The use of Distributed Ground Station System for very low power communication

Marcin Stolarski

Warsaw University of Technology
Faculty of Electronics and Information Technology
Institute of Radioelectronics
Nowowiejska Street 15/19, 00-665 Warsaw, POLAND
M.Stolarski@elka.pw.edu.pl

Abstract: *The Paper concerns radio amateur satellites that are built by international student teams. In order to contact a satellite, a single ground station is usually used. In this configuration and with the satellite on the Low Earth Orbit, teams have contact only for about 40 minutes per day. If the satellite has service for radio amateurs, they use it for 20 hours per day. A lot of them have connection to the Internet as well. This generates new opportunities of connecting all of them, and building a big communication system. This paper shows how they can use the radio amateur transceivers and antenna systems in order to build ground stations network named Distributed Ground Station System. Frequencies, types of modulations, calculation of power budge, the ways to control amateur stations through the Internet, and a proposal of implementing dedicated DGSS system for radio amateurs with and without the use of APRS network are also shown. These are essential procedures, because radio amateurs have their standards and habits. Finally, a proposal to use DGSS for receiving very low power signal from satellite is put forward. Some mathematical calculations (implemented in author's "DGSS Calculator" software [Figure 14]) of power request for creating stable radio channel with bit error rate lower then 1E-4 and receiving standard signals (Power=5W) with bit error rate lower then 1E-32000 are also shown.*
Distributed Ground Station is one of the experiments on "PW-Sat" satellite, which is being build on the Warsaw University of Technology.

1. Introduction

The connection between Earth and the satellite is usually made via one ground station. Only in special situations and for a particular mission, stations situated all around Earth are being used. But this solution is much more expensive, which is not acceptable in amateur space missions, for example in AMSAT [1] programme. On the other hand, a single ground station has restricted range, which depends on the position of ground station and a satellite's orbit. Because of this, the greater part of the mission does not have contact with the satellite, which in turn causes the reduction of the amount of data transmission between Earth and the satellite. A lot of radio amateurs have proper devices for radio amateur satellite communication and Internet connection. If they would like to cooperate, the communication through most of the orbit would be possible. Additionally, due to the comparative analysis, obtaining very low BER, low power of transmitter or faster bitrate in the same physical radio channel is possible. In this article, the results of mathematical analysis carried out with author's software named Distributed Ground Station System Calculator (Figure 13) will be shown. This software simulates optical visibility between the satellite and a Ground Station [2,3,4,5], and calculates parameters like Free Space Loss (FSL) [3,4] or Bit Error Rate (BER) [3]. It can also calculate position of a satellite due to Keplerian elements [2,3,4,5].

2. Single Ground Station Analysis

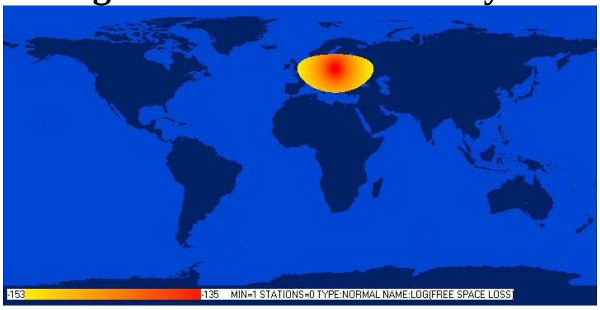

Figure 1. Free Space Loss [dB].

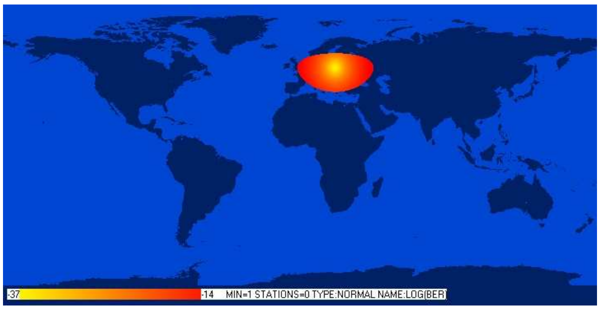

Figure 2. Bit Error Rate.

On Figure 1 and Figure 2 one can see an analysis of a single ground station radio-wave range for International Space Station (the orbit of 370km has been chosen to emphasise the differences shown later in the paper). Figure 1 shows FSL (2.1) in relation to distance between the satellite and a ground station for frequency f=433MHz in the optical horizon.

$$FSL[dB] = 10\log((\frac{4\pi R}{\lambda})^2) \qquad (2.1)$$

$$\lambda = \frac{c}{f} \qquad (2.2)$$

R - distance, c - speed of light

Beyond the horizon FSL is assumed to be equal to 1. Next, the Bit Error Rate (2.3) is calculated on the basis of FSL.

$$BER = \frac{1}{2} e^{(\frac{SN[dB]*B}{-2*BR})} \qquad (2.3)$$

$$SN[dB] = TX\_power[dBw] + TX\_gain\_anten[dBi] + RX\_gain\_anten[dBi] - FSL[dB] \qquad (2.4)$$

$$SN = \frac{C}{N_O}$$

For the calculation the following parameters have been established: FSK modulation, bit rate BR=1200bps, channel bandwidth B=7kHz, power of transmitter 5W, gain of transmitter antenna 0dBi, gain of receiver antenna 6dBi. The calculated BER was between 1E-14 and 1E-32.

3. Distributed Ground Station System Analysis

The Automatic Position Reporting System (APRS) [6,7] is used by a lot of radio amateurs. Its job is to send the radio station position via radio to the APRS network. A typical APRS station can receive packets from other stations via radio and forward them via radio or the Internet. In one week the activity of around 14000 stations may be observed (Figure 3), and the amount of data transferred by Internet servers is close to 250MB per day. Most of it is generated in USA and the European countries (Figure 4).

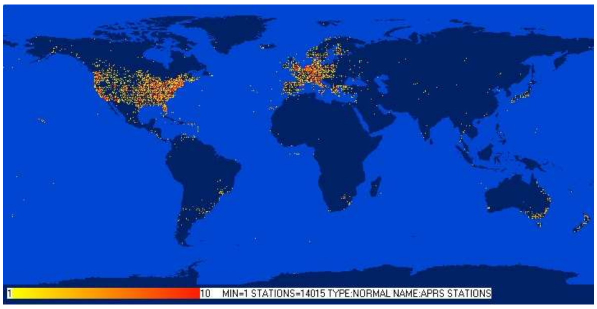

Figure 3. APRS Stations.

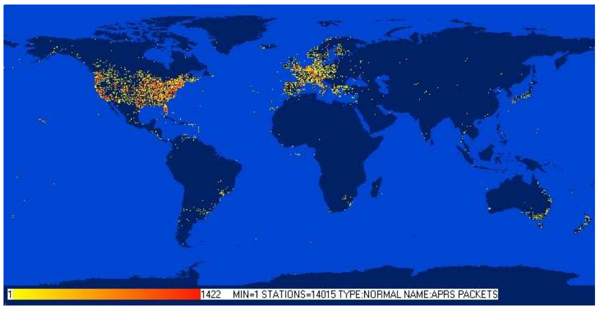

Figure 4. APRS Packets.

APRS stations function also in other parts of the word. If the range of the satellite at 370km would be simulated, it could be seen that a satellite will be able to communicate with the APRS net in most of the areas. Over USA and the EU the number of APRS stations within the range of the satellite exceeds 600. The results of theoretical FSL_T (3.1), assuming that the received energy will be summed, are visible on Figure 6.

$$FSL_T[dB] = 10\log(\sum_{i=1}^{n} 10^{\frac{FSL_i[dB]}{10}}) \qquad (3.1)$$

In comparison with FSL of a single ground station, the FSL here is lower by about 25dB.

Figure 5. Stations in range.

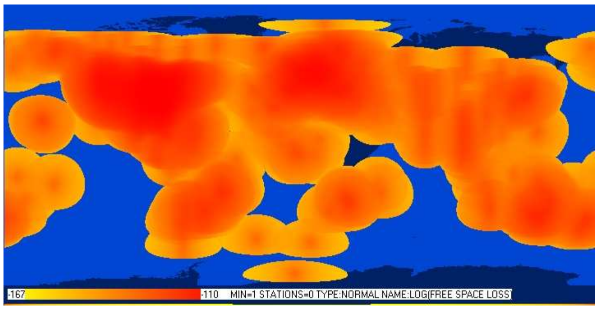

Figure 6. Free Space Loss T[dB].

Because it is rather impossible to connect all the antennas to a single receiver, the author proposes to carry out a comparative analysis of the received packets. The formula (3.2) is used for calculating the optimal value of BER (Figure 8), which is obtained when one ore more stations received the correct bit. This is the theoretical minimum, because it is unknown which station that was. The minimal calculated is BER_O=1E-30789.

$$BER_O = \prod_{i=1}^{n} BER_i \qquad (3.2)$$

The author suggests a few ways of reducing BER values using software comparative methods.

The first idea is to compare BER of all the stations within a range, and choose the packet for the lowest one. This method will ensure keeping BER_{MIN} (3.3) between 1E-4 and 1E-36 (Figure 7).

$$BER_{MIN} = \operatorname*{MIN}_{i=1}^{n}(BER_i) \tag{3.3}$$

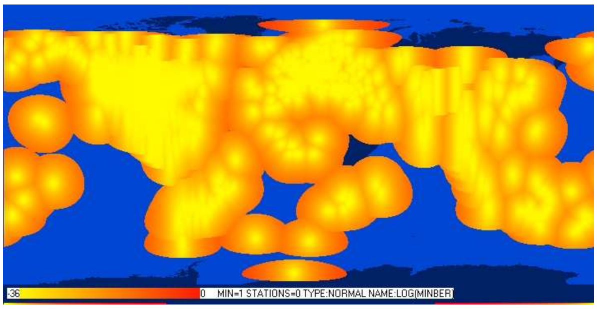

Figure 7. Minimal Bit Error Rate.

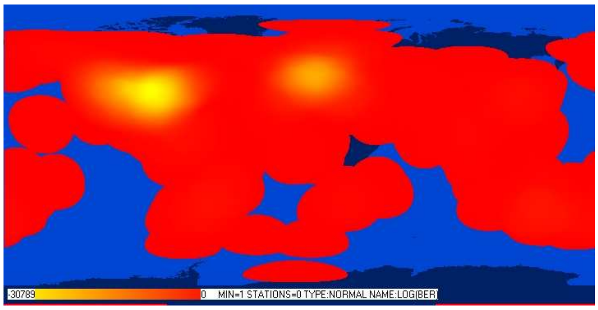

Figure 8. Optimal Bit Error Rate.

A more advanced solution is also possible. The author's second proposition is to send raw data to the server, which would make the comparative analysis through voting between particular bits of particular packets. With the large number of stations we get a large number of packets to compare, which allows reducing BER_V (3.4).

n	Amount of stations in range
BER_i	BER of single "i" station
$Y(x)=(a_1, a_2, \dots , a_n)$ $Y(0)=(0, 0, 0, \dots , 0, 0, 0)$ $Y(1)=(0, 0, 0, \dots , 0, 0, 1)$ $Y(2)=(0, 0, 0, \dots , 0, 1, 0)$ $Y(3)=(0, 0, 0, \dots , 0, 1, 1)$ … $Y(2^n-1)=(1, 1, 1, \dots , 1, 1, 1)$ $x=0, 1, 2, \dots 2^n-1$	Binary elements
$S(x)= a_1 + a_2 + \dots + a_n$	Amount of stations which received correct bit
$PR(x) = \begin{cases} \sum_{i=1}^{n} a_i * BER_i & S(x) > \frac{n}{2} \\ 0 & S(x) \le \frac{n}{2} \end{cases}$	More then half received correct bit.

$$BER_V = \sum_{k=1}^{2^n-1} PR(k) \tag{3.4}$$

Calculating BER_V for such a large number of stations as 600 is far too complex. The demonstration results of author's calculations for 5 stations are shown in Table 1.

No	Distance 1	Distance 2	Distance 3	Distance 4	Distance 5	BER_V	BER_{MIN}	BER_O	BER_{FSLT}
1	4,00E+05	8,00E+05	1,20E+06	1,60E+06	2,00E+06	1,07047E-61	4,58E-36	9,5E-125	3,68E-38
2	4,00E+05	4,00E+05	4,00E+05	4,00E+05	4,00E+05	9,60E-106	4,58E-36	2,01E-177	6,41E-45
3	8,00E+05	8,00E+05	8,00E+05	8,00E+05	8,00E+05	7,25928E-83	1,94E-28	2,7E-139	2,71E-37
4	1,20E+06	1,20E+06	1,20E+06	1,20E+06	1,20E+06	1,75E-69	5,60E-24	5,50E-117	7,84E-33
5	1,60E+06	1,60E+06	1,60E+06	1,60E+06	1,60E+06	5,49E-60	8,19E-21	3,68E-101	1,15E-29
6	2,00E+06	2,00E+06	2,00E+06	2,00E+06	2,00E+06	1,27334E-52	2,34E-18	6,94E-89	3,27E-27
7	1932734,2	438732,8	1958263	1292416	655346,1	9,46386E-59	3,78E-30	1,3E-112	1,16E-33
8	541008,38	1393606	1424484	1164636	593913,7	1,15E-67	1,29E-33	1,46E-128	3,57E-37
9	1707289,6	1942426	1302841	1725870	1676875	1,71345E-63	3,54E-28	4,5E-117	8,68E-34
10	820160,88	1715394	757211,8	437146,8	716189,7	1,95E-56	8,12E-33	8,33E-110	1,17E-34
11	1563788,3	798902,9	647638,8	1134254	1181712	3,79512E-59	7,16E-32	3E-112	2,66E-34
12	1015703	1487494	1432476	1337165	1388474	1,9632E-74	8,4E-33	5E-138	2,03E-38
13	1867244,3	798933,8	1015667	1716554	1736990	5,70705E-64	1,68E-32	6,1E-119	3,08E-35
14	850986,82	1997405	954857,9	1220468	684500,8	1,43504E-62	6,04E-25	1,9E-111	2,98E-32
15	1979432,1	1415420	1933110	1084696	1438463	3,76908E-57	1,5E-29	6,5E-107	1,43E-32

Table1. Demonstration of BER calculations.

With such low BER one can considerably reduce the power of a transmitter, or increase transmission speed to the point where it would be possible to receive the packets with BER not higher than 1E-4 on a given area. This would allow reducing the power on the satellite or increasing the amount of transmitted data. The formula (3.5) allows to calculate theoretical signal to noise rate when signal is received with BER=BER_O. With the next formula (3.6), the SNR needed to keep BER lower than 1E-4 can be calculated. When one value is subtracted from the other (3.7), surplus SNR (3.8) is obtained. This surplus SNR is the cause of the very low BER_O values. If the requirements of the satellite-ground link assume BER at the level of 1E-4, the power of the transmitter may be reduced by the SN_{SUB} value (3.9).

$$SN_O[dB] = \frac{-2BR[bps]*\ln(2*BER_O)}{B[Hz]} \tag{3.5}$$

$$SN_{E-4}[dB] = \frac{-2BR[bps]*\ln(2*1E-4)}{B[Hz]} \tag{3.6}$$

$$SN_{SUB}[dB] = SN_O[dB] - SN_{E-4}[dB] \tag{3.7}$$

$$SN_{SUB}[dB] = \frac{2BR[bps]*\ln(\frac{1E-4}{BER_O})}{B[Hz]} \tag{3.8}$$

$$TX\_power_{LOW}[dBw] = TX\_power[dBw] - SN_{SUB}[dB] \tag{3.9}$$

The mathematical simulation (Figure 9) shows that thanks to this process, the correct reception of the signal from the satellite, when its transmission power is only TX_power=-24296dBw, is possible (however, probably only in theory).

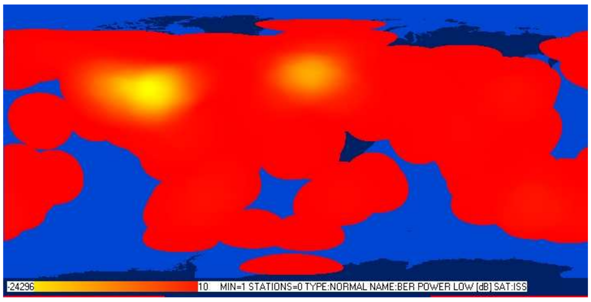

Figure 9. TX_power$_{LOW}$ (BERo).

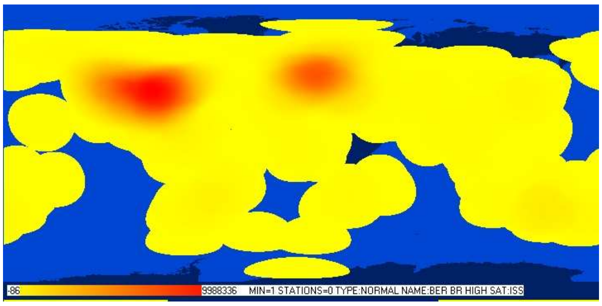

Figure 10. Bit Error Rate$_{HIGH}$ (BER$_O$).

The next proposition of the use of the surplus SNR is to enlarge bitrate at the expense of the BER parameter. The formula (3.10) allows calculating maximum bitrate without enlarging bandwidth and the power of the transmitter, to keep BER on the level of 1E-4.

$$BR_{HIGH}[bps] = \frac{SN_O[dB]*B[Hz]}{-2*\ln(2*1E-4)} \tag{3.10}$$

The mathematical simulation (Figure 10) shows that enlarging bitrate to the value BR$_{HIGH}$=9988336bps is possible (however, probably only in theory too). BER$_{MIN,}$ which is responsible for receiving data through distributed network without the Packet Voting System (e.g. APRS-IS), may be used as input data for the calculations. The results of the simulation are TX_power$_{LOW}$=-18dBw (Figure 11) and BR$_{HIGH}$=11858bps (Figure 12).

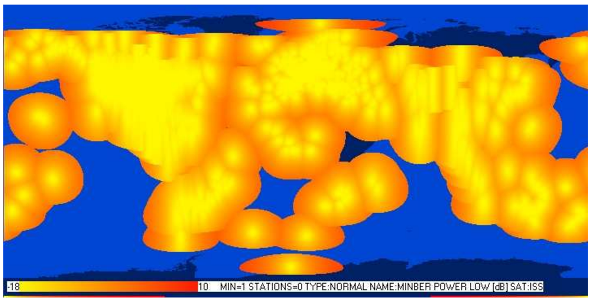

Figure 11. TX_power$_{LOW}$ (BER$_{MIN}$).

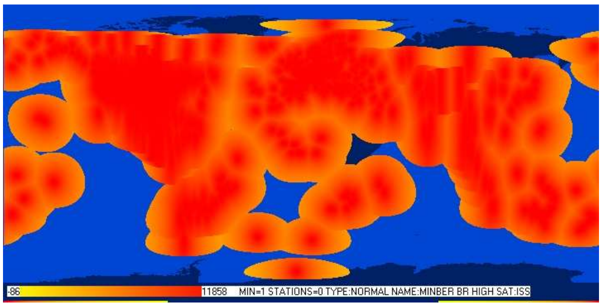

Figure 12. Bit Error Rate$_{HIGH}$ (BER$_{MIN}$).

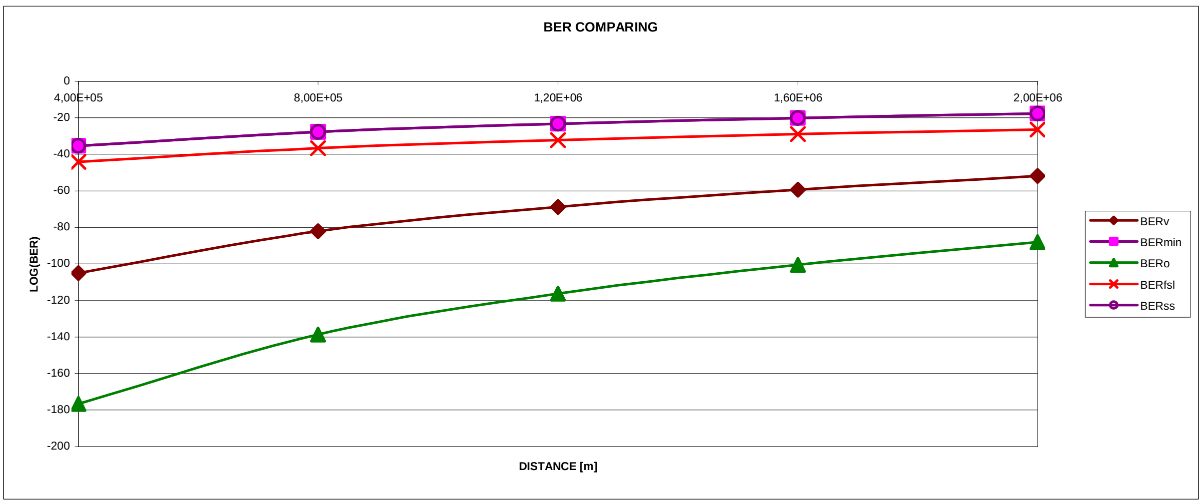

Figure13. The comparison of BER reduction methods.

Figure 13 shows the comparison of BER reduction methods carried out for 5 stations located in the same distance (from 400 km to 2000 km from a satellite). The detailed results may be found in Table 1. BER_{FSLT} is calculated by means of the formulas (3.11 and 3.12) and it is used only for comparing hardware methods (like using bigger antenna systems) to software methods (like voting systems).

$$BER_{FSLT} = \frac{1}{2} e^{\left(\frac{SN_{FSLT}[dB]*B}{-2*BR}\right)} \qquad (3.11)$$

$$SN_{FSLT}[dB] = TX\_power[dBw] + TX\_gain\_anten[dBi] + RX\_gain\_anten[dBi] - FSL_T[dB] \qquad (3.12)$$

It is clearly visible that voting system has the lowest BER values of all the real methods (without the optimal theoretical method) and is far better than, for instance, using single ground station (BER_{SS}) or minimal BER method.

The above simulations were carried out with the author's software named Distributed Ground Station Calculator (Figure 14).

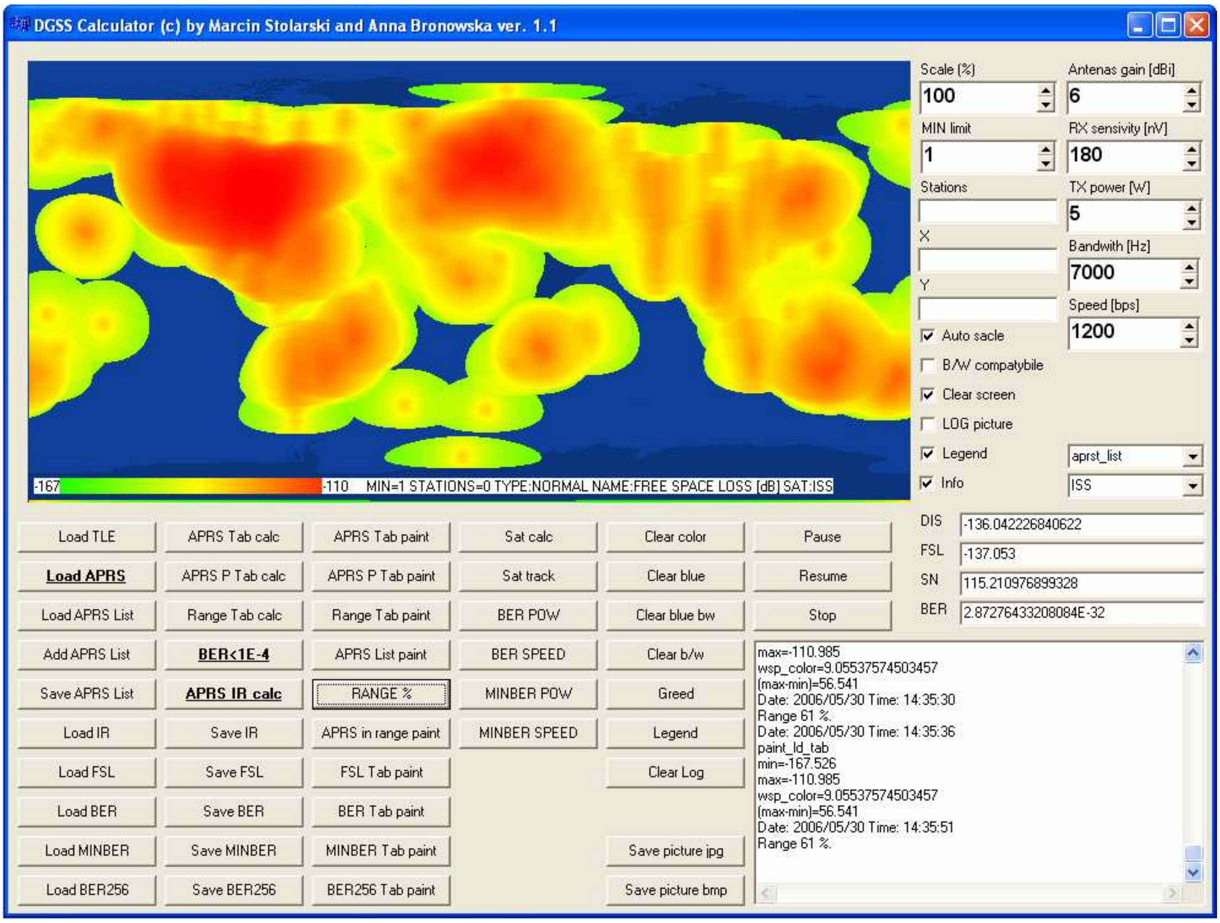

Figure14. "Distributed Ground Station System Calculator" software.

4. Automatic Position Reporting System

The empirical verification of the proposed methods of reducing BER could be performed in the APRS net. There are different kinds of communications transmitted via this net. The first one contains the geographical situation of a station and some additional information, for instance the speed of the vehicle on which a station in located. The second kind of packets is telemetry. Its main use is transmitting information from weather stations, but any other kind of information can also be transmitted. The third kind of communications is short messages. The packets of the first two kinds are broadcasted to all units of the APRS net. The amount of packets sent via radio is territorially restricted on account of radio wave link capacity. The full stream of data may be received via Internet. Short messages are being sent in a different manner. The messages are of two kinds. The first one is the bulletins, which are sent to all stations. The second one is private messages, which are sent to specific recipients. The APRS net sends this kind of messages for re-transmitting to all stations connected to the Internet. If one of the stations hears the station of the addressee on a radio port within a specific period of time (usually 30mins), the re-transmission of the message via the radio port goes through. When the addressee receives the message, he sends a confirmation message to the sender. This way of communication is not 100% successful, but it is sufficient for radio amateurs. It is also used for communication with radio amateur satellites [1]. However, it has some flaws. While the system enables receiving telemetry from the satellite when it is within the range of the net, sending messages to the satellite via the net is virtually impossible. When the satellite is, for instance, over USA, it is within the range of over 600 stations, and if all of them re-transmit the message to the satellite at once (because they all heard the satellite within the last 30mins) the packets will collide in the radio wave and will not be received correctly. Because of this, transmission to the satellite is possible only when it is directly over the main ground station. The author proposes to solve this problem by providing radio amateurs with special client software. Such a client would receive the re-transmission packet by a separate channel, which would allow for the message to be transmitted only to the chosen station. The second problem concerns the legal aspects of working with the APRS net. The national and international regulations demand that transmissions via radio amateur systems be overt (not encoded). This makes a satellite vulnerable to an unauthorised access of other radio amateurs. The author proposes to carry out the authorisation by means of an electronic signature. Every message to the satellite would be signed electronically by the Operation Team and the satellite would only accept the commands signed in this way. Still, there is a risk of a signed message being intercepted and re-transmitted again by an unauthorised sender. To eliminate this risk, the addition of an incremented counter to the message is proposed, which would allow eliminating the already used packets.

5. Distributed Ground Stations System

In order for the experiment to take advantage of all the possibilities of a diffused packet analysis, the author proposes [10] to construct a system of a diffused ground station. Such a system would make use of a couple of subsystems.

DGSS elements (Figure 15):

- Local Ground Station System
    - Local Ground Station (for a direct communication with a satellite in case of unavailability of the distributed system)
    - Distributed Ground Station System Client (also known as Virtual Ground Station; the system would allow for a remote managing of a radio amateur

station through the remote turning of radio amateur antennas and altering the radio frequency)

- Distributed Ground Station Network
  - Distributed Ground Station Network Server (for collecting raw data from the station in order to process it later; the packets to be send to a satellite would be sent in a return channel)
  - Distributed Ground Station Network Management Server (for managing users, channels, network, selecting a sender, time synchronization; this system would assess the quality of data (it would foresee BER on the basis of the location of a station and a satellite), it would also decide which station would be most suitable for sending the packets to a satellite (on the basis of the quality of the received packets and theoretical capabilities resulting from a mathematical model))
- Distributed Ground Station System Management Server (for managing the satellite telemetry and telecommands)
  - Packet Voting System (a system for comparing many packets (even the damaged ones) received simultaneously by many stations (Parallel Receiving System); eventually, the correct packets with the information from a satellite would be received)
- Satellite Management Console (a panel for receiving the decoded telemetry of a satellite with PVS, and creating the packets with commands for a satellite; this is a system for remote managing of the satellite)

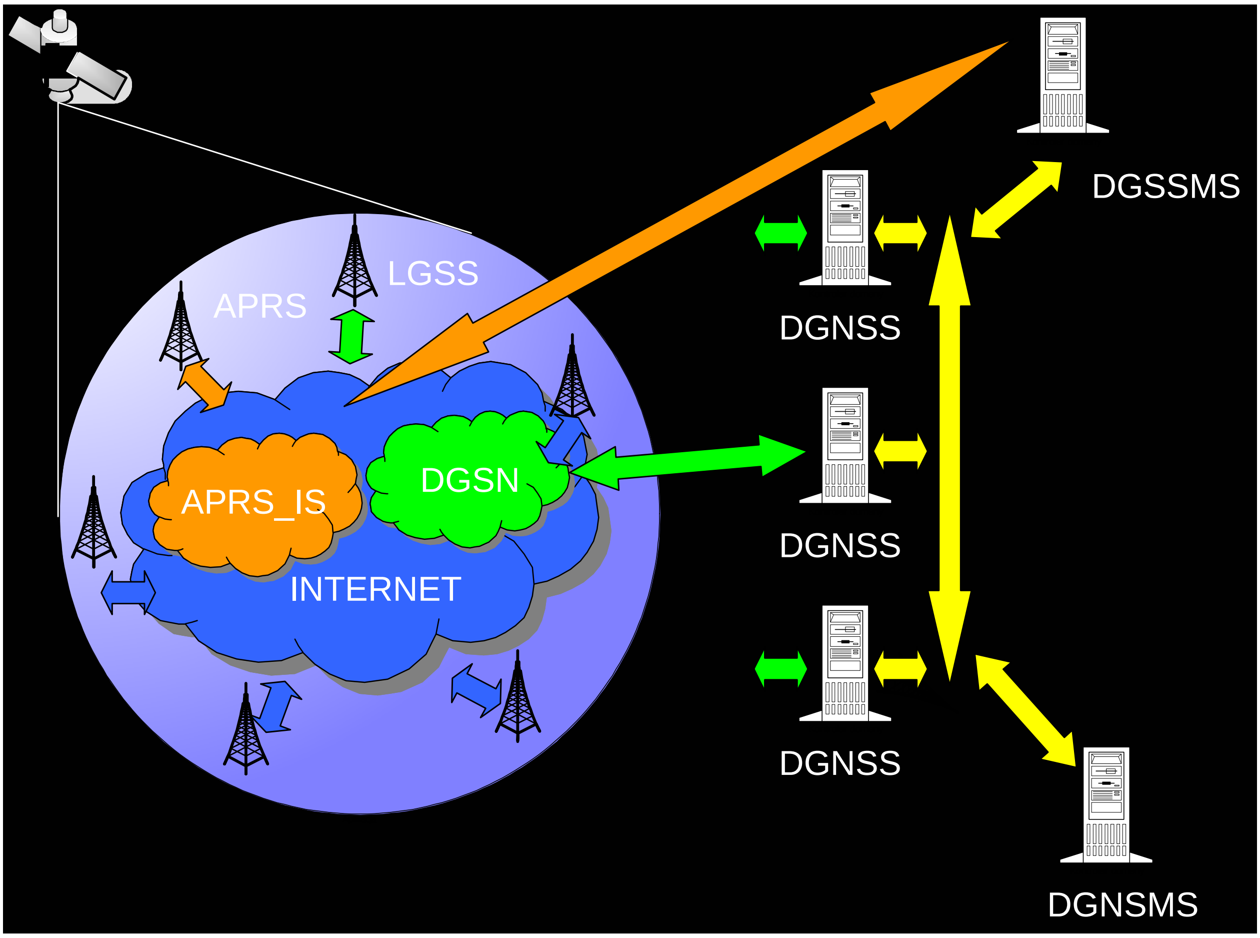

Figure15. Distributed Ground Station System.

A separate section should be devoted to the Packet Voting System (Figure 17), which reduces BER through the comparative analysis of packets. The source of the packets are such networks as APRS-IS and DGSN. First task is to check whether any of the received frames is correct (check CRC sum). If all of the frames are incorrect then they enter the Packet Voting System. In the system bits comparison between the packets takes place. The bit which wins is in most of the packets (Figure 16). When enough packets are gathered (new packets from the same frame do not come in), the system generates voting frame and checks its CRC sum. If the sum is correct then it means that the frame is correct. If not, then the system sends information that the frame is incorrect.

Source packets	011010010 100101010 100100110 100110101 010100010
Destination packet	100100010

Figure16. The comparison of packet in Packet Voting System.

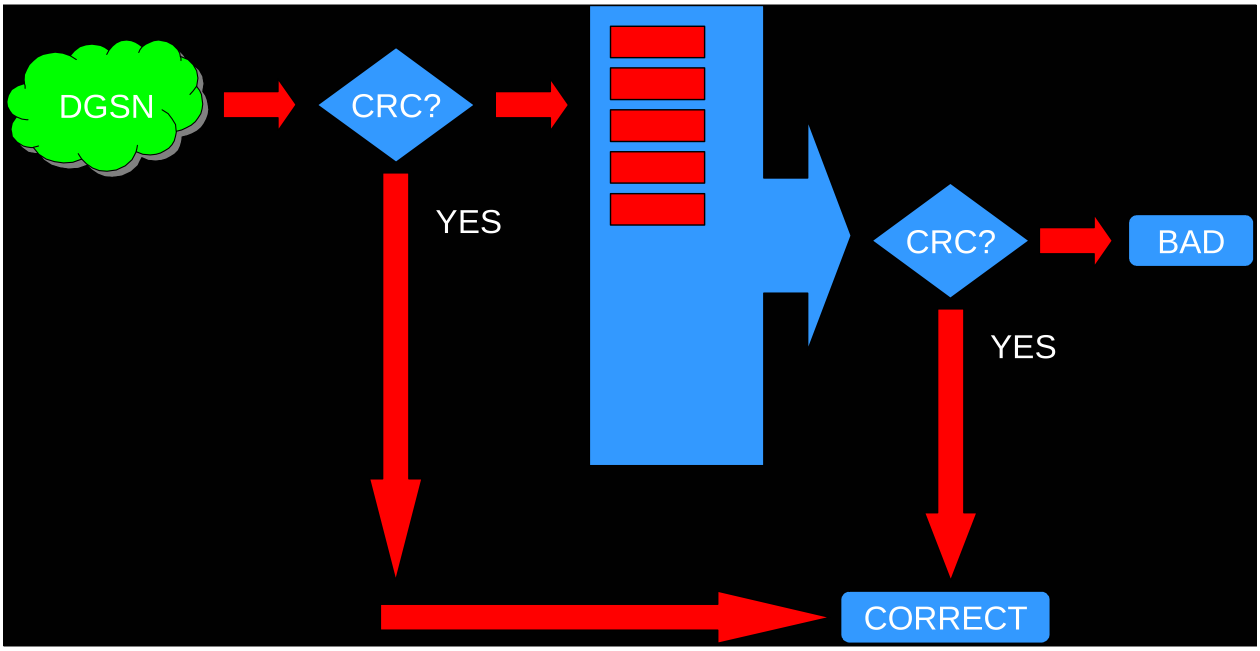

Figure17. Packet Voting System.

6. Summary

The author presented a new method of space communication, which uses a parallel data reception from the satellite and proposed a subsequent analysis in order either to reduce BER or power of the transmitter or enlarge bitrate with mathematical methods. The calculation results show a great improvement of transmission when using a parallel reception, like Packet Voting System. A practical verification of the method could be carried out using APRS communication with certain modifications, which would allow further improvement of BER, TX_POWER and BR. The experiment is planned as a part of space mission PW-Sat [9], which consist in the Warsaw University of Technology sending a small satellite in order to check a possibility of bringing satellites from the orbit by using aerodynamic resistance at the orbit.

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Marcin Stolarski was born in Warsaw, Poland, in 1976. He received the M.Sc. degree in computer science at the Warsaw University of Technology in 2004. He is currently a Ph.D. student at the same university. His research interests and work are related to space technology, focusing on communication systems, distributed networks and fault tolerant systems. He is a member of the Student Space Engineering Scientific Group and works in space projects like SSETI ESEO Satellite, PW-Sat and YES2. He is the author and co-author of many documents concerning space systems.

e-mail: M.Stolarski@elka.pw.edu.pl
Warsaw University of Technology
Faculty of Electronics and Information Technology
Institute of Radioelectronics
Nowowiejska street 15/19, 00-665 Warsaw POLAND