# Cold Start Strategy of the CubeSat GPS Receiver

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*Abstract*—**The cold start of the LEO satellite GPS receiver is complicated due to a large Doppler frequency shift, Doppler frequency rate of the navigation signals and a rapid change of the satellite visibility. The cold start time can be shortened by a proper strategy of a selection of the satellites to be searched for. The cold start simulator was developed and used for optimization of the sequence of the satellites search, for development and testing of an advanced satellite selection algorithm that utilizes information on the satellites already detected and for optimization of a frequency search range. The best performance was achieved by using an advanced selection strategy.**

**The strategy is based on the selection of the satellites nearest to the detected satellite, using the average angle between the Earth center (apex) and the satellites.**

**Furthermore, the simulation shows that it is not practical to investigate all frequencies within the range of the maximum possible Doppler frequency shift of the carrier wave of the navigation signal, but investigate approximately +/- 35 kHz range and, if not successful, switch to the next satellite.**

**The simulations proved that a simple GPS receiver with the sequential search algorithms can operate in the LEO orbit.**

*Index Terms*—**cold start, CubeSat, LEO orbit, space GPS receiver.**

## I. Introduction

The CubeSats [1] are standardized Pico-satellites for low cost space research. They are launched as secondary payload and usually operate on Low Earth Orbits (LEO). The CubeSat standard defines several satellite sizes; the basic 1U size has a volume of one liter and a mass of no more than 1.33 kilograms. The power budget is approximately 1 W.

Many of the physical and technological space experiments require precise knowledge of the satellite position. Despite the fact that the CubeSats are mostly designed from Commercial Off-The-Shelf (COTS) components [2], a commercial GPS receiver cannot be used due to the International Traffic in Arms Regulations ITAR [3] that introduces speed and altitude limits. The standard GPS receiver cannot produce navigation results above 60 000 feet or 1000 knots.

This paper analyses requirements for a CubeSat GPS receiver and compares them with the requirements for the commercial version. The LEO satellite GPS receiver operates in almost ideal conditions except for space radiation [4-5], large Doppler frequency shift [6-7] of the carrier frequency of the received signals, and variations in temperature. The Doppler frequency shift, being greater in LEO, mainly complicates and prolongs a cold start of the GPS receiver. The aim of this paper is to develop a strategy of the cold start for a simple GPS receiver that uses a sequential search of the satellite signal [8-10].

The cold start strategy was developed for a GPS receiver that is being developed within the framework of the CzechTechSat [11] project at the Czech Technical University in Prague.

## II. Space Operation Conditions

This paragraph compares a LEO and a land mobile environment from the GPS receiver operation point of view.

The operation of a terrestrial receiver is influenced by the vicinity of the Earth surface and objects built on it [12]. These objects reflect or block satellite signals. Consequently, multipath transmission reduces the precision of pseudo range measurement. The visibility of the satellites is rapidly changing in mobile applications. The navigation receiver should be capable of rapidly detecting navigation signals and synchronizing onto them. This process is called acquisition or reacquisition.

The CubeSat navigation receiver operates on a small spacecraft on the LEO orbit [8-9]. The visibility of the navigation satellites is similar to that on the Earth surface but there are no obstacles to block the navigation signals. The navigation antenna has a perfectly clear view of the sky. In addition, the size of the CubeSat is very small, so the reflections of the navigation signals from the satellite body have only minimal impact on the position precision. Other reflected signals are not presented; therefore the implementation of the multipath mitigation techniques into the signal processing or special antenna is purposeless.

The navigation signals are not blocked by obstacles. The rapid satellite reacquisition capability used in the mobile GPS receivers is therefore unnecessary.

The power level of the received signal is similar to that on the Earth surface. Because the satellite orbits are above the atmosphere, the navigation signals are not attenuated by troposphere humidity. A signal to noise ratio $C/N_0$ is high, above 40 dBc – Hz.

The satellite orbit is perfectly smooth. The CubeSats are not equipped with any rocket engines for maneuvering; the satellite is moving inertially in the Earth gravity field. The movement is perfectly described by the Kepler principles. The precise model of the movement simplifies the position filtering [13].

The main problem of the operation of the GPS receiver operating on the LEO orbit is huge Doppler frequency shift of the navigation signal carrier waves caused by the mutual

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movement of the navigation and LEO satellites (see Fig. 1). The compensation of this frequency shift requires knowledge of the navigation satellite almanac, Kepler parameters of the LEO satellite trajectory and precise time.

As the CubeSat must be completely switched off; any circuits including a real time clock may not be supplied during the satellite launch, the navigation receiver has no information of the time. This is why the cold start of the LEO satellite GPS receiver is very complicated, especially for the simple receiver that uses a sequential search method.

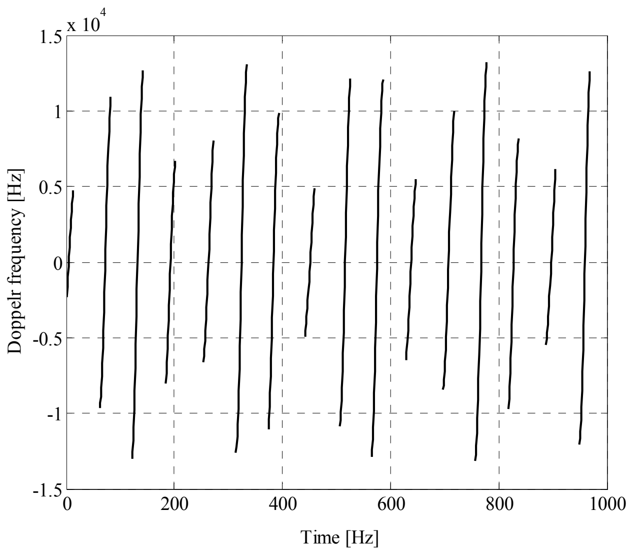


Figure 1. One day track of the Doppler frequency Shift of GPS L1 C/A signal at the LEO satellite (Elevation Mask 10°)

The space environment causes some additional difficulties to the receiver operation. The main problem is space radiation [4-5], [14] and the second one is the periodic temperature variation.

The space radiation could cause malfunction or damage to integrated circuits and significantly decreases their lifetime. Fortunately, the LEO orbits are below the Van Allen radiation belts, so the radiation is not so severe as in the deep space or inside the radiation belts. It allows designing CubeSat electronics from COTS components (semiconductors), but the designer should count with shorter lifetime than on the Earth surface.

The periodic temperature variation caused by the alternation of the sun lighting and the Earth shadow (i.e. cold temperature) shortens the lifetime of satellite electronics and changes the frequency of the satellite clock standard too.

## III. CubeSat GPS Receiver

This paragraph describes a target receiver (Fig. 2.) that is being developed within the framework of the CzechTechSat program [11]. The main design criteria are low power consumption and weight. The receiver will process GPS L1 C/A navigation signals only. A multi-frequency receiver would be too complicated and would have an unacceptable power consumption and size.

The easiest way to develop an LEO satellite GPS receiver is to reprogram the commercial receiver. This would require an access to confidential information and programming tools of the chipset manufacturer. This is why the receiver has to be designed from general components. We use GPS L1 C/A chip for mobile devices (Fig. 3.). A signal processor is implemented into an FPGA. A receiver control and a position calculation run inside a 32 bits ARM microcontroller.

The FPGA is programmed with 15 GPS correlators (channels), no acquisition unit is implemented due to its hardware complexity. The size of the receiver printed circuit board is 63 x 30 mm. Estimated power consumption is about 160 mW. Since the receiver is fully programmable we plan to reprogram several GPS channels for reception of the Galileo satellites as the next step of the receiver development.

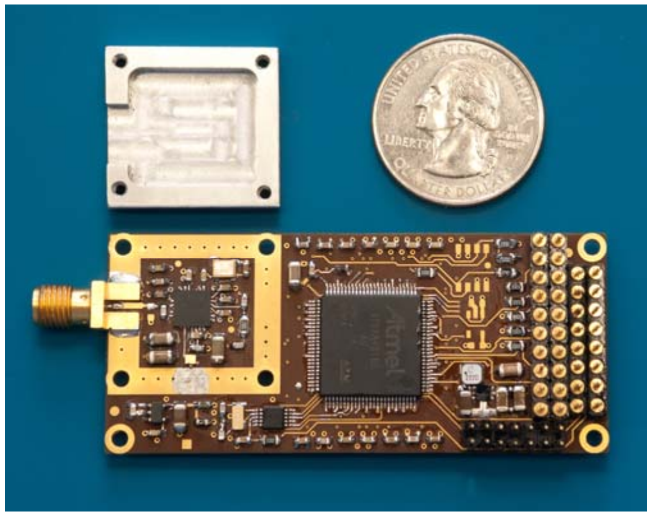

Figure 2. Photo of the CubeSat GPS receiver

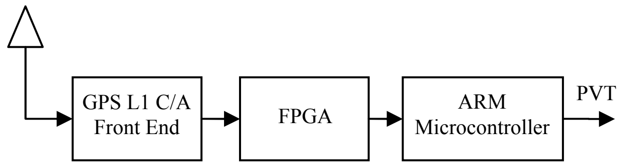


Figure 3. Block diagram of the CubeSat GPS receiver

## IV. Signal Acquisition

The GPS navigation satellites transmit direct sequence spread spectrum signals (DSSS) [15-16] that are modulated by the navigation data $D(t)$ and the ranging code $C(t)$.

$$s_{L1\_C/A}(t) = C(t)D(t)\cos 2\pi f_{L1} t \quad (1)$$

As the signals are very weak, the signal must be processed by a correlation reception method. The navigation receiver generates a local replica of the received signal which then serves for signal despreading.

The processing of the signal is divided into two steps: signal acquisition and signal tracking.

The signal tracking uses electronic circuits called correlators that calculate the correlation between a received signal and a replica signal for a single frequency shift and two or several delays. Either the signal delay or the frequency shift is tracked by a feedback system called delay-or frequency- or phase- locked loops (DLL, PLL or FLL). Before locking the feedback the tracking loops must be initiated for a proper delay and the frequency shift, otherwise the tracking loops cannot operate properly.

The signal acquisition is an estimation of the received coarse signal delay and the carrier frequency shift for initiation of the DLLs, PLLs and FLLs. The receiver should search through a two-dimensional search space (see Fig. 4). The search space is divided according to frequency and code delay on to the frequency and delay bins as drawn in Fig. 4.

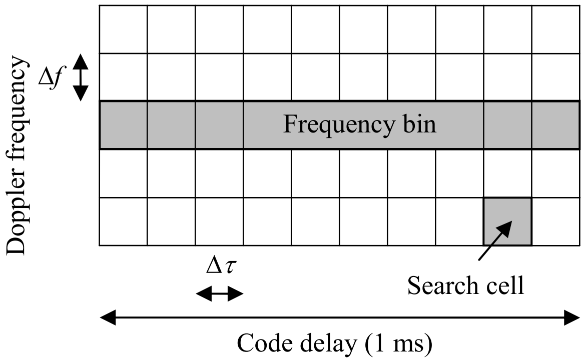


Figure 4. Sampling of the search space

As the ranging code $C(t)$ is periodic with a period of 1 ms, a dimension of the search space in delay must be equal to this period. A sampling step $\Delta\tau$ is usually set up to one half of the ranging code chip duration. As the ranging code length is $N_C = 1023$ chips, the sampling period is $\Delta\tau = T_I / (2N_C) = 0.489\ \mu\text{s}$.

The maximum dimension of the search space in frequency is determined mainly by the maximum Doppler shift (Fig. 1.). Setting up an optimum search range for the fastest receiver start is an object of this research and will be determined by a computer simulation. A sampling step in frequency $\Delta f$ is inversely proportional to a coherent integration time $T_I$ ($\Delta f = 2/3T_I$) in the receiver correlator. The frequency step is 666 Hz for the standard 1 ms integration.

The search space can be investigated sequentially, cell by cell or in a parallel method that calculates a cross correlation function for a large number of cells in one integration step.

The serial search is usually realized by a standard GPS correlator that is used for signal tracking. No additional hardware is needed in this case, but the search rate is very slow.

The parallel search requires special complex hardware called an acquisition engine. Unfortunately, the engine is rather complicated; therefore the CubeSat GPS receiver must make do without it.

The sequential search algorithm successively measures an envelope of the cross correlation function of the received signal and the locally generated replica and compares it with a threshold $V_t$ [15].

The probability of the signal detection [15], [17-19] for AWGN (Additive White Gaussian Noise) channel is calculated as a probability, that the envelope of the signal plus noise exceeds the threshold $V_t$. As the probability density function of this signal has Rice distribution, the probability of the signal detection is then given by

$$P_d = \int_{V_t}^{\infty} \frac{x}{\sigma_n^2} e^{-\left(\frac{x^2}{2\sigma_n^2} + C/N\right)} I_0\left(\frac{x\sqrt{2C/N}}{\sigma_n}\right) dx\,, \tag{2}$$

where $I_0$ is a modified Bessel function and $\sigma_n$ is a noise standard deviation.

The probability of the false alarm is equal to the probability, that the noise envelope exceeds the threshold $V_t$. As the probability density function has a Rayleigh distribution, the probability of the signal detection is given by

$$P_{Fa} = \int_{V_t}^{\infty} \frac{x}{\sigma_n^2} e^{-\frac{x^2}{2\sigma_n^2}} dx = e^{-\frac{V_t^2}{2\sigma_n^2}} \tag{3}$$

where C/N is a predetection signal to noise ratio $C/N = (C/N_0)T_I$. In order to achieve high probability of the detection and decrease the probability of the false alarm for a given $C/N_0$, the coherent integration time must be long enough.

Alternatively, we can setup the threshold $V_t$ at a level which would achieve the required detection probability $P_d$ at the cost of high false alarm probability $P_{Fa}$.

The frequent false alarms can be solved by a confirmation algorithm [15], [17]. For instance the confirmation algorithms are the Tong Algorithm or the M of N detector. An average duration of an investigation of the search cell after the confirmation algorithm has been used is given by

$$T_{cell} = T_I + P_{Fa} T_{confirm} \tag{4}$$

where $T_{confirm}$ is the time of the confirmation of the correlation maximum detection.

## V. Cold Start Strategy

The cold start of the navigation receiver is a start without usable information of navigation satellite positions, user position, and time. The cold start ends in the moment, when the receiver gets a position fix. It happens when the receiver acquires and tracks at least four satellites and has received their ephemeris.

As the number of the $N_{ch}$ channels of the navigation receiver is usually optimized for tracking of the required number of navigation satellites for the positioning procedure. The receiver cannot start searching for all 32 GPS satellites defined in the interface control document [16] simultaneously. Therefore, the receiver should use a strategy of a satellite selection, a strategy of when to terminate the search of the satellite and switch to another one etc. The cold start strategy covers selection of searched satellites and utilization of the information obtained during the receiver start.

The LEO satellite selection strategy will radically differ from the satellite selection strategy of the land mobile GPS receiver. The land mobile receiver in contrast to the LEO receiver has operational real time clock and sufficient knowledge of its position. The possibility of the receiver movement by the thousands of kilometers in switched off state is uncommon.

The satellite selection strategy of the LEO satellite receiver should expect that the GPS constellation is changed infrequently and the changes are not large. The receiver could therefore use information of the satellites that are usually visible together as a group for the satellite selection. When the first one is acquired then the process of the cold start is accelerated.

The next course of action is based on the reduction of the frequency search range. This is because the exploration of the entire search space could use up more time than investigation of a smaller frequency range covering a higher number of satellites. In practice, when a satellite in the small frequency range is not found we switch onto the next satellite. This optimization is an objective of the computer simulation described further.

## VI. Cold Start Simulator

Since an analytical solution of this cold start problem is very complicated, a cold start simulator was developed for its investigation and optimization. The simulator models the following:

1. GPS constellation
2. User movement,
3. Receiver behavior

The simulation is controlled by set of simulation parameters. The main parameters are:

1. GPS Almanac
2. Keplerian parameters of the trajectory of the LEO satellite
3. Time of the acquisition start
4. Number of receiver channels
5. Elevation mask
6. Size of the frequency search range
7. Satellite selection strategy.

The GPS satellite positions are calculated from the Keplerian orbital parameters:

- Orbit inclination,
- Longitude of the ascending node,
- Argument of perigee,
- Square root of semimajor axis,
- Orbit eccentricity,
- Mean anomaly.

The algorithm is described in [10]. The same method is used for enumeration of the LEO satellite trajectory. The parameters of the GPS satellite orbits were obtained from the GPS Almanac, the orbit parameters of the LEO satellite are defined by user.

The developed cold start simulator is ranked among the high level simulators as it does not model the complete signal processing of the GPS signal on a received signal samples level. The GPS receiver behavior is modeled by high level characteristics, e.g. the probability of the signal detection, the probability of the false alarm, the probability of the satellite tracking failure etc. This high level approach saves a huge amount of computation. The simulation therefore runs very quickly.

The simulation step $T_{step}$ was setup for an average time of the search of one frequency bin (Fig. 4). This is given as:

$$T_{step} = T_{cell} .2N_C \tag{5}$$

In each simulation step the simulator calculates:

1. Satellite visibility
2. Doppler frequency of the visible satellites
3. Simulates behavior of the receiver channels
4. Checks the number of the tracked satellites and terminates the simulation attempt

The simulated receiver channel behavior comes out from the channel behavior of the common GPS receiver. As the acquisition process is described by the high level parameters we need not to model complete receiver operation as signal detection, signal confirmation or coarse and final tracking of the signal.

A state diagram that describes a developed receiver channels behavior is in Fig. 5. The receiver channel has three states: search, tracking and a new satellite acquisition. In the search state the simulator investigates whether the received signal of the searched satellite is available (the searched satellite is under the elevation mask and its Doppler frequency is in the proper search bin). If a signal is detected, the search channel passes into the tracking state. If a signal is not detected, the simulator switches to the next search frequency bin and checks whether the setup bin does not exceed the search limit. If the search limit is exceeded the channel is reinitiated by the next satellite.

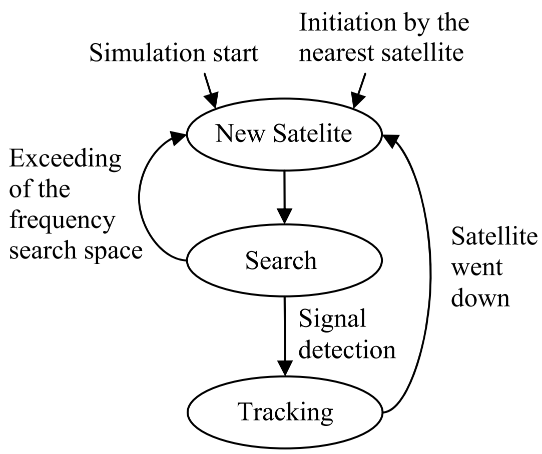


Figure 5. Channel behavior state diagram

If the channel is in the tracking state the simulator checks whether the tracked satellite is under the elevation mask. In the opposite case the receiver reinitiates the channel by the next satellite.

The search space within the frequency is investigated from the centre of the range, see Fig. 6. The search frequencies are gradually setup in the following order:

$$0, \Delta f, -\Delta f, 2\Delta f, -2\Delta f, 3\Delta f, ... \tag{6}$$

There are two implemented satellite selection strategies:

1. **Strategy 1**: The satellites are processed in a

predefined order.

2. **Strategy 2**: After acquisition of the first satellite, the remaining channels are reinitiated by the nearest other satellites.

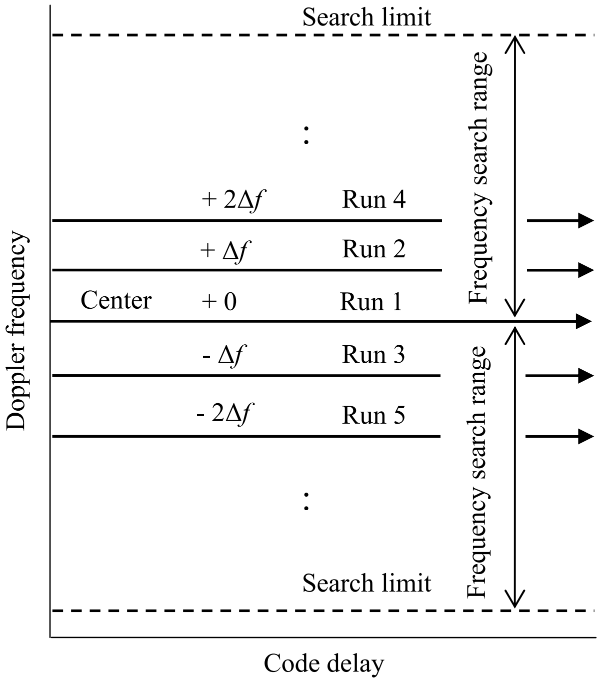


Figure 6. Investigation of the search space

The list of the relative positions of the satellites that are nearest to the given satellite is calculated in advance by a special Matlab script. The script calculates an average angle between the direction vectors from the Earth centre to the satellites. The averaging time is one day.

To obtain relevant data for the statistical processing of the simulation results, a simulation session consists of 864 attempts; a start time of the attempts is uniformly distributed over one day. The duration of the period between startup steps is 100 seconds.

The probability of the detection of the signal with $C/N_0 = 40\,dBc-Hz$ was setup at approximately 99.95% [8-9]. The probability of a false alarm is $P_{Fa} = 16\,\%$ . The 5 out of 8 confirmation algorithms was used. The probability of the confirmation algorithm failure is lower than $10^{-6}$. The average cell investigation time $T_{cell}$ is 2.28 ms. The simulation step $T_{step}$ is 4.66 s.

## VII. Simulation Results

The simulation results of the LEO satellite GPS receiver with the sequential search algorithm are summarized in Fig. 7 and 8. Fig. 7 shows the worst case of the cold start time for the navigation receiver with a different number of channels and its dependence on the frequency search range. Fig 8 shows the average cold start time.

The shortest average cold start time is obtained for the frequency search space of approximately 35 kHz, see Fig, 8. The optimum is considerable especially for the receivers with a low number of channels. The receiver starts reliably for a wide frequency search range, but the startup could be significantly slower. The hot start of the receiver is also possible for a narrow frequency search range. This can be described by the relatively fast Doppler frequency change. The receiver waits for proper Doppler frequency for satellite acquiring.

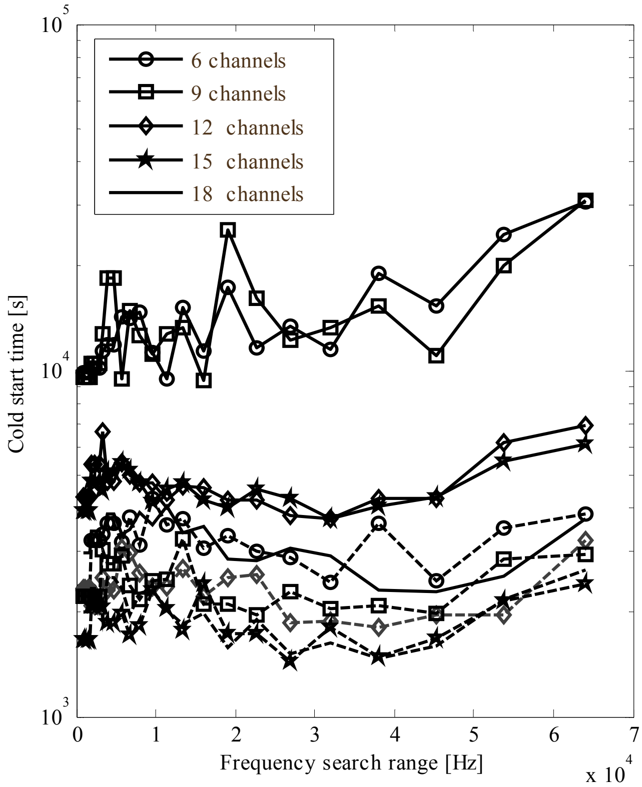


Figure 7. Cold start time - worst case, (strategy 1 solid, strategy 2 dash)

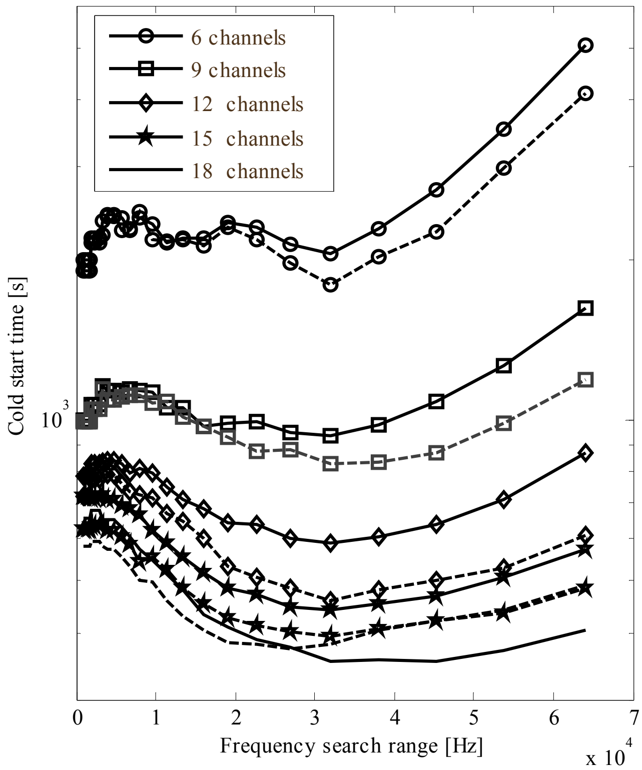


Figure 8. Cold start time – mean value, (strategy 1 solid, strategy 2 dash)

The cold start time substantially depends on the number of receiver channels. The average cold start time of the six-channel receiver is in the range of 2000 seconds while the average startup time of the eighteen-channel receivers is about 350 seconds.

The cold start time depends on the satellite selection strategy. The simple strategy 1 is worse than the strategy 2. The worst case of the cold start time of the six-channel receiver that implements strategy 2 is up to 5 times shorter than the receiver with strategy 1. These differences become smaller for the receiver with more channels. In the case of the eighteen-channel receiver, the strategy 1 is faster than the strategy 2. This behavior can be explained by the hold-up at channels initiation after acquisition of the first satellite.

In the frame of these simulations we also studied the impact of the LEO satellite orbit parameters (altitude 100 – 500 km, inclination 0 – 360°, eccentricity 0 – 0,3, etc.) on the cold start time. We have concluded that the impact is practically negligible.

## VIII. Conclusion

The feasibility study of the realization of the LEO satellite GPS receiver shows, that the receiver cold start is the most critical receiver operation because of the huge Doppler frequency shift of the GPS signals and rapid changing of the satellite visibility. Therefore the main objective of this research was to answer the question whether a simple GPS receiver with sequential search can dependably operate on the LEO satellite and under what conditions. The answer on this question is very critical. The complex GPS receiver equipped with the acquisition unit that solved the cold start problem requires high performance hardware. This hardware based on proprietary ASIC is unavailable and the hardware based on FPGA or processors easily exceeds the energy budget of the pico-satellite. The usable receiver should be therefore as simple as possible.

For investigation of this problem the cold start GNSS receiver simulator was developed and the receiver cold start was thoroughly analyzed under various conditions.

The research shows that the mean cold start time of the developed 14-channel GPS receiver is approximately 500 seconds and the optimal frequency search range is approximately +/-35 kHz. The worst case is about 1800 seconds.

The research proved that the cold start of the GPS receiver with at least 9 channels is very robust. The receiver has started in all cases even when equipped with 6 channels only, but the startup time was very long.

The application of the satellite selection strategy 2 mainly improves the average startup time of the receiver with low number of channels. The worst case of cold start time has been reduced up to five times.

The research proved that the proposed simple GPS receiver equipped with 14 channels and sequential search algorithm can reliably operate at the LEO orbit. The number of channels is more than two times higher than the minimal necessary number of channels. This fact enables to reprogram several channels for reception of Galileo E1 signal. The implementation of this upgrade is planned for after the completion of the development of the GPS version.

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