GPS, GLONASS, Galileo, and BeiDou for Mobile Devices

From Instant to Precise Positioning

Get up to speed on all existing GNSS with this practical guide. Covering everything from GPS, GLONASS, Galileo, and BeiDou orbits and signals to multi-GNSS receiver design, AGPS, network RTK systems, and VRS, you will understand the complete global range of mobile positioning systems. Step-by-step algorithms and practical methods provide the tools you need to develop current mobile systems, whilst coverage of cutting-edge techniques, such as the instant positioning method, gives you a head start in unlocking the potential of future mobile positioning. Whether you are an engineer or a business manager working in the mobile device industry, a student or a researcher, this is your ideal guide to GNSS.

Ivan G. Petrovski leads the development of GNSS applications at iP-Solutions, Japan. He has over 25 years' worth of research and development experience in the GNSS field, and has previously led GNSS-related R&D for DX Antenna, GNSS Technologies Inc., and the Institute of Advanced Satellite Positioning at TUMSAT. He has academic experience working as an associate professor with MAI and as a guest professor with TUMSAT. As an engineer he has developed RTK software, the algorithms and software for indoor and outdoor positioning with pseudolites, in addition to instant positioning algorithms, real-time GNSS software receivers, and the GNSS DIF recorder and RF signal simulator.

Cambridge University Press
978-1-107-03584-3 - GPS, GLONASS, Galileo, and BeiDou for Mobile Devices
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GPS, GLONASS, Galileo, and BeiDou for Mobile Devices

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CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE
UNIVERSITY PRESS

University Printing House, Cambridge CB2 8BS, United Kingdom

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9781107035843

First published 2014

Printed in the United Kingdom by TJ International Ltd. Padstow Cornwall

A catalog record for this publication is available from the British Library

Library of Congress Cataloging in Publication data
Petrovski, Ivan G., 1962–
GPS, GLONASS, Galileo, and BeiDou for mobile devices : from instant to precise positioning / Ivan G. Petrovski, iP-Solutions, Tokyo.
pages cm
ISBN 978-1-107-03584-3 (Hardback)
1. GPS receivers–Design and construction. 2. Mobile communication systems.
3. Global Positioning System. 4. Galileo satellite navigation system.
5. Artificial satellites in navigation. I. Title.
TK6565.D5P45 2014
910.285–dc23 2013032821

ISBN 978-1-107-03584-3 Hardback

Additional resources for this publication at www.cambridge.org/9781107035843

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Foreword by Glen Gibbons

The Law of Unintended Consequences – case in point: the mandate for enhanced 911 (E911) services for mobile devices.

In 1996, the Federal Communications Commission (FCC), a US regulatory agency with broad powers over telecom providers and services, issued its first report, order, and notice of proposed rule-making (NPRM) regarding E911. The FCC action sought to require wireless telephone companies to be able to report automatically the location of an emergency caller.

This initiative proposed to bring to the rapidly expanding wireless space a requirement previously established for wireline providers. Unlike telephones at fixed locations, the whereabouts of a mobile phone was not readily known in emergencies, often not even to the callers themselves.

In issuing the NPRM, however, the Global Positioning System – let alone other GNSS systems – was not on the minds of the FCC commissioners. Indeed, if FCC staff and officials were aware of GPS in 1996, which had only reached full operational capability the year before, it was probably as the precise timing technology providing synchronization to wireline and some wireless networks.

No, in 1996, the FCC assumed that the positioning solutions for E911 would arise from within the networks themselves, using such techniques as angle of arrival (AOA), time of arrival (TOA), and time difference of arrival (TDOA).

This is where the unintended consequences enter in, and why the AOA of Dr. Petrovski's latest book – *GPS, GLONASS, Galileo, and BeiDou for Mobile Devices: From Instant to Precise Positioning* – is a particularly resonant and relevant point of entry.

With E911, the FCC was focused on helping first responders (e.g. police, ambulance, and fire department personnel) reach people in need quickly. The agency probably assumed that, as with many other regulatory mandates, the telecom industry would resist or at least seek to delay the imposition of the new rules. In fact, the full accuracy and reporting conditions of E911 only took effect in December 2012, nearly 16 years after the original FCC report and order.

For our purposes, however, we can leave the prolonged story of E911's implementation, filled as it is with bureaucratic woes and bewildering discoveries about the nature of emergency services' communications infrastructure and processes. Long before E911 arrived, a much more remarkable thing happened: GNSS capabilities began appearing voluntarily on almost every cell phone sold into the US market. Moreover, GNSS has spread to many other mobile devices, such as cameras and notepad computers, not intended primarily for communications.

What happened?

Well, to answer that question we need to return briefly to 1996 and consider the state of the GPS industry – GPS being the only practically accessible GNSS technology at the time. By the mid 1990s, GPS had become well accepted within certain professional and commercial sectors: surveying and mapping (including geographic information systems), along with the previously mentioned timing applications, and – in the wake of the first Persian Gulf war – the military community.

What GNSS did not have in 1996 was a mass market. In large part, this situation stemmed from the US policy of "Selective Availability" or SA – an effort to maintain an advantage for US and allied military forces. This measure imposed a timing dither on the open GPS C/A code signal that degraded the real-time positioning accuracy to "no worse than" 100 meters 95 percent of the time, typically in the range of 60 to 70 meters.

Aside from a few fisherman and recreational boaters, who were happy to use something that would provide them with a better accuracy than the quarter-mile or so then possible with Loran-C, nothing approaching a consumer market had emerged yet for GPS. (Marine users' counterparts in general aviation also found that a GPS receiver – even one that cost thousands of dollars – was still a lot cheaper and a lot more accurate than other types of navigation aids.)

At the time, visionaries and pioneers in a newly named, but underpopulated, world of location-based services (LBS) were looking to the automotive industry for the platform that would lift GPS into the popular imagination. For Americans, cars are the quintessential consumer product. With millions of them sold every year, automobiles seemed the ideal vehicle (no pun intended) for carrying GPS into a mass market.

In addition to SA, however, a couple of things turned out to be wrong with that paradigm. First, the complex network of interlocking hardware and software vendors and LBS providers had not sorted themselves out sufficiently to have found a successful business model. Second, demand for navigation systems among car owners, who do 90 percent of their driving on familiar local routes, remained unencouraging – it suffered from the "So what?" factor. And, more importantly, the US auto industry with a typical seven-year design cycle and price sensitivities, was distinctly uninterested in a largely untested technology that would add hundreds of dollars to the price of a new car.

The FCC's E911 mandate, however, changed that calculus. Mobile phone manufacturers, who had a much shorter design cycle, began thinking about how they might meet the federal mandate with a handset-based solution, rather than a network-based one. And they began looking more closely at the opportunity to build in money-making applications that took advantage of the regulatory mandate for location – a classic lemons-into-lemonade scenario.

By the time Selective Availability was removed in 2000, a substantial and ultimately irresistible momentum had begun for adding GNSS capabilities to mobile devices. Fast-forward to the recent Lightsquared controversy in which the massive installed base of GNSS receivers – driven largely by GPS in mobile phones – created a major obstacle to rollout of a high-powered wireless broadband system in frequencies adjacent to GNSS.

Thus, mobile phones had popularized GNSS with a speed and widespread adoption that vehicle telematics could not.

One further aside: the popularization of affordable, precise location brought about by GNSS has actually fed back and rejuvenated interest in other positioning technologies. Because, as we well know, GNSS does not work everywhere that people live, work, and play, but now that they have experienced its utility and even come to depend on it, people want the capability everywhere and all the time.

So, product developers and service providers have redoubled their efforts to find tools and methods to provide ubiquitous positioning – not merely among the network-based solutions mentioned earlier, but also in exploiting such things as WiFi, magnetic fields, inertial sensors, signals of opportunity, and even echoes. Sometimes alone, but more often in combination with GNSS in mobile devices.

So, about this book. . . .

First off, it could not be more timely. GPS, of course, is well established – there are easily more than a billion receivers in operation around the world, both as standalone tools in the hands of, for example, geocachers or integrated into other devices and systems.

At the same time, after 16 years of decline, restoration, and modernization, Russia's GLONASS system has returned to full operation and appears to be here to stay, despite recent troubles in its space program. Europe's Galileo, finally escaping a long series of political misadventures and technical travails, is on the threshold of a rapid build-out of the constellation – with a public interface control document (ICD) and Galileo-capable receivers already available.

China's GNSS program, BeiDou (actually, BeiDou-2, reflecting the second phase of a satnav program that began in 2000) has shown the fastest evolution – launching its second-generation program with a 2007 launch and following up over the next five years placing another 15 spacecraft into orbit, including two dual-satellite launches. That led to the declaration of regional service and the publication of a B1 civil signal ICD in December 2012.

With these systemic developments and the worldwide adoption of GNSS by all categories of users in mind, I believe that we have arrived at one of those axial ages of technology: a turning point at which a door opens into a world of myriad possibilities, in which familiar endeavors take on new forms and entirely novel ways of working and living appear.

Dr. Petrovski's discussion begins, as so many previous publications rightfully have, with the GNSS infrastructures themselves: the ground control and monitoring segment, the satellite constellations, and the signals. Dr. Petrovski continues by taking up the design of GNSS receivers, both hardware and software, before leading the reader into the application realm of mobile positioning – as my preface to these remarks should make clear, what I consider the pivotal development of GNSS for the general population.

As he has done in previous works, Dr. Petrovski brings his long-established expertise in the GNSS field to bear. The scope of the text's discussion is wide ranging but detailed, thorough without losing perspective and a sense of proportion, sober and informed yet piquant at points, reflecting the personality of the author. In the penultimate Chapter 10, "Trends, opportunities, and prospects," Dr. Petrovski wraps up his examination of GNSS with a thoughtful reflection on prospects for advancing receiver technology in the future. The final chapter of the book – on testing mobile devices – is essentially a practical "how-to" appendix for which the preceding discussion has well prepared the reader.

Let me now step away from the contents of Dr. Petrovski's book again. I must leave to others with far more expertise in the engineering and scientific disciplines the task of assessing, interpreting, and communicating the lessons provided within its covers.

Instead, I want to place this publishing project in a wider context, to highlight the book's purpose against a backdrop of social and historical factors that have informed GNSS technology even as it has altered some of our most quotidian human activities.

Such matters are easy to underestimate or overlook, because GPS had barely reached the public consciousness before it began to disappear back into the context of daily life, increasingly invisible within its applications and the unconscious expectations of location users – like light switches or water faucets, noticeable only by its absence.

In human affairs, we may describe some things as game-changing events, or watershed moments, or even sea changes. But such characterizations are inadequate to describe the pervasive and far-flung effects of GNSS. The changes brought about by this still-young technology are more on the scale of plate tectonics or gravity. And this is not mere hyperbole, not when we are speaking of a technology that is used to measure the wobble in the Earth's rotation itself.

Indeed, had it not been appropriated by the environmental sciences, we would speak of GNSS in terms of global change to capture its true dimensions. Because, since the advent of GNSS, the world has changed – and it almost certainly is not changing back.

Of course, the intersection of GNSS with the routines of average citizens does not have the weightiness of its applications in geodesy, weather monitoring, or spacecraft navigation. Rather, for almost all of us, GNSS manifests itself on a human, even mundane, scale. Nonetheless, we can no more think of people abandoning their location-based applications – traffic guidance, photo-georeferencing, rendesvouzing, friend finding, ATM finding, cinema finding, whatever finding – than we can imagine them giving up the Internet or social media.

So, what are some of the hallmarks of this technology that has so transformed the world? Let me suggest just a few.

GNSS are incremental and cumulative For all of their transformative effects, GNSS build on earlier endeavors, discoveries, and achievements. In fact, it was in the context of GNSS that I first heard the expression, "We stand on the shoulders of giants." Thus, Galileo and BeiDou have largely recapitulated GPS and GLONASS while bringing their own advances and novel contributions. The Soviet Union's GLONASS almost certainly reflected a security-related response to GPS, only using a different orbital configuration and adding an FDMA element to the spreading-code design of GPS's CDMA.

But the lineage of cause and effect, of research and practice, goes back much further. Most immediately, GPS built on earlier Defense Department initiatives, including the Navy's TRANSIT (Doppler) system and Timation program, the Air Force 621B Project, the Army's SECOR satellites, and OMEGA.

Looking further back, however, the Earth's first artificial moon, Sputnik, sent aloft by the Soviet Union in 1957, inspired researchers at Johns Hopkins Applied Physics Lab to use the satellite's radio signal to determine its orbital location by means of Doppler measurements. And soon they speculated that the reverse was possible: to determine a receiver's position on the ground if the satellite's orbital location was known. That, in turn, led to efforts to replicate in space the radionavigation capabilities seen in such terrestrial systems as Loran and DECCA.

If we broaden the bandwidth on our scan of history for GNSS antecedents, however, we will ultimately assemble a pantheon of pioneers in physics, astronomy, math, and engineering – from Einstein, to Kepler and Newton, Tycho Brahe, Copernicus, and on back to Archimedes and Euclid.

GNSS clearly is a "disruptive" technology, a term much in vogue. In the words of that familiar repository of knowledge, Wikipedia, "A disruptive innovation is an innovation that helps create a new market and value network, and eventually goes on to disrupt an existing market and value network (over a few years or decades), displacing an earlier technology."

Oddly enough, Wikipedia does not yet include GNSS in its list of these innovations – where such inventions as telephones, automobiles, and personal computers appear – but GNSS certainly fits the bill.

Moreover, GNSS has put a previously inconceivable capability into the hands of millions. Before GPS, positioning was not a term of art known to the general public. Yes, people were familiar with such concepts as navigation, with mapping, with surveying. But these were understood to be in the bailiwick of professionals, of people who trained for years with expensive, specialized equipment, and not a matter of concern for the rest of us.

How that view has changed! The quotation from Ralph Waldo Emerson on page xix with which Dr. Petrovski introduces this book is as true today for GNSS as it was for the disruptive technologies of the nineteenth century.

A GNSS is a strategic national or regional asset Undertaking a GNSS reflects the relative weight and aspirations of nations around the world. In the bipolar world of the 1970s, that meant the United States and the Soviet Union. In the twenty-first century, Europe and China have joined the club, with India and Japan adding regional satnav systems. These roles have been enshrined by membership in the UN-sanctioned International Committee on GNSS.

Consider this: as Europe was exploring the possibility of developing its own GNSS, it posed a variety of benefits – commercial opportunities, a boost to the manufacturing economy, education and employment of high-tech professionals, a civil alternative to "military" systems such as GPS and GLONASS. But the real argument that persisted through the years of studies, debates, and indecision, and ultimately persuaded the European Union to launch Galileo, was the desire for political sovereignty and control over a critical infrastructure.

GNSS are complexly global and universal By this, I do not mean the obvious physical reach of the system infrastructures themselves. Here, "global" refers to the scale and "universal" to the degree of penetration that GNSS technology has already achieved into so many areas that cross national and ethnic boundaries: transportation, communications, economics, politics, sociology, law, and on and on.

For example, a truly global technology like GNSS intrinsically points toward a global market. And along with such an expansive geography of business comes a panoply of related activities: intellectual property rights, trade issues (subsidies, "dumping," taxes, and tariffs), compatibility and interoperability of technologies, international rule-setting and adjudication of disputes, and so forth. In the meantime, location-based advertising has emerged as one of the fastest-growing revenue streams associated with mobile devices.

Another example: Use of GNSS by law enforcement agencies has become a contentious issue in many countries, having already reached the US Supreme Court. At the same time, concern about its potential misuse by private individuals is rising. In fact, by one measure we might even say that a technology has truly "arrived" when it begins being put to undesirable uses. That appears to be the situation with GNSS, where we see such misapplications of the technology as virtual stalking, warrantless surveillance, road toll avoidance, deceiving truck dispatchers, and manipulating stock markets.

At the same time, GNSS-inspired position/location has become part of the common ground of human experience. It has entered into our language and our mental maps – our sense of where we come from, where we are, where we are going. GNSS and associated technologies orient us to the world and its inhabitants around us – both known and unknown.

So, thank you Ivan for giving us new insights and access into use of the remarkable technology and tool of GNSS.

About this book

As far as GNSS is concerned there are four main areas: mobile applications, geodesy, geophysical applications, and INS-aided navigation. This book covers the first topic, and the last two topics are covered in the book written together with Dr. Toshiaki Tsujii and published by Cambridge University Press, *Digital Satellite Navigation and Geophysics*.

This book is different from *Digital Satellite Navigation and Geophysics* in one other respect. In this book I take a pragmatic approach, providing algorithms and methods, in comparison with an holistic approach in *Digital Satellite Navigation and Geophysics*, where we tried to explain how GNSS is related to other manifestations of the physical world and physical science, and to the nature of things.

Acknowledgments

I would like to thank colleagues and friends without whom this work wouldn't be possible: Dr. Toshiaki Tsujii from JAXA, Mr. Ken Satoh from Amtechs Corporation. Prof. Harumasa Hojo and Prof. Emeritus Akio Yasuda from Tokyo University of Marine Science and Technology, Mr. Andrew Addy from Spirent Communications, and Dr. Takuji Ebinuma from Tokyo University.

I would also like to thank Mr. H. Torimoto from GNSS Technologies Inc. for his support during the years I was working with him.

I would like to thank my wife Tanya for her support and for encouraging me to share my knowledge and experience in this book.

Figures 8.3 and 9.1 were created by Natalia I. Petrovskaia, BA (Cantab), MPhil (Cantab), PhD (Cantab).

Credits for cover image and Figure 2.29: ESA– J. Huart; for Figure 10.1: ESA– S. Corvaja.

Abbreviations and acronyms

ADC	analog-to-digital converter
AGPS (AGNSS)	assisted GPS (GNSS)
AMP	accelerated massive parallelism
API	application programming interface
ARAMIS™	adaptive receiver applied for monitoring of ionospheric scintillation
ASC	audio sub-channel
ASIC	application-specific integrated circuits
BDT	BeiDou Navigation Satellite System time
BOC	binary offset carrier
bps	bits per second
BPSK	binary phase shift keying
C/A	coarse/acquisition
CDGPS (CDGNSS)	carrier differential GPS (GNSS)
CDMA	code division multiple access
CEP	circular error probable
CGCS2000	China geodetic coordinate system 2000
CODE	Center for Orbit Determination in Europe
CPLD	complex programmable logic device
CPU	central processing unit
CUDA	computer unified device architecture
DFF	D-type flip-flop
DFT	digital Fourier transform
DGPS (DGNSS)	differential GPS (GNSS)
DIF	digitized intermediate frequency
DLL	delay-locked loop
DOP	dilution of precision
ECEF	Earth-centered, Earth-fixed
ECI	Earth-centered inertial
ECO	Earth-centered orbital
EGNOS	European Geostationary Navigation Overlay Service
EMC	electromagnetic compatibility
EOP	Earth orientation parameters

FCC	Federal Communications Commission
FDMA	frequency division multiple access
FFT	fast Fourier transform
FIFO	First In First Out
FLL	frequency-locked loop
FPGA	field-programmable gate array
FTF	fundamental time frame
GATE	Galileo test and development environment
GEO	geostationary Earth orbit
GIS	geographic information system
GLONASS	Global Navigation Satellite System
GMT	Greenwich Mean Time
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
GPU	graphic processing unit
GSI	Geographical Survey Institute (Japan)
GST	Galileo system time
GUI	graphical user interface
HEO	highly elliptical orbit
HIO	highly inclined orbit
ICAO	International Civil Aviation Organization
ICD	Interface Control Document
ICRF	International Celestial Reference Frame
IERS	International Earth Rotation and Reference Frames Service
IF	intermediate frequency
IGP	ionospheric grid point
IGS	International GNSS Service
IGSO	inclined geosynchronous satellite orbit
IMES	indoor messaging system
INS	inertial navigation system
IONEX	ionosphere exchange format
IP	intellectual property
IPP	ionospheric pierce point
ISC	inter-signal correction
ITRF	International Terrestrial Reference Frame
ITU	International Telecommunication Union
JAXA	Japanese Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
LAAS	local area augmentation system
LEO	low Earth orbit
LNA	low-noise amplifier
LO	local oscillator
LOS	line-of-sight (between a receiver and a satellite)
LSE	least-squares estimation

LTO	long-term orbit
L2C	GPS civil signal on L2 frequency of L-band
LUT	lookup table
MEO	medium Earth orbit
MODIP	modified dip latitude
Mps	megasamples per second
MSAS	Multi-functional Satellite Augmentation System
NAV	navigation
NCO	numerically controlled oscillator
OCXO	oven-controlled crystal oscillator
OEM	original equipment manufacturer
PDF	probability density function
PLL	phase-locked loop
PPP	precise point positioning
PRN	pseudorandom noise
QPSK	quadrature phase shift keying
QZSS	Quasi-Zenith Satellite System
RAIM	receiver autonomous integrity monitoring
RF	radio frequency
RHCP	right-hand circularly polarized
RINEX	Receiver Independent Exchange Format
RMS	root mean square
RPS	record and playback system
RTCM	Radio Technical Commission for Maritime Services
RTK	real-time kinematic
RTOS	real-time operating systems
SA	selective availability
SARP	Standards and Recommended Practices
SAW	surface acoustic wave
SBAS	space-based augmentation system
SDCM	system of differential correction and monitoring
SDR	software-defined radio
SEP	spherical error probable
SIMD	single instruction on multiple data
SMA	sub-miniature version A
SNR	signal-to-noise ratio
SoL	safety of life
SOW	seconds of week
SP	standard precision
SV	space vehicle
SVID	space vehicle identification number
SVN	space vehicle number
TCXO	temperature-compensated crystal oscillator
TEC	total electron content

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TOT	time of transmission
TOW	time of week
TTA	time to alert
TTFF	time to first fix
2DRMS	twice distance RMS
URA	user range accuracy (GPS)
UTC	Coordinated Universal Time
VCXO	voltage-controlled crystal oscillator
VLBI	Very Long Baseline Interference
VRS	virtual reference station
WAAS	Wide Area Augmentation System
WGS-84	World Geodetic System 1984

Definitions

Code phase measurements	Ambiguous code phase measurements are measured by receiver baseband processor. These measurements do not require any information to be decoded from navigation message.
Observables	Observables are formed using receiver raw measurements in various combinations. Pseudorange observables are just pseudoranges.
Pseudoranges or pseudorange observables	Pseudoranges are created from code phase measurements properly aligned with each other (removing time skew) and made unambiguous using time mark either from navigation message or external sources.
Receiver measurements	Receiver measurements usually refer to antenna coordinate measurements, when observables are processed in the receiver navigation processor.
Receiver raw measurements	Receiver code phase and carrier phase raw measurements are unambiguous pseudoranges and ambiguous carrier phase measurements.