

Design of Software-Based GPS/ Galileo Receiver for Applications

Liu Xiaoli¹²³ Liu Jingnan² Li Tao² He Xi²

¹School of Electronic Information, Wuhan University, 129 LuoyuLu, Wuhan, Hubei China

²GNSS Engineering Research Center, Wuhan University, China

³School of Electrical Engineering, Wuhan University, China

ABSTRACT

Modernized GPS and Galileo systems will be available to civil users at the end of this decade, thus there is a need for unified platform that can receive multi-frequency signals of GPS/Galileo to develop and test a variety of applications. The unified platform for various applications will speed up the design process and reduce its cost. Such a platform needs an open architecture and design flexibility so that modifications and testing can be done conveniently and efficiently. The flexible, reconfigurable, combined and software-based Global Navigation Satellite Systems (GNSS) receiver will allow development, test and measurement of a variety of receiver architectures.

This paper presents a design of a software-based GPS/Galileo receiver, including a structure of combined software GPS/Galileo receiver with multipath mitigation and Receiver Autonomous Integrity Monitoring (RAIM), which can utilize the planned GPS and Galileo publicly available signals.

Key words: GPS, Galileo, Software-Based Receiver, Navigation, Signal Processing, FPGA

I. INTRODUCTION

As it seems certain to include the modernized U.S. GPS, the restored Russian GLONASS and the evolving

Galileo system of the European Commission (EC) in the Global Navigation Satellite Systems (GNSS), different government institutions in the world are working toward their navigation plans, such as Chinese BEIDOU system, then the design of a new hybrid architecture could be expected. Considering all the navigation/positioning systems and techniques that will be available in the near future, it is clear, if navigation signals from different sources will be available, the unique possibility to obtain the best navigation performance from the user perspective will be the employment of enhanced receivers which are able to fuse different data. Also, while both the modernized U.S. GPS signal and Galileo signal are neither completely approved nor available, in a quest for flexibility, upgradeability and versatility, the reconfigurable, software-based GPS/Galileo receiver will be an ideal way to receiver design. Furthermore, since a deep integration at the raw signal level between GPS and the future Galileo has been obtained with software-based GPS/Galileo receiver, the design benefits effectiveness of both multipath mitigation and RAIM in terms of accuracy and reliability.

This paper presents an architecture of reconfigurable GPS/Galileo receiver over a Field Programmable Gate Array and Digital Signal Processor (FPGA & DSP) prototype platform, which consists of a hardware multi-frequency front end responsible for both capturing part

of planned civil satellite-based radio-navigation signals: in case of GPS, the L1, and L5 signals; in the Galileo side of the fence, the signals will be involved in L1, E5a-E5b bands and down-converting the signal to a suitable IF and sampling it.^[1] A followed digital signal processing module using reprogrammable high-speed hardware (FPGA & DSP) is able to achieve a deep integration at the raw signal level between GPS and the Galileo, and thus guarantee the reconfigurability, upgradeability and flexibility. The interoperability issue among different systems is then solved at the receiver level. Since the receiver is able to deal with GPS/Galileo different input signals in view, system diversity and higher signal availability, which benefit improvement for multipath mitigation and RAIM, can be obtained via both constellations.

Both the hardware/software partitioning strategies and applications of software-based GPS/Galileo receiver are reported in this paper. The receiver presented is just a baseline scheme, but it is designed to be an efficient and cost-effective manner to achieve various applications including multipath mitigation, RAIM and "what if" scenarios, and assist researchers to design and develop future multi-standard GNSS receiver.

II. SOFTWARE-BASED GPS/GALILEO RECEIVER STRUCTURE

The GPS/Galileo software-based receiver based on software radio definition will meet the needs of navigation, position and velocity with GPS-alone, Galileo-alone or combined GPS/Galileo system. In addition, the receiver will provide more precise navigation and position than the GPS only, since the optimal constellation is chosen with more satellites available, which are tracked by 24 channels. In order to improve the reliability, the receiver is comprised of block modules to optimize the performance with flexibility, integrity, and updating. Also the receiver has a function of RAIM so as to warn and protect system under failure.

For each satellite being monitored, one channel is needed. Modernized receivers have an array of channels, which can be operated in parallel, independent of each other. Under GPS modernization, the next generation GPS satellites will have the capability to broadcast new

military and civil codes. The reprogrammability inherent in the GPS/Galileo software receiver will allow these new PRN codes to be tracked by making software and firmware changes to the software radio. In this case, a system level functional block diagram of a combined software GPS/Galileo receiver including multiplex channels for multiplex A/D output is shown in Figure 1. Except for power supply, the receiver consists of the following five functions: 1) radio frequency (RF) End; 2) A/D conversion; 3) signal processing; 4) data processing; and 5) graphic user interface (GUI). A hardware multi-frequency front end is responsible for both capturing planned civil satellite-based radio-navigation signals. A followed programmable processor performs signal correlation. The correlator output then goes on signal processing totally using software. The correlator can be implemented using Field Programmable Gate Array (FPGA) for real time processing. The software modules for signal processing with multipath mitigation algorithm are easily updated. Improvements in accuracy and integrity are also achieved by GPS/Galileo RAIM. The software-based implementation of processing modules makes this system a truly versatile receiver suitable for various applications.

2.1 RF end

The RF end is composed of an antenna, usually in L-band, a low noise amplifier (LNA) and the RF front-end component itself. In the RF-component, the conversion, which depends on the implementation that is done in one or more steps, to an intermediate frequency is performed. Parallel RF front-ends are designed for combinations of different GPS/Galileo signals, such as L1, E5a/L5, and E5a/L5/E5b etc, so that navigation data of both GPS and Galileo could be read out synchronously, then better performance of RAIM and anti-multipath, compared to GPS standalone case, could be achieved.

GPS L1 (1575.42 MHz) with code frequency 1.023 MHz and length 1023, so a code period is 1 ms. Minimum received power is -154 dBW, and bandwidth is 2.4 MHz. GPS L5 (1176.45 MHz) with code frequency 10.23 MHz and length 10230, so a code period is 1 ms. Minimum received power is -154 dBW, and bandwidth is 24 MHz. This signal consists of a QPSK modulation with one data channel and one pilot channel

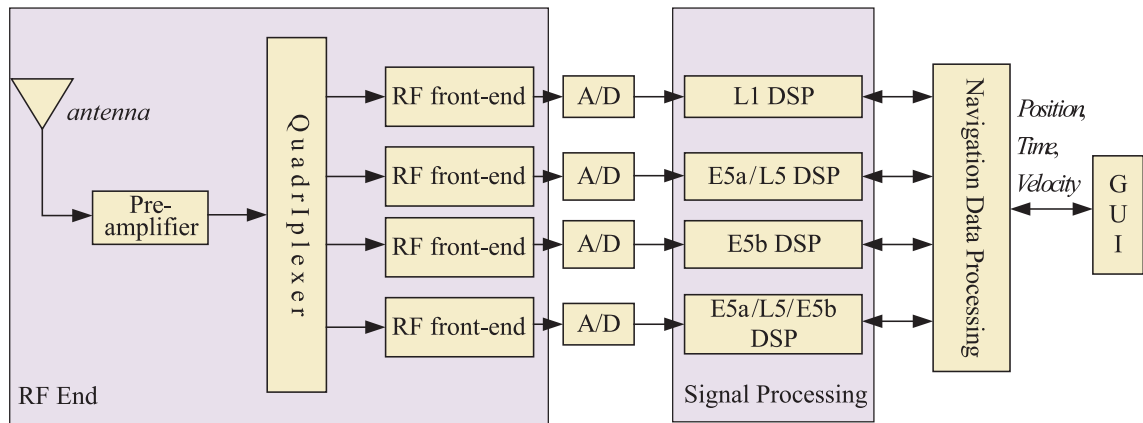


Fig.1 Structure of software-based GPS/galileo receiver

both modulated with a Neuman-Hoffman code. A Forward Error Correction (FEC rate $1/2$, constraint length 7) convolutional code will be used to lower the BER. The data rate is 50bps and 100 sps after coding. Galileo E5a (1176.45 MHz) with code frequency 10.23 MHz for length 10230, so a code period is 1 ms. Minimum received power is -155 dBW, and bandwidth is 24MHz with also one data and one pilot channel (QPSK modulation). Galileo E5b (1207.14 MHz) with code frequency 10.23 MHz and length 10230 chips, minimum received power is -155 dB W, and bandwidth is 24 MHz with one pilot channel (QPSK modulation).^[3]

An active GPS/Galileo antenna feeds a series of amplifiers and bandpass filters. Approximately 100 dB of gain was applied to the signal. In order to isolate the GPS and Galileo signals, a splitter was used followed by individual narrow-band filters. For GPS L1, the filter had a center frequency of 1575.42 MHz and a 3-dB bandwidth of 3.2 MHz. The Galileo E5b filter was centered at 1207.14 MHz and had a 3-dB bandwidth of 24 MHz.

2.2 A/D conversion

The construction of a software receiver is based on the design goal: the analog-to-digital convertor (ADC) should be placed as close to the antenna as possible in the chain of radio frequency (RF) front-end components. Without the real time programmable processing technology, an alternative sampling implementation is called bandpass sampling that can receive signals in a significantly reduced bandwidth. This design would be well within the bounds of the ADC, yet the implementation of the digital filter/decimation network is

computationally expensive. The absolute minimum is determined by the information bandwidth, which is designated as the 3-dB bandwidths of the final filters of the signals of interest. This can be expressed mathematically for two signals as:^[7]

$$|F_{IF_1} - F_{IF_2}| \geq \frac{BW_{I_1} + BW_{I_2}}{2}$$

where the subscripts 1 and 2 refer to the IF (FIF) and information bandwidths (BWI) of each signal. So the minimum possible sampling frequency for this technique will be the sum of the BWI of the desired signals. For example, the sampling rates may be 48 MHz and 72 MHz for E5a/L5 signal and E5a/L5/E5b respectively in terms of the minimum direct sampling method. The output of the A/D converter is a high-frequency data stream. The digital signal now consists of an effective carrier with frequency IF modulated with the spreading code and navigation data.

2.3 Signal processing

Signal processing is responsible for acquiring and tracking the GPS/Galileo satellites. First, the algorithm performs a search for satellites in view, or, if valid almanac information and approximate receiver position and time are available, estimates which satellites are visible and attempts to acquire them. After acquisition, the code phase and Doppler of each acquired satellite are used to initialize the tracking loops. These loops (carrier and code loops) are updated continuously so that satellite and receiver dynamics can be tracked. Also, the receiver has to be synchronized with the 50 bps or 250 bps bit stream that is transmitted from each GPS or Galileo satellite

respectively to obtain navigation data defining the satellite orbits and other relevant parameters, and also to be able to correctly determine satellite pseudo ranges and pseudo range rates (timing information).^[1] The pseudo ranges and pseudo range rates are collected and passed to the Navigation Data Processing block. The digital signal processing functions are realized on an FPGA based Software Defined Radio (SDR). This approach allows the same device to be shared between the GPS and Galileo signal processing and also allows the SDR to be software upgradeable to accommodate the next generation GPS or Galileo signals and waveforms. The FPGA is used to perform the high speed code generation and correlation functions needed to acquire and track the GPS/Galileo signals. A detailed block diagram of C/A-code acquisition & tracking is shown in Figure 2. Here, the real input signal is first multiplied by sine and cosine to generate I and Q signals, respectively. Next, early, prompt and late code generator outputs are multiplied by I and Q signals and integrated. The integrator outputs are passed to carrier and code discriminators and from there to carrier and code loop filters. Numerically controlled oscillators (NCOs) are used to track carrier and code phase. Carrier and code NCO biases are at the nominal IF frequency and code chipping rate respectively. Carrier aiding is used to help the code tracking loops track the signal dynamics by scaling carrier Doppler shift to the C/A-code rate. The carrier tracking loop is FLL assisted PLL, which offers both accuracy (from the PLL component) and robustness (from the FLL component).

2.3.1 Acquisition

The acquisition process consists in a two-dimensional search both in time and in frequency. Indeed, because the user/satellite range is unknown, the received code phase must be searched. Moreover, relative changes in user/satellite distance over time and receiver's time uncertainty imply a Doppler frequency that needs to be searched as well. In future, both systems will be based on direct sequence-code division multiple access (DS-CDMA) spread-spectrum technique signal structures with a pilot channel. Future Galileo E5a and E5b signals are similar to GPS L5 signals and can therefore be modeled as two QPSK modulations carrying navigation data on the data channel (Inphase component) and without any data on the pilot channel (Quadrature component). The digital

signal stream from A/D output is multiplied with the reference code in each channel and accumulated. This is the correlation process. The instantaneous values in the accumulation buffers can be read out by the tracking loops for code and carrier tracking.

2.3.2 Tracking

Tracking needs acquisition information to start functioning. Signal tracking is the process that a receiver synchronizes the GPS/Galileo signal. If the acquisition estimations are available, tracking processes (or loops) synchronize the local generated code and carrier with the received signal. Tracking loops then remove the carrier and the code to read the navigational data, which also provide critical timing information used in the position solution.^[13]

2.4 Navigation data processing

The navigation data processing unit controls the signal processors, reads out the code and carrier for tracking loops as well as demodulating the navigation messages. Further it calculates the position and synchronizes to the system time. The transmission of similar signals from both systems and the comparable satellite constellation may provide the combination of Galileo and GPS data in the analysis of navigation data processing. Major parts of the computation software for the calculation of GPS satellite positions and the processing of the observations may be used for Galileo without too many modifications. The same processing steps have to be performed and the improving accuracies expected for combined Galileo and GPS analysis are available. The combination of Galileo and GPS doubles the number of available satellites. This will increase the effectiveness of RAIM, Realtime Kinematic (RTK) and troposphere estimates. The usage of two autonomous systems should also improve the system reliability.

In order to combine the GPS and Galileo systems, both a unique time scale for all observations and satellite ephemerides, and a unique reference system for all satellite and receiver positions, are required. For GPS Time and Galileo System Time (GST), the current Minimum Operational Performance Requirements (MOPS) algorithm and model of measurements do not account for this. It will lead to a displacement of the user

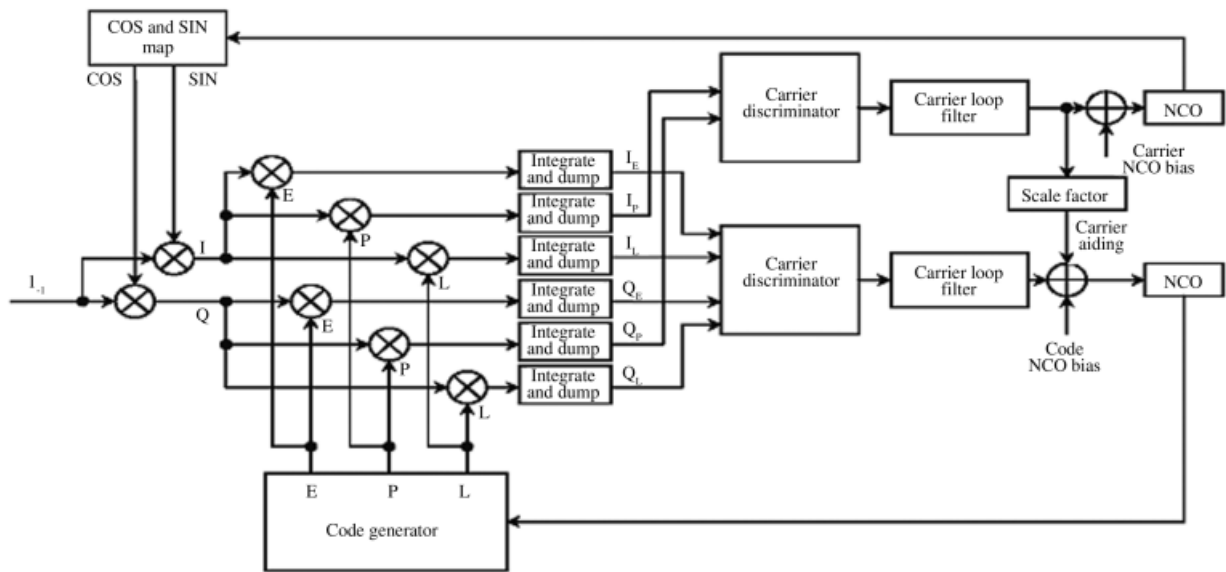


Fig.2 A block diagram of C/A code acquisition & tracking

positioning solution from the true position. This displacement will depend on the geometry of GPS and Galileo constellations observed by user. The same thing will happen with the positioning solution of users who apply the broadcast GPS Galileo time offset (GGTO) correction: the (residual) displacement will appear due to the uncertainty of this correction, but will be smaller compared to the solution without GGTO corrections. If GGTO is to be determined at the user level, the least squares solution can be made for five unknowns: 3D position, user clock offset, and GGTO (or 3D position and two user clock offsets - one versus GPS Time and the second versus GST). Obviously, alternative algorithms can be proposed to reduce the impact of GGTO on their positioning solution. Users may either: [3]

- correct their measurements with the GGTO value broadcast by Galileo and/or GPS and then utilize the MOPS algorithm solving for four parameters, or
- make no measurement corrections, but implement a modified MOPS algorithm that solves for GGTO as an additional (fifth) unknown.

The first option corresponds to GGTO determination at the system level, and the second do that at the user level.

2.5 Graphic user interface (GUI)

GUI, providing for requests setting up, data input

and output displays, is a system control unit, which is needed to control all the functional blocks: antenna, front-end (e.g., digital front-end), ADC, signals acquisition and tracking, and information processing. A particular Aux I/O is used for special control signals like smart antenna setting, and all the data processed by the receiver are made available to users through an interface.

III. APPLICATIONS

With the ability to modify existing modules and build completely new ones, a software-based receiver enables us to create and test the systems suitable to almost any applications. Either modifying existing modules or new modules are being built to add GPS/Galileo receiver capabilities, such as improved navigation accuracy, RAIM, anti-jamming processing, kinematic processing, multipath rejection algorithms etc. Typically, multipath mitigation and RAIM will benefit from both GPS and Galileo constellations, which increase signal availability above 95% even in urban canyon.

3.1 Multipath mitigation

Many multipath mitigation solutions have been devel-

oped in the past 20 years at different stages of the receiver: (1) the antenna through an efficient design of the gain pattern, (2) the navigation module through the rejection of blunders using RAIM or other types of residual checking, and finally, (3) the tracking loops which will constitute the main core of the present research. All these methods are easy to be implemented using the software GPS/Galileo receiver. The Solutions at the tracking loops level have an advantage on multipath mitigation techniques as, theoretically, multipath can come from anywhere and thus go through the antenna without being significantly affected, while residual checking is greatly dependent upon the measurements and redundancy obtained from the tracking loops themselves. As a result, tracking loop is a tremendously important stage to mitigate multipath. A method to mitigate carrier phase noise and code multipath has been proposed in using both the data and pilot channels that will be available in most of the future GNSS signals [10,11]. This method, which may be implemented via hybrid GPS/Galileo software receiver, has two components. Firstly, it concerns carrier tracking, providing robust tracking driven by an extended arctangent discriminator on the pilot channel. Secondly, the method also concerns code delay tracking.

We simulate parts of a software based GPS/Galileo receiver, consisting of the dual frequency RF front-end of L1/E5a and of the tracking channel. At the preliminary design, we use only two frequency bands of L1/E5a that they are common for GPS and Galileo and have the maximal frequency separation. Another advantage is the simplicity of antenna design: dual-frequency L1/E5a antennas will probably be typical antenna products when

Galileo comes into being; in fact the same kind of antenna has to be developed for GPS L1/L5 receivers. The matching Galileo and GPS pairs of observables (Galileo L1/E5a and GPS L1/L5) will have exactly the same frequency ranges and similar noise characteristics.^[17] Simulation result shown in figure 3 has shown that this method is very effective for low C/N0, and it can be well seen that the multipath performance of the Galileo codes is superior as compared to the C/A code, which is the only GPS code currently available for direct tracking (the future GPS L2C signal will have the same multipath performance as the C/A code). It is noteworthy that the multipath performance of the Galileo E5a signal with BPSK(10) code is identical to the performance of the GPS P-code, which is not available for civilian geodetic receivers. Among all the signals, the multipath performance of the Galileo Alt-BOC modulation is by far the best. In addition, the performance of the binary offset carrier (BOC) signals, which will be part of Galileo as well as of the modernized GPS, is quite different from the current GPS signals, thus next we need to develop analytical formulas and methods in more details and implement new tracking techniques utilizing combined software-based receiver. Furthermore, software-based GPS/Galileo receiver

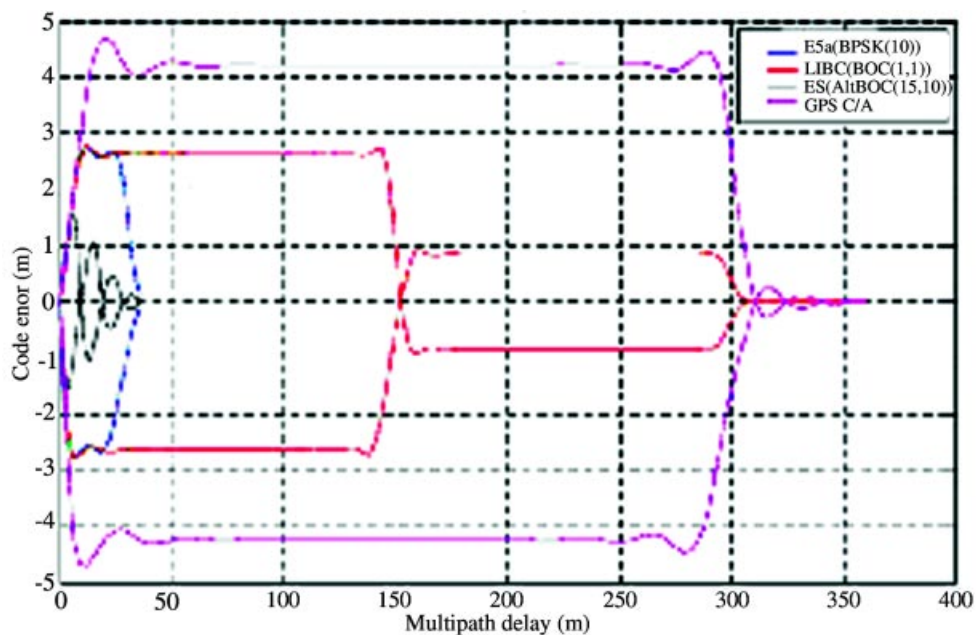


Fig.3 Multipath error envelop of GPS/galileo codes for SNR=6dB

will be developed in a complete package, including L5/E5b signals as shown in figure 1.

3.2 RAIM

RAIM is a technique used to provide a measure of the trust which can be placed in the correctness of the information supplied by the total system. It is also a condition for RAIM to deliver the user with timely and valid warnings when the system's performance exceeds specified tolerance levels. The RAIM technique monitors the integrity of the navigation signals independently of any external monitors via measurement consistency check operations. The performance is measured in terms of the 'maximum allowable alarm rate' and the 'minimum detection probability' and is dependent on the failure rate of measurement sources, range accuracies and measurement geometry. Optimal RAIM algorithms should exhibit high detection rates and low false alarm rates. Since the GPS/Galileo receiver is able to deal with different input signals in view, and can operate with present GPS signals or with the Galileo signals, RAIM will benefit from system diversity, which will be hybrid software approach taking advantage of both constellations, and increasing signal availability above 95% even in demanding environments such as the downtown area. Theoretically, for the time of simulation, an outlier of 24m for combined GPS/Galileo systems can be separated from any other measurement. Corresponding values for the GPS only are approximately 1277m, whilst, the availability of RAIM only failed in the GPS only scenario. So GPS/Galileo scenario is more reliable and stable than the GPS only case.^[9]

IV. CONCLUSIONS

The accuracy of the GPS/Galileo observables are functions of the (C/No) values of the input signals, the system dynamics, receiver design parameters, and the signal processing algorithms of the digital baseband processing. The significance of our works are the edges of the modeled software receiver over hardware-based receivers in analyzing the effects of the GPS/Galileo

receiver design parameters, the system (including both the satellites and the receiver) dynamics and the signal propagation media (such as ionosphere, troposphere, multipath, GPS/Galileo antenna, etc.) on the GPS/Galileo observables. Compared with software methods, hardware methods may be very difficult, inaccurate, or prohibitively costly. The noticeable advantages of the software-based GPS/Galileo receiver for applications are summarized below.

High Performance Operation The digital signal processing inherent in the software radio approach allows the GPS/Galileo observations to be derived to high levels of accuracy. The low level access to the GPS/Galileo signal structure also allows optimized signal processing techniques to be applied to further improve signal processing, such as multipath minimization techniques, and RAIM methods.

Multi-Frequency, Multi-Mode Operation The nature of the software radio simplifies the introduction of additional frequency channels and the tracking of new codes.

Flexibility and Upgradeability The reprogrammable nature of the GPS/Galileo software radio allows it to be upgraded through firmware and software modifications. This provides a forward upgrade path for adding capability with the modernized GPS satellite signals, and Galileo signals etc.

Low Cost, Low Power Hardware Implementation Since both the GPS and Galileo functions are performed in a single device, the component costs are reduced and power saving is also achieved through sharing of common components.

As for quite different multipath performance between GPS and Galileo, it will be important for us to develop analytical formulas and methods in more details and implement new tracking techniques with respect to GPS/Galileo signal based combined software receiver. Furthermore, software-based GPS/Galileo receiver will be developed in a full package, including L5/E5b signals shown in figure 1.

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