Beacon satellite receiver software for ionospheric tomography

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Abstract

We first give a short introduction to dual-frequency satellite tomography. We then introduce a beacon satellite receiver software that we have developed using the Universal Software Radio Peripheral (USRP). We also discuss the cost of a receiver station when implemented using this concept.

1 Introduction

There are various methods for performing tomographic measurements of ionospheric electron density. The most commonly used method uses delays of electromagnetic waves transmitted from satellites and received at ground stations. These are linearly related to line integrals of the refractive index of medium. There are two different families of satellites that can be used for this purpose, low earth orbit VHF dual frequency beacon satellites [?] and GPS satellites.

In the most optimal case, a receiver should be capable of observing both of these types of satellites and there should be a fairly dense network of stations to allow good tomographic reconstructions at lower altitudes[1]. The most practical way of implementing such a receiver is using a software defined radio, which basically means that most of the signals processing is performed with software on a general purpose computer instead of custom-designed signal processing hardware.

A software defined beacon satellite receiver consists of the following parts:

1. RF frontend (antenna, amplifiers and filters).
2. Personal computer with a sampler and a suitable RF front-end
3. Satellite ephemeris program that provides the geometry, timetables and frequencies for passes.
4. Recording software, which records the dual-band signals from satellites at given times and stores them to disk.
5. Phase curve calculation software, which calculates the relative phase of two beacon frequencies.

[1] More specific details of geometry are currently being studied in the thesis work of Johannes Norberg

This approach has several advantages compared to custom made black-box type solutions as the software is more easily customizable and in most cases results in cheaper hardware. We will thus focus on this approach.

The main part of this work has been to program VHF beacon satellite phase curve measurement software that can be used automatically to record multiple different satellites simultaneously and produce phase curves, which can then be used in further analysis. We have also studied various other practical issues, such as antennas, amplifiers, filters, existing satellites, ephemeris calculations etc.

The software that has been produced in the course of this work is in most parts usable for routine ionospheric measurements. We have also designed a RF front-end and found a suitable antenna that can be used.

Provided the necessary software and RF frontend hardware, the digital receiver used in this study should also be capable of GPS TEC measurements, although this work does not explore this possibility further.

It should be noted that Prof. Mamoru Yamamoto has been working on a relative TEC estimation software [?] that has many similarities with the system that we are building. It is likely that our projects will also collaborate on some level, as there are many possible synergies.

However, our purpose is to build a fully automated receiver that can be used for a large semi-autonomous chain of receivers. For this reason we have opted to implement our own software from scratch. While our programs are independently developed, we also will publish our software under the GNU open source license.

2 Theory

The phase velocity of high frequency radio waves in plasma is

$$v_p = cn^{-1}, \tag{1}$$

where n is the refractive index of plasma defined as

$$n = \left(1 - \omega_p^2/\omega^2\right)^{\frac{1}{2}}. \tag{2}$$

Here

$$\omega_p = \sqrt{\frac{N_e e^2}{\epsilon_0 m_e}} \tag{3}$$

is the plasma frequency (rad/s) and ω (rad/s) is the frequency of the electromagnetic wave propagating in the plasma. N_e is the electron density, e is the charge of an electron, ϵ_0 is the permittivity of vacuum, and m_e is the mass of an electron.

The electric field amplitude of an electromagnetic wave propagating along z from a satellite at $z = 0$ with phase velocity v_p is described as

$$E(z,t) = E_0 \cos(\omega(t - z/v_p)). \tag{4}$$

From this we can determine the phase $E(z,t) = \cos(\phi(t))$ of a signal at a ground station at $z = L$ that has been transmitted from the satellite

$$\phi(t) = \omega t - \frac{\omega}{c}\int_0^L n(z)dz. \tag{5}$$

In order to convert this into an integral of $N_e(z)$ we remember that $n(z)$ is a function of $N_e(z)$

$$N_e(z) = -\frac{\epsilon_0 m_e \omega^2}{e^2}(n(z)^2 - 1), \tag{6}$$

and we can with reasonable accuracy approximate this as a first order Taylor polynomial expanded around $n(z) = 1$

$$N_e(z) \approx -\frac{2\epsilon_0 m_e \omega^2}{e^2}(n(z) - 1), \tag{7}$$

and now inserting this into Eq. 5 we get

$$\phi(t) = \omega t - \frac{\omega L}{c} + a\omega^{-1} \int N_e(z) dz, \tag{8}$$

where

$$a = \frac{e^2}{2\epsilon_0 m_e c}, \tag{9}$$

which relates phase difference to the line integral of electron density between a transmitter and a receiver.

Now assuming that our geometry is known, we could directly use Eq. 8 to infer about electron density along the ray path. However, in typical satellite measurements there are time dependent errors in satellite range $r(t)$, which causes an additional term to the measured phase and assuming that this error is small enough, the measured phase is:

$$\phi(t) = \omega t - \frac{\omega L}{c} + a\omega^{-1} \int N_e(z) dz + \frac{\omega r(t)}{c}, \tag{10}$$

Now if there are two measurements at different frequencies ω_1 and ω_2

$$\begin{cases} \phi_1(t) & = a\omega_1^{-1} \int N_e(z) dz + R(t)\omega_1 \\ \phi_2(t) & = a\omega_2^{-1} \int N_e(z) dz + R(t)\omega_2 \end{cases}, \tag{11}$$

there are two measurements and two unknowns, here $R(t) = t + (r(t) - L)c^{-1}$. which can be solved:

$$\int N_e(z) dz = \text{TEC} = a^{-1} \left(\frac{\omega_2}{\omega_1^{-2}} - \frac{1}{\omega_2} \right)^{-1} \left(\omega_2 \omega_1^{-1} \phi_1(t) - \phi_2(t) \right), \tag{12}$$

and

$$r(t) = \left(\frac{\omega_1 \phi_1(t) - \omega_2 \phi_2(t)}{\omega_1^2 - \omega_2^2} - t \right) c + L. \tag{13}$$

The first equation is the basic principle behind dual frequency total electron content measurements (measurements of the electron density line integral). The second equation is also useful, e.g., for accurate orbital elements determination, and this equation might also be useful if the chain of tomography receivers, as it provides a way of measuring orbital elements of “secret” beacon satellites, such as DMSP F15. More precise orbital elements can also be used to further improve phase curve measurements.

In practice, a single receiver station cannot measure the full phase difference $\omega_2 \omega_1^{-1} \phi_1(t) - \phi_2(t)$. Instead, the receiver measures a relative phase curve, which measures the phase difference which the satellite transits over the receiving station, and there will be an unknown phase difference factor that cannot be measured using one station only because the initial phase difference (when the satellite is first observed) can only be measured up to modulus of 2π:

$$m(0) = [\omega_2 \omega_1^{-1} \phi_1(0) - \phi_2(0)] \mod 2\pi \tag{14}$$

This is why single station measurements are called relative total electron content measurements, as the initial unknown phase difference contributes to an unknown additional total electron content, that must be added in order to obtain the true line integral of the electron density. This can be done e.g., by using prior information on electron density or using multiple receiver stations observing the same volume.

3 Hardware

Our hardware consists of a dual band QFH antenna by Nagara Ltd (shown in Fig. 2), a dual band preamplifier, and additional amplifiers. The signals are connected to a USRP1 equipped with two WBX (50-2200 MHz) daughterboards. In addition to the 150 and 400 MHz frequencies used by LEO beacon satellites, the daughterboards are capable of receiving L1 (1575.42 MHz) and L2C (1227.6 MHz) GPS channels, which might be useful in future applications.

For the next generation receiver, we will use the USRP N210 and TVRX2 daughterboards, also provided by Ettus Research. The software itself is generic enough that it supports both types of hardware.

A full block diagram of the whole system is described in Fig. 1.

4 Usable satellites

There exist many known beacon satellites that can be used by the receiver, but many of them do not transmit above scandinavia at the moment. Some of the satellites also are on equatorial orbits, so they cannot be observed[2].

- OSCAR 23,-80
- OSCAR 25,-80
- OSCAR 31,-145
- OSCAR 32,-80
- COSMOS 2279,-400
- COSMOS 2407,-200
- COSMOS 2414,-200
- COSMOS 2429,200
- COSMOS 2454,-400

[2]Information on coherent frequency pairs can be found here: `http://www.zarya.info/Frequencies/FrequenciesCoherent.php`

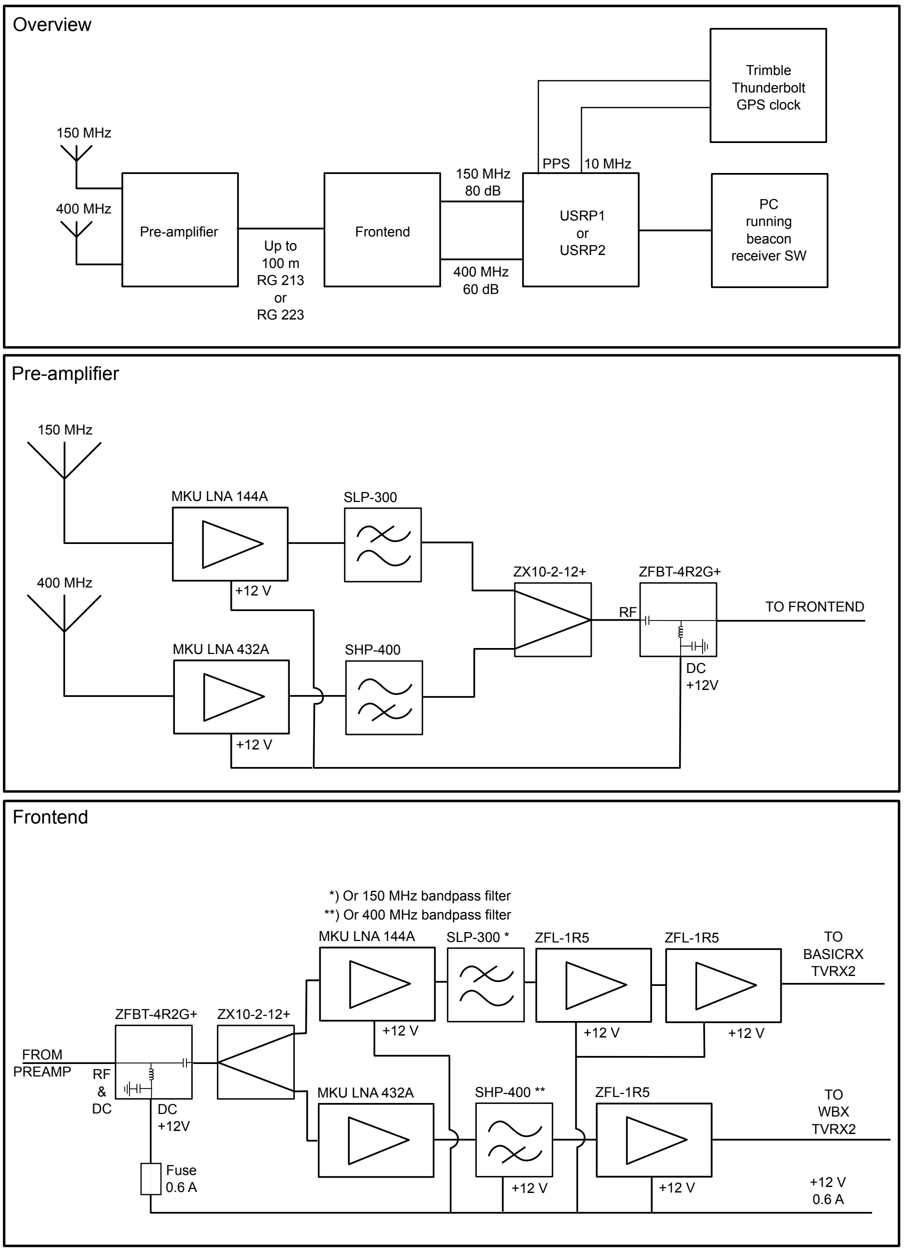

Figure 1: A block diagram of the beacon satellite receiver.

Figure 2: The dual band 150/400 MHz quadrifial helical antenna.

- COSMOS 2378,-400
- COSMOS 2398,-600
- COSMOS 2341,-600
- COSMOS 2389,-400
- COSMOS 2336,-200
- FORMOSAT-3 FM1,80
- FORMOSAT-3 FM2,80
- FORMOSAT-3 FM3,80
- FORMOSAT-3 FM4,80
- FORMOSAT-3 FM5,80
- FORMOSAT-3 FM6,80
- GEOSAT,80
- COSMOS 2463,-400
- RADCAL,80
- C/NOFS,80
- DMSP F15,80

We have detected signals from the following satellites in Sodankylä:

- COSMOS 2407,-200
- COSMOS 2414,-200
- COSMOS 2429,200
- COSMOS 2454,-400
- COSMOS 2463,-400
- RADCAL,80
- DMSP F15,80

These result in approximately 60 to 70 passes on each day.

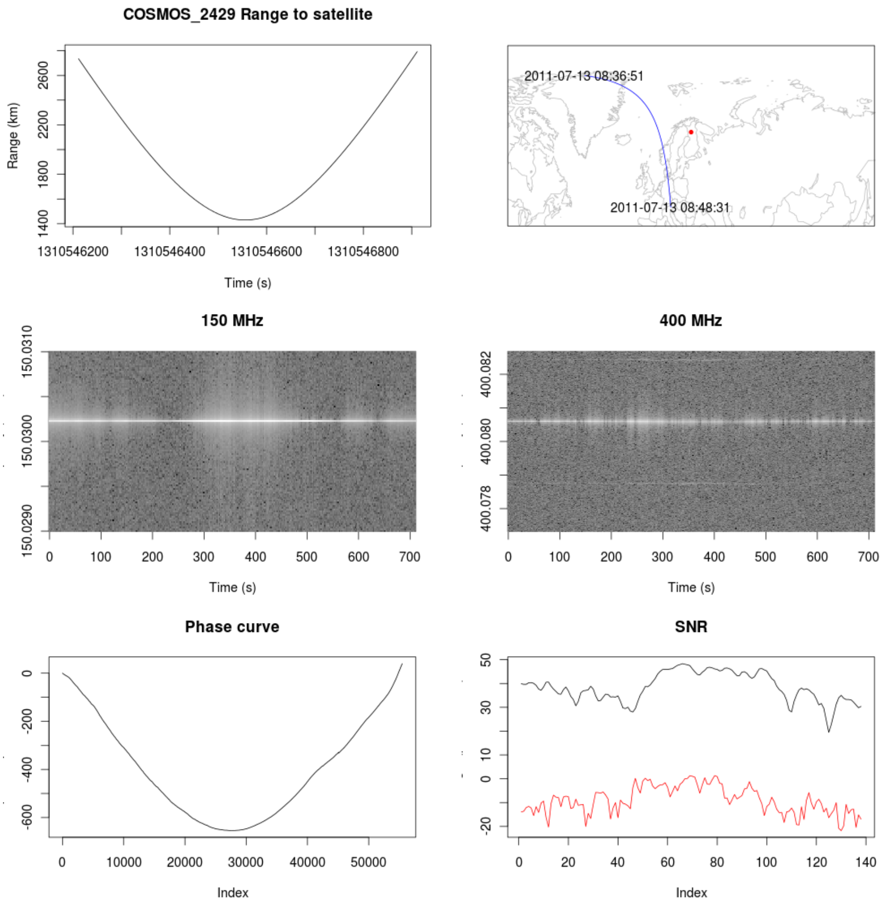

Figure 3: Example beacon satellite measurement.

5 Software

The software consists of the main modules: The *data recorder* and the *phase curve analysis*. These are implemented with two independent programs `beacon.r` and `beacon_calc.sh`. These two programs should be run in parallel. The `beacon.r` command starts the data recording process and automatically downloads satellite ephemeris files from celestrak on a daily basis from the internet. It also predicts satellite passes. The `beacon_calc.sh` script scans the data directory for newly recorded passes that haven't been analyzed yet, and then performs a phase curve analysis of the results. An example of a measurement is shown in Fig. **??**. The software produces such a quick-look plot from each satellite pass.

Detailed installation and operating instructions for the software can be found in the README file of the software distribution.

6 Cost

An estimated minimum price for a beacon satellite receiver station hardware is 5000 e, depending on how many receivers are built and what type of analogue front-end is needed. However, a better antenna might increase costs significantly. The minimum price estimate is based on the cost of the cheapest components that have been found for the purpose. However, the final cost depends on the

Device	Price (e)
USRP N210	1300
PC	500
TVRX2	200
Preamplifiers and filters	1000
Antenna	600
GPS clock and antenna	850
Cabling	300
Total	≈ 5000 e.

Table 1: Cost breakdown of the digital beacon satellite receiver components.

specific choice of components, cost of labor and design of the receiver antenna.

7 Grand unified geophysical observatory

As the USRP is a general purpose radio acquisition device capable of operating on a very large swath of radio spectrum, it is possible to also perform other geophysical measurements with the device. In the introduction, we mentioned the possibility of using the system also for GPS TEC measurements. But with little additional hardware and software, one can also use the system for ionospheric HF soundings. For example, with an additional USRP2 and a magnetic loop antenna, it is possible to perform oblique ionosonde soundings. Fig. **??** shows an ionosonde sounding performed with a USRP2 using the Sodankylä FM-CW chirp transmission. Due to the software defined nature of USRP2, very little effort was required to produce an ionospheric sounding with the hardware.

The Sodankylä ionosonde signal should be usable in all of the planned ionospheric tomography sites. And in addition to the Sodankyl ionosonde, there are also several other ionosondes that can be used.

8 Conclusions

We have implemented a working beacon satellite receiver system for 150/400 MHz dual band transmissions. The current software can be used for operational measurements. Once configured and operational, the receiver software automatically downloads the satellite ephemeris files and records all satellite passes. The software then performs a phase curve analysis on these measurements with another background process.

The software and hardware itself can also be used for other bands too (for example the Chinese 180/480 MHz transmission), but we have not implemented

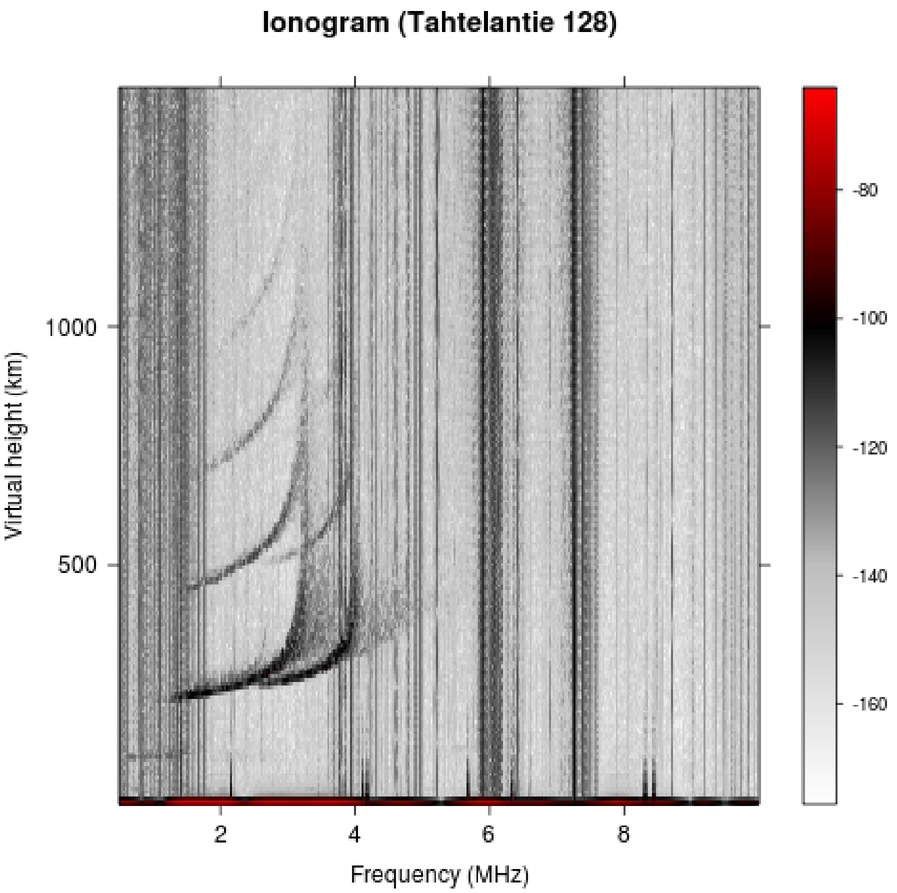

Figure 4: An ionosonde sounding performed with a single magnetic loop antenna and a USRP2 listening to the Sodankylä transmitter.

a RF frontend for it, and we also do not have a suitable antenna at the moment for these satellites.

References

[1] M Yamamoto. Digital beacon receiver for ionospheric tec measurement developed with gnu radio. *Earth Planets Space*, 60, 2008.