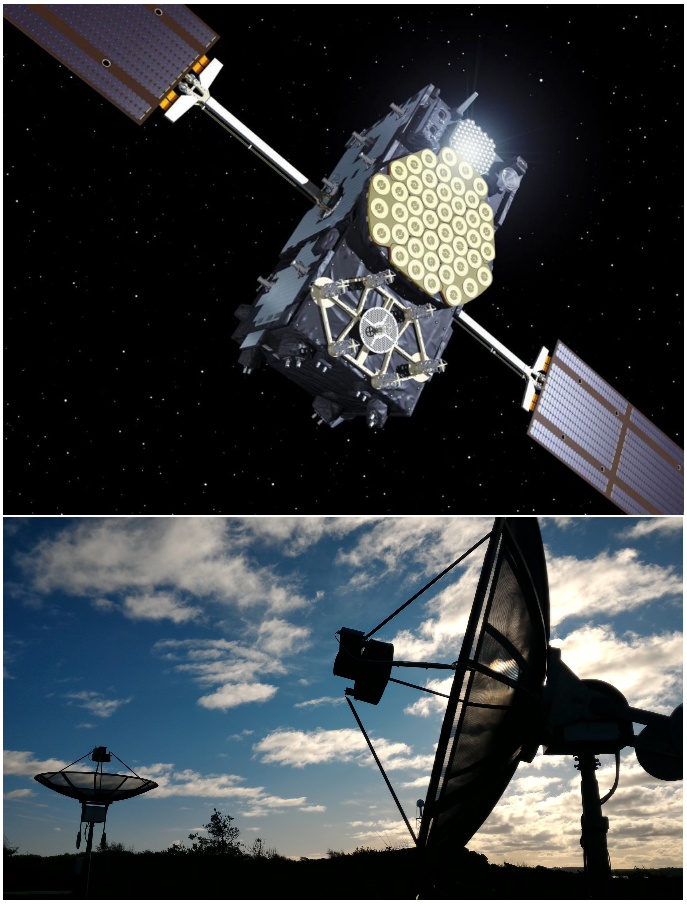
SALSA project documentation: GNSS signal spectra with SALSA



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Abstract

SALSA ('Such A Lovely Small Antenna') are two 2.3-m-diameter radio telescopes built at Onsala Space Observatory in Sweden to introduce pupils, students and teachers to the marvels of radio astronomy. This receiving system allows users to detect radio emission from atomic hydrogen located far away in our galaxy, the Milky Way. SALSA can also be utilized in other types of observations. In the following document, we describe how SALSA can be used to investigate spectra of signals emitted by satellites that are part of the Global Navigation Satellite Systems (GNSSs).

First, we give a brief introduction to GNSS as well as highlight its common applications. Next, we describe the structure of GNSS signals and explain the basic principles of the global positioning through the use of GNSS. Finally, we give a detailed account in words on how to use SALSA to detect signals transmitted by GNSS satellites.

Please note that this document focuses only on one application of SALSA. General instructions on how to operate telescopes can be found in the document entitled *SALSA users manual* available at the SALSA website.

Cover image: A GALILEO satellite (upper, credit: European Space Agency) and SALSA telescopes (lower, credit: Grzegorz Klopotek).

Chapter 1

Global Navigation Satellite Systems

Progress in space sciences and an increasing interest in the exploration of the universe caused that nowadays many satellites are present at the Earth's orbit and used in different fields of our lives such as telecommunication, meteorology or environmental monitoring. Design of the Doppler TRANSIT system (Navy Navigation Satellite System) by the United States Navy, and making it available to the public, started the era of satellite positioning. Experiences that had been gathered during the TRANSIT era were utilized in the establishment and development of the Navigation Satellite and Ranging Global Positioning System (NAVSTAR GPS). The latter system completely replaced its forerunner in the end of 1996 (Teunissen and Montenbruck, 2017). Currently, GPS serves millions of users around the globe and finds its applications in science and industry. It is one of the two fully operational global navigation satellite systems (Tab. 1). Nowadays, GLONASS (Globalnaya Navigatsionaya Sputnikova Sistema) is the second positioning system in operation, with a global coverage and of similar precision. The fully civil GALILEO system is a project of European Union (EU) and European Space Agency (ESA). Currently, it is at the phase of introduction of satellites at the Earth's orbit. Future launches will bring the GALILEO constellation to its full strength of thirty (twenty four and six spare) satellites by 2020 when fully operational services with higher accuracy and availability will begin. In addition, in 2015 the Chinese navigation satellite system called BeiDou began its transition towards a global coverage. When coping with satellite navigation systems, the term one often encounters is GNSS, which stands for the Global Navigation Satellite System. This is a generic name used to describe any global system of satellites that transmit signals for navigation purposes.

Tab.1 Global and regional navigation satellite systems.

System	Owner	Intended coverage area	Orbital altitude [km]	No. and type of operational satellites[a]	Frequency bands [MHz]
GPS	United States	Global	20 180	31[b] MEO[c]	1575.42 (L1) 1227.60 (L2) 1176.45 (L5)
GLONASS	Russian Federation	Global	19 139	23 MEO	1598.0625–1605.375 (G1) 1142.9375–1248.625 (G2) 1201.743–1207.242 (G3)
GALILEO	EU and ESA	Global	23 222	14 MEO	1575.42 (E1) 1176.45 (E5a) 1207.14 (E5b) 1278.75 (E6)
BeiDou	China	Global	21 150	4 MEO 7 GEO[d] 6 GSO[e]	1561.098/1589.42/2575.42 (B1) 1589.742 (B1-2) 1207.140 (B2) 1268.52 (B3)
IRNSS	India	Regional	36 000	4 GSO 3 GEO	1176.45 (L5) 2492.03 (S1)
QZSS	Japan	Regional	32 000 – 40 000	1 GSO	1575.42 (L1) 1227.60 (L2) 1176.45 (L5) 1278.75 (E6)

[a] Valid at 04-04-2018
[b] The full constellation consists of 24 satellites
[c] Medium Earth Orbit
[d] Geostationary Orbit
[e] Geosynchronous Orbit

Each of the navigation satellite systems consists of space, control and user segments. The space segment comprises satellites located at few orbits and transmitting signals between 1.2 and 1.6 GHz (a part of the so-called L-band). The control segment is a group of ground-based stations, which monitor the space segment in order to know very precisely where the satellites were, are and will be in the future. The last segment includes civil as well as military users equipped with GNSS receivers. Depending on the equipment type, users can determine their position with different precision in real time or during the post-processing of observations recorded over periods of hours or days (Teunissen and Montenbruck, 2017).

Satellite positioning finds its applications not only in navigation and timing services, but also in the interdisciplinary research on Earth. GPS has introduced significant changes in the process of monitoring of the movement of tectonic plates or horizontal and vertical deformation of the Earth's crust caused by e.g. melting glaciers or earthquakes (Wake et al., 2016). In the last few microseconds of their journey, the incoming GNSS (radio) signals encounter propagation effects while passing through the atmosphere. This knowledge can be quantified and utilized in meteorological observations and atmospheric studies. Moreover, GNSS does not only reveal geophysical phenomena in space and time, but also contributes to the establishment and maintenance of global reference frames, which the observed phenomena and their spatio-temporal variability can be properly referenced to (Altamimi et al., 2016).

1.1 GNSS signals

GNSS signals are electromagnetic waves propagating at the speed of light. An oscillator located on the board of a GNSS satellite generates the fundamental frequency f_0 which is then used to generate radio signals that are sent towards the Earth. GNSS signals are created through the multiplication of f_0 by different predefined integer values[1]. Each GNSS system provides signals on at least two different frequencies in order to deal with the signal delay caused by the ionosphere. In order to convey digital data, the generated signals are also modified by changing (modulating) their phase. In the case of the biphase modulation (BPSK) there will be a 180° shift in the phase of the signal whenever a change in the value of the bit (symbol) will appear (Fig. 1.1). In each satellite navigation system, the aforementioned digital data consist of ranging codes and downlink system data codes (broadcast navigation message). Ranging codes are used to estimate the position of a receiver on the ground. Information such as satellite's oscillator (clock) offset from the GNSS system time, satellite's three-dimensional position, status messages or correction data are transmitted in the navigation message.

In each navigation system satellites transmit signals with the same strength. Different power levels are assigned however to different frequency bands. As an example, GPS transmits on L5 with power levels reaching 263 W, whereas on L2 it is only 4 W. Users on the ground receive signals with varying strength and that are sometimes discontinuous. A loss in the singal strength is proportional to the distance to the satellite, which means that the further the ground receiver is located from a satellite, the signal is weaker[2]. Signals transmitted on L-band do not suffer from high attenuation under harsh weather conditions, compared to e.g. signals at frequencies above 10 GHz. A satellite signal is often diminished by radio interference or obstacles such as high buildings or trees located close to a GNSS receiver.

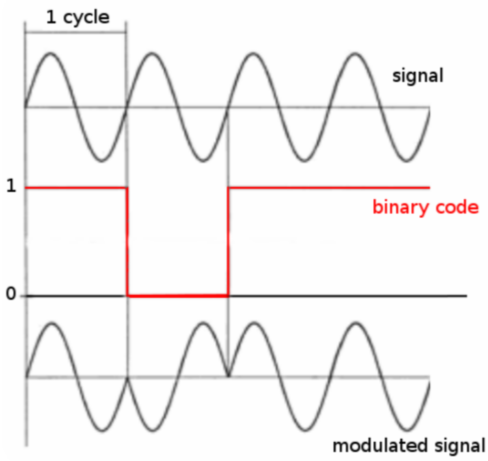


Figure 1.1: BPSK signal modulation.

Multiple access techniques allow to distinguish between signals transmitted by different satellites. With Code-Division Multiple Access (CDMA) it is possible to use the same frequency spectrum by all satellites of the navigation system. In GLONASS however, Frequency-Division Multiple Access (FDMA) in both G1 and G2 bands is utilized instead. As a consequence, slightly different frequencies are used by each satellite[3]. However, new generation of GLONASS satellites will transmit CDMA signals in addition to the system's traditional FDMA. In general, development and modernization programs of all contemporary navigation satellite systems aim for better accuracy, multipath resistance and especially, greater interoperability with other navigation systems.

[1] In the case of GPS L1 band, this is 154×10.23 MHz which gives 1575.42 MHz. For GPS L2 the integer value amounts to 120 which gives 1227.60 MHz. [2] This effect is known as the free-space loss (L_{FS}). It depends on the distance (R) from the receiver to a satellite and the used frequency (f): $L_{FS} = \left(\frac{4 \cdot \pi \cdot R \cdot f}{c}\right)^2$, where c is the speed of light. [3] In practice, two satellites, located on antipodal sides of a single orbital plane, transmit signals using the same frequency.

1.2 GNSS positioning principle

The basic measurement carried out by any GNSS receiver, for navigation purposes, is the signal propagation time from a satellite to the receiver. It is determined by comparing (correlating) the received binary code (pseudorandom noise) embedded in the signal with the internally-generated replica at the local receiver time (Fig. 1.2). This measured quantity can be easily converted to a distance (pseudorange) by multiplying it by the speed of light and used to localize the receiver w.r.t the satellite, which signal was sent from. It is possible to determine the three-dimensional position of the receiver if it simultaneously observes signals coming from many satellites, which position is well known thanks to the ground segment. In principle, we would need to measure ranges to at least three satellites. However, the internal oscillator (clock) of the receiver is mis-synchronized with respect to the satellite clocks. Therefore, an offset of the receiver clock with respect to the system time is estimated for each observation epoch. This implies that one needs to have at least four satellites to be able to solve for the receiver's position with a usable accuracy. Satellite clocks are also not perfectly in sync with each other and the system time. This is however dealt with by estimating the offsets and drifts of satellite clocks with respect to the system time. These parameters are then used by GNSS receivers as corrections to the measured ranges.

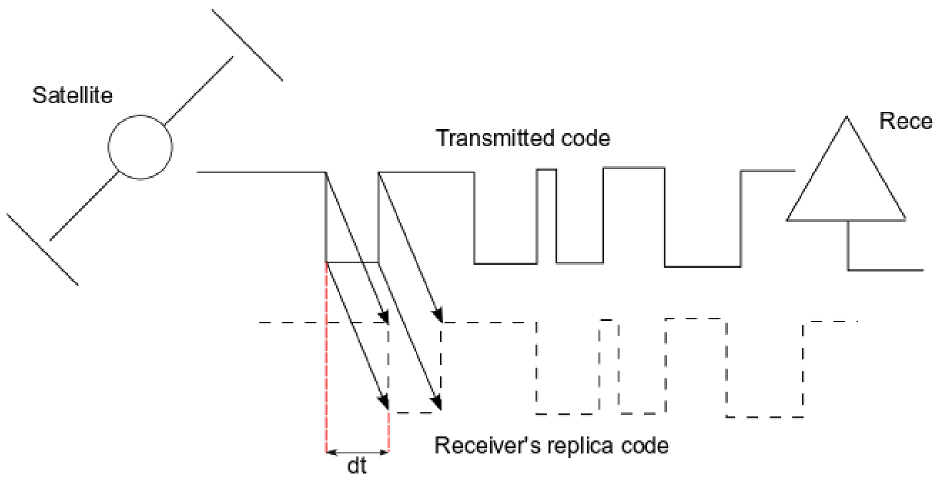


Figure 1.2: GNSS pseudorange measurement principle.

Under the assumption of receiver and satellite clocks being in sync and in the presence of no additional errors, our position uncertainty would be only proportional to the error in determination of the position of satellites. When one includes satellite clock and atmospheric propagation errors as well as receiver's noise into the error budget, all expressed in units of distance, the current positioning accuracy from range measurements amounts to few meters. This quantity tends to vary as it is related to e.g. the location of a GNSS receiver (cities, open fields), number of used satellites and their location on the local sky (Teunissen and Montenbruck, 2017).

Chapter 2

Observing signal spectra of GNSS satellites

In this chapter, we describe how SALSA can be utilized in observations of signals transmitted by GNSS satellites. Note that in this project we are currently able to investigate signals in a relative sense as an absolute flux density calibration of SALSA antennas has not been implemented yet.

2.1 How does SALSA know where to point at ?

Finding the location of GNSS satellites of interest on the sky can be tricky as they are in a continuous motion. The SALSA control program can however calculate the position of any GNSS satellite at any given time. It uses a so-called two-line element set (TLE) to localize an artificial Earth-orbiting object on the sky and be able to follow (track) it. TLE is a data format that encodes a list of orbital elements of an Earth-orbiting object for a given point in time. As the name suggest, a trajectory of a target can be described using just two lines:

```
1 29486U 06042A   16001.47634844 -.00000070  00000-0  00000+0 0  9996
2 29486  55.7430 303.5601 0084444 331.9182 116.9546  2.00564670 67931
```

With a sufficient prediction formula, the position and velocity of an object can be calculated, to some accuracy[1], at any point in the future or in the past. New element sets are generated with varying frequency, depending upon the object's orbit type. The interested reader is referred to CelesTrak for more information on TLEs and an access to the TLE database.

2.2 Tracking GNSS satellites

In this subsection, we describe how to use SALSA interface to track GNSS satellites. For general introduction to the Graphical User Interface (GUI), the reader is referred to *SALSA user manual* available at the SALSA website.

[1] The accuracy of TLE data is dependent upon few factors such as the target's orbit type or the amount of collected data. These factors usually vary for each generated element set, which, of course, affects our accuracy.

Once we are familiar with the GUI of SALSA, one can start tracking GNSS satellites. In case SALSA telescopes (Vale/Brage) are started for the first time, it is necessary to reset the chosen telescope using the `Reset` button located in the main window. This makes sure that the telescope tracks chosen objects correctly.

The module that allows us to cope with GNSS satellites is available after choosing *GNSS* from the *Desired* list in the main window of SALSA. The GNSS-related part of the GUI consists of a combo box (in the main window) with a list of GNSS satellites available for tracking[2] and a separate window displaying current (calculated) positions of satellites on the sky. To track a satellite, choose one from the second combo box in the control program and press `Track`. The telescope will start moving towards the chosen satellite. Note that it may take up some time to reach your desired position if you started pointing far away on the sky. Once the telescope reaches the desired position, the yellow color of the labels in the main window will disapear. This means that the telescope is now tracking the chosen satellite. To switch to a different satellite, click `Stop`, choose a satellite from the list and click `Track` again. The step-by-step demonstration for tracking a satellite is shown in Fig. 2.1.

It is also possible to observe at different angular separations relative to the satellite that is being tracked. Conveniently, the SALSA control program can automatically track positions relative to the chosen satellite by specifying local (altitude, azimuth) offsets. For example, if we are currently tracking a satellite and we want to point at the part of the sky that is always three degrees offset in azimuth from this satellite, click `Stop`, enter an azimuth offset of 3 in one of the dedicated text boxes in the main window and press `Track`. To switch to another relative position, you have to first press `Stop` to be able to input new offsets, and then `Track` again to choose a new position.

When you are done with your observations and would like to exit the program, choose *Stow* as *Desired*, press `Track` to move the telescope into the stow position and wait until it reaches its destination. This step puts telescopes in a save position that prevents them from being damaged while they are not used.

2.3 Observing signals of GNSS satellites

Once we are following the chosen GNSS satellite on the sky, one can start recording signals and investigating the obtained spectra[3]. To avoid obstacles or disturbing radio emission from the Earth, it is good to observe when the target GNSS satellite is as high above the horizon as possible. To find out where the chosen satellite is currently on the local sky, you may use the Azimuth-Elevation window available under the `GNSS Az-El View` button (Fig. 2.2). The Altitude-Elevation (Az-El) coordinate system that is present there uses the observer's (telescope's) local horizon as the fundamental plane. In this system, the position of a target on the sky is expressed in terms of the altitude (or elevation) and azimuth angles. The former (El) is the angle between the target and the observer's local horizon. For visible objects it is an angle between 0 and 90 degrees. The latter (Az) is the angle of the object measured around the horizon, with zero at north and increasing values towards the east (0–360 degrees).

The SALSA control program, as described in *SALSA user manual*, was developed to measure the radio emission from neutral hydrogen. In this case, it is crucial to find out how the

[2] This means satellites that are above the local horizon. [3] A plot of the radio emission as a function of the frequency within a specific frequency range.

emission changes with different frequencies close to 1420 MHz. However, when observing signals transmitted by GNSS satellites, we are only interested in the total power received by the antenna in some frequency range (band).

Since SALSA's default observing frequency is 1420 MHz, one needs to change it to one of the frequencies utilized by GNSS satellites (See Tab.1). This is done on the *Advanced* tab in the *Receiver control* part of the control program. The default bandwidth does not need to be changed for this exercise, but 5 MHz can be set as the bandwidth that we would like to observe at. By default, the program will observe in the *Switched* mode which is used for spectral line observations of hydrogen. Since we want only to look at the signal strength, we need to change this mode to *Signal*. This can be also done on the *Advanced* tab in the *Receiver control* part. An example of the frequency/measurement setup for GNSS L1/E1 band is shown in Fig. 2.3.

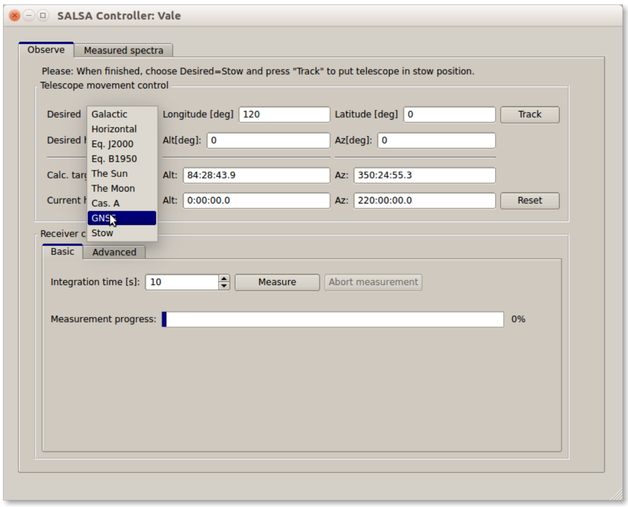
Once we have specified the frequency and the observing mode, we are ready to measure. A default integration time of 10 seconds is enough to detect GNSS signals. The shorter observation time can be chosen on the *Basic* tab in the *Receiver control* part of the GUI. Make sure that you are tracking the satellite of interest and then press `Measure`. The recorded spectrum will appear on the *Measured spectra* tab. An example of the GPS signal spectrum obtained with SALSA is shown in Fig. 2.4. In addition, the results can be displayed in the dB scale[4] and normalized by clicking the corresponding check boxes above the plot with the signal spectrum.

Currently, the measured signal strength is expressed as 'Uncalibrated antenna temperature [K] ' and can be interpreted only in a relative sense, i.e. with respect to other radio sources (the Sun, ground noise, other satellites) as measuring the true signal strength with SALSA has not been implemented yet.

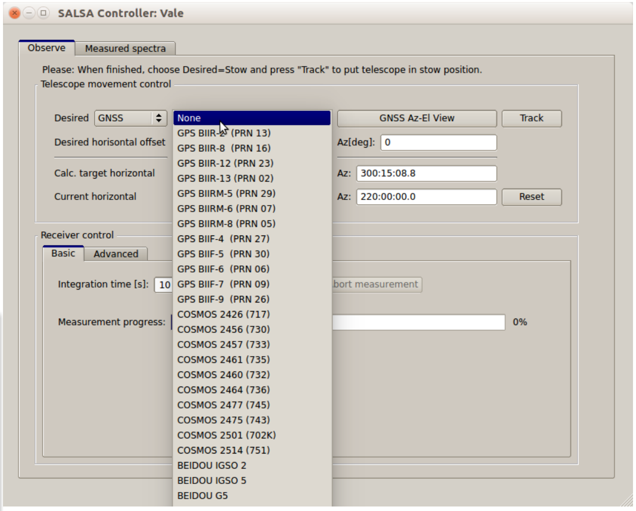
2.4 Related questions

- Can you name other applications of GNSS not mentioned in the following document ?
- Each GPS satellite is visible at the same position on the sky every $11^h58^m2^s$. Asumming that the radius of the Earth is 6371 km, what is the orbital speed (in km/s) of GPS satellites[5] ?
- What is the free-space loss (in dB) for signals at L1-band and a distance of 25 000 km between a satellite and an observer ? What would happen to the free-space loss if we would like to use frequencies amounting to 10-12 GHz ?
- Choose any GNSS satellite located close to the horizon and carry out observations. How does the spectrum look like ?
- The GPS L1 signal spectrum is shown in Fig. 2.4. How does it look like for GALILEO satellites ?
- Choose any GLONASS satellite and measure the signal. Can you see the spectrum ? If not, why ?

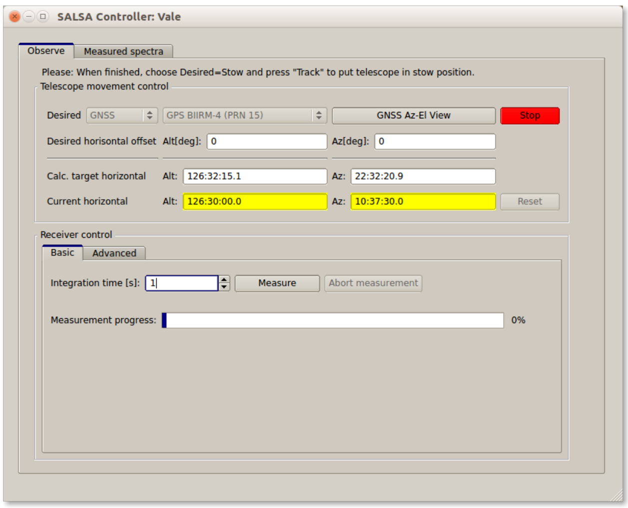
[4] For 100 K the result would be $10 \cdot log_{10}(100K) = 20\,dBK$ [5] $v \approx 2\pi(R_{Earth} + a)/T$



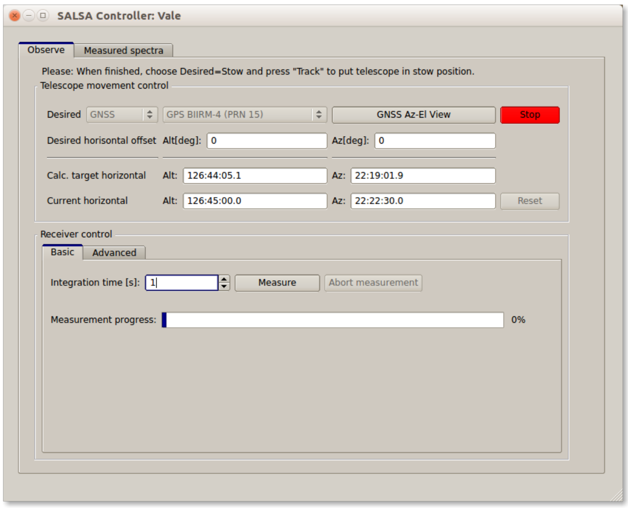
(a) Choose *GNSS* as *Desired*.



(b) Choose a satellite from the list and click *Track*.



(c) Telescope moves towards the chosen satellite.



(d) Telescope is tracking the object and SALSA is ready to measure.

Figure 2.1: GNSS satellite tracking with SALSA.

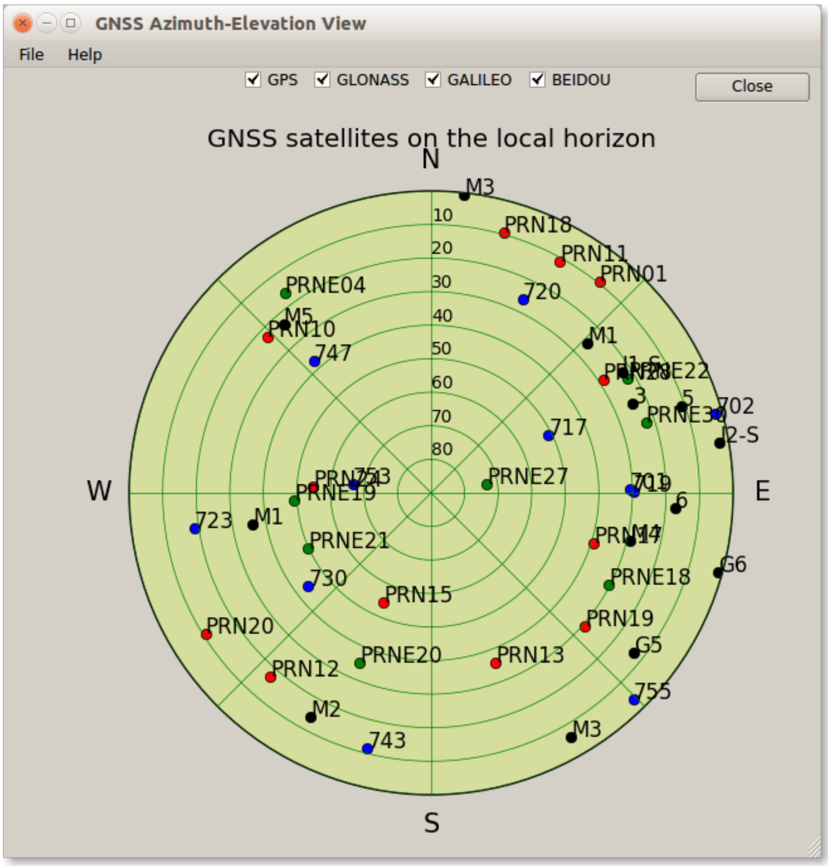


Figure 2.2: Window with distribution of GNSS satellites on the local horizon.

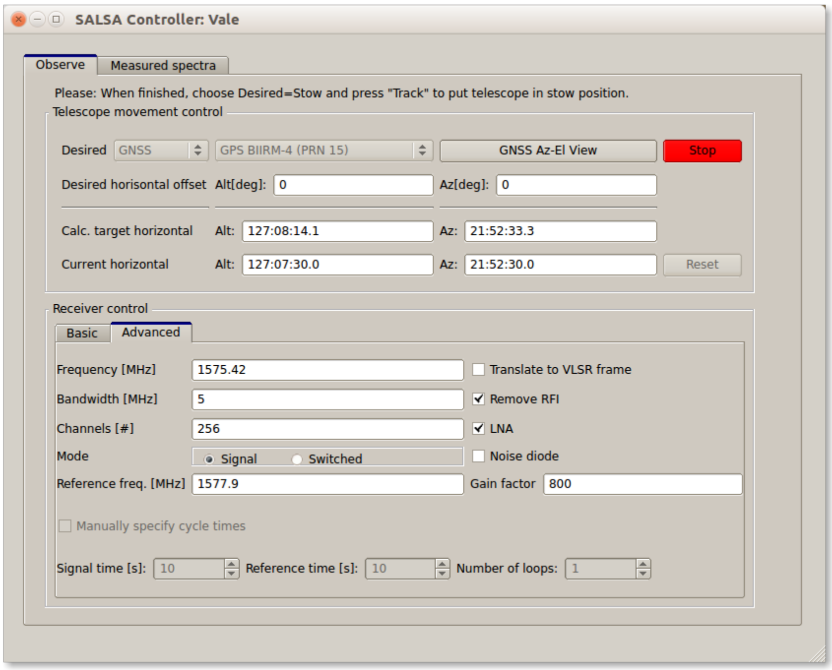


Figure 2.3: Frequency and measurement setup for E1 / L1 band.

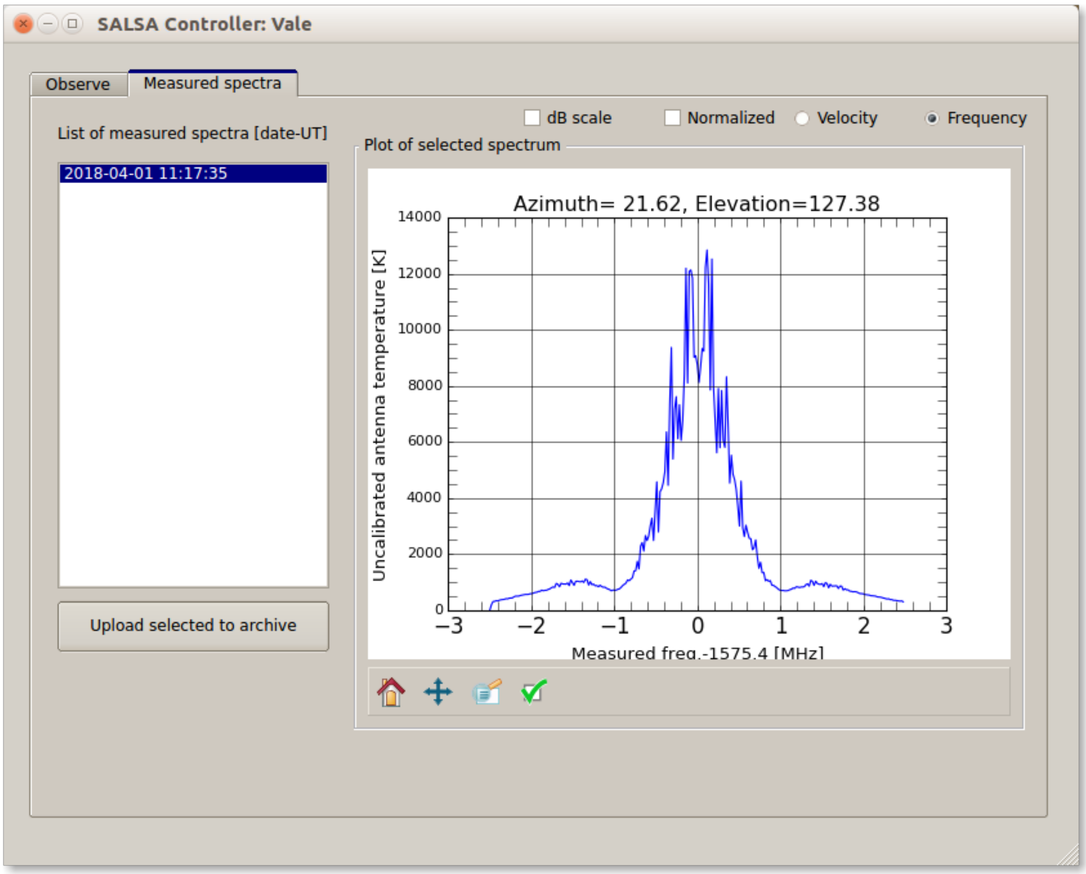


Figure 2.4: Signal spectrum of PRN 15 (GPS) at L1 for the measurement time of one second. Note that the radio button in the upper right part of the window is set to *Frequency*.

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