on the basis of MATLAB [7]. It is a Model-Based Programming environment that allows to model and analyse multi-domain dynamic systems, and is also suitable for data transmission modelling. The main disadvantage of this environment is the high entry threshold.

2.2. ConSat system in MATLAB
In the MATLAB environment [7] there is a ConSat system [8], built on the basis of Simulink, which was used in the PoSAT-1 microsatellite project. ConSat is an open-source system [9].

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2.3. SPICE (Spacecraft Planet Instrument Camera-matrix Events)
SPICE software toolbox [10] was created in 2017 and includes:
1. user-level APIs;
2. library (API, routines and functions provided as source code);
3. ready-made applications with user manuals;
4. technical documentation for applications;
5. bindings and software modules for connecting from languages or environments such as C, FORTRAN, IDL, MATLAB, JNI.

2.4. Open MCT (Mission Control Technologies)
Open MCT (Mission Control Technologies) is a flight control environment [11] that allows data visualization on a computer / phone. With the help of this environment, it is possible to analyse data from spacecraft flights, or use it for planning missions of rovers. Based on MCT, it is possible to create applications designed for planning and analysing any telemetry systems.

MCT is one of the universal environments that can be used to combine calculations and overview of various parameters that need to be monitored when planning and implementing a mission.

2.5. Python. Pyorbital, python-sgp4, pyshp libraries.
Developed for Python programming language, pyorbital [12], python-sgp4 [13] and pyshp [14] libraries allow to integrate the trajectories of the spacecraft according to the available differential equations describing the trajectory of motion, and to obtain data from the satellite and convert the result to geodata format.

2.6. Orbit Determination Tool Kit (ODTK)
Orbit Determination Tool Kit (ODTK) [15] allows the user to process a wide range of measurements. Among them: object tracking from earth, as well as from space using GNSS, optical and RF corners, transmission and reception time and frequency differences, cosmic optics and more.

2.7. Mathcad
Mathcad is a computer algebra system belonging to the class of computer-aided design systems. Mathcad is focused on preparation of interactive documents with calculations and visual support. PTC Mathcad [16] [17] has an easy-to-use and familiar interface with natural mathematical notation and intelligent unit control. PTC Mathcad allows multi user access for participants which helps to work with information more efficiently. The system can implement a program for integrating satellite orbits.

3. “Data transfer from satellite to ground station emulator” model
“Data transfer from satellite to ground station emulator” (hereinafter, the emulator) is based on the client-server architecture. Due to the nature of the process as well as to allow for further use in frame-based transmission simulation, data is processed all at once instead of an iterative approach. Regarding the interface, the client passes an encoded data-containing (usually, an image) string to the server, where that string is processed and returned to the client. Lastly, the client decodes the string back to the original data type. Such behaviour is similarly described as an RPC with the encoded data serving as both an input and an output.

Due to the solution being implemented as a web application, “base64” [18] is used as an encoding method, since it is supported by both the most widespread web browsers and most of the server development libraries in one way or another.

Regarding modelling of the data transfer, a model similar to the one described in [4] is used. Based on the signal strength, noise level, symbol rate and bandwidth, either computed or defined by user, symbol energy per spectral noise density is inferred. Alongside the data on the encoding, modulation index and error correcting code used, raw bit error rate (BER) can be computed. In [4] it is further processed, yet for the solution described raw BER also represents the probability of any given bit being erroneously received (or, in other words, inverted). By using this value, it is possible to generate a bit mask M equal in length to the received data D. In the result $S = bitwiseXOR(D, M)$, each bit is inverted relative to the corresponding bit in D with probability equal to the raw BER.

For computing the strength of the received signal, the radar equation [19] (in a form $P_r = \frac{P_t G_t A_r F^2}{16 \bullet \pi^2 R^2}$ with P_r being the received signal strength, P_t - the transmitter power, G_t - the amplification of the transmitter antenna, $F = 1$ - the loss coefficient, R - the distance, $A_r = G_r \frac{\lambda^2}{4\pi}$ - the aperture, G_r - the receiver amplification, λ - the wavelength) is used. Additionally, rain attenuation is inferred by following the model defined in [ITU-R], using the rain rate (long term statistical rain rate, not exceeded 99% of the time), signal polarization angle and frequency, spacecraft distance and elevation as viewed from the receiver. Distance and elevation are a part of the user input, but can also be computed using the SGP4 model [2] from the “Simplified general perturbations” group (which also includes SGP, SDP4, SGP8 and SDP8 models). The purpose of the SGP4 model, similar to all the models in the class, is to compute the velocity and earth-centric inertial (ECI) coordinates of a satellite. Those coordinates can be projected onto the reference ellipsoid to get geodetic coordinates of the satellite (longitude, latitude and altitude). The model predicts the effects of perturbations caused by the shape of the Earth, resistance of the medium, radiation and gravitation of the sun and the moon. SGP4 model can be represented as a sequence of linear computations and is suitable for algorithmization.

4. Overview of “data transfer from satellite to ground station emulator”

“Data transfer from satellite to ground station emulator” is a web application that simulates the process of image transmission from a small spacecraft to a mission control center. In order to decrease minimal system requirements to the user's personal computer the client-server architecture was used in the development. This architecture allows to redirect a part of calculation to the server.

The client side of the software is a web page that consists of application description and application implementation itself. Users are presented with input form in which they can set data transfer process parameters (figure 1). Other all, form consists of 13 input fields for tuning such factors as:

1) Location of satellite, most importantly elevation and distance;
2) Equipment to be used in the process of transmission and transmission channel parameters such as frequency, bandwidth, system noise, symbol rate, transmitter and receiver’s gain, transmitter power level, polarisation angle;
3) detection parameters and error correction (error correcting code) and weather affection.

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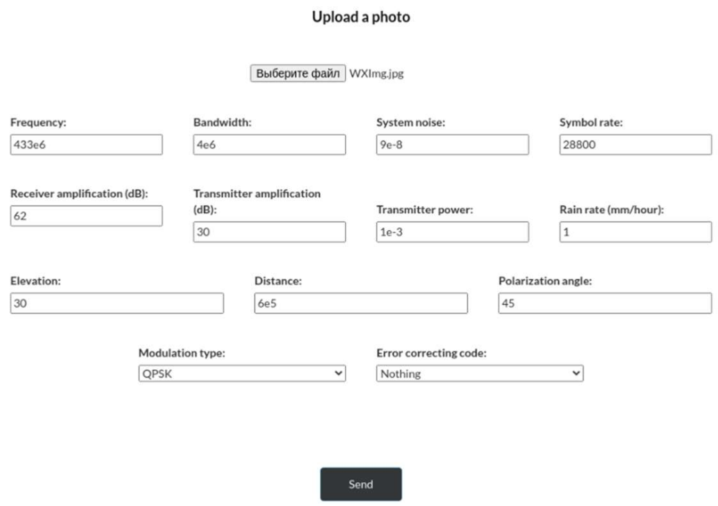

Figure 1. “Data transfer from satellite to ground station emulator” user interface

After filling in the transfer parameters, the user uploads the original image (figure 2), which is immediately displayed in the corresponding field. After that, by pressing the "Send" button, the image is encoded according to the base64 standard and sent to the server using the gRPC-web technology. The server processes the image with the user-defined noise configuration in mind and sends a response. After receiving the string, the client side again decodes the data from base64 into an image and displays it to the user.

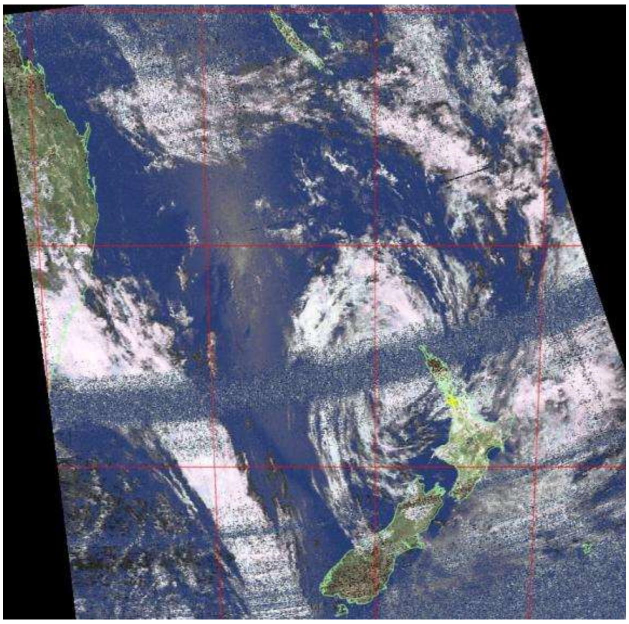

Figure 2. The original image uploaded by the user

The server side of the software consists of a data processing service. The service receives user specified transmission data parameters and data itself from the client, represented as a base64 string. The resulting string is decoded into binary format. Depending on the user instructions, data either remains unchanged or restorative coding is applied. Based on the parameters provided by the user, a mathematical model is used to calculate the BER value, which determines the signal transmission quality. All bits that will be selected are inverted and a string with applied noise is obtained. If the string has undergone reconstruction coding, then it is decoded. After that, the changed data (figure 3) is sent back to the client.

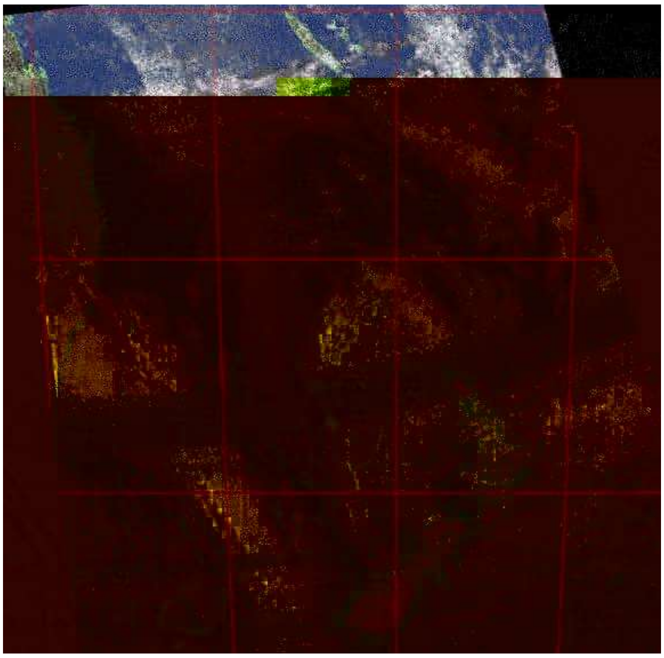

Figure 3. Morphed image received by user

To implement client-server interaction, the gRPC-web technology was chosen. The communication interface is written in Protobuf (Google Protocol Buffers) and for data transport HTTP/2 is used, gRPC is based on the idea of defining a service interface as a set of methods for remote call. By default, Google Protocol Buffers is used along with gRPC as the interface definition language for describing services and message structure. Within the software, services are defined as separate computational modules capable of receiving and executing remote procedure calls, allowing communication between a client and a server, as well as between certain server services.

5. Introduction to the design and training activities

The developed application, “Data transfer from satellite to ground station emulator” was tested at partner schools of the National research university “Higher school of economics”. For the first stage, a group of teachers - supervisors of Russian school students participating in space-themed competitions - received access to the application and conducted the preoperative testing. In the feedback, they provided their rating of the product. Throughout the successful tests, a number of possible improvements were suggested by the teachers at the partner schools and later implemented. After that, in the second stage, the product was tested on the students of the partner schools. At the Laboratory of Space Vehicles and Systems' Functional Safety the students attempted a series of practical works targeted at using the application to attempt transmitting telemetry from a satellite to a ground station. According to the received feedback, the product has a convenient interface with a number of hints and tooltips allowing most students to successfully complete the series of practical works. In the future, the application can be used in both the education of high school and university students and additional professional training programs for teachers interested in space technologies.

6. Conclusion

The developed solution allows to simulate the transfer of telemetry from a satellite to a ground station. In the future, integration with “Virtual space virtual satellite” application is planned in order to later create a united set of practical works targeted at students of partner schools of the National research university “Higher school of economics” and students.

The application is based on a model of bit error rate analogous to the one developed in [4] and model of attenuation due to rain rate described in ITU-R P.838-3 [5].

The target audience of the applications consists of students of varying grades and backgrounds.

To facilitate the development and deployment of the application a server was bought, allowing to lessen the load on the client system as well as the system requirements by performing most of the computations on the server. The developed product features the capability of monitoring the practical works and visualising the results. The product can be used in additional education programs as well as in space-themed student projects and competitions.

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