USING SINGLE FREQUENCY RECEIVERS FOR FUTURE CUBESAT GPS-RO MISSIONS

Danijela Ignjatović Stupar [1]
Vukan Ogrizović [2]

UDK: 528.28
DOI: 10.14415/konferencijaGFS2018.069

Summary: *Due to evolution of the Global Navigation Satellite Systems (GNSS), their features and capabilities are constantly increasing to the point that being possible to use their radio signals by other means than the main, original implementation. The innovative methodologies use direct, reflected, or refracted GNSS radio signals to analyse the atmospheric properties or to observe the Earth's surface behaviour. This paper tests the feasibility of the active GPS refracted signals and their capability to identify the refractivity profile pressure, temperature and water vapour during their pass through the atmospheric layers. The objective is to put together theory, methodology, and application of the GPS radio occultation (GPS-RO) concept, considering the advantages and disadvantages of existing missions with possibility to develop and implement similar techniques in future cubesat missions*

Keywords: *GPS-RO, water vapour, temperature, pressure, TEC*

1. INTRODUCTION

The transmitted radio signals travel through different atmospheric layers. Depending on how the signals reach the receiver, two non-standard GNSS applications can be introduced: GNSS-Reflectometry (GNSS-R) and GNSS-Refractometry or also named GNSS Radio Occultation (GNSS-RO). The radio signals which are reflected from the Earth's surface belong to the GNSS-R technique. They provide information on soil moisture, altimetry of sea/ocean levels, ocean wind speed and the direction, classification of snow and ice thicknesses, and many other remote sensing applications related to wet surfaces. Other radio signals which are refracted by the atmosphere pertain to GNSS-RO observations. They involve the permanent measurements of the atmospheric parameters which provide the accurate weather results. This slanted propagation path yields to information about the profile density and the temperature in different atmospheric layers, including the Total Electron Content (TEC).

While analysing weather in the lower thermosphere using GNSS-RO, the main goal of this research is to develop a system for post-process the downloaded raw data into useful

[1] Danijela Ignjatović Stupar, International Space University, 1,rue Jean Dominique Cassini, Illkirch, France, danijela.stupar@isunet.edu
[2] Vukan Ogrizović, University of Novi Sad, Faculty of Civil Engineering Subotica, Kozaračka 2a, Subotica, Serbia, tel: ++381 24 554 300, e – mail: vukan@gf.uns.ac.rs

information using the L1 GPS frequency. The GPS receiver will be located in the cubesat in a low Earth orbit (LEO). To achieve the goal for this theoretical experimental RO mission, there are several requirement sets. At any time, a large number of the observables are taken, as far as the satellites are visible to the satellite in the LEO.
According to the theoretical orbital altitude of approximately 320 km, it is suggested to integrate the single frequency RO receiver to obtain ionospheric profiles. Looking through many RO missions and their results, only the Canadian Advanced Nanospace eXperiment (CanX-2) mission fits the required conditions for this experiment. The CanX-2 radio occultation mission used L1 for ionospheric profile research and that is the main reason for choosing that example for our case study.
Long-term scientific goals of this research refer approaching of the GNSS-RO fundamentals to future users, including students/readers from various scientific backgrounds. To achieve this statement, several steps are done:

- Studying state of art of signal processing algorithms for GNSS-RO and selecting the most relevant one(s) which use the forward scattered range-coded signals from the GPS in order to measure the atmospheric parameters,
- Modelling the propagation of the GPS signals in the atmospheric environment,
- Investigating weather data repositories from different radio occultation satellite missions, from the ground based GPS instruments, and meteorological stations,
- Developing the algorithm for GPS–RO single frequency measurements, and
- Modelling comparison for the future cubesat data collection.

2. BACKGROUND AND METHODS

2.1 THEORETICAL BACKGROUND OF GPS -RO

The first model of the radio occultation was applied to study the thin atmosphere of Mars. Later on, the study was extended to Venus. Both projects were more than successful in the sense of the accurate atmospheric retrievals. The same radio occultation principles from these models can be applied to study the Earth's atmosphere. In the case of the Earth, the satellites with the GPS receivers on board are placed in the LEO receiving the signals from the transmitter based in the GPS constellation. The LEO satellite sees the transmitted signal from the GPS satellite as it rises or sets behind the Earth. The signal passes through the atmosphere and detects the atmospheric weather parameters such as: water vapour, temperature, pressure and ionospheric electron density.
The GPS transmits three L band radio frequencies, but only L1 and L2 are used for the RO measurements. The signals beam from all available GPS satellites which orbit at an altitude of approximately 20,200 km above the Earth's surface. The constellation is configured in such a way to cover almost the whole globe and conveniently also covers approximately 3000 vertical km of the atmosphere, the ionosphere and the space above the Earth. Every LEO satellite may see the GPS satellite when it rises or sets. For 24 GPS satellites it is possible to have 16 occultations per LEO every 100 min. That theoretically offers 600 occultations per day for each LEO. This number is a little bit

optimistic as it is not possible that all occultations could be tracked due to limitations of the receiving antennas in the field of view. More realistically, each LEO satellite could observe 400-500 occultations per day, limited by the position and the capability of the antennas [1].

The effect of the ionosphere on the signal is proportional to the squared inverse of the carrier frequency, and therefore L2 frequency is more affected than L1. The difference between L1 and L2 frequencies allows one to determine the ionospheric effects on the signals. This effect is removed from RO data in neutral, or ion free atmosphere, and is also useful for measuring the ionospheric properties in the higher altitudes above 100 km [2].

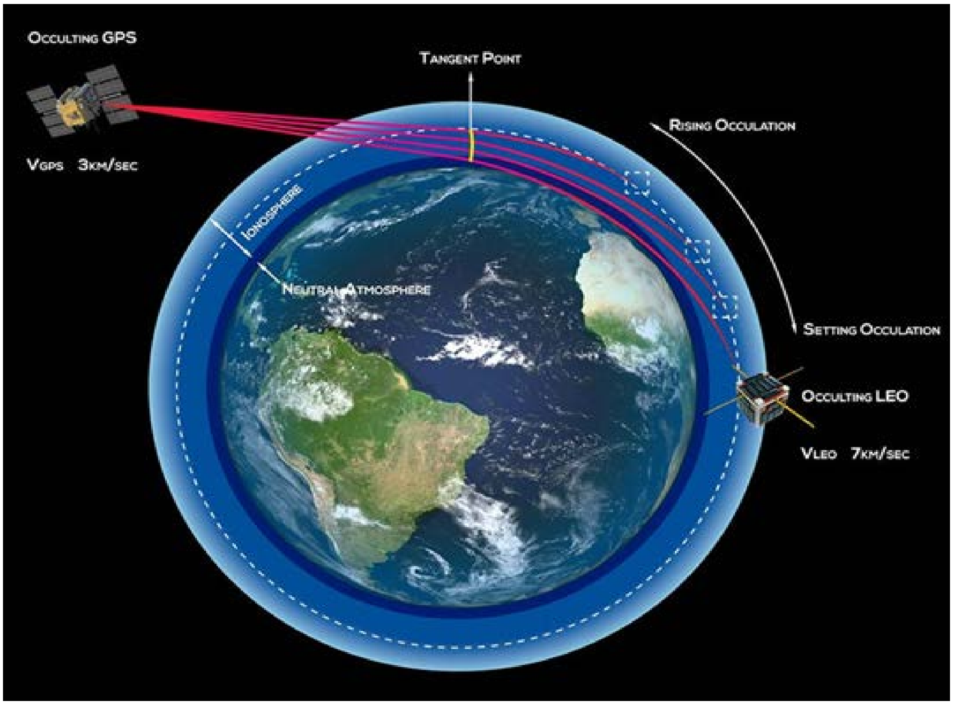

Figure 1: Working principles of GPS-RO

Fig. 1 depicts the main principle of GPS-RO. The GPS receiver on the LEO satellite tracks the GPS transmitter when it sets behind the Earth's limb and observes the signal delay. The radio waves bend continuously over time as the satellite sets (red lines). The yellow line contains the tangent points of the signal when they bend above the Earth's surface signal. The tangent point is the change in the longitude and the latitude during the occultation. In order to determine the profiles of the atmospheric parameters of RO, the GPS and the LEO satellites velocities must be estimated very accurately.

The velocity of the GPS satellites is 3 km/s and for the LEO satellites it is 7 km/s. For precise determination of the temperature profiles, accuracy of orbit estimation has to keep relative velocity of the receiver with approximate accuracy of 0.2 mm/s. On the other side, all possible forces acting on the satellites are present as well, such as the

gravitational field, the gravitational effects on planets, Moon and the solar radiation pressure, but they can be compensated with sophisticated processes and techniques [3].
Combining ground based and space based GPS receivers, it is possible to observe atmospheric sounding, including tropospheric perceptible water vapour (PWV), ionospheric TEC, and atmospheric vertical profiles (consisting of pressure, temperature, humidity and electron density from the ionosphere and the tropopause).

2.2 OPERATING PRINCIPLES IN THE BASIC RO MEASUREMENTS AND DATA PROCESSING

At the moment when the signal slices the atmosphere, the receiver on the LEO orbit observes the changes of the signal delay caused by bending and the descending the signal path. The reconstruction of the bending angle α and the vertical refractivity profile at the ray tangent point are allowed by the change of the delay. The total bending angle as the function of the asymptotic ray-miss distance *a* is, actually, the impact parameter. From this statement, the effect of the atmosphere can be reviewed through the measurements of the phase and the amplitude of the received signal [4], [5].
It is theoretically explained by a simplified RO geometry (Fig. 2), where □ is the bending angle and *r* is the tangent point radius.

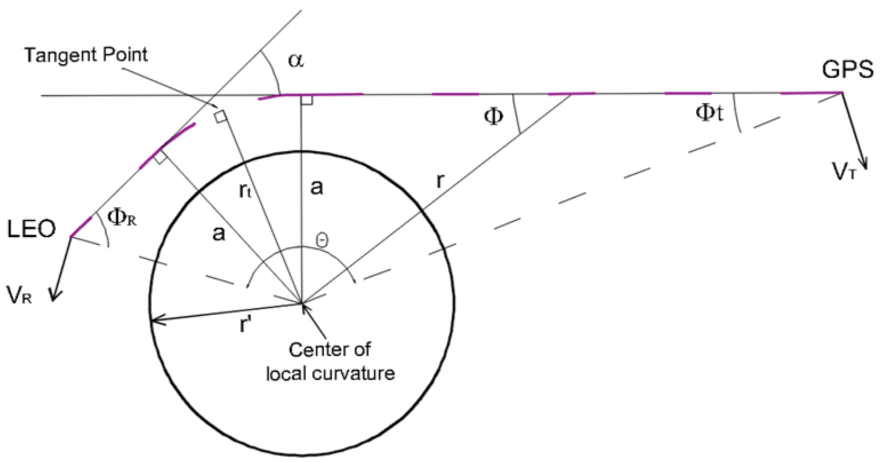

Fig. 2: Principle geometry of GPS-RO

The measured parameters of the radio waves which propagate through the atmosphere depend on the refracted index (*n*). The refracted index is presented by a ratio of the speed of light in a vacuum (*c*) to the speed of light in the atmosphere (*v*). The value of the atmospheric refractivity (*N*) is very close to:

$$N = 10^6 (n - 1). \quad (1)$$

In the neutral atmosphere (above the mesopause), the refractivity depends on the pressure (P), the temperature (T) and the partial pressure of the water vapour (P_w) but not on the frequency, yet still depending on the electron density (n_e) and the frequency of the radio waves (f) in the ionosphere. The refractivity equation is expressed as:

$$N = Dry\ Term + Wet\ Term - Ionospheric\ Term + (Scaterring\ Term), \quad (2)$$

where:

- *Dry Term*: dry neutral atmosphere $77.6\ \frac{P[\mathrm{hPa}]}{T[\mathrm{K}]}$
- *Wet Term*: water vapour $3.73 \cdot 10^5\ \frac{P_w[\mathrm{hPa}]}{T^2[\mathrm{K}]}$
- *Ionospheric Term*: free electrons in the ionosphere $40.3 \cdot 10^6\ \frac{n_e[\mathrm{m}^{-3}]}{f^2\,[\mathrm{Hz}]}$
- *Scattering Term*: liquid water droplets and ice crystals $1.4W_{liquid} + 0.6W_{ice}$ [3].

To obtain the accurate atmospheric products such as P, T or P_w, it is required to use linear Abel's inversion through TEC with respect to spherical symmetric atmospheric assumption.

The ionospheric terms for calculation of the electron density profile (n_e) are taken from (2):

$$n_e = (1-n)\frac{f^2}{40.3}, \quad (3)$$

where deviation of the atmospheric profiles is addressed to the refractive index n. In the ionosphere, TEC along a ray is related to n_e, n and the excess phase S by the following equation [3]:

$$\mathrm{TEC} = -\frac{f^2}{40.3 \cdot 10^{16}}\int (n-1)\,dl = -\frac{f^2 S}{40.3}. \quad (4)$$

Because the L1 and L2 signals propagate along different paths due to the dispersive characteristics of the ionosphere, the obtained TEC results slightly differ [4]. To mitigate or to solve the problem, it is required to calculate TEC from the excess ionospheric delay S_1 and S_2 at two frequencies, but only after removing the orbital and the clock errors during the calibration process.

Applying the bending angles and the ionospheric retrievals into (2), the vertical profile in the terms of the pressure, the temperature and the water vapour can be estimate. Those steps are presented in the Fig. 3 as a flow chart summarising RO data processing.

3. RESULTS AND DISCUSSION

Before discussing further the strategy for the assimilation of the ionospheric profiles, it is important to review the missions that already performed the radio occultation observations, and to follow the proposed theoretical steps (Fig.3).

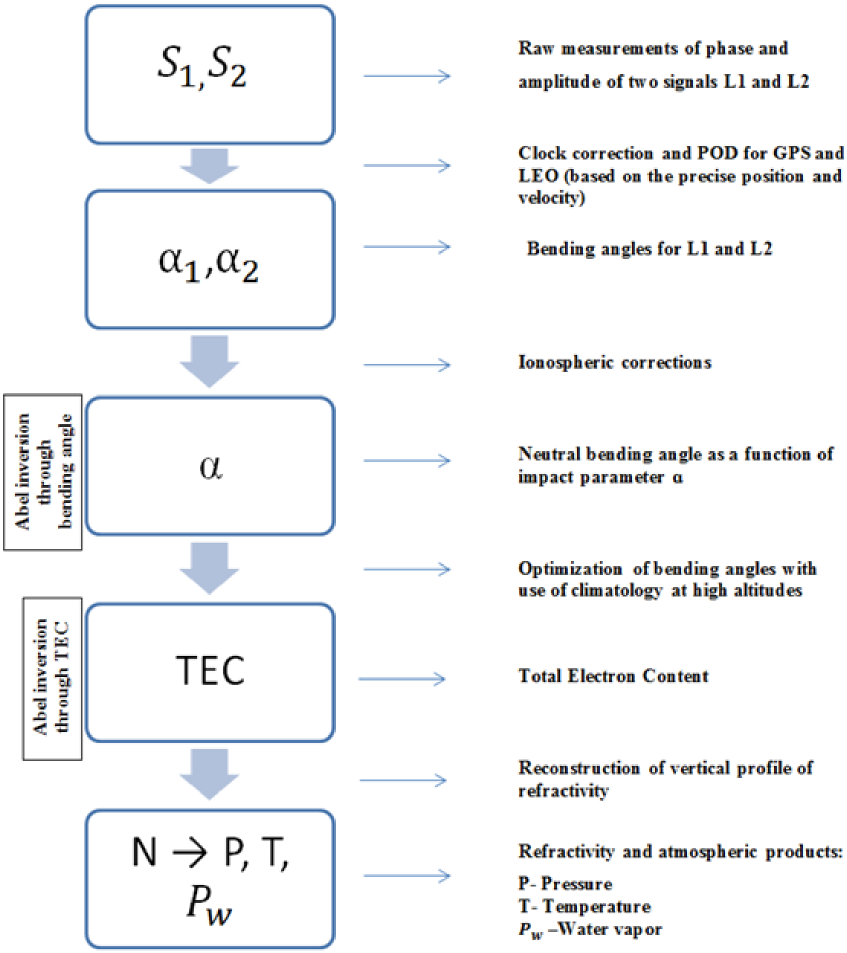

Fig. 3: Summary of GPS-RO data processing

For the future cubesat GPS-RO experiments, the specific hardware and the software requirements are demanded. As the hardware requirement, it is needed to point the space craft to align the antenna through the limb. It is demanded to develop two software packages, one to boost the sensitivity of the signal reception and the other one to run the experiment. The technical information of the payload, the receivers and the cubesat design are beyond the scope of this paper. The main point will be focused on pre-processing the data and overviewing the results, to assure that the computing code is ready to calculate the TEC profiles before the cubesats' missions.
Data pre-processing is the required step for the final data analysis. In this study, we used equations from CanX-2 mission as a theoretical background, as well as the CHAMP (CHAllenging Minisatellite Payload) data, collected during the 2008, representing millions of measurements. For the effective analysis of information, this large database is available in the form of RINEX (Receiver INdependent EXchange) files, with the data prepared for automated processing, in order to obtain the requested results. Though the COSMIC (Constellation Observing System for Meteorology, Ionosphere and Climate) has better vertical resolution of 100 m, to deal with different but similar opportunity, it is decided to use CHAMP data for this case study. CHAMP mission has been activated on around 300 km altitude what for our experiment does not make any significant difference regarding the theoretical premises. The CHAMP mission ended on the 19th of September 2010 after 58277 orbits and collected millions of RO measurements [6].
The Kalman filter, Bandpass filter, Moving Average filter and Polynomial filter are the possible proposed options for single frequency excess phase smoothing methods. Each of those smoothed sections needs validation. For the CanX-2 mission evaluation of the Polynomial method was chosen, which is explained in detail in [7]. For CanX-2 another method of smoothing using a polynomial filter was used. It is based on dividing data into the segments and afterwards fitting a curve to each segment. The electron density profiles were compared to the profiles from the excess phase data. Therefore, with this comparison (or "truth"), the single frequency smoothing method was validated. The "truth" data, hereafter, will be referred to the optimal excess phase curve (code minus carrier). This curve presents all possible extractions of the ionospheric signal while minimalizing all unwanted effects [8].

The zero mean white noise is calculated by subtracting the smoothed difference (code-carrier) on L1 from their corresponding raw ones:

$$(R_{L1} - \phi_{L1}) - (R_{L1} - \phi_{L1})_{smooth} \approx \text{Zero Mean White Noise}, \tag{5}$$

which is presented in Fig. 4. The *x* axis is expressed in seconds, in the way that the first epoch gets the value 0. So, this is not the absolute time, but rather the relative time marker within the selected segment from the raw observation data file. Two lines are expressed in meters, where the red one is the raw difference, and the green the smoothed one.

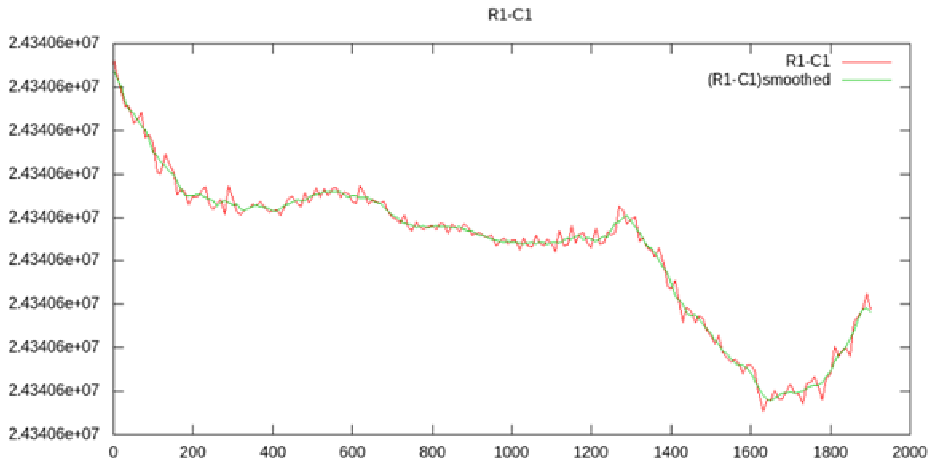

Fig. 4: (Code-carrier on L1) and smoothed values

The difference between two lines is graphically represented in Fig. 5.

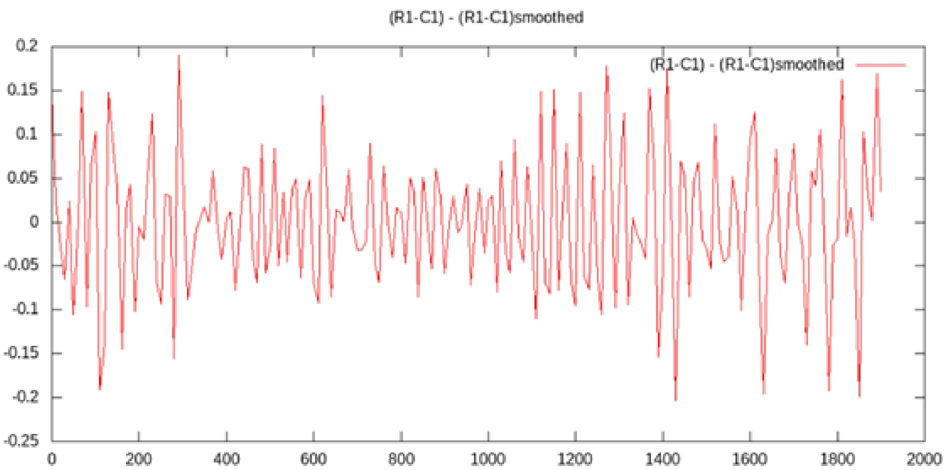

Fig. 5: (Code–carrier on L1)-(Code –carrier on L1) smoothed values

As one can notice from the Fig. 5, the difference between the raw and its smoothed value does not exceed 0.2 m in the absolute value, which proves the level of smoothing, which falls into the requested interval. If the smoothing was bad, the smoothing window could be changed, by altering the input parameters.
Autocorrelation of the difference between the raw and the smoothed data is depicted in Fig. 6, based on the equation:

$$(\phi_{L1} - \phi_{L2})\frac{f_{L2}^2}{f_{L2}^2 - f_{L1}^2} - \frac{(R_{L1} - \phi_{L1})_{smooth}}{2} \approx \text{cm level noice} + \text{const.} \tag{6}$$

A proof of correctness is the fact that the largest values are grouped around the epoch 0, and the values drastically decrease when going left and right of the 0 value. This code can be applied to the post processing data, which will be collected during the future cubesat experiments.

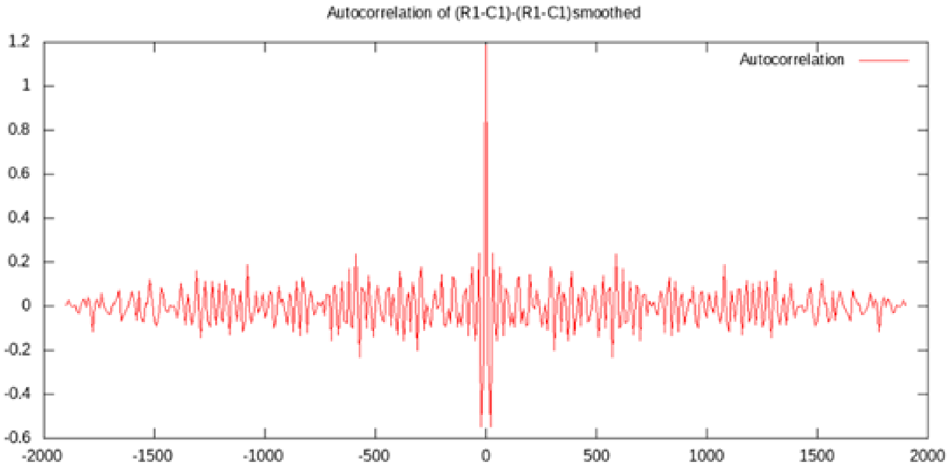

Fig. 6: Autocorrelation of the difference between code-carrier and the smoothed values

4. CONCLUSIONS

This paper presented the possibilities and opportunities of GNSS-RO, a relatively new remote sensing application.

As an example, the CanX-2 experience was used, and due to that, a similar code for future cubesat missions has been made. The developed algorithms are based on the radio occultation theory and the correlation function of the data collected during the CHAMP mission. However, the real data from the CHAMP mission is provided, so as an adapted solution is proposed in the case when the real data from the cubesat will come. Through the CanX-2 experiment, the satellite had the technical constraints which had an impact on the quality of the RO measurements. On the board, the constraints were low antenna gain used for GPS-RO measurements and for attitude control. Due to the position of the antenna, only a low level of useful data were collected which decreases the accuracy of the final result. The lack of L2, the satisfactory results of the neutral atmosphere and the ionosphere are not on the high level. They are acceptable but not perfect as the dual frequency receiver can offer. But on the other hand, the single frequency has a potential to provide TEC via a combination of L1 and C1 data with an accepted level of accuracy.

The potential where actually the single frequency can be used is in the case where the subset of the L2 tracking data from the dual frequency mission has failed.

REFERENCES

[1] Jin, Shuanggen and Komjathy. Attila 2010. GNSS Reflectometry and Remote Sensing: New Objectives and Results. [online] Available at: <http://arxiv.org/ftp/arxiv/papers/1010/1010.2281.pdf>.

[2] Jin, S.,, Feng, G.P., and Gleason, S., 2011. Remote sensing using GNSS signals: Current status and future directions. *Advances in Space Research*, 47(10), pp.1645–1653.

[3] Jin, S.,, Cardellach, E., and Xie, F., 2013. *GNSS remote sensing: theory, methods and applications*. [online] Available at: <http://dx.doi.org/10.1007/978-94-007-7482-7> [Accessed 9 Jun. 2015].

[4] Schreiner, W.S.,, Sokolovskiy, S.V.,, Rocken, C., and Hunt, D.C., 1999. Analysis and validation of GPS/MET radio occultation data in the ionosphere. *Radio Science*, 34(4), pp.949–966.

[5] Kuo, Y.–.,, Sokolovskiy, S., and Anthes, R.A., 2000. Assimilation of GPS radio occultation data for Numerical Weather. In: *Prediction, Terrestial, Atmospheric and Oceanic Science*. p.186.

[6] Reigber, C., 2002. A high-quality global gravity field model from CHAMP GPS tracking data and accelerometry (EIGEN-1S). *Geophysical Research Letters*, [online] 29(14). Available at: <http://doi.wiley.com/10.1029/2002GL015064> [Accessed 20 Aug. 2015].

[7] Hajj, E.R.K.G.A., 2002. A technical description of atmospheric sounding by GPS occultation. J Atmos Solar-Terr Phys. *Journal of Atmospheric and Solar-Terrestrial Physics*, 64(4), pp.451–469.

[8] M.Swab, K.O'Keefe and S.Skone 2012. Single-frequency Ionospheric Profiles from the CANX-2 Nano-satellite.

УПОТРЕБА ЈЕДНОФРЕКВЕНТНИХ ПРИЈЕМНИКА ЗА ВУДУЋЕ GPS-RO CUBESAT МИСИЈЕ

Резиме: *Еволуција глобалних навигационих сателитских система (GNSS), доноси констатан напредак особина и могућности, до тачке кад постаје могуће користити њихове радио-сигнале на начине другачије од оригиналне имплементације. Иновативне методологије користе директне, рефлектоване или преломљене GNSS радио сигнале за анализу особина атмосфере или за опажање понашања Земљине површи. Овај рад испитује изводљивост активних GPS преломљених сигнала и њихову могућност идентификације профила преламања, температуре и водене паре, током проласка кроз атмосферске слојеве. Циљ је објединити теорију, методологију и примену GPS радио-окултационог (GPS-RO) концепта, узимајући у обзир предности и мане постојећих мисија, с могућношћу развоја и имплементације сличних техника у будућим cubesat мисијама.*

Кључне речи: *GPS-RO, водена пара, температура, притисак, TEC*