Benefits of the New GPS Civil Signal

The L2C Study

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National Science Foundation photo

Power grids could be one of the infrastructures benefitting from a second civil GPS signal

How much will civilians benefit from further GPS modernization efforts? A recent study conducted on behalf of the U.S. departments of commerce and transportation focused on L2C applications other than those of aviation and military users. The analysis concluded that L2C will substantially benefit dual-frequency applications until alternative signals are widely used and could be a long-term boon for applications requiring three or more frequencies.

GPS has had enormous benefits to the economy and society that go well beyond military and civil aviation applications – that is becoming ever more widely understood. What has been more open to discussion are the civilian non-aviation benefits of further U.S. efforts at GPS modernization, particularly the introduction of additional signals.

In an effort to define and measure civilian benefits, the U.S. departments of commerce and transportation commissioned some economic analyses of civil signal modernization. Particular emphasis was placed on the value of the L2C signal centered at 1227.60 MHZ, which recently began broadcasting from the first modernized GPS Block IIR-M satellite. This article is an outgrowth of that effort.

The analysis focused on the value of signals at more than one frequency for precision non-aviation use by business and government. It considered how utilization of the second civilian signal and its benefits would evolve in the coming decades as the L2C constellation expands and as additional signals become available from GPS and other GNSSes.

In the study, projections were developed under four scenarios — with the "moderate benefit" scenario seeming most likely — that reflect combinations of developments, including the strength of markets, the timing of L2C signal availability, the timing of Galileo availability, and complementary and competitive relationships with augmentations.

The main findings of the study are:

- The projected number of U.S. high precision users of any signal nearly doubles from 39,000 to 75,000 from 2004 to 2008, and reaches 146,000 in 2012 and 333,000 in 2017.
- Under a "moderate benefits" scenario, the number of L2C users reaches 64,000 by 2017, of which 35,000 are dual frequency users and 29,000 use three or more frequencies.
- Civilian benefits of L2C net of user costs range from $1.4-$9.6 billion under alternative scenarios and civilian net benefits are about $5.8 billion under the moderate benefits scenario.

- Results are robust.
  - Positive present values of benefits net of user costs are obtained in all tests.
  - The ratio of benefits to user costs ranges from 8 to 20 in all tests.

In addition to the domestic benefits examined, L2C will undoubtedly have important international benefits.

This article presents in more detail how we defined the problem, approached the study, and arrived at those conclusions.

The L2C Evolution

L2C, together with the present L1 C/A-code signal and the future modernized civil signal L1C, will provide an alternative to augmented single frequency GPS for precision users. Separate investigations have outlined the incremental benefits of L1C (See sidebar, "The L1C Studies.")

L2C signals can be used for both horizontal and vertical measurement and positioning along with L1 C/A as satellites become available over more areas and in more times of the day. The first satellite can be used for improved timing. L2C also can be used in configurations of three or more frequencies in combination with the forthcoming GPS L5 signal and with signals from Galileo and GLONASS.

At various times in each signal's deployment and development of markets, other signals will, to varying degrees, provide complements to L2C and competitors to it. L2C has its greatest potential to generate benefits for dual frequency applications until alternative signals are widely utilized, and for long-term use in applications taking advantage of three or more frequencies.

The L2 signal is currently being widely used for augmentations, and the new signals can be used in that way along with the existing constellation. However, L5's use as a competitor to L2C and as a partner to L2C in multiple frequency implementations primarily depends on the launch timeline for satellites carrying the L5 signal since L5, centered at the 1176.45 MHz frequency, is not currently in service. Plans call for its implementation on the GPS Block IIF satellites, with the first IIF now expected to be launched in 2008.

L2C deployment requires a commitment to operational capability. Decisions will be required as to launch dates and signal activation for each successive satellite containing the signal. The L2C benefits study is intended to contribute to decisions about L2C deployment with consideration of alternative scenarios informed by quantitative and qualitative analysis.

To explore the implications of L2C evolution, we make projections about the numbers of U.S. precision users, incremental benefits, and user costs, based on examination of applications and available evidence on value of benefits, and consider how these can unfold over the period 2006–2030.

The analysis focuses on precision users of L2C who use two or more frequencies, although we do include estimates for supplementary multiple-frequency users and single-frequency users. However, the estimates of these types of use are more conjectural and do not contribute much to the overall value of benefits.

Benefits net of user costs are measured according to the widely accepted economic productivity approach, which includes productivity gains and cost savings. This comprehensive approach is more appropriate than one that measures benefits simply by expenditures on equipment and services.

Incremental benefits and user costs are defined to include all differences in outcomes from what would be expected in the absence of L2C.

The L1C Studies

Before the L2C study, important progress had already been made in understanding the benefits of additional GPS signals. These activities included the discussion of civilian applications in the report of the Defense Science Board Task Force on GPS, released last December, and the L1C Study undertaken by the Interagency GPS Executive Board in 2004. (See the "Additional Resources" section at the end of this article to find out how to obtain these studies on line.)

Upper limits of total benefits of L1C for the single year 2005—including those obtained by single- and multiple-frequency users in private households, businesses, governments—were estimated at approximately $2 billion: $640 million for mobile and wireless location services, $62.5 million for information/data services, $990 million for "commercial GPS," and $490 million for in-vehicle information and navigation services (telematics).

The L1C study approximated a "rough order of magnitude" dollar value of L1C applications based on 2005 spending by applying a "team consensus" for an assumed incremental benefit as a percentage of market value (revenue) for each of 13 user categories. Spending in user group categories was based on a compilation of trade estimates.

Signal Advantages and Availability

The L2C signal, scheduled to be the first of the modernized civil GPS signals, is intended for civilian purposes other than aviation and safety-of-life. It will provide greater accuracy and robustness and faster signal acquisition than the current L1 C/A-code signal. Higher signal power and forward error correction will improve GPS mobile, indoor, and other uses.

The L5 signal that will arrive within a few years will be in a protected aeronautical radionavigation system (ARNS) band intended for aviation and other safety-of-life uses and will have broader applications.

Multiple signals will allow many users to obtain greater precision and availability at lower cost than achievable with proprietary augmentation systems. However, signal combinations combined with public and private augmentations for even greater precision and reliability will support applications with some of the greatest potential benefits. Combined use of L2C with L1 C/A and L5 will also enable some precision users to achieve even greater reliability and accuracy. Although available simulations differ on the size of benefits of three signals over two, many professionals expect important advantages from such "tri-laning" techniques.

L2C Benefit Scenarios

The four scenarios developed to support the L2C benefits study, along with the assumptions underling each, include the following:

High Opportunity

- Timely signal availability
- Larger than expected markets
- High complementarity with L5
- Success of High-Accuracy Nationwide Differential GPS augmentation
- Full Galileo deployment in 2012 with less than complete technical performance

Moderate Benefits

- Timely L2C availability
- Large potential markets
- Benefits moderated by competition from other signals and augmentations
- Full Galileo deployment in 2011

Diluted Benefits

- Large potential markets
- Gradual L2C deployment and uncertainty about schedules slows investment in innovation and market development
- Many users wait for L5 and for Galileo, which is expected in 2010
- Improvements in public and private augmentations make single signal use more attractive

Opportunity Lost

- Late signal initiation and protracted pace of L2C deployment
- Slow introduction and adoption of user equipment
- Some users wait for Galileo
- Moderately large potential market size, moderate effects of availability of other signals and delay in Galileo FOC to 2011
- Attractiveness of augmentations

The U.S. Air Force launched first satellite containing the L2C frequency on September 25, 2005, and the signal became available on December 16. Going forward, two to four Block IIR-M satellites are expected to be launched each year. With six to eight satellites anticipated to be available by about December 2007, users will be able to access at least one single satellite with L2C at almost all times. Eighteen L2C-capable satellites (including the Block IIF generation) will be available by about 2011 and 24 L2C signals, around 2012. (These statements are based on official 2005 launch schedules and are subject to revision.)

The first L5 launch is scheduled for March 2008. L5 does not have a GPS signal in use at its frequency, so it will not be usable to any great extent until a large part of its constellation is available. In contrast, L2 is in place to transmit the military P(Y) code and the carrier signals of the satellites are currently being used along with L1 C/A for higher-accuracy applications. Consequently, the L2C signal can be used immediately as a second frequency. The GPS signal L1C, which is being planned now for implementation on the GPS III satellites scheduled for launch beginning in 2013, will be able to be used immediately, even for single frequency use, without augmentation because it is at the same frequency as the L1 C/A-code.

Using Multiple Frequency GPS

Many private and government precision applications could potentially benefit from multiple frequency GPS.

For example:

- Centimeter accuracy is important to many land and marine surveying applications including planning, zoning, and land management; cadastral surveying, harbor and port mapping, aids to navigation, coastal resources management, mapping, and surveys of sensitive habitats.
- Machine control applications using high precision GPS have grown rapidly in a number of sectors, including agriculture and forestry, mining, construction, energy, transportation, structural monitoring and positioning for mapping and geographic modeling..
- Civil applications that rely on precise timing will benefit from increased GPS signal availability and elimination of atmospheric effects possible using dual-frequency techniques. Beneficiary industries include those operating cellular telephone, power, and financial information networks.

Scope of Benefits and Costs

Incremental benefits — those that arise because of the availability of L2C— include far more than the comparison of multiple frequency with augmented single frequency use. Companies adopting GPS in the future may even skip single-frequency options and instead choose multiple-frequency equipment (incorporating L2C) over non-GPS alternatives. Large candidate markets include construction, agriculture, and other applications where technological alternatives exist.

In some organizations, dual-frequency GPS will be the catalyst for extensive changes in systems that will occur earlier than if dual frequency GPS had not been adopted.

In the L2C study, benefits are measured according to the "economic productivity approach," which is superior to the expenditure/economic impact approach because:

- Productivity gains and cost savings, which this approach emphasizes, are the main purpose of much of GPS deployment and can be much larger than expenditures.
- Benefits may accrue to a large number of customers of the purchaser, as occurs with use of GPS timing in communications, financial services, and electric power and in use of GPS positioning for mapping, structural monitoring, and weather.
- The more common approach (economic impact) gauges benefits by added GPS spending without deducting the

L2C has its greatest potential to generate benefits for dual frequency applications until alternative signals are widely utilized and for long-term use in applications requiring three or more frequencies.

loss of benefits of non-GPS expenditures that are replaced.

L2C benefits can take both market and non-market forms, including increases in the productivity of business and government operations, user cost savings, benefits to the public through provision of public services and saving lives, and through improved health and environment.

Net benefits are benefits minus user costs. Incremental user costs include all additional costs that are expected with the availability of L2C, not simply the difference in costs between single- and dual-frequency receivers. These can take the forms of enhancements and accessories purchased when adding L2C capability (e.g. better displays, controllers and software) or costs associated with users upgrading to multiple frequency GPS from less sophisticated single-frequency GPS systems or non-GPS systems. However, incremental user cost is net of savings from use of receivers with less proprietary technology and any reduced use of private augmentation subscription services.

Expenditures to develop the GPS system infrastructure (satellites and ground segment) are not included, however, because most represent nonrecurring, sunk costs. Moreover, if we added them to our L2C analysis, we would need to include benefits to aviation and military users as well as their associated equipment costs.

Scenarios

The analysis takes into account alternative conditions of timing and impact of alternatives through the use of scenarios. Projections of signal use and value of benefits are developed through the year 2030 under four scenarios: High Opportunity, Moderate Benefits, Diluted Benefits, and Opportunity lost.

These scenarios reflect combinations of developments, including the strength of markets, the timing of L2C signal availability, the timing of Galileo availability, and complementary and competitive relationships with augmentations. (See the sidebar, "L2C Benefit Scenarios" for details of assumptions behind each.) Probabilities are not given for the scenarios because the likelihood of alternative Galileo delays cannot be evaluated quantitatively. Moreover, the diluted benefits and opportunity lost scenarios are significantly affected by U.S. GPS policy, which is also not predicted.

Estimates of GPS Users

The L2C study projections shown in Figure 1 are based on assumed rates of decline in prices for user equipment and services and increases in the number of users in response to price changes. Projections reflect assessments of market sizes and patterns of market penetration under each scenario. Allowance also is made for effects of economic growth on market size. Table 1 provides a detailed breakdown of results by scenario.

Within each scenario, projections are made for precision L2C users of three or more frequencies, dual frequency precision users, multiple frequency supplementary users, and single frequency users of L2C.

The starting point for determining the number of high precision users is a widely relied–upon estimate of 50,000 high precision users *worldwide* in 2000. We assumed that the

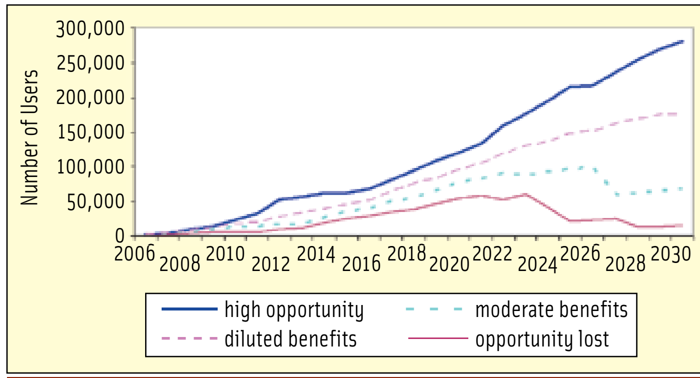

FIGURE 1. Total Number of L2C Multiple Frequency Precision Users

Total Number of L2C Multiple Frequency Precision Users				
year	high opportunity	moderate benefits	diluted benefits	opportunity lost
2006	1,296	1,080	432	432
2007	4,511	3,536	2,255	1,414
2008	8,720	7,404	6,321	4,708
2009	14,422	12,093	10,627	5,686
2010	24,091	16,912	13,434	6,287
2011	33,750	19,477	13,407	6,560
2012	51,652	27,701	16,976	10,035
2013	56,951	32,469	17,744	11,361
2014	62,150	38,983	26,706	19,607
2015	62,066	44,214	34,822	25,505
2016	67,254	50,429	41,049	29,438
2017	81,114	64,485	49,427	34,757
2018	94,005	75,756	56,527	38,598
2019	108,190	83,988	66,483	46,590
2020	119,931	94,771	78,278	53,387
2021	133,950	104,552	83,266	57,780
2022	158,488	118,185	90,953	52,103
2023	176,176	130,184	87,096	59,096
2024	194,918	136,262	92,235	40,026
2025	214,485	147,966	96,189	22,140
2026	216,972	151,632	98,327	23,948
2027	235,308	161,200	59,197	25,689
2028	252,866	168,997	62,867	13,641
2029	268,709	174,020	65,941	14,308
2030	281,575	174,953	68,084	14,773

TABLE 1. L2C Users by Benefit Environment Scenario

Benefit Variables

Overstatement could result from competition from other signals, from augmentations and from other technologies that is greater than anticipated. For example,

- Greater attractiveness of other signals because of the availability of satellites from Galileo in addition to those from GPS at the L1 and L5 frequencies
- Advances in augmentations that make single frequency use more attractive
- Slower price declines for L2C user equipment
- Less triple frequency use when additional satellites are available from Galileo and/or greater use of Galileo signals at frequencies that do not correspond with L1 and L5
- More users waiting for L5 for non-aviation civilian dual frequency use than allowed for in the study.

Understatement could result from

- More important and/or numerous applications than were allowed for in the calculations
- Faster price declines for multiple frequency user equipment (e.g. if competition squeezes high end margins even more) and/or larger price sensitivity of demand
- Non-market benefits greater than the 25% of market benefits assumed
- Impacts of L2C on long run economic growth, which were not included in the calculations and perhaps could add perhaps 20% to benefits.

United States had 40 percent of precision users in that year.

The study further assumes that the number of U.S. high-precision GPS users will grow by 18 percent per year from 2000 to 2030. This projection is based on a rate of price decline for user equipment of 15 percent per year and a corresponding a 1 percent increase in users for each 1 percent decline in price. Finally, we include an assumption of general growth in the economy (i.e., independent of GPS receiver price) that adds 3 percent per year.

These assumptions and calculations produce a projection of U.S. high precision GPS users — those using augmentations, of 38,776 in 2004. The estimated number of U.S. high precision users of any signal or combination nearly doubles to 75,177 from 2004 to 2008 and reaches 145,752 in 2012 and 333,445 in 2017.

We computed the numbers of multi-frequency GPS users by applying an estimated percentage to the number of high-precision users for each scenario. The number of multi-frequency precision users adopting dual versus three or more frequencies was then calculated using projected values for the percent of each category. Finally, the number of L2C users was calculated based on projections of the percent of multiple frequency users that use L2C, constructed to reflect the dynamics of each of the scenarios.

Rapid growth is projected in the numbers of U.S. precision multiple-frequency L2C users. In the moderate benefits scenario, the number of L2C users reaches 64,000 by 2017, of which 35,000 are dual frequency users and 29,000 use three or more frequencies. The numbers of L2C users vary widely among scenarios.

Average Net Benefits per User

The study defines average incremental net value of benefits per L2C user as the incremental value of benefits per L2C user above the incremental user cost of equipment and services. Benefits largely reflect productivity gains and/or cost savings. Estimates reflect a review of available evidence ranging from formal studies to case histories and expert opinion across a wide range of applications.

Our research suggests that average annual incremental benefit per precision L2C user net of costs could reach the range of $8,000–$16,000 per year. This includes benefits across systems that are not attributable to specific numbers of users and non-market benefits, such as safety and environmental advantages, as well as market benefits associated with the value of goods and services transactions. Market benefits attributable to numbers of users are estimated at 60 percent of all incremental net benefits.

These are peak values after benefits have had an opportunity to rise with experience using the new signal. The values decline from their peaks as new users with lower benefits are attracted by declining costs and some high benefit users move to alternatives.

In considering the plausibility of these figures, consider that:

- If a worker saved one hour a week by avoiding rescheduling due to signal unavailability, slow signal acquisition, loss of lock and additional work due to phase ambiguities, and further assuming labor costs of $80 per hour (including salary, fringe benefits, equipment, support staff and other overheads), — the saving would total $4,000 per year. Improvements in the organization's processes with better work flow could make the savings even greater.
- If the telecommunications, electricity generation, and financial industries together had system benefits that together were valued at $20 per customer over 20 million customers, the benefits would be $400 million per year. Market benefits of $400 million per year, if divided by 100,000 dual frequency users, for example, would amount to an average of $4,000 per user per year.
- $400 million in non-market benefits over 100,000 precision users would equal an additional $4,000 per user per year. (This could result, for example, from avoiding 100 deaths due to industrial accidents or environmental impacts at a value of $4 million per incident.)

The present values of incremental user costs range among scenarios from $175 million to $514 million in year 2005 purchasing power. Costs represent one eighth or less of the total value of benefits in each scenario.

Value of Benefits

Civilian net benefits per user are incremental, net of incremental costs, and derive from prospects for major areas of application. The patterns incorporate some high-value initial use, assume that higher benefit users switch earlier to newer signals, factor in a buildup of productivity gains with experience, and project lower values for late-entry users attracted by lower equipment prices as well as later increases in higher benefit users switching to alternative signals.

We calculate the value of civilian net benefits of L2C through multiplying civilian net benefits per user by the number of L2C users for the user type and scenario. Higher net benefit scenarios result from higher benefits per user and larger numbers of users.

At a 7 percent real (above inflation) discount rate, present values of total net civilian market benefits range from $9.6 billion to $1.4 billion dollars. (See Table 2.) Benefits under the moderate benefits scenario have a present value of $5.8 billion and those under the high opportunity scenario $9.6 billion. (Values are discounted using annual data to calendar year 2006. That essentially places the values at the middle of 2006.)

Nearly all of the incremental benefits of L2C stem from precision use of two or more frequencies. That is both because of moderate numbers of other types of users in these and their low benefits per user.

The timeframe in which other signals become available after L2C plays an important role in the size of estimated benefits. In the high opportunity scenario, for example, dual-frequency net benefits appear higher than benefits from use of three or more frequencies because the latter applications start later as additional frequencies become available. In the other scenarios, benefits from applications using three or more signals are higher than dual-frequency benefits because the benefits of dual frequency remain as strong when competing frequencies become available.

New spending can encourage greater long run economic growth, especially when it is associated with new technology for widely usable infrastructure. The spending may induce others to innovate, invest in greater capacity, take risks and/or provide financing. While direct estimates of the size of long run economic multipliers are not readily available, analyses of determinants of growth suggest that effects are modest, perhaps adding 20% to market benefits. Because of the uncertainty surrounding such estimates, no allowance is made for growth multiplier effects in the estimates shown.

Cost-Benefit Analysis

The ratio of incremental civilian benefits to user costs is calculated by dividing the present discounted value of *total* incremental benefits (including net benefits and costs) by the present value of incremental costs. These are shown with a 7% real (above inflation) discount rate in Figure 2.

The ratios of benefits to costs range from a multiple of 20 in the high opportunity scenario to 9 in the opportunity lost scenario. It would be surprising if benefit/cost ratios were not high because only direct user expenses (and not system costs) are included to get a picture of incremental costs of each set of outcomes.

The moderate benefits scenario, which has a ratio of 20, is considered more likely than the others. Because of the interest in obtaining the greatest benefits, focusing on the present value of net benefits is appropriate for policy rather than using the benefit/cost ratio when all ratios are high.

Present Value of Net Benefits
(millions of year 2005 dollars, 7% discount rate)

	high opportunity	moderate benefits	diluted benefits	opportunity lost
TripleFrequencyorMore	4,054	2.917	1,627	864
Dual Frequency	5,260	2.799	1,433	573
MultipleSupplementary	132	23	10	0
Single	194	108	43	0
Total	9,640	5,847	3,113	1,437

TABLE 2. Present values of total net civilian benefits

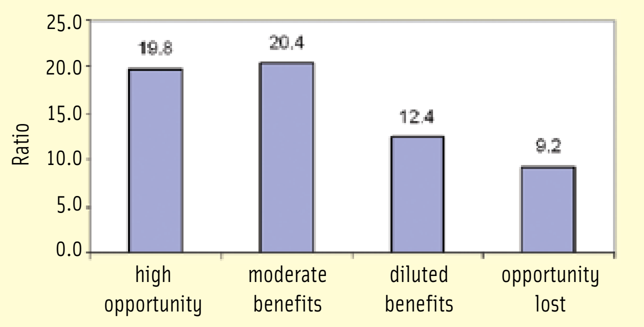

FIGURE2.RatioofPresentValueofL2CbenefitstoUserCosts,AllUsers (7% discount rate)

As mentioned, changes in various factors could substantially affect the outcomes of L2C benefits and produce either an overstatement or an understatement of these. See the "Benefit Variables" sidebar for a listing of the most important factors.

Conclusions

Rapid growth is projected in the numbers of U.S. precision GPS users and in most scenarios for the numbers of high-precision multiple frequency L2C users. Substantial L2C benefits can occur along with availability of other signals and constellations, augmentations, and alternative technologies. While Galileo will compete with L2C, Galileo signals also can increase precision L2C use in multiple frequency applications, an alternative that will become increasingly affordable.

The economic productivity approach offers a means of considering benefits in a comprehensive way. Benefits and costs are incremental. They are defined to include all changes that occur as a result of the existence of L2C.

Defined comprehensively, benefits can encompass results from more extensive changes in equipment and systems and include both benefits that are attributable to specific numbers of users and those that may be incorporated in systems and spread over a broad population. They include both market and non-market benefits — those that are not bought and sold in markets, such as benefits to life, health, security and the environment.

(Continued on page 56)

GNSS Software Defined Radio

Real Receiver or Just a Tool for Experts?

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The ability to replace some hardware components in a GNSS receiver with software-based signal-processing techniques has already produced benefits for prototyping new equipment and analyzing signal quality and performance. Now some developers are attempting to extend the flexibility and cost-benefits of software defined radios to commercial end-user products, including mobile devices incorporating GNSS functionality. This column takes a look at the history of GNSS software receivers, the opportunities and practical engineering challenges that they pose for manufacturers, and the state of the art and related applications of them.

In recent years, a new trend in designing GNSS receivers has emerged that implements digitization closer to the receiver antenna front-end to create a system that works at increasingly higher frequencies and wider bandwidth. This development draws on an earlier software receiver (SR) or software defined radio (SDR) approach originating from signal processing technologies used in military applications.

Today, GNSS software receivers have achieved a level of considerable technological maturity and use, particularly in signal analysis and receiver engineering, and appear poised for much wider adoption in commercial equipment and applications. This column expands on an abbreviated introduction of this topic in our discussion of platforms for future GNSS receivers in a previous "Working Papers" (March, 2006).

In this column, we will briefly describe the history of SR development, introduce the categories of GNSS SR design and implementations to date, provide an overview of commercial SR products and applications, and the future outlook for GNSS SRs.

History of GNSS Software Receivers

In the early 1990s the U.S. military services were facing several communications-related challenges. These included such matters as ensuring communication with current allies and a global support structure, denying interception of radio messages by hostile elements, taking advantage of the rapid technology changes, and controlling costs of R&D and purchasing.

At that time, military radio designs were based on hardware technology optimized for a single, specific field application and typically assumed a 30-year development life span, that is, the time from product release to the use of its next-generation replacement in new designs. During the 1990s, however, commercial applications started driving technology development so that the effective lifetime of a commercial component design fell to less than two years.

As a result of this change in the equipment design and development environment, a U.S. Department of Defense (DoD) multi-phase joint service project named Speakeasy was undertaken with the objective of proving the concept of a programmable waveform, multiband, multimode radio. (See the paper by R. J. Lackey and D. W. Upmal in the "Additional Resources" section near the end of this article.) The Speakeasy project demonstrated an approach that underlies most software receivers: the analog to digital converter (ADC) is placed as near as possible to the antenna front-end, and all baseband functions that receive digitized intermediate frequency (IF) data input are processed in a programmable microprocessor using software techniques rather than hardware elements, such as correlators.

The flexibility of the programmable implementation of all baseband functions allows rapid change and modifications not possible in analog implementations. This flexibility is an advantage in the military environment where communication at different ranges and to different command levels may require different radio frequency (RF) bands,

The flexibility of the programmable implementation of all baseband functions in software allows rapid change and modifications not possible in analog implementations.

modulation types, bandwidths, and spreading/despreading and baseband algorithms.

SDR is the underlying technology behind the Joint Tactical Radio System (JTRS) initiative to develop software programmable radios that enable seamless and real-time communication for the U.S. military services with coalition forces and allies. The functionality and expandability of the JTRS is built upon an open framework called the Software Communication Architecture.

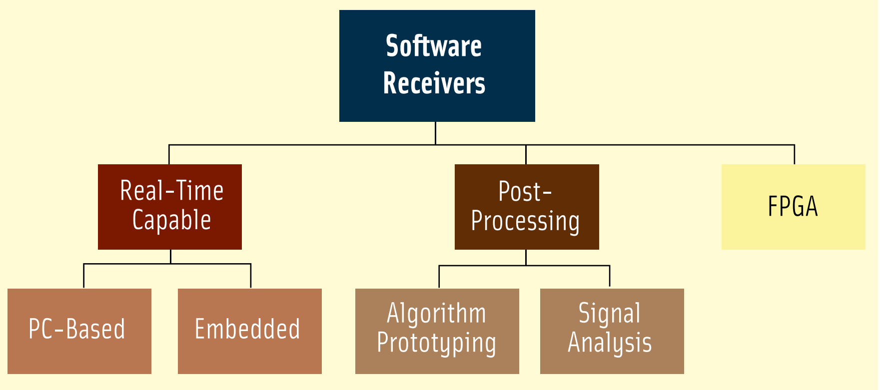

FIGURE 1 Different categories of software receivers

SR: A Functional Definition

Among researchers and engineers in field of communications and GNSS, some confusion has arisen over the terminology used to define a software receiver. For example, some communication engineers regard a receiver that contains multiple hardware parts for diverse systems, which can be reconfigured by setting a software flag or hardware pins of a chipset, to be an SR. In this article, however, we will use the widely accepted SR definition in the field of GNSS, that is, a receiver in which all the internal digital signal processing is carried out in a programmable processor by software techniques.

The internal functions of a modern GNSS receiver include an RF front-end block (typically including an antenna, low-noise amplifier, and RF integrated circuit or RFIC), initial signal acquisition, continuous signal tracking, bit and frame synchronizations, and navigation. A hardware-based receiver accomplishes the mixing of incoming and replica signals in a hardware correlator. Until the late 1990s the signal mixing function could only have been practically implemented in a hardware correlator due to the limited processing power of microprocessors at the time.

In 1990, however, researchers at the NASA/Caltech Jet Propulsion Laboratory introduced a signal acquisition technique for code division multiple access (CDMA) systems that was based on Fast Fourier Transform (FFT). This technique was enhanced by the work of researchers at the Technical University of Delft to apply FFT and inverse-FFT–based signal acquisition techniques for GPS. (For details, see the articles by D. J. R. van Nee, and A. J. R. M. Coenen cited in the "Additional Resources" section.) Since then, this method has been widely adopted in GNSS SR because of its simplicity and efficiency of processing load.

In 1996 researchers at Ohio University provided a direct digitization technique — called the bandpass sampling technique — that allowed the placing of ADCs closer to the RF portions of GNSS SRs. Until this time SRs implemented in university laboratories had a form of postmission processing because of the lack of processing power mentioned earlier. Finally, in 2001 Stanford University researchers implemented a real-time processing–capable SR for the GPS L1 C/A signal. (See the paper by Dennis Akos, P. L. Normark, and P. Enge in the "Additional Resources" section).

SR Types

Nowadays GNSS software receivers can be grouped into three main categories as shown in Figure 1. The majority of receivers are definitely found in the postprocessing subgroup "algorithm prototyping," which refers to the possibly countless number of small software tools or lines of code that are developed to test a new algorithm.

If the algorithm were tested with a real (or realistic) signal, one could already possibly speak of a software receiver. Another typical application of a postprocessing software receiver is GNSS signal analysis, for example, to investigate GPS satellite failures or to decrypt unpublished Galileo codes.

However, the GNSS SR boom really started with the development of real-time processing capability. This was first accomplished on a digital signal processor (DSP) and later on a conventional personal computer (PC). Today DSPs have been partially replaced by specialized processors for embedded applications, which have different features.

The hardware environment (processor speed, memory, available hard disk space) of the two platforms varies considerably; so, PC-based and embedded software receivers also differ substantially in the overall software design, even if they share common signal processing and navigation algorithms.

On a PC, C++ or even Matlab is the development environment; in the embedded sector, the C or assembler language dominates. Because the embedded sector (typically represented by mobile devices) has limited computational and power resources, high-end (and, thus, multifrequency) receivers will most likely always be PC-based receivers or eventually run on a workstation.

The last category, FPGA-based receivers, sometimes is also programmed in a C-like language. As they can be reconfigured in the field, one also can speak of them as being a software receiver. However, because their overall design (especially their integration with other hardware) is so different with respect to other PC-based and embedded GNSS SRs, FPGA-type receivers are not considered further in this article.

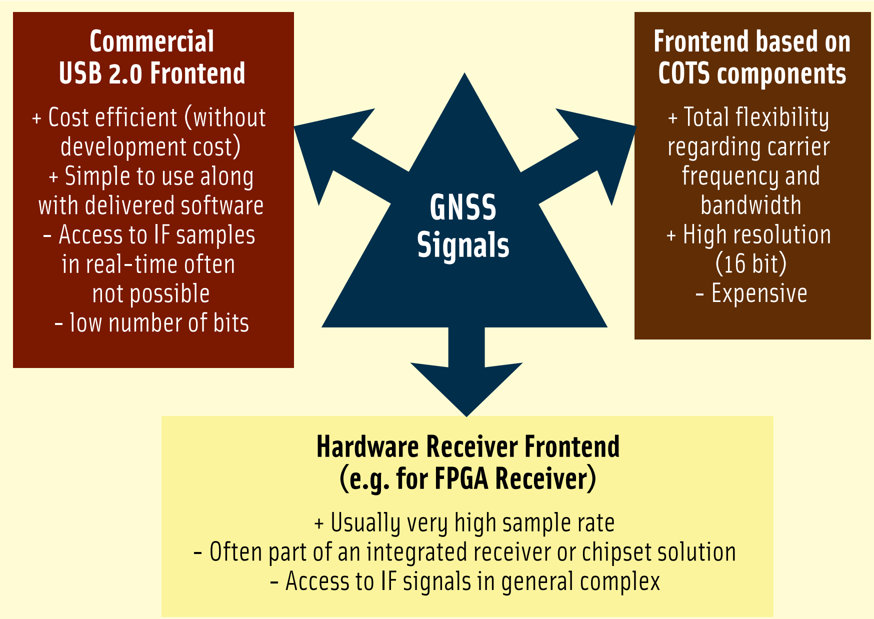

FIGURE 2 Overview on advantages (+) and disadvantages (-) of GNSS SR front-end developments

Frontends for PC-based Receivers

Software receivers can nowadays be found at the commercial and university level. SR development not only includes programming solutions but also the realization of dedicated front-ends.

From the very beginning, the development of GNSS software receivers was undertaken side by side with the development of dedicated front-ends. PC-based software receivers in particular require a comparably complex interface to transfer the digitized IF samples into the computer's main memory. Historically, most GNSS SR developments started with the GP-2010, awell known GPS L1 RF chip from GEC (or Mitel) that provided the analog plus the digital IF at 4.309 MHz. ADC cards from ICS or National Instruments allowed continuous transfer of data into the PC and eventually storage on a hard disk for postprocessing.

Two classes of PC-based GNSS SR front-end solutions can be found today. The first one uses a commercially available ADC. This may be connected — for example, via the PCI bus — to the PC, or the ADC works as a stand-alone device. The ADC directly digitizes the received IF signal, which is taken from a pure analog front-end.

The second solution is based on integrating an ADC plus an USB 2.0 interface into the front-end, simultaneously providing the power supply to the ADC and the front-end. Regarding the analog part of the front-end, very different solutions exist based on either superheterodyne, low-IF or direct RF sampling. They are built using existing RF chipsets, discrete analog components, or commercial off-the-shelf (COTS) components. Figure 2 compares the relative advantages and disadvantages of the two types of solutions.

From the very beginning, the development of GNSS software receivers was undertaken side by side with the development of dedicated front-ends.

The first type of solution is still used at the university and research institute level, where a high amount of flexibility is required. For example, at the Department of Geomatics Engineering of the University of Calgary, a researcher uses a Novatel Euro-3M board from which they extract the digital IF samples. The samples are transferred via an FPGA board to a National Instruments NI-6534 data acquisition card plugged into a PC. L1 and L2 signals are sampled at 40 MHz but decimated to 5 MHz when they are transferred into the PC. (See the paper by Zheng, B. and G. Lachapelle cited in the Additional Resources section.)

Researchers at Cornell University (in work done cooperatively with the University of Texas at Austin) came up with a very interesting and cost-efficient solution for an L1/L2 front-end using the Zarlink GP-2015 chip. This chip is originally a GPS L1 front-end, and two GP-2015s were used to implement the L1 and the L2 signal path.

Because it was impossible to directly use the GP-2015 for L2, the L2 signal was upconverted to L1 by mixing the L2 RF signal with a signal whose frequency is 347.82 MHz, the difference between L1 and L2. L1 and L2 IF signals were then sampled within the GP-2015 at a rate of 5.714 MHz, and a National Instruments PCI-DIO-32HS (6533) digital I/O card was used to bring the data into the PC. (See the paper by B Ledvina, M. Psiaki, S. Powell, and P. Kittner in Additional Resources.)

At the University FAF Munich's Institute of Geodesy and Navigation, we started front-end development by opening a GPS architect receiver based on the GP-2010 chipset. We connected its analog IF signal via a National Instruments NI-5112 ADC plugged into the PC.

In the next step we specified an L1/L2 wide bandwidth (13 MHz) front-end, which the Fraunhofer Institute for Integrated Circuits then developed using discrete components for the analog part. Again the NI-5112 card was used to digitize the analog IF at about 8 MHz. A maximum transfer rate of 33 MHz (L1 only) or of 2x20 MHz (L1/L2) could be achieved in continuous mode with a resolution of 8 bits.

USB Solutions

Whereas our laboratory front-end solution is quite flexible, the development of front-ends with a universal serial bus (USB) 2.0 connector have arisen quickly, because this allows the front-end to be installed easily on the PC and provides a more cost-efficient solution. Currently, a number of commercial and R&D front-end are available which are summarized in Table 1.

NordNav and Accord were among the first to provide USB-based solutions, and recently the NordNav front-end was extended to permit connecting up to four antennas, which allows users to perform investigations in beam forming, indoor positioning, and GPS reflectometry. Accord is one of the first providers for a L2 frontend, suitable for tracking the new GPS L2 civil signal.

IfEN has announced (available Q3 2006) a high bandwidth L1 front-end, NavPort, shown in Figure 3, capable of processing GPS and Galileo signals. IfEN also plans a second generation NavPort, which additionally allows capturing a second (non-GNSS) signal, which can be synchronized to the GPS L1 signal. NavPort can record these arbitrary analog signals on the PC and automatically time-stamp them with an accuracy better then 1 microsecond on a sample per sample basis.

For instance, these could be signals from geophysical instruments such as a seismograph, generic radio signals, or many others. By using a flexible software signal decoder connected with for example the RS232 output pin of an inertial measurement unit (IMU), the serial output of the IMU could also be decoded and the IMU data is then synchronized to the GNSS measurements.

Another interesting development comes from the University of Colorado, which in an OpenGPS forum published all details on the RF and USB section. (See the paper by S. Esterhuizen in Additional Resources.) The Fraunhofer Institute for Integrated circuits provides single- or dual-frequency front-ends. These are built using discrete components for the analog section; front-end parameters — such as bandwidth, sample rate, or bit resolution — can be adapted to specific user demands.

FIGURE 3 Picture of a typical GPS/Galileo front end with USB connector

In September, the Birkhäuser unit of Springer Science+Business Media will publish a textbook on software receivers, A Software-Defined GPS and Galileo Receiver, by Kai Borre and others. Accompanying the book will be a USB front-end based on the SiGe SE4110L chipset that, according to the manufacturer SiGe Semiconductor, specifically targets software GPS applications in the embedded sector.

In summary then, the USB port is altogether very well suited for SR developments. Its maximum transfer rate of 480 MBit/s are even sufficient to realize a GPS/Galileo multi-frequency high bandwidth frontend. Such a front-end is currently specified at the University FAF Munich and under development at the Fraunhofer Institute for Integrated Circuits.

This new SR will receive GPS and Galileo signals on L1, L2, and L5 each with a bandwidth of 18.5 MHz. In triple-frequency mode, the transfer of large amounts of data into the PC uses two USB ports. As it receives all GPS signals and all Open Service Galileo signals, the receiver will facilitate research in high-precision applications and Galileo signal processing algorithm development.

A growing number of commercial software receivers are being developed for the embedded market that supports development of mobile devices with GNSS capabilities.

With the availability of USB 2.0, PC-based software receivers have to be considered as a true GNSS SRs, not just an assembly of a bunch of components. The USB approach thus is one of the most important cornerstones of SR development. Currently the high transfer rate already poses few restrictions, and although wireless USB technology is on its way to the market, we expect that USB 2.0 will not be replaced in the near future.

Regarding the RF section, work still remains for the development of multifrequency and high bandwidth chipsets. In the meantime, software receivers for high precision applications will have to incor-

Source	Frequency Band	Bandwidth	Sample rate	Comment
NordNav	L1	Low, High	16 MHz	1, 2, or 4 RF channels
Accord	L1/L2	Low (2 MHz)	2-6 MHz	-
Fraunhofer	L1/L2	4 – 20 MHz	10-40 MHz	Tailored on user demands
Akos, Borre	L1	-	-	-
IfEN	L1	High 10 MHz	23 MHz	-
Univ. Colorado	L1	Low (2.2 MHz)	-	PCB and schematic available
Univ. FAF Munich/Fraunhofer	L1/L2/L5	18.5 MHz	20 or 40 MHz	In development

TABLE 1. Overview of currently available fronts-ends for PC-based software receivers employing USB 2.0 connectors.

porate discrete components or use the RF part of existing hardware receivers.

SRs for the Embedded Market

A growing number of commercial software receivers are being developed for the embedded market that supports development of mobile devices with GNSS capabilities. Here are brief descriptions of some of the companies developing SRs.

NordNav. NordNav introduced the first software-based satellite navigation package at the commercial level. The embedded SR uses a host CPU to calculate position, saving space and processing power. It consists of a USB-type frontend, digital IF data sample streamer, a real-time 24-channel software receiver, and an application toolkit for research, development, test and verification purposes.

SiRF. As one of the leaders in GPS chip set development, SiRF Technology, also provides a software receiver for wireless handheld devices, called SiRFSoft. Using the software approach, the GPS baseband chip is replaced by optimized software running ultimately on an Intel XScale processor. The XScale family of applications processors is a frequent component in current mobile devices, such as smartphones and wireless PDA market segments, enabling these to maximize GPS performance while minimizing the load on the applications processors.

According to SiRF, the software receiver has a sensitivity of -159 dBm (which is the same value as for the SiRFstarIII receiver). The software receiver automatically adapts to utilize whatever network assistance data is available.

Center For Remote Sensing (CRS). CRS has released its Software GPS Builder for development and operation of advanced high performance GPS systems based on the SR approach. The company's solution includes the antenna and RF front-end, SR open architecture, a software GPS signal simulator, and the hard disk–based storage system for GPS L1 and L2.

All components are tuned in C-code, allowing direct implementation in a variety of platforms (microprocessors, DSP, FPGA, and ASIC). A series of CRS's utilities mentioned before allows whole design procedures including simulation, test, validation and implementation of a various kind of GNSS SR in one step process.

NAVSYS. A series of SR-related products provided by NAVSYS Corporation seem to be designed to focus on design and development for future GNSS requirements. The company's products have a capability of signal simulation in digital or RF level, logging digital data onto a storage device, and processing in real-time or play-back mode.

In addition, as one of the special applications of NAVSYS's GNSS SR technology, the company provides a network-based communication system in conjunction with a GPS SR, namely, the Position/Location tracking and Communications (POSCOMM) SDR. This unit combines observables from GPS and communication systems, such as pseudorange, carrier phase, and time-of-arrivals (TOAs), in an effort to solve weak signal problems caused by signal blockage, indoor environments, foliage attenuation, or jamming.

One of the most obvious and valuable applications of software GNSS receivers is their use in teaching and for training.

Philips. In 2005, Philips announced its new GNSS SR product, Spot, for mobile market. Spot eliminates the need for an expensive baseband processor by performing the required calculations on the application processor of the mobile device. An intellectual property (IP) approach, Spot performs position fixes in either an autonomous mode or, if assistance data is available from the communications network, in assisted-GPS mode. Depending on operational mode, it requires minimum performance specifications from the host processor.

RF Micro Devices (RFMD). RFMD has also unveiled their software-based GPS solution specifically for mobile devices, named as RF8110. As with SiRFsoft, the RF8110 software was optimized for use on the Intel XScale. In order to shorten customers' development cycles, RFMD also provides platform-specific hardware and software evaluation kits, for instance, Intel PXA270 applications processor and the Windows Mobile 5.0 operating system.

CellGuide. CellGuide has also announced the release on their GPS L1 C/A code SR, for mobile devices CDSoft. According to the released specification, CDSoft can run on most ARM and/or DSP-based processors with a variety of operating systems and provide time-to-first-fix of less than 6 seconds and sensitivity down to -157 dBm.

Commercial PC-Based Receivers

NordNav provided the first commercial GNSS SR that can be compared to a normal GPS receiver (and that was not a complete receiver development environment). The pioneer work, a GPS/SBAS L1 receiver, was also probably the first solution based on a USB front-end. Together with a software signal generator, Galileo signals can be tracked as well. Furthermore NordNav provides an application programming interface (API).

IfEN has announced to present at the Institute of Navigation's GNSS 2006 conference an SR solution capable of tracking GPS and Galileo signals on L1. This receiver uses large signal bandwidth to achieve highly accurate code and phase measurements based on a configurable multipath-mitigating correlator.

The receiver outputs two dimensional (delay/Doppler) multi-correlator values as well as FFT acquisition results suitable for signal quality monitoring. IfEN's solution can be reconfigured during runtime and comes with a hardware-based GPS/Galileo signal simulator.

SRs as Teaching Tools

One of the most obvious and valuable applications of software GNSS receivers is their use in teaching and for training.

In particular, receivers for which the source code is available allow inspection of almost all signal data by the researcher. Of course, commercial software receivers are also of interest, because they allow real-time configuration and nice visualization possibilities.

Textbooks already have been published on GNSS SRs. The pioneer in this area is definitely James Bao-yen Tsui who authored the first book on GNSS software receiver algorithms in 2000, *Fundamentals of Global Positioning System Receivers: A Software Approach* (Wiley-Interscience, publisher, updated in 2004).

As mentioned earlier, a new book by Kai Borre et al will appear in September. In it, the authors focus on real-time SR operation. Other web-based resources on software receivers can be also be found in the article by R. Babu cited in Additional Resources.

The European Union is fostering the development of receivers for the upcoming Galileo system. One of the projects it has funded through the Galileo Joint Undertaking is the Galileo Receiver Analysis and Design Application (GRANADA) simulation tool. Running under Matlab, GRANADA is conceived as a modular and configurable tool with a dual role: test-bench for integration and evaluation of receiver technologies, and SR as asset for GNSS application developers.

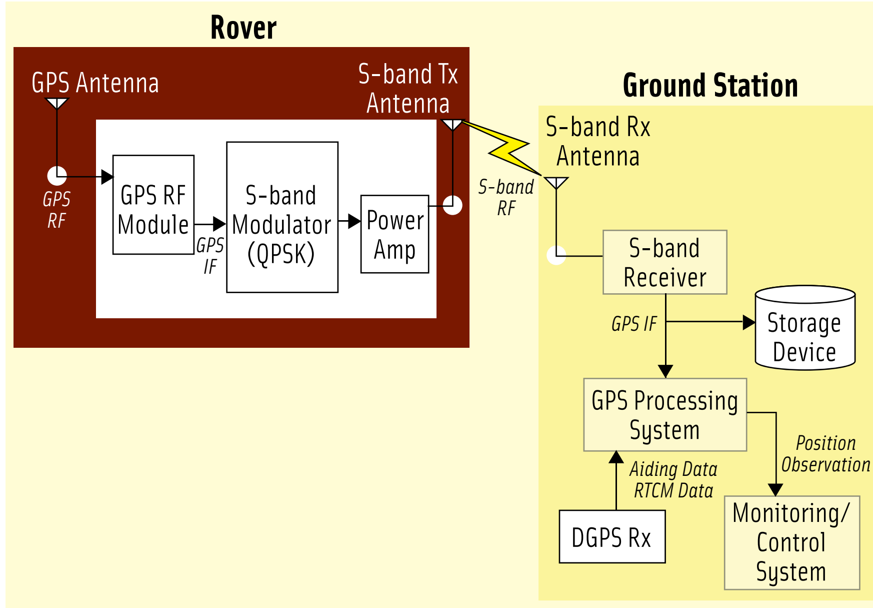

FIGURE 4 Scheme on GPS Translator

The Data Fusion Corporation (DFC) provides an IF-level GNSS SR toolbox in Matlab and C and for DSP configurations, which seems ideal for research and development work in postprocessing mode. The toolbox consists of a GPS baseline receiver and GPS signal generator toolboxes, of which all sources are open to customers and can be modified to a specific algorithm test.

NAVSYS Corporation also provides a signal simulation and analysis tool to simulate the effect of GPS satellite signals on a conventional GPS receiver's code and carrier tracking loops as a form of Matlab Toolbox. This signal simulation tool can be used as an analysis aid to help test and evaluate GPS receivers beyond the capability of conventional RF signal simulators, which frequently do not provide low-level insight into the operation of a GPS receiver.

The NAVSYS product consists of geographical tools, satellite geometry tools, and receiver design and analysis tools. A particular aspect of its signal simulation tool is the ability to simulate both GPS L1 and L2 datasets for playback and analysis by built-in receiver modules within the Matab tools. However, the system is also able to play back data into a GPS receiver under test as live digital or RF signals using an advanced GPS simulator product.

Selected SR Applications

Apart from the previously mentioned uses (algorithm prototyping, the embedded sector, and teaching), SRs are especially suited for some other GNSS applications (shown in Table 2) due to their outstanding flexibility. In this section, we will discuss a selection of these.

GPS Translator System. The GPS translator system was designed initially as a proof-of-principle system for U.S. DoD military missile development programs. This system consists of a missile-based GPS measurement sensor (the rover

Application	Why
GPS/INS integration	Easy access to tracking loops and convenient development environment
GPS reflectometry	Detailed signal analysis in postprocessing, with arbitrary number of correlators
Indoor reference receiver	Combine indoor and outdoor signals at signal processing level yielding an accurate determination of signal attenuation
Phased array antennas	Simple dataflow inside the receiver of the different antennas and easy access to signals
GPS translator system	Flexible receiver at server side. RF frontend as part of weapon which is finally destroyed is cheaper than complete receiver.
Network based positioning of mobile phones for E911	Flexible receiver at server side
Signal analysis tool	Possibility to implement dedicated analysis and monitoring algorithms with visualization capabilities
High-end receiver	Possibility to implement high-end signal processing and navigation algorithms such as frequency domain signal processing, multi-correlator, vector delay lock loop, and so on.

TABLE 2. Current (black) and future (red) applications of software receivers

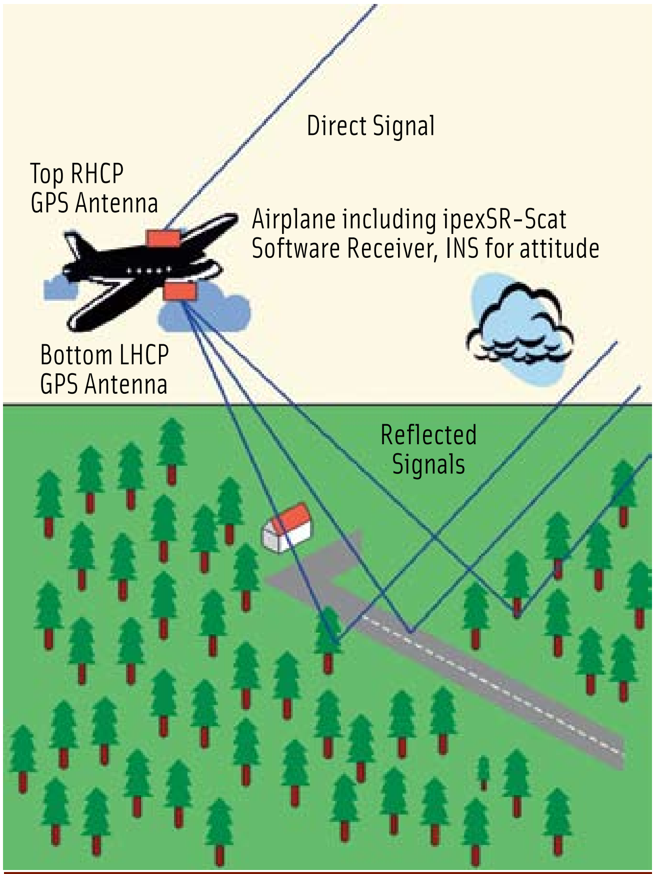

FIGURE 5 Scheme for GPS reflectometry

unit) and a ground-based server system (ground station) as shown in Figure 4.

The rover system comprises a GPS receiver RF front-end and a wireless S-band transmitter. The ground station system incorporates an S-band receiver, a GPS processor, a differential GPS (DGPS) reference receiver, and a monitoring/control system.

The GPS signal (RF) is received at the end of the GPS antenna in the rover system and down-converted into a lower IF. This IF signal is modulated, up-converted, and then transmitted through the S-band channel to the ground station. At the ground station, the received S-band signal is down-converted again to a lower IF and processed by the high performance ground processor to provide the position of the rover. Thus, all the digital signal processing on the GPS signal are performed in the ground station not in the rover.

This system design makes it possible to employ advanced processing techniques without any constraint in cost. The DGPS technique includes Doppler and ephemeris-aiding techniques in signal acquisition/tracking and determining the position of the rover accurately and robustly. In addition, as recommended by the military specifications, the IF signal in the rover should be collected and recorded to storage devices, enabling playback after the test for more precise analysis.

Figure 4 shows that the overall structure of the translator system is similar to that of a software receiver, excluding the S-band data-link.

GPS Science and GPS Reflectometry. In GPS science we use GPS or GNSS signals to investigate scientific phenomena by analyzing the received GNSS waveform in great detail. For example, in GPS meteorology atmospheric parameters such as humidity and temperature are evaluated in terms of the signal path delay.

In GPS reflectometry, reflected GPS signals from the Earth's surface are used to determine parameters like surface height, sea-level height, wave height (and thus wind speed and direction), salinity, humidity, etc. In a typical airborne system, as shown in Figure 5, the GPS receiver is connected to two antennas, one at the bottom and one at the top of the aircraft. The top mounted antenna receives the direct GPS signal, and the bottom antenna the signal reflected from the Earth's surface.

The top-mounted antenna is typically right-handed circular polarized (RHCP) and the bottom-mounted antenna, left-handed circular polarized (LHCP). The GPS satellites emit RHCP signals and, when they are reflected, their polarization changes to LHCP. GPS reflectometry systems have initially been realized using FPGA boards, but recently the PC-based SR approach seems to be more promising.

For example, in the article on GPS backscatter measurement by T. Lingren et al, cited in Additional Resources, about 100 minutes of data were collected using a dual-antenna NordNav front-end. This data was analyzed in a postprocessing phase using dedicated in-house software. This postprocessing method enabled the researchers to re-analyze the reflected signal in very fine detail.

Occasionally their investigation found — apart from the surface echo — an additional echo of unknown origin. The analysis later showed that this echo originated from single objects (for example, a farm). By using signals from multiple satellites, the researchers could locate the reflector on a map. In the context of this column, we should note that this new scientific finding was most likely only possible by having used a software receiver in postprocessing mode.

Generic Signal Analysis Tools. One of the essential goals of a high-end software receiver is its application as the ultimate signal analysis tool. Such a receiver should be an instrument that combines digital storage, oscilloscope, spectrum analyzer, GPS receiver, and possibly also INS data.

An example of such an instrument is described in the article by A. Soloviev, S. Nawardena, and F. van Graas. With it, one simply connects a GNSS antenna and the system reveals everything that you can possibly know about this signal, in real-time or postprocessing (including of course the position). In this context, the processing of the GPS P(Y)-code on L2 is important, because analyzing the propagation effects on that signal — in combination with the L1 signal — is still the only way of eliminating ionospheric errors, and thus allowing high precision applications. The instrument described by Soloviev et al. has accomplished this goal in a software receiver.

Our own developments at the Institute of Geodesy and Navigation also go in this direction. Of special interest are signal quality monitoring and spectral monitoring applications. For signal quality monitoring, multiple correlators are used, each located at a certain code phase offset and Doppler offset with respect to the prompt correlator.

The values (or special combinations of them) are compared against their nominal values permanently. Failures in the transmitter (satellites) or high multipath causes deviations from the nominal values and thus can be detected. By monitoring the spectrum, we are able to assess the quality of the RF environment, including detection of intentional or unintentional jamming.

A recent improvement in our software is the waveform multi-correlator (inspired by Novatel's Vision correlator), which correlates the received signal with a PRN code convoluted with Dirac's Delta-function. This method allows us to reconstruct the waveform of the received satellite signal. The waveform is a more direct measure of the GNSS signal compared to the correlation function. Thus, failures — for example, in the satellite — can be more easily detected and analyzed.

In Figure 6 the same wideband signal for GPS satellite PRN3 is correlated once with a normal multi-correlator (screenshot on left) and once with the waveform multi-correlator (right). In the standard multicorrelator plot the distortions due to the filter in the receiver's frontend can be barely identified, but they are clearly visible in the waveform correlator.

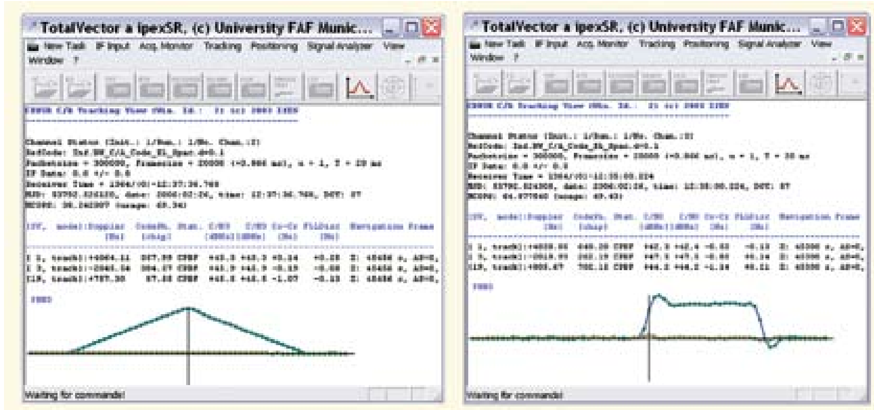

FIGURE 6 Comparison of standard (left) and waveform (right) multi-correlator

Outlook

For a long time, software receivers have already found their place in the field of algorithm prototyping. Nowadays they also play a key role for certain special applications. What remains unclear is whether they will succeed as generic high-end receivers or if they can penetrate the embedded market.

A GNSS SR has multi-phase advantages including design flexibility, faster adaptability, faster time-to-market, and easy optimization at any algorithm stage. As a result, it is emerging as an important technology in both commercial and military applications. However, a major SR drawback persists, namely, the slow throughput compared to application specific integrated circuits (ASICs), its hardware counterparts.

In order to overcome this drawback, GNSS SRs embedded into a single microprocessor or DSP in a software form is emerging in the marketplace. Until now and for the near future, this development is driven by the mobile application market, for example, mobile phones with PDA functionality based on location based services (LBS) applications.

This application requires location-enabling chips located in the handset (or handset adaptation package) or as a software package with minimal modification to the handset. Without any doubt, a GNSS SR integrated into existing platform and operating system of mobile devices should be one of the good solutions for this application.

A major SR drawback persists, namely, the slow throughput compared to application specific integrated circuits (ASICs), its hardware counterparts.

The remaining competition will be over the type of platform and operating system best suited for increasing performance of SRs. Conversely, the question could be posed as how a GNSS software receiver should be designed or modified for the existing platforms and operating systems of mobile devices.

On the opposite end of the spectrum from the mass market, the following factors seem to ensure that, sooner or later, high-end software receivers will be available:

- High bandwidth signals on L1/L2 can already be transferred into the PC in real-time and processed. Development of triple-frequency USB front-ends for GPS and Galileo is underway
- Due to the increasing processing power, real-time processing with a limited amount of multi-correlators is already possible, and software receivers will definitely benefit from the introduction of new multi core processors as discussed in the March issue's Working Papers.
- Postprocessing is one of the major benefits of a software receiver as it allows re-analysis of the same signal several times with all possible processing options, and the rapidly increasing hard disk capacity allows storage of very long time spans and datasets.
- Some signal processing algorithms, such as frequency domain tracking (e.g., the symmetric phase-only matched filter as introduced by the U.S. Air Force Research Lab and Sigtem) or maximum likelihood tracking for high dynamics applications, are much easier to implement in software than in hardware. Those methods require complex operations

at the signal level or multiple reprocessing of the received signal.

Regarding the development and integration costs, embedded and high-end software receivers definitely beat their hardware counterparts and, on the other side, power consumption, especially of high-end SRs, is still problematic. Just one thing is for certain: this new technology increases the options one has to solve a particular positioning problem.

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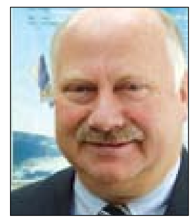
"Working Papers" explore the technical and scientific themes that underpin GNSS programs and applications. This regular column is coordinated by PROF. DR.-ING. GÜNTER HEIN Prof. Hein is a member of the European Commission's Galileo Signal Task Force and



organizer of the annual Munich Satellite Navigation Summit. He has been a full professor and director of the Institute of Geodesy and Navigation at the University FAF Munich since 1983. In 2002, he received the United States Institute of Navigation Johannes Kepler Award for sustained and significant contributions to the development of satellite navigation. Hein received his Dipl.-Ing and Dr.-Ing. degrees in geodesy from the University of Darmstadt, Germany. Contact Professor Hein at <Guenter.Hein@unibw-muenchen.de>.

(Continued from page 47)

User costs also are incremental, including all changes that occur with the availability of L2C, and are net of savings from moving to less sophisticated and less proprietary equipment.

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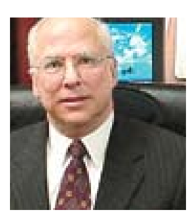

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