Engineering Satellite-Based Navigation and Timing

Global Navigation Satellite Systems, Signals, and Receivers

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PREFACE

The world of satellite-based navigation and timing opened for me in 1997, when Alan Moore, then the project leader of MITRE's GPS work for the Air Force, asked me a question in the corridor about how to design a new military signal that could share the same frequency band as existing GPS signals while being spectrally separated from civil signals. My off-the-cuff suggestion of a coherently modulated pair of subcarriers led to my development of Binary Offset Carrier and then involvement in other aspects of satnav. Since I had worked on spread spectrum communications, radar, sonar, and other signal-processing applications, satnav seemed to be a natural outlet for my interests and experience. There was a rich corpus of deep technical work to learn from, as well as many challenging problems still demanding innovative solutions. The GPS Joint Program Office was the place to be—full of excitement and plans for the future of GPS, with GPS legends roaming the halls.

Galileo, emerging in the early 2000s, provided an opportunity for collaboration with European colleagues to meet mutual goals of compatibility and interoperability. Japan's QZSS, Russian interest in CDMA signals, China's BeiDou, and India's IRNSS all also emerged, providing additional challenges to be addressed, as well as additional colleagues to learn from.

In 2006, Dr. Chris Hegarty put me in touch with Ms. Carolyn McDonald of NavtechGPS, and Carolyn agreed to sponsor my development and teaching of a short course emphasizing modernized satnav signals and receiver processing. Later versions of this course benefitted from course blocks developed by other experts under my direction. That course, and its extensions over the years, forms the basis of this book.

As my work on GPS and other satnav systems continued, it became clear that system engineering and signal engineering interact strongly with system design and receiver design. Such thinking was innate to legends like Dr. Charlie Cahn, but not necessarily to less experienced engineers. Also, design involves continual trades between implementation complexity and performance, further complicated by the need to assess implementation complexity in the context of future technologies, when signals would be used and receivers would be developed. Yet, no textbooks existed that depicted satnav system engineering and signal engineering in an organized and comprehensive way, or that clearly portrayed complexity and performance trades. Many books summarized the history of GPS and described the original GPS signals, but no text provided a balanced description of all current and planned satnav systems and their signals, including the modernized GPS signals. Multiple texts captured decades of experience in processing the original GPS signals, but books were not available to describe explicitly the processing of new and modernized signals with their different features and technical characteristics. Further, new techniques have been developed and the satnav literature has been enriched by many excellent papers over the past decade, yet these new contributions have not been captured and integrated into a single resource.

This book is my attempt to provide a set of more comprehensive and current perspectives.

John W. Betz

ACKNOWLEDGMENTS

Long before I began working on GPS, I was benefitting from colleagues and mentors. Mr. Roger Boyell, who worked with me at RCA Government Systems, was an exemplar of how to skillfully blend technical work and technical communication. Professor John Proakis, whose clear teaching style and excellent textbooks were essential to my graduate education, was kind enough to serve as my PhD advisor. At The Analytical Sciences Corporation (TASC), working with Mr. Robert Pinto was like graduate school all over again, while Dr. Seymour Stein, through his consulting work at TASC, demonstrated how theoretical analysis could guide and affect real-world applications.

At MITRE, Mr. Alan Moore provided me with the opportunity to work on GPS, and was extremely supportive of our efforts. Dr. Kevin Kolodziejski, who originally was my graduate student, became a colleague and co-author on multiple award-winning papers. From the beginning Dr. Chris Hegarty, one of the world's premier satnav engineers, has been an extremely helpful colleague. I was fortunate to serve on two signal design teams with Dr. Charlie Cahn, whose contributions to the design of every GPS signal demonstrated his unparalleled insight, productivity, technical breadth, and technical depth, combined with admirable humility and absence of self-promotion.

Much of my work on satnav has been with or for the US Air Force, and I have benefitted from the resulting association with outstanding Air Force officers. As GPS Chief Engineer early in this century, Col. Rick Reaser (Retired) was a mentor and guide in the challenging areas of spectrum management and international interactions. Col. Jon Anderson, PhD (Retired), was the Air Force Captain in 1997 who hosted the meeting where I introduced the Offset Carrier concept; he has remained a friend and colleague over these years as we have worked in different areas of satnav together. It was a pleasure to work with Col. Mark Crews, PhD (Retired), who served as GPS Chief Engineer; Mark made fundamental decisions related to GPS Modernization while leading GPS's international outreach with Europe, Russia, and Japan during critical times. Lt. Bryan Titus was a partner during the early days of GPS–Galileo discussions, and Lt. Col. Bryan Titus remains a colleague and friend as our careers have intersected again. Col. David Goldstein, PhD, in my opinion the prime example of a technical leader in the Air Force, has been a trusted colleague.

Mr. Thomas Stansell, through his consulting work for the US Air Force and US State Department, has had tremendous effect on GPS in this century and on me. I admire his style and his influence, and appreciate what he has done for me.

The Institute of Navigation (ION) and its members have provided a welcoming, stimulating, and educational environment for me and thousands of others in the field of satnav. Thanks to Ms. Lisa Beaty and the staff at the ION National Office for all they do to make the ION a very special professional organization.

Ms. Carolyn McDonald, and her company, NavtechGPS, have been integral to GPS and to satnav for decades. NavtechGPS's early close relationship with the ION, and continuing support of instructors like me, has provided opportunities for our professional growth while literally educating a generation of satnav engineers. Thanks to Carolyn for her friendship and support over these many years, and for originally sponsoring the preparation of course notes that led to many of the chapters of this book.

More recently, I have had the distinct pleasure of working with two other giants of satnav. Dr. Pratap Misra, a gentleman in the truest sense of the word, has been as kind and thoughtful a colleague as one could ever desire. Dr. Frank van Diggelen, with his deep insights combined with entertaining and stimulating style, has been an enjoyable and thought-provoking colleague and collaborator.

My daughter, Dr. Sharon Molly (Betz) Marroquin, carefully reviewed the first 15 chapters in their original manuscript form, providing valuable corrections and suggestions before the births of Hannah Molly and, later, Joseph Daniel, rightly diverted her attention and time.

This manuscript, in its entirety, had to be reviewed by the Air Force before its public release. Thanks to the Air Force officers, especially Capt. Nate Howard and Capt. Doug Pederson, for performing these reviews in addition to all of their other duties working on GPS and serving the nation. Also, I cannot thank enough the following colleagues who reviewed the manuscript in its entirety, providing many valuable comments and corrections: Dr. Frank van Diggelen, Dr. Jon Anderson, Professor Jade Morton, and Dr. José-Ángel Ávila Rodríguez. In addition, many thanks to Mr. Phillip Ward, Dr. Sergey Karutin, Professor Yuanxi Yang, Dr. Jeffrey Hebert, Dr. Alex Cerruti, and Professor Michael Braasch for their reviews of selected chapters. The resulting book benefits considerably from the careful attention and thoughtful suggestions of these reviewers.

My father, the late Edward S. Betz, MD, who was an electrical engineer before becoming a physician, influenced me to select electrical engineering as an undergraduate major, leading me to a fascinating and rewarding professional career. Thanks to my mother, Joanna Wells Betz, who has been everything a mother should be. She has been a continual source of encouragement during this effort.

Most importantly, thanks to my wonderful and loving family, especially my wife, Donna, who endured the countless evenings and weekends required to write this manuscript and go through the challenging process of publication. Thanks also to our four children, Christopher, Sharon, Peter, and James, along with their spouses and children, for their encouragement and support.

Thanks be to God.

USEFUL CONSTANTS

Boltzmann constant: $k_B = 1.3806488 \times 10^{-23}$ Joules/K (equivalently, watts/(K-Hz)) [1]

Earth gravitational constant: $\mu_e = 3.986005 \times 10^{14}$ m^3/s^2 [2]

Earth radius: [3]

Equatorial radius: 6,378,137.0 m

Arithmetic mean radius of semi-axes: 6,371,008.7714 m

Radius of sphere of equal area: 6,371,007.1809 m

Radius of sphere of equal volume: 6,371,000.7900 m

Earth rotation rate: $\Omega_e = 7.2921151467 \times 10^{-5}$ rad/s [2]

Pi: $\pi = 3.1415926535898$ [2]

Speed of light: $c = 2.99792458 \times 10^8$ m/s [2]

Note: Some values may vary slightly with different satnav systems and geodetic reference systems.

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LIST OF ACRONYMS AND ABBREVIATIONS

2DRMS	twice the distance root mean square
AAI	Airports Authority of India
ADC	analog to digital conversion, or analog to digital converter
AGC	automatic gain control
A-GPS	assisted GPS
ARAIM	Advanced Receiver Autonomous Integrity Monitoring
ARNS	Aeronautical Radio Navigation Service
AS	anti-spoof
AS	Authorized Service
ASCII	American Standard Code for Information Interchange
ASIC	application-specific integrated circuit
AWGN	additive white Gaussian noise
BAW	bulk acoustic wave
BCH	Bose, Chaudhuri, and Hocquenghem
BDS	BeiDou System
BDT	BeiDou Time
BGBES	BeiDou Ground Base Enhancement System
bps	bits per second
BRSD	Between Receiver Single Differencing
BSQ	bandlimiting, sampling, and quantization
BSSD	Between Satellite Single Differencing
C/A	Coarse/Acquisition
C/N_0	carrier power to noise power spectral density
CAF	cross-ambiguity function
CC	composite clock
CE50	Circular Error 50%, the radius of a circle centered at the true value containing 50% of the estimates
CE90	Circular Error 90%, the radius of a circle centered at the true value containing 90% of the estimates
CED	clock correction and ephemeris data
CEP	Circular Error Probable, the same as CE50
CFAR	constant false alarm rate
CGCS2000	China Geodetic Coordinate System 2000
CNSS	Compass Navigation Satellite System
CORS	continuously operated reference station
CRC	cyclic redundancy check

CRPA	controlled reception pattern antenna
CS	commercial service
CSC	carrier-smoothed code
CSK	code shift keying
DASS	Distress Alerting Satellite System
dB	decibels
dBi	decibels referenced to an isotropic antenna
dBic	decibels referenced to an isotropic circularly polarized antenna
dBil	decibels referenced to an isotropic linearly polarized antenna
dBm	decibels referenced to one milliwatt
dBW	decibels referenced to one watt
DFT	discrete Fourier transform
DLL	delay-locked loop
DOP	dilution of precision
DRMS	distance root mean square
DSSS	direct sequence spread spectrum
ECEF	Earth-centered, earth-fixed
ECI	Earth-centered, inertial
EGNOS	European Geostationary Navigation Overlay Service
EKF	extended Kalman filter
ENU	East-North-Up coordinate system
EOP	Earth Orientation Parameters
FAA	Federal Aviation Administration (of the United States)
FDE	fault detection and exclusion
FEC	forward error control
FFT	fast Fourier transform
FIR	finite impulse response
FLL	frequency-locked loop
FPGA	field-programmable gate array
FRPA	fixed reception pattern antenna
GaAs	gallium arsenide
GAGAN	GPS And Geo-Augmented Navigation
$\mathbf{G_{agg}}$	Aggregate gain of interference power
GCS	Galileo control system
GEO	geostationary
GGTO	GNSS to GPS Time Offset
GIVE	Grid Ionosphere Vertical Error
GLONASS	GLObal NAvigation Satellite System
GMS	Galileo mission system
GNSS	Global Navigation Satellite System
GoJ	Government of Japan
GPS	Global Positioning System
GST	Galileo System Time
GTRF	Galileo Terrestrial Reference Framework
HDOP	horizontal dilution of position

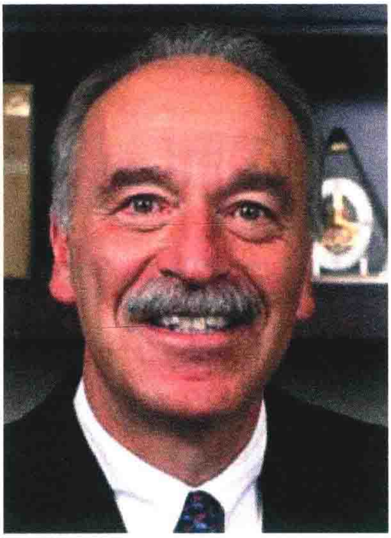
HEO	highly elliptical orbit
HOW	handover word
I/S	interference to signal ratio (power ratio)
ICAO	International Civil Aviation Organization
ICD	Interface Control Document
IDFT	inverse discrete Fourier transform
IF	intermediate frequency
IGP	ionospheric grid point
IGS	International GNSS Service
IGSO	inclined geosynchronous orbit
IID	independent and identically distributed
IMES	Indoor MEssaging System
IMU	inertial measurement unit
INS	inertial navigation system
IP3	third-order intercept point
IR	image reject
IRNSS	Indian Regional Satellite System
IS	interface specification
ISRO	Indian Space Research Organization
ITRF	International Terrestrial Reference Frame
ITU	International Telecommunications Union
ITU-R	International Telecommunications Union Radio Sector
JGS	Japan satellite navigation Geodetic System
KF	Kalman filter
L2CL	long spreading code used for the GPS and QZSS L2C signals pilot component
L2CM	medium length spreading code used for the GPS and QZSS L2C signals data component
L5I	the Inphase data component of the GPS L5 signal
L5Q	the Quadraphase pilot component of the GPS L5 signal
LAMBDA	Least-squares AMBiguity Decorrelation Adjustment
LC	inductor-capacitor
LDPC	low density parity check
LEO	low Earth orbit
LEX	QZSS experimental signal
LHCP	left-hand circularly polarized
LNA	low noise amplifier
LO	local oscillator
LTI	linear time invariant
MAI	multiple access interference
MC	master clock
MDR	multipath-to-direct path ratio
MEO	medium Earth orbit
MMIC	monolithic microwave integrated circuit
MOOC	Massively Online Open Course

MS	mobile station
MSAS	MTSAT-based Satellite Augmentation System
MTSAT	Multifunctional Transport Satellite
NANU	Notice Advisory to Navstar Users
NAQU	Notice Advisory to QZSS Users
Navwar	navigation warfare
NCO	numerically controlled oscillator
NDGPS	nationwide differential GPS
NGA	National Geospatial Agency
NICT	Japan's National Institute of Information and Communications Technology
NMCT	navigation message correction table
NRC	National Research Council
OCXO	oven-controlled crystal oscillator
OLS	ordinary least squares
ONSP	Office of National Space Policy (of Japan)
OS	Open Service
P(Y)	precision(encrypted)
PAPR	peak to average power ratio
PDOP	position dilution of precision
PDP	power-delay profile
PFD	power flux density
PLL	phase locked loop
PN	pseudo-noise
PNT	positioning, navigation, and timing
ppm	parts per million
PPP	precise point positioning
PPS	precise positioning service
PRN	Pseudo-Random Number
PRS	Public Regulated Service
PSD	power spectral density
PVT	position, velocity, and time
PZ-90	Parametri Zemli (English translation, Parameters of the Earth) 1990
Q	quality factor (of a filter)
QOC	quadrature offset carrier
QPSK-R	quadrature phase shift keying with rectangular spreading symbols
QZS	Quasi-Zenith Satellite
QZSS	Quasi-Zenith Satellite System
QZSST	QZSS Time
RAAN	right ascension of the ascending node
RAIM	Receiver Autonomous Integrity Monitoring
RC	resistor-capacitor
RDSS	Radio Determination Satellite System
RF	radio frequency

RHCP	right-hand circularly polarized
RMS	root mean-squared
RNSS	radio navigation satellite service
R-S	Reed-Solomon
RS	restricted service
RSS	root sum-squared
RTK	real-time kinematic
SA	selective availability
SAIF	submeter class augmentation with integrity function
SAR	search and rescue
SAR/GPS	search and rescue GPS
SARS	search and rescue service
SAW	surface acoustic wave
SBAS	Satellite-Based Augmentation System
SC	super critical
SDCM	System for Differential Correction and Monitoring
SE50	Spherical Error 50%, the radius of a sphere centered at the true value containing 50% of the estimates
SE90	Spherical Error 90%, the radius of a sphere centered at the true value containing 90% of the estimates
SEP	Spherical Error Probable, the same as SE50
SiGe HBT	silicon-germanium heterojunction bipolar transistor
SIR	signal-to-interference power ratio
SISRE	signal in space ranging error
SNR	signal-to-noise ratio
SoL	Safety-of-Life
SPP	standard point positioning
SPS PS	SPS Performance Specification
SPS	standard positioning service
sps	symbols per second
SSC	spectral separation coefficient
SUD	Standard Under Damped
SV	space vehicle
TCXO	temperature compensated crystal oscillator
TDOP	time dilution of precision
TGP	tropospheric grid point
TLM	telemetry word
TOA	time of arrival
TOI	time of interval
TT&C	telemetry, tracking, and command (sometimes telemetry, tracking, and control)
TTIS	time to initial synchronization
UDRE	User Differential Range Error
UEE	user equipment error

UERE user equivalent ranging error
URA user range accuracy
USNO United States Naval Observatory
UTC (NICT) Coordinated Universal Time as maintained by National Institute of Information and Communications Technology
UTC coordinated universal time
UTC ultra-tight coupling
UTC(USNO) Coordinated Universal Time as maintained by USNO
VDOP vertical dilution of precision
VGA variable gain amplifier
VLL vector locked loop
WAAS Wide Area Augmentation System
WGS84 World Geodetic System 1984
WLS weighted least squares
XO crystal oscillator

ABOUT THE AUTHOR



Dr. John W. Betz

Dr. John W. Betz is a Fellow of The MITRE Corporation, providing technical contributions and leadership to MITRE's work program, spanning research to applications. His work has involved satellite-based navigation, signal analysis and signal processing, communications, sensors, electronic warfare, and systems engineering.

With MITRE since 1989, Dr. Betz has held a variety of positions supporting the Air Force and the Department of Defense. He has led activities involving research and application of signal processing to problems in sensing, communications, navigation, and intelligence. From 2001 to 2002 he was Chief Engineer of the Intelligence, Surveillance, and Reconnaissance Integration Systems Program Office at the Air Force Electronic Systems Center, Hanscom Air Force Base.

His work on satellite-based positioning and timing (satnav) began in 1997, when he led the design of modulation and acquisition for the new GPS military M-code signal. He developed the binary offset carrier (BOC) spreading modulation selected for the GPS M-code signal and also adopted by all of the world's satellite-based navigation systems. He also has contributed to theory and practice of satellite-based navigation receiver processing, signal quality, security, and radio frequency compatibility. He also helped design the GPS L1C civil signal, and developed the multiplexed-BOC (MBOC) spreading modulation adopted for GPS L1C and for other interoperable signals on the European Galileo system and the Chinese BeiDou system, along with the time-multiplexed BOC waveform used for the GPS L1C signal. He has been a lead technical contributor to the U.S. delegation in negotiations leading to the 2004 Agreement between the U.S. and European Community concerning GPS and Galileo. Since 2004, he has contributed to U.S. activities on working groups addressing topics in compatibility and interoperability with Europe, Japan, the Russian Federation, China, and India, leading to other satnav systems' adoption of civil signals compatible and interoperable with GPS and each other.

He continues to be involved in signal and system engineering for GPS, and played a lead role in the GPS Enterprise Modernization Analysis of Alternatives that recommended substantial changes to planned military GPS, identifying more affordable and robust capabilities for warfighters. Most recently, his work has emphasized development and application of more secure and robust satnav capabilities for military and civilian applications.

He was a member of the Air Force Scientific Advisory Board (SAB) from 2004 through 2012, leading the Science and Technology Reviews of Air Force Research Laboratory, and from 2008 to 2011 was Chairman of the SAB. He has also served as a consultant to the SAB and the Defense Science Board, and since 2013 has served on the National Space-Based Positioning, Navigation and Timing Advisory Board, a Presidential advisory committee.

Before joining MITRE, he worked at The Analytic Sciences Corporation and RCA Automated Systems, and has been Adjunct Professor of Electrical and Computer Engineering and lecturer at Northeastern University.

He has authored or co-authored more than 50 research publications in journals, book chapters, and conferences, and is co-inventor on four patents and patent applications. Awards include the International Association of Institutes of Navigation's John Harrison Award (2015); Secretary of the Air Force Distinguished Public Service Award (2014), the highest public service award to private citizens by the Air Force; Institute of Navigation Satellite Division's Johannes Kepler Award (2013); Institute of Navigation Thurlow Award (2011); Fellow of the IEEE (2009); Carlton Best Paper Award, IEEE Aerospace and Electronic Systems Society (2009); MITRE Trustees' Award for international leadership in advancing global positioning, navigation, and timing (2008); named one of GPS World Magazine's "Fifty Leaders to Watch in GNSS" (2008); Fellow of the Institute of Navigation (2006); U.S. State Department Superior Honor Award (2004); MITRE President's Award for Contributions to GPS/Galileo Negotiations (2004); Burka Best Paper Award, Institute of Navigation (2001); MITRE President's Award for Contributions to GPS Modernization Design (1999); MITRE Best Paper Award (1995); Best Paper Award, IEEE Acoustics, Speech, and Signal Processing Society (1986); doctoral studies sponsored by the RCA Graduate Studies Program. He was awarded a BSEE (high honors) from University of Rochester (1976), and Masters (1979) and PhD (1984) Degrees in Electrical and Computer Engineering from Northeastern University.