L1C Signal Design Options*

John W. Betz, *The MITRE Corporation*
Charles R. Cahn, *Independent Consultant*
Philip A. Dafesh, *The Aerospace Corporation*
Christopher J. Hegarty, *The MITRE Corporation*
Kenneth W. Hudnut, *United States Geological Survey*
Capt Amanda J. Jones, *United States Air Force, GPS NAVSTAR Joint Program Office*
Richard Keegan, *Independent Consultant*
Karl Kovach, *ARINC Engineering Services*
Lt Lawrence S. Lenahan, *United States Air Force, GPS NAVSTAR Joint Program Office*
Howard H. Ma, *The MITRE Corporation*
Joseph J. Rushanan, *The MITRE Corporation*
Thomas A. Stansell, *Stansell Consulting*
Charles C. Wang, *The Aerospace Corporation*
Soon K. Yi, *ARINC Engineering Services*

BIOGRAPHIES

John W. Betz is a Fellow of The MITRE Corporation. His PhD in Electrical and Computer Engineering is from Northeastern University. He contributed to the design of the GPS M-code signal, including leading the Modulation and Acquisition Design Team, and developing the binary offset carrier (BOC) modulation. He has contributed to many aspects of GNSS engineering, and has participated in international efforts to achieve compatibility and interoperability between GPS and other satellite navigation systems. He received the ION Burka Award in 2001, and is a member of the US Air Force Scientific Advisory Board.

Dr. Charles R. Cahn has been an independent consultant since 1998. Participant in GPS Modernization study for JPO and definition of new L5, L2C, and L1C civil signals. VP Technology, PROXIM Corp, 2000 to 2002. Chief Scientist, SiRF/STS, 1995 to 1998. Independent consultant, 1990 to 1995 after retiring as Vice President and Chief Scientist, Magnavox Advanced Products and Systems Company, 1962 to 1990. Analyzed spread spectrum multiple access during two summer studies organized by IDA (1964 and 1966). Proposed pseudo noise/frequency hopping modulation schemes for ICNI during a summer study (1967) at RADC. Studied next generation satellite communications during a summer study (1971) for DDR&E. Presented lectures on spread spectrum for NATO-AGARD (1973) and to the IEEE Section in India (1980). Bissett-Berman Corporation, 1960 to 1962; TRW, 1956 to 1960; Syracuse University, 1949 to 1956. Member Sigma Xi, IEEE Fellow, Honorary Fellow, ION, NAVSTAR Hall of Fame Award, GPS JPO, The Johannes Kepler Award, ION, 2004. BEE, Syracuse University, 1949; MEE, Syracuse University, 1951; PhD in Electrical Engineering, Syracuse University, 1955.

Dr. Phil Dafesh is the Associate Director of the Digital Communication Implementation Department at The Aerospace Corporation. He provides management and technical direction of staff conducting design, development and implementation of next-generation software defined radio, GPS and wireless systems. He has contributed to the development of the modernized GPS signal structure and associated receiver processing. Dr. Dafesh received B.S. degrees from California State Polytechnic University, Pomona in Electrical Engineering and Physics. He received M.S. and Ph.D. degrees in Electrical Engineering from UCLA. He is currently a member of IEEE, ION, Sigma Pi Sigma and Tau Beta Pi.

Christopher J. Hegarty is a Senior Principal Engineer with The MITRE Corporation's Center for Advanced Aviation System Development. He received a D.Sc. in Electrical Engineering from The George Washington University. He is a member of RTCA's Program Management Committee and co-chair of RTCA Special Committee 159. He was a recipient of the 1998 ION Early Achievement Award and the 2005 Johannes Kepler Award. He currently serves the ION as Editor of *NAVIGATION: Journal of the Institute of Navigation* and as Eastern Region Vice President.

Kenneth W. Hudnut is Project Manager for GPS L1 Civil Signal Modernization (L1C) – Interagency GPS Executive Board Project #204. Dr. Hudnut studies earthquakes, using GPS and imaging methods, as a geophysicist for the U. S. Geological Survey in Pasadena, California. He currently serves as Geodetic Coordinator for the U. S. Earthquake Program Council, and as Chief of the Southern California Earthquake Hazards Assessment Project. Since receiving his Ph.D. from

*The contents of this material reflect the views of the authors. Neither the GPS NAVSTAR JPO, US Air Force, the Federal Aviation Administration, nor the Department of the Transportation makes any warranty or guarantee, or promise, expressed or implied, concerning the content or accuracy of the views expressed herein.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2006**	2. REPORT TYPE	3. DATES COVERED **00-00-2006 to 00-00-2006**
4. TITLE AND SUBTITLE **L1C Signal Design Options**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **MITRE Corporation,202 Burlington Road,Bedford,MA,01730-1420**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**13**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Columbia in 1989, and his A.B. (high honors) from Dartmouth in 1983, he has published over 65 scientific papers. He is a Visiting Associate in Geophysics on the faculty of the California Institute of Technology..

Capt Amanda J. Jones has been with the GPS Joint Program Office since 2001 and currently works in the Engineering and Advanced Technology Branch, where she was the L1C Project Military Co-Chair from 2004 through September 2005. Capt Jones received a B.S. in Astronautical Engineering from the United States Air Force Academy and a M.S. in Aerospace Engineering, Astronautics from the University of Southern California.

Richard Keegan is an independent GPS Consultant specializing in receiver architecture and signal processing, including consumer and embedded GPS. He has been involved in radio navigation receiver development for more than 30 years, including over 20 years of GPS commercial receiver development. Prior to becoming a consultant Mr. Keegan was the Director of Engineering for Magnavox Commercial GPS and Technology Director for Leica GPS. He holds numerous GPS related patents and participated in the L2C signal specification development.

Karl Kovach is a Fellow with ARINC Engineering Services, LLC in El Segundo, California. Karl has over a quarter century in various aspects of the GPS program, including 3 years as the Air Force Officer-in-Charge of the GPS Control System when it was at Vandenberg AFB, California (1983-1986). He received his BS degree in Mechanical Engineering from UCLA in 1978.

Lt Lawrence S. Lenahan is the L1C Project Military Co-Chair and works for the GPS Joint Program Office in its Engineering and Advanced Technology Branch, after 3 years with the 2d Space Operations Squadron as its Engineer On-Call for Spacecraft Anomalies. Lt Lenahan received a B.S. degree from the United States Air Force Academy in Astronautical Engineering and is currently a member of ION and AIAA.

Howard H. Ma received the B.S. degree in communication engineering from National Chiao-Tung University, Taiwan, in 1974, the M.S. degree in electrical engineering in 1978, and the Ph.D. degree in electrical and computer engineering from University of Massachusetts, Amherst, Mass, in 1985. Dr. Ma has been with the MITRE Corporation, Bedford, Mass, since 1978, where he has been engaged in research in digital communications and coding. From 1985 to 1988, Dr. Ma left MITRE to work at MIT Lincoln Laboratory, Lexington, Mass, on LPI design for three years. He came back to MITRE in 1988. Dr. Ma received the 1984 MITRE Best Paper Award for the paper "Error-Correction Codes against the worst-case partial-band jammer."

Joseph J. Rushanan is a Principal Mathematician in the Signal Processing Section of the MITRE Corporation. His expertise includes discrete mathematics, including binary sequences, and general security engineering. He has a BS and MS in 1982 from the Ohio State University and a Ph. D. from the California Institute of Technology in 1986, all in mathematics. He has been with MITRE since 1986.

Tom Stansell heads Stansell Consulting, after 8 years with the Johns Hopkins Applied Physics Laboratory, 25 years with Magnavox (Staff VP), and 5 years with Leica (VP), pioneering Transit and GPS navigation and survey products. He served on the WAAS Independent Review Board (2000); led technical development of the GPS L2C signal (2001); and is coordinator of the GPS L1C project. ION and other awards: Weems Award (1996), Fellow (1999), Kershner (PLANS-2000), GPS JPO Navstar Award (2002), and Johannes Kepler (2003). He was technical chair ('84, '86, and '88) and general chair ('94, '96, and '98) of PLANS conferences, technical chair of ION GPS-91, and general chair of ION GPS-92. He also is Western Regional VP of the ION.

Dr. Charles C. Wang is the Associate Director of the Communication Systems Engineering Department at The Aerospace Corporation. He received his B.S. degree in Communication Engineering from National Chiao-Tung University in Taiwan, and his M.S. and Ph.D. degrees in Electrical Engineering from the University of California, Los Angeles. As the Associate Director, Dr. Wang provides management and technical direction to staff conducting development, analysis, and simulation in communication architecture trade, physical layer design and evaluation, end-to-end system modeling and study, and communication network design. His current interests include turbo coding, trellis coded modulation, bandwidth-efficient modulation, OFDM, and space-time coding. He has published more than 80 technical papers in various journals and conference proceedings. He is a member of IEEE, AIAA, and Phi Tau Phi Honor Scholastic Society.

Soon K. Yi graduated with a BS in Electrical Engineering and Computer Science from University of California at Berkeley and received MSEE degree in Satellite Communication from University of Southern California. He is currently working as a Systems Engineer for ARINC and has been involved with GPS for the past 18 years providing systems engineering services to the GPS Joint Program Office. His current work includes duties of Interface Control Contractor for IS-GPS-200, IS-GPS-705 and some of his past work includes participating in the design and development of M-code, L5, and L2C signals.

ABSTRACT

Design activities for a new civil signal centered at 1575.42 MHz, called L1C, began in 2003, and the Phase 1

effort was completed in 2004. The L1C signal design has evolved and matured during a Phase 2 design activity that began in 2005. Phase 2 has built on the initial design activity, guided by responses to international user surveys conducted during Phase 1. A common core of signal characteristics has been developed to provide advances in robustness and performance. The Phase 2 activity produced five design options, all drawing upon the core signal characteristics, while representing different blends of characteristics and capabilities. A second round of international user surveys was completed to solicit advice concerning these design options. This paper provides an update of the L1C design process, and describes the current L1C design options. Initial performance estimates are presented for each design option, displaying trades between signal tracking robustness, the speed and robustness of clock and ephemeris data, and the rate and robustness of other data message contents. Planned remaining activities are summarized, leading to optimization of the L1C design.

INTRODUCTION

The Global Positioning System is undergoing continual modernization, providing ongoing improvements for users worldwide. While various enhancements in system features have been under development since the mid-1990s, modernization first benefited users when Selective Availability was set to zero in May 2000. Subsequently, other improvements in accuracy have been obtained through enhancements to capabilities and operation of the control and space segments, even using the original set of GPS signals with spectra shown in the first row of Figure 1. The launch of the IIR-14(M) satellite in Fall 2005 began a new era with transmission of the L2 civil (L2C) signal, along with the modernized military signal—the M-code signal, with spectra shown in the second row of Figure 1. A third civil signal, called L5, will be transmitted from Block IIF satellites, with spectra shown in the third row of Figure 1. All the while, improvements in monitoring, satellite technology (e.g., clocks) and operations yield continuing increases in accuracy. The United States (US) plans to continue providing these capabilities free of user fees, also providing free and open signal descriptions and other technical information needed for development of receivers and services using civil signals.

In the meantime, development of the next generation of satellites, called GPS III, and a modernized Control Segment, called OCX, continues, which will lead to greatly enhanced capabilities beginning early in the next decade. An integral part of the GPS III capabilities being developed is a new civil signal, called L1C, which will be transmitted on the L1 carrier frequency in addition to the C/A code signal, as shown in the bottom row of Figure 1. The development of L1C represents a new stage in international GNSS; not only is the signal being designed for transmission from GPS, it will also be interoperable with GALILEO’s Open Service signal centered at the same frequency. Coordination is also under way to make it highly interoperable with signals from the Quazi-Zenith Satellite System (QZSS).

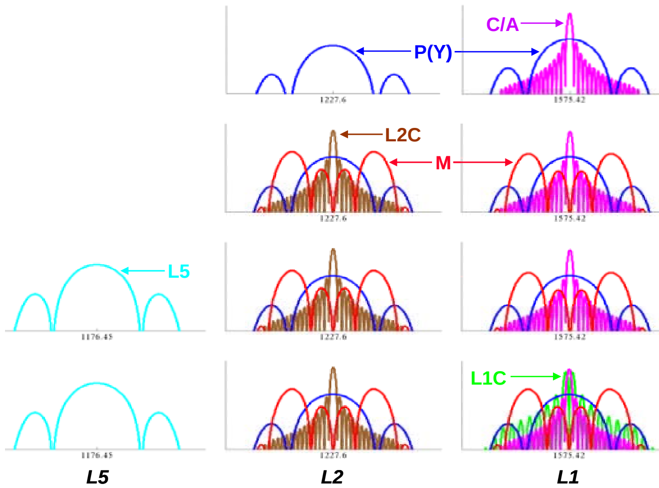

Figure 1. Evolution of GPS Signal Spectra: Original, Block IIR-M, Block IIF, Block III

L1C is being designed to take advantage of many unique opportunities. Its center frequency of 1575.42 MHz is the pre-eminent GNSS frequency for a variety of reasons, including the extensive existing use of GPS C/A code, the lower ionospheric error at L1 band relative to lower frequencies, spectrum protection of the L1 band, and the use of this same center frequency by GPS, GALILEO, QZSS, and SBAS signals for open access service and safety-of-life applications.

Other unique opportunities that the L1C design takes advantage of include advances in signal design knowledge, improvements in receiver processing techniques, developments in circuit technologies, and enhancements in supporting services such as communications. The L1C design is being optimized for superior performance, while providing compatibility and interoperability with other signals in L1 band.

This paper summarizes the L1C signal design. The next section provides an overview of the L1C design process, from its beginnings in 2003. L1C design goals are then presented, followed by an overview of L1C signal characteristics. The next section describes five design options that have been identified to represent different tradeoff points in L1C design characteristics. Some performance characteristics of these design options are then summarized. The summary of this paper includes a description of the next steps in L1C development.

OVERVIEW OF THE L1C DESIGN PROCESS

The L1C signal project was commissioned in August 2003 by the Interagency GPS Executive Board (IGEB). (The IGEB has since been disbanded and replaced by the Positioning, Navigation, and Timing Executive Committee consistent with the updated US policy on GPS [1]). At the time that the L1C project was initiated, neither the desirability nor the feasibility of an L1C signal for GPS had been established. The resulting effort over the next 11 months is documented in [2]. A technical team determined that it is possible to add an L1C signal on GPS III satellites, in addition to the other GPS L1 signals, while transmitting a constant-modulus composite signal on the L1 carrier for efficient transmission from the satellites.

In parallel, information and questionnaires were provided to various organizations possessing GPS expertise, including US government agencies, GPS equipment manufacturers, user groups, and university departments specializing in GPS applications. Fifty-five responses were received from around the world, unambiguously indicating the desire for a L1C signal.

Additional results of the survey responses provided more specific technical guidance and challenges for the detailed design activity conducted in Phase 2. The principal technical guidance involved modulation design, where, when given a choice between two binary offset carrier (BOC) spreading modulations [3], respondents preferred BOC(1,1) over BOC(5,1) based primarily on the shape of the correlation function and the smaller minimum receiver precorrelation bandwidth needed to receive the signal.

The primary technical challenge, in contrast, involved what [2] terms the "Message Data Rate Dilemma": when asked whether they preferred a data rate of 25, 50, or 100+ bits per second (bps), 41% of the respondents wanted 25 bps, and 41% of the respondents wanted 100 bps or higher.

In parallel with the conduct of the Phase 1 study, the United States and the Member States of the European Community signed an Agreement on the Promotion, Provision, and Use of GALILEO and GPS Satellite-Based Navigation Systems and Related Applications [4]. As part of this Agreement, the US agreed to provide a future GPS III civil signal centered at 1575.42 MHz—in effect, the L1C signal. Thus, L1C unequivocally became part of the GPS III signal set.

The IGEB funded the L1C Phase 2 activity in late 2004, and the development of a detailed L1C design progressed throughout 2005. Among the many aspects of signal design addressed during Phase 2, data message issues remained pivotal. Perhaps the most persistent issue was the future of out-of-band (OOB) data messages (i.e., provision of data messages by means other than the L1C signal-in-space, such as Internet, broadcast using terrestrial transmitters, broadcast by other satellite systems, etc.). While the L1C design team believes that of OOB data messages is likely to increase, it has struggled to predict with confidence which users might be able to rely on OOB data message. If OOB data messages were available to users in challenged environments (such as indoor users), then the need to provide robust messaging in L1C would be alleviated. Conversely, if OOB data messages were available to users who desire fast clock and ephemeris data (CED) or information that provides very high accuracy positioning, then the need to provide high rate messages would be alleviated.

The data message issues, combined with consideration of modern forward error control (FEC) techniques, affect many aspects of signal design including the channel symbol rate, the length of the spreading codes, signal acquisition, and even the fraction of signal power allocated to the data message. The design team evaluated all of these considerations, while also exploring numerous options involving other aspects of signal design and performing preliminary assessments of their performance. Ultimately, it became clear that some aspects of the signal design were universally desirable, while tradeoffs were involved with other aspects. The team assembled a large number of signal design options that included the universally desirable aspects, combined with different choices of the other aspects. Through performance assessments, a downselection process identified a set of five candidate design options for further consideration.

The description of these five design options and their performance has been provided to many dozens of groups of international experts on GPS, as part of a Phase 2 survey process [5]. The results of these surveys are being evaluated, guiding the finalized design for L1C.

L1C DESIGN GOALS

The L1C design goals fall into two categories. The high-level design goals in the first subsection represent strategic goals to be taken into account in the design. The Phase 1 Survey and additional background investigations, on the other hand, produced specific guidance and challenges that complement the high-level design goals. This section summarizes both the high-level goals and the challenges that guided the design activity.

High-Level Design Goals

The Phase 2 detailed design process has focused on meeting an ambitious set of design goals that are consistent with, but not limited to, the civil requirements for GPS III. Since current plans are to transmit the C/A code signal indefinitely to support legacy receivers, the L1C signal must, at minimum, be compatible and interoperable with the C/A code signal. A goal is for the L1C signal to complement the C/A code signal, allowing future receivers to obtain even better performance by exploiting the combined presence of C/A code and L1C.

In addition, L1C should be compatible with other current and planned signals in the L1 band. Another goal is for it to be as interoperable as possible with signals to be transmitted by other systems, except when increasing interoperability would unacceptably degrade a desired characteristic of L1C. At a minimum, the L1C design should comply with relevant international agreements and regulations.

The L1C design should also, however, be forward-looking in many respects. Digital processing technology is expected to advance based on Moore's Law (stating that digital processing power will double approximately every 18 months), allowing consideration of design options that require an increase in receiver processing. Mobile telephone, satellite broadcast, terrestrial broadcast, and Internet links will continue to improve in availability and access, allowing some users to obtain the data message through OOB communications. Users continue to seek satellite navigation in more stressing environments, including indoors, in urban areas, and under foliage, motivating more robustness than provided by the C/A code signal. Better satellite geometry will be available as other systems come on line, particularly when these systems transmit signals on common center frequencies with GPS, providing increased accuracy and availability of signals.

The difficulty of forecasting how L1C will be used, combined with the expected diversity of future uses, motivated considerable attention to building flexibility into the signal design wherever possible. Of particular interest were signal features that allow receivers to employ different processing strategies to obtain varied performance benefits in different situations.

Perhaps most importantly, the L1C design strategy has emphasized broadly optimizing the entire signal design with respect to a wide-ranging set of criteria and applications, rather than narrowly optimizing only selected characteristics with respect to a limited set of criteria.

In particular, the L1C design optimization accounts for the simplicity of transmitting signals where each component is constant modulus, receivers use two-level replica signals, and there is no intentional transmit filtering (besides the inevitable bandlimiting by the RF components in the satellite) that degrades performance by smoothing the sharp edges that provide highly accurate code tracking.

Data Message Challenges

The results of the Phase 1 survey, summarized in the previous section, provided additional and more specific technical guidance and challenges for the detailed design activity in Phase 2.

The primary technical challenge has been solving the Phase 1 "Message Data Rate Dilemma" [2]. The comments that accompanied the responses provided insights that pointed the way to a solution of the dilemma:

- Those preferring low data rate actually were stating their desire for a more robust data message, not a low data rate,
- Those preferring high data rate actually desired some or all of three characteristics: "room" in the data message for additional information including messages that enable higher accuracy, longer-lasting CED, and CED that can be read more quickly for a faster initial fix and earlier use of a rising satellite.

Interpreting the responses literally as requests for contradictory data rates leads to the dilemma, while recognizing the actual underlying desires opens up possible solutions to the dilemma—namely, data messages that can be read robustly while providing rapid read times for CED, along with adequate message capacity.

Thus, the design goals for the data message were recognized to be a combination of:

- Robustness: to enable critical functions such as tracking and data demodulation in challenging environments with low effective carrier-power-to-noise-density ratios (C/N_0) and fading channels,
- Fast read times to support quick access to CED,
- Capacity for navigation-related message contents besides CED and time, such as time offsets with other satellite navigation systems, almanac updates, inter-signal corrections, and possibly other uses that provide improved accuracy, authentication, and integrity.

Perhaps the most persistent and unresolved issue has been the future of OOB data messages. No one can predict with confidence which types of users might be able to rely on OOB data messages (relieving their need to rely on the in-band L1C data message), and which types of users might not be able to rely on OOB data messages. Consequently, the goal became to design L1C to support all classes of users with its own data message, while also enabling better performance with an OOB data message.

L1C SIGNAL CHARACTERISTICS

The Phase 2 detailed design involved many different aspects of the signal. This section summarizes those characteristics that are common to the current design options, while introducing the aspects addressed by the design options described in the next section. Except for center frequency and power level, the characteristics described here are preliminary and subject to change as the L1C design continues to be optimized.

Center Frequency and Power

The L1C signal center frequency is 1575.42 MHz, maximizing interoperability with C/A code and with the GALILEO Open Service signal to be transmitted at 1575.42 MHz. The received power in all L1C signal components combined, defined consistent with GPS conventions in [6], is currently planned to be a maximum of –154 dBW and a minimum of –157 dBW.

Spreading Modulation

The spreading modulation is important for interoperability and compatibility, as well as for many aspects of performance including interference resistance and ranging accuracy. The current plan is to use a BOC(1,1) spreading modulation, consistent with the baseline modulation called out in [4]. BOC(1,1) provides compatibility with other signals in the frequency band, interference resistance, and good code tracking performance, along with simple implementation in receivers and satellite transmitters.

Pilot and Data Components

Like many modern navigation signals, all L1C designs have a separate pilot component that is not modulated by data, along with one or two data components. The pilot component allows the receiver to employ phase-locked loop (PLL) carrier tracking (which is more robust than suppressed-carrier phase tracking using a Costas loop or equivalent, and eliminates the half-cycle ambiguity of suppressed carrier tracking), and to use correlation integration times that can be extended beyond the channel symbol period. Data symbols are biphase modulated; designs with one data component broadcast messages sequentially, while designs with two data components broadcast two messages concurrently.

Spreading Codes

Spreading codes influence various aspects of performance ranging from initial synchronization for signal acquisition to the ability to accommodate wide dynamic ranges in received power of different signals. Longer spreading codes tend to provide more robust performance, although the selection of a code family with good characteristics is also important. All of the current L1C design options employ spreading codes with length of 10230 bits, corresponding to a 10 msec repetition period at the spreading code rate of 1.023 MHz. Furthermore, having the same length spreading code on pilot and data components allows receivers to use both pilot and data components in initial synchronization processing, noncoherently combining the pilot and data correlations in order to improve performance (using parallel correlators for the different components). The channel symbol rate on data components is 100 symbols per second, matched to the spreading code repetition rate, providing excellent smoothing of spectral lines and avoiding the need for data bit synchronization processing.

The selection of spreading codes has emphasized those that can be generated in a receiver, avoiding "memory codes" that must be permanently stored. Since the number of bits in the primary spreading code is the same as that of L5 codes [7], one option has been merely to reuse the L5 spreading codes for L1C as well. This alternative has the advantage of simple implementation using linear shift registers. A new family of spreading codes, having somewhat better correlation characteristics than the L5 codes, has also been developed and is also under consideration.

The L1C pilot component also uses a secondary code whose length is the same as the number of symbols in a data message. Each bit of the secondary code has a period of 10 msec. The secondary codes are unique to a satellite and modulate periods of the pilot channel's primary spreading codes. The secondary code reduces cross-correlation effects, spreads out spectral lines that would otherwise arise from repeating code periods, and allows a receiver to synchronize to data messages by aligning to the timing of the secondary code. Design of the secondary codes is proceeding, but has not yet been completed. One candidate approach is to use disjoint sections of a long maximal length sequence.

Data Message Structure

The data message must contain three different types of information:

- Broadcast time in terms of the week number and time within the week,
- Satellite-specific CED,
- A large amount of system-related data such as almanac, ionospheric model, time offsets to other systems and to coordinated universal time (UTC), Earth-orientation parameters, and other information that various users need.

Different data message designs are reflected in the L1C design options. While there are differences among them that are described in the next section, there are also many common characteristics summarized here. The CED messages (and also some bits that represent broadcast time) are designed to be invariant over a known period of time referred to as the CED interval, which could be as short at five minutes or as long as multiple hours. Within this CED interval, the CED does not change. The channel encoding is designed so that many of the channel symbols also do not change over this CED interval.

Receiver processing can benefit in two ways from the invariance of the encoded and interleaved CED symbols within a CED interval. The first benefit is the ability for a receiver to perform code combining [10] to read the unchanging CED under stressed conditions. When the receiver detects uncorrected errors, it can use various approaches to combine soft or hard decisions from two or more repeats of the CED portion of the data message. This combining is facilitated by unambiguous phase-locked carrier tracking of the pilot component.

Soft combining, which is optimal in a stationary additive white Gaussian noise channel, involves coherently adding the soft decisions from two repeats of the CED, then determining if uncorrected errors remain, as indicated by failure of the cyclic redundancy check (CRC). If there are no remaining uncorrected errors, the message has been read at 3 dB lower C/N_0 than would have been possible without code combining. If there still are uncorrected errors, the code combining process can be prolonged for three or more repeats, as long as carrier phase tracking is maintained to enable coherent combination of the soft decisions.

As described in [10], receivers can optionally use other combining approaches for channel conditions other than stationary additive white Gaussian noise.

The key effect of this feature is that the CED can be provided at a high data rate to satisfy users operating with adequate C/N_0. Meanwhile receivers that otherwise could not read the message at all, instead can read it at lower C/N_0, but more slowly. While use of code combining sacrifices some coding gain from the use of higher-rate codes, the flexibility it provides outweighs this disadvantage.

The second benefit of the repeated invariant CED occurs when the receiver does not need to read CED, having received it OOB or previously read it from the signal-in-space during the same CED interval. In this circumstance, the interleaved and encoded CED symbols that modulate the spreading codes are completely known in advance to the receiver, just like the secondary code on the pilot channel. The receiver can then wipe the data symbols associated with CED from the data component, using these symbols like an additional pilot component with longer correlation times for code tracking and also coherently combining them (using coherent Maximal Ratio Combining) with the despread pilot component for PLL tracking.

To maximize the amount of invariant data within a CED interval, the parts of broadcast time that do not change within a CED interval are blocked together with the CED. Less significant bits of broadcast time, which do change within a CED interval, are handled separately, as are the "variable message data" that includes system parameters and other messages that are transmitted at different times.

Channel Encoding

One type of channel encoding is used to protect both the invariant data and the variable message data. The channel encoding involves both forward error control (FEC) and interleaving. After considerable evaluation of different FEC approaches using criteria including performance, implementation complexity, and intellectual property issues, low density parity check (LDPC) codes with message-passing iterative decoding [8, 9] were identified. Compared to the very mature convolutional codes and Viterbi decoders used on previous modernized GPS signals, LDPC codes offer significantly more coding gain. Despite their greater decoding complexity, they are well suited for use in the GPS III time frame. The choice of FEC and the resulting performance are affected by the restriction of coding latency to a single message—while even better coding gain could be obtained if latencies exceeding 1000 bits were permitted, such designs are inconsistent with providing fast access to CED.

While different design options presented in the next section offer different data rates, all employ the same channel symbol rates. The different data message bit rates are attained by using different coding rates: the current options use either rate 1/2 or rate 3/4 codes.

Interleaving of the encoded symbols (except perhaps those encoding the rapidly varying time bits) is also provided, using a fixed block interleaver over no more than one message. As in the case of FEC design, the decision was made to forego any additional performance benefits that might accrue in fading channels from interleaving over more than one message, but instead not to increase message latency and to accept whatever performance enhancement is achieved by interleaving over a single message.

Forward error control is separate for the approximately 10 bits of broadcast time that change within a CED interval. These bits will be encoded using a strong BCH code. Receivers can employ maximum-likelihood decoding in real time, since the number of correlations is relatively small and a replica code word is easily generated by a short shift register. The large minimum distance of the high redundancy BCH code ensures that the resulting performance (in terms of C/N_0 required for very low error rate in additive white Gaussian noise) is lower than that of the FEC used for invariant parts of the message. While code combining over time cannot be used for these ever-changing time bits, all satellites can transmit the same time, since their CED intervals will be synchronous. The receiver can then either rely on reading these bits from the strongest satellite signal, or perform code combining across multiple satellite channels.

There currently is no plan to transmit high-rate integrity information within the L1C data message, due to the high data rate that would be needed and the resulting degradation to data message robustness. Instead, other means are being developed to indicate failure conditions with very rapid times to alarm.

Multiplexing

Currently, specific approaches for multiplexing the L1C components, along with P(Y), M, and C/A, to form a constant-modulus composite signal on the GPS L1 carrier, have not yet been selected. Based on preliminary evaluation of multiplexing, there is a variety of approaches that can be used, and different approaches provide different efficiencies for different relative power levels of the constituent signals. As long as the L1C signal components remain binary-valued, it is expected that satisfactory multiplexing approaches will be available for a range of relative power levels.

Time multiplexing of the different L1C signal components into a single composite binary signal is not favored, since time multiplexing effectively reduces the length of the spreading code length, and it is desired that the full 10230 length of the spreading code period be retained to maintain low correlation sidelobes.

L1C SIGNAL DESIGN OPTIONS

Five different L1C design options have been retained, each based on the common signal characteristics described in the preceding section, while offering different performance characteristics. The design options differ in number of data components, data rate, and fraction of power in the pilot. The characteristics described here are preliminary and subject to change as the L1C design continues to be optimized.

Single Data Component Designs

The single data component designs are similar to the designs of previous modernized GPS signals, with signal power divided between the pilot component and a single stream of data message symbols. For L1C, the pilot component and the data component are code division multiplexed—each transmitted continuously using different spreading codes. Depending upon the multiplexing approach used to form a constant-modulus composite signal from these two components as well as P(Y), M, and C/A, they may or may not be on the same carrier phase. As shown in the upper part of Figure 2, the single data message component is based on a 900 bit message divided into three blocks, each separately encoded:

- The rapidly varying time block using approximately 30 bits of space for rate 1/2 coding and approximately 40 bits of space for rate 3/4 coding,

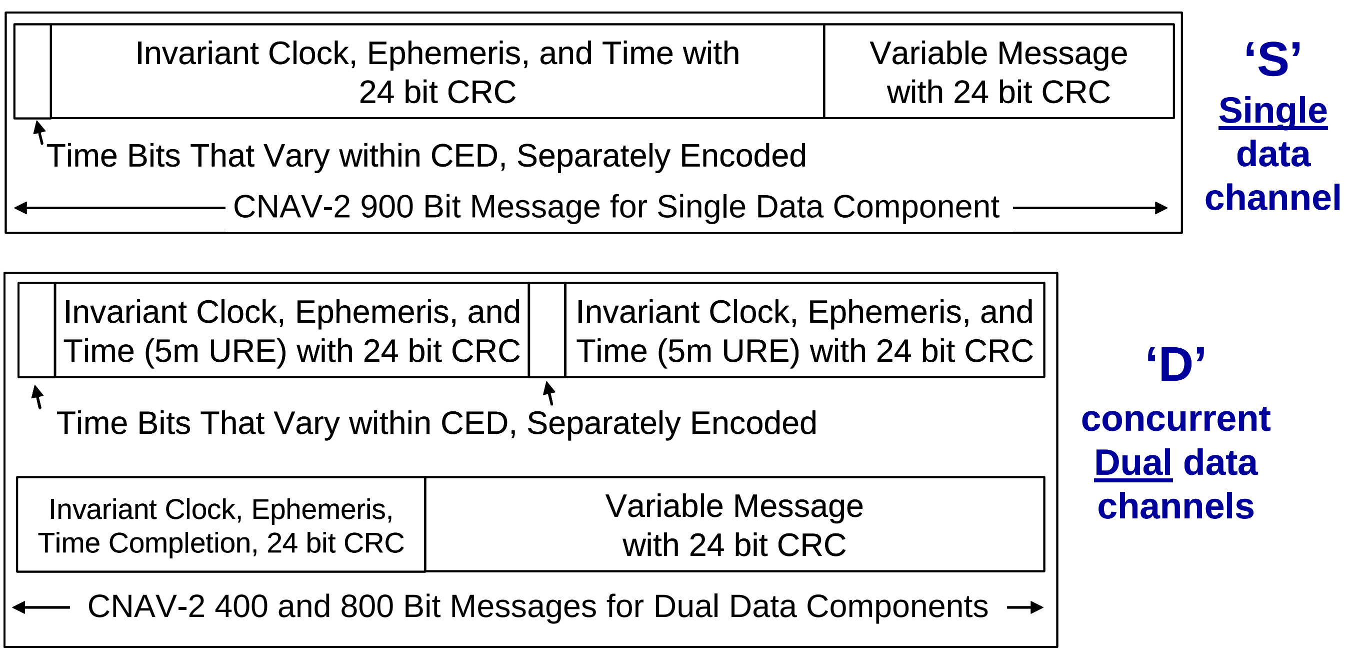

Figure 2. Overview of Two Candidate Preliminary Data Message Structures

- The block containing clock, ephemeris, and invariant time bits, using approximately 600 bits,
- The variable data block that completes the message and provides approximately 240 bits for paged system-related information.

Interleaving over the entire 900 bit message (except, perhaps, for the rapidly varying time symbols) requires the receiver to observe as many as 900 bits before it has the CED. However, it provides more robustness in fading channels and distributes CED bits to enable data wiping without multiple second gaps that would otherwise occur from the variable data message.

If the receiver already has the CED (having read it already or has received it in advance through OOB messaging), it can wipe the symbols representing the channel-encoded CED and time, and use approximately 60% of the data message as an additional pilot component. The PLL can then perform carrier phase tracking using the combined power in the pilot and the data-wiped portion of the data message.

There are three design options that use a single data component, each named beginning with the letter "S" to designate the single data component. The S50/25% design option uses a 50 bps data message (using rate 1/2 FEC) and allocates 25% of the composite signal power to the data message. The 900 bit message is encoded as 1800 symbols with duration of 18 seconds. The S50/50% and S75/50% options use 50 bps and 75 bps data messages respectively (75 bps uses rate 3/4 FEC), while allocating 50% of the composite signal power to the data message. For S50/50%, the 900 bit message is encoded as 1800 symbols with duration of 18 seconds, while for S75/50%, the 900 bit message is encoded as 1200 symbols with duration of 12 seconds. As described in the previous section, the CED bits remain constant over regularly spaced CED intervals, in order to support code combining and data wiping of the CED.

Dual Data Component Designs

Dual data message components represent a new concept for addressing the "Data Message Dilemma" encountered during L1C Phase 1 as discussed earlier. In these designs, the signal power is divided between the pilot component and two separate streams of data message symbols. The pilot component and each data component are code division multiplexed—each transmitted continuously using different spreading codes. Depending upon the multiplexing approach used to form a constant-modulus composite signal from these three components as well as P(Y), M, and C/A, they may or may not be on the same carrier phase.

As shown in the lower part of Figure 2, both dual data message components are based on 800 bit messages, divided into blocks that are separately encoded. (Block lengths are nominal and may change slightly in the optimized design.)

One component, called the fast start message, constantly repeats CED and system time, with no variable data. In order to keep the number of bits small, the CED in this message is represented with lower precision (corresponding to nominal range error of 5 m), consistent with ranging accuracy provided by a receiver in a stressed environment (with low C/N_0 and multipath) or when it has been tracking a signal for only 10 or 20 seconds, before high accuracy tracking has been achieved. Each fast start message consists of:

- The rapidly varying time block using approximately 30 bits of space for rate 1/2 coding and approximately 40 bits of space for rate 3/4 coding,
- The block containing clock, ephemeris, and invariant time bits, using approximately 350 bits.

The current plan is to interleave over the 400 bit message (possibly excluding the rapidly changing time symbols), so a receiver need observe only 400 bits before it has the first CED.

The completion message component of the dual data message, shown in the lower part of Figure 2, contains an 800 bit message including:

- The block containing remaining clock, ephemeris, and invariant time bits for full precision using approximately 300 bits,
- The variable data block that completes the message and provides approximately 475 bits for paged system-related information.

Just as for the single message designs, if the receiver already has the CED (having read it already or received it through OOB messaging), it can wipe the phase from symbols representing the channel-encoded CED and time, and use approximately 60% of the data message as an additional pilot component. The PLL can then perform carrier phase tracking using the combined power in the pilot and the data-wiped portion of the data message.

There are two L1C design options based on a dual data component, each named beginning with the letter "D" to designate the dual data component. The D50/25% option uses 50 bps data messages (using rate 1/2 FEC) for both message components and allocates 25% of the composite signal power to each data message. Each 400 bit fast start message is encoded as 800 symbols with duration of 8 seconds, while the 800 bit completion message is encoded as 1600 symbols with duration of 16 seconds.

The D75/25% option uses 75 bps data messages (using rate 3/4 FEC) for the fast start message and 50 bps data message for the additional message component, again allocating 25% of the composite signal power to each data message. Nominal values for the D75/25% data message involve 400 bit fast start messages encoded as 533 symbols with duration of 5.3 seconds, and a 800 bit completion message encoded as 1600 symbols with duration of 16 seconds.

Table 1 summarizes some of the important characteristics of the five design options, which represent a range of candidate capabilities for L1C.

Table 1. Summary of L1C Design Options

Option Name	% Pilot Power	Full Accuracy & Variable Messages		Fast Start Messages	
		Data Rate (bps)	% Power	Data Rate (bps)	% Power
S50/25%	75	50	25	-	0
S50/50%	50	50	50	-	0
S75/50%	50	75	50	-	0
D50/25%	50	50	25	50	25
D75/25%	50	50	25	75	25

PERFORMANCE ASSESSMENT

While complete performance assessment of the options, including all receiver functions under a range of environmental conditions, is beyond the scope of this paper, this section provides initial performance results for some of the critical characteristics, under the assumption of a stationary additive white Gaussian noise channel.

The new family of spreading codes, still being constructed as a candidate for L1C, provides low autocorrelation and crosscorrelation sidelobes. Table 2 compares the current state of the candidate L1C family of codes with other comparable code families having the same length: GALILEO E5 [11], GPS L5 (original and expanded families) [12], GPS L2C CM [13], and random codes. The maximum sidelobes are given using 0 Hz Doppler and no data modulation. Assessment of the crosscorrelation performance for the GALILEO pilot (p) and data (d) codes together, while not available at this time, could lead to higher crosscorrelation sidelobes than shown here. The values indicated for random codes are the median values over all random families of size 200 of length-10230 sequences, i.e., half of the time such random families will have sidelobes values at least as high in the table.

Table 2. Maximum Sidelobes at 0 Hz Frequency Shift for Different Length 10230 Spreading Code Families

Code Family	Number of Codes	Max. Auto Sidelobe	Max. Cross Sidelobe
Candidate L1C	109	–31.0 dB	–28.0 dB
GALILEO E5a-d [11]	100	–28.9 dB	–26.0 dB
GALILEO E5a-p [11]	100	–28.7 dB	–25.5 dB
GALILEO E5b-d [11]	100	–28.8 dB	–25.5 dB
GALILEO E5b-p [11]	100	–28.8 dB	–25.5 dB
Original L5 (I5 and Q5) [7]	74	–29.0 dB	–26.4 dB
Expanded L5 (I5 and Q5) [7]	420	–28.5 dB	–26.4 dB
L2C CM [12]	37	–26.9 dB	–25.4 dB
Random Codes	200	–26.2 dB	–24.7 dB

Phase coherent tracking of the carrier is essential for robust demodulation of the data, for carrier-aided code tracking, and for greatest accuracy. Figure 3 shows the minimum C/N_0 where carrier tracking can maintain lock, using a criterion that the PLL loop signal-to-noise ratio (SNR) must remain above 10 dB to ensure lock. The results for C/A code are based on a Costas loop with a 6 dB higher loss-of-lock criterion, taking into account that all of the signal power is used for carrier tracking. The performance in this figure and subsequent figures is reported in terms of the total (combination of pilot and data components) C/N_0 at the correlator output, after all effects of antenna gain and implementation losses have been accounted for. The results are shown for two situations:

- CED message block is not known to the receiver, so that the PLL can track only the pilot,
- CED message block is known to the receiver, which can then PLL track a combination of the pilot and (data-wiped) CED symbols. (These results assume interleaving over entire messages, otherwise performance of the single message options would be poorer.)

Figure 3 shows that all design options outperform C/A code, whose performance may degrade more than is shown for lower values of C/N_0. All except S50/25% have 50% power in the pilot, and so exhibit the same loss-of-lock performance. In pilot-only tracking, S50/25% allows the receiver to maintain lock at 1.8 dB lower C/N_0 than the other options, or to use a 50% wider loop bandwidth for handling higher dynamics or phase noise at the same loss of lock threshold. When the receiver has access to the CED (either having read it recently or received it OOB) and performs data wiping, however, all options achieve very similar performance.

Since much of the discussion of L1C characteristics during Phase 1 involved data rate and data robustness, this aspect of performance is of particular interest. Figure 4 compares the maximum time to read first CED from the different designs, at different values of C/N_0. Better performance is indicated by curves that are low and to the left. The C/N_0 values are established based on a message error rate of 0.03, calculated for LDPC codes and summarized in Table 3. The effect of code combining is evident in the staircase patterns, where if the C/N_0 is so low that there are uncorrected errors, then the receiver can combine symbols from sequential CED blocks until it obtains adequate energy-per-bit-to-noise-density-ratio (E_b/N_0). Since carrier phase tracking is needed for coherent data demodulation, it may not be possible to achieve values on the far left of Figure 4, unless very small PLL loop bandwidths can be employed, as shown in Figure 3. D75/25% provides the fastest access to first CED for higher values of C/N_0, while D50/25% is fastest in most cases for the lower values of C/N_0.

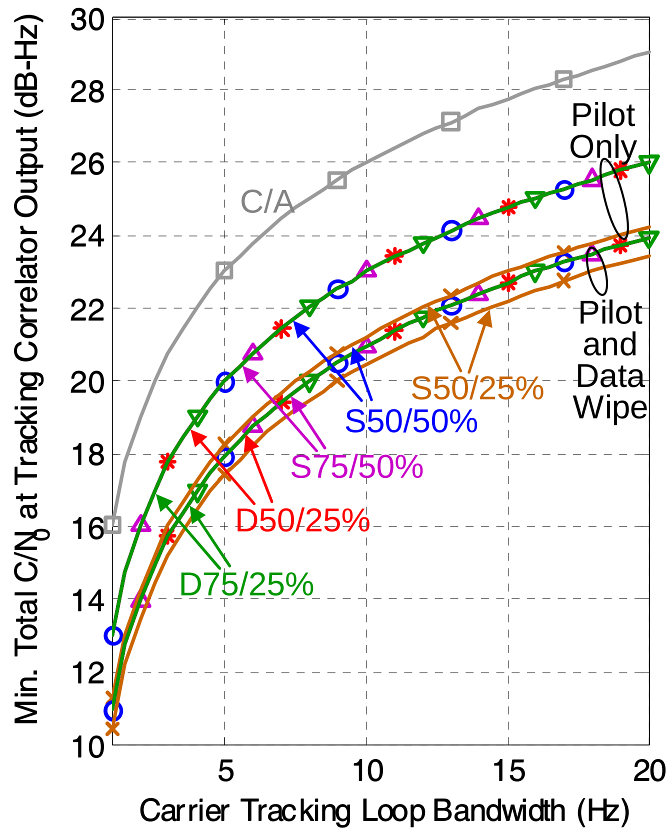

Figure 3. Minimum Total C/N_0 for Maintaining Lock in Carrier Tracking

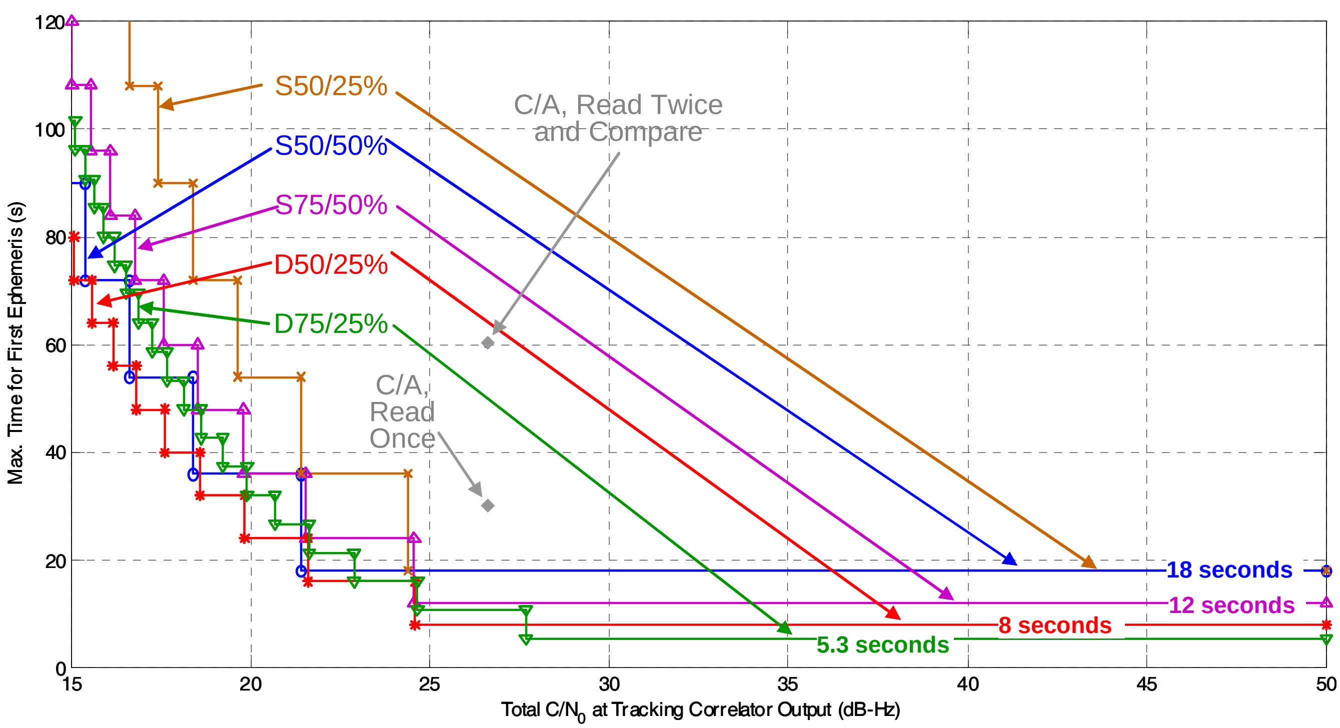

Figure 4. Comparison of Times to Read First Clock and Ephemeris at Different Levels of C/N_0

Table 3. E_b/N_0 Required for 0.03 Message Error Rate Using LDPC Codes

Message Length (bits)	Required E_b/N_0 (dB)	
	Rate 1/2 Code	Rate 3/4 Code
300	1.7	3.1
400	1.6	2.9
600	1.4	2.8
800	1.3	2.7

The value shown for the C/A code message read once provides an equivalent message error rate, but higher undetected error rate than of the L1C options, whose CRC is much stronger than that of the C/A code parity check. If C/A code is read twice and compared to detect errors more reliably, the time to read C/A code doubles.

While Figure 4 shows that all L1C design options outperform C/A code (even read only once), the tradeoff between speed and robustness is particularly evident. Figure 3 shows that S50/25% is 1.8 dB more robust in tracking when the receiver does not already have the data message, but Figure 4 shows that S50/25% takes more than twice as long as D50/25% to read first CED, for any value of C/N_0. While the single data message options provide CED with full accuracy, the fast read CED for dual data message options in Figure 4 have lower precision, providing accuracy consistent with an initial fix.

Figure 5 shows the maximum time to read full accuracy CED, at different levels of C/N_0, for each of the design options. Although S50/50% and S50/25% provide the slowest times for C/N_0 values greater than 25 dB-Hz, S50/50% provides the fastest times below 25 dB-Hz.

Since the number of variable message bits per message is much larger in the dual message options than in the single message options, an equitable way to compare the variable message capability is on the basis of average data rate available for variable message bits. Table 4 shows the variable data rate capabilities of the different options. All options support C/N_0 down to below 25 dB-Hz, with the dual data message options providing more capacity for variable data than the single message options. Three of the options provide higher variable data rates than C/A code.

Table 4. Variable Data Message Capabilities

Option Name	Effective Variable Data Rate (bps)	Data Message Threshold—Minimum Total C/N0 at Tracking Correlator Output (dB-Hz)
S50/25%	13.9	24.4
S50/50%	13.9	21.4
S75/50%	20.8	24.6
D50/25%	29.8	24.6
D75/25%	29.8	24.6
C/A Code	15.3	26.6

While the dual data message options provide more than

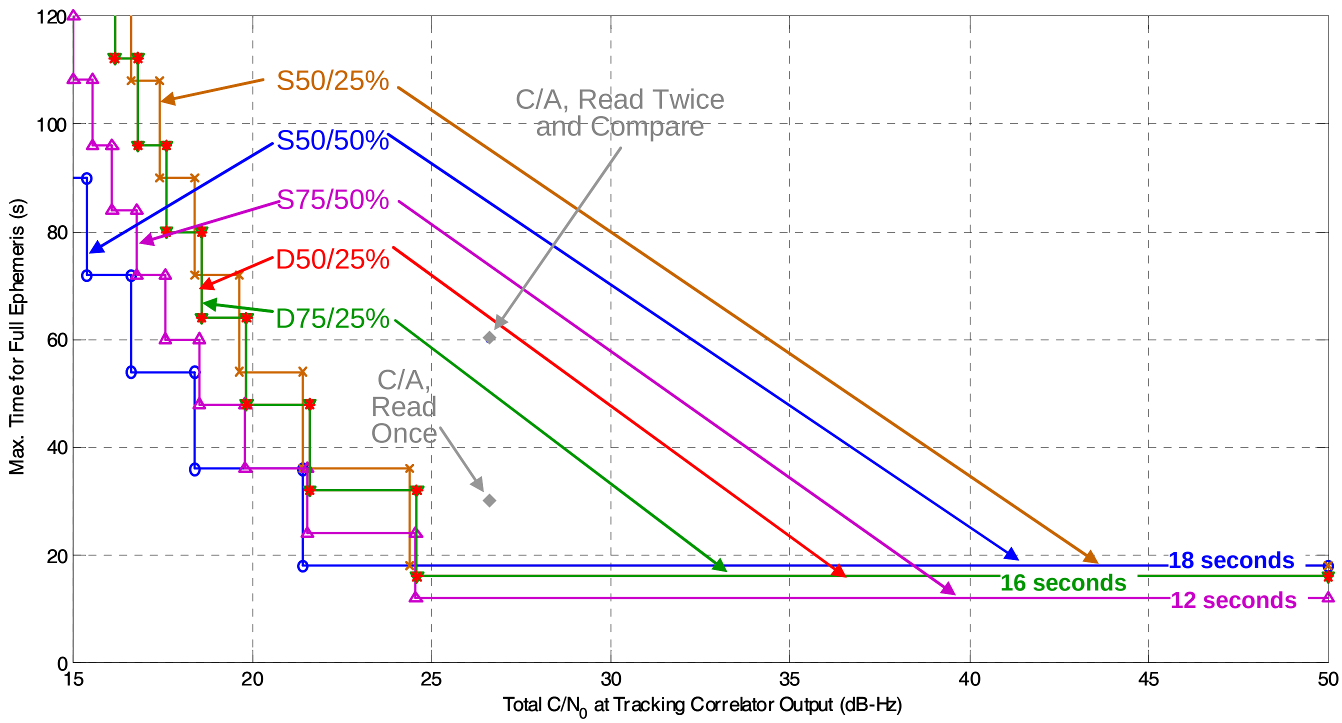

Figure 5. Comparison of Times to Read Full Clock and Ephemeris at Different Levels of C/N_0

twice the variable data rate of S50/50%, S50/50% allows variable messages to be demodulated at approximately 3 dB lower C/N_0. More robust variable data messages, using the same symbol rate but half the information bit rate, could be defined for the dual rate message options to provide equivalent robustness and data rate to S50/50%.

CONCLUSIONS AND NEXT STEPS

An ambitious L1C design effort has produced innovative design options with unparalleled capabilities. The detailed design process being completed has been responsive to the very informative survey responses received during Phase 1. While all of the five design options that have been identified provide excellent performance, each offers a different mix of advantages and compromises between the conflicting objectives of robust data performance and fast access to data. These designs options will be refined, and an optimized design will be selected, based on further design work and on consideration of the responses to the Phase 2 surveys.

The current plan is for completion of L1C design, and drafting of the formal interface specification, by March 2006.

ACKNOWLEDGMENTS

The Interagency GPS Executive Board provided major funding for the L1C Project, with matching support provided through significant contributions from the Air Force and Federal Aviation Administration. The authors express their appreciation to Dean Sklar, Aerospace, for his support in the analysis of error control codes and interleaving. MITRE's work was supported by the Air Force under contract FA8721-04-C-0001 and by the Federal Aviation Administration under contract DTFA01-01-C-00001. Work by Stansell Consulting, Dr. Cahn, and Mr. Keegan was supported by the U. S. Geological Survey under Purchase Order 05WRCN0005. Aerospace's work was supported by the Air Force under contract number FA8802-04-C-0001. ARINC's work was supported by the Air Force under contract number F04701-00-A-8002.

REFERENCES

1. "U.S. Space-Based Positioning, Navigation, and Timing Policy," December 15, 2004, available at www.ostp.gov/html/ FactSheetSPACE-BASEDPOSITIONINGNAVIGATIONTIMING.pdf
2. K. W. Hudnut and Capt B. M. Titus, "GPS L1 Civil Signal Modernization (L1C)," Final Report of Interagency GPS Executive Board Stewardship Project #204, July 30, 2004. Available at www.PNT.gov and www.navcen.uscg.gov/gps/modernization/.
3. J. W. Betz, "Binary Offset Carrier Modulations for Radio Navigation," NAVIGATION: The Journal of the Institute of Navigation, Vol. 48, No. 4, Winter 2001-2002.
4. "Agreement on the Promotion, Provision and Use of GALILEO and GPS Satellite-Based Navigation Systems and Related Applications," June 2004.
5. K. W. Hudnut, et al., "L1C Issues and Options," Viewgraph presentation available at ftp://l1data@mavericks.gps.caltech.edu/, password = chestnut.
6. "Navstar GPS Space Segment/Navigation User Interfaces," IS-GPS-705, 20 April 2005.
7. "Navstar GPS Space Segment/User Segment L5 Interfaces," IS-GPS-705, 20 April 2005.
8. R. G. Gallager, *Low-Density Parity-Check Codes*, Cambridge, MA: MIT Press, 1963.
9. T. J. Richardson and R. Urbanke, "The Capacity of Low-Density Parity-Check Codes under Message-Passing Decoding, " IEEE Transactions on Information Theory, Vol. 47, pp. 599-618, February 2001.
10. D. Chase, "Code Combining - A Maximum-Likelihood Decoding Approach for Combining an Arbitrary Number of Noisy Packets," IEEE Transactions on Communications, Vol. 33, pp. 385-393, May 1985.
11. "Galileo Codes Properties," Ester Armengou Miret, European Space Memorandum, ESA-DEUI-NG-MEMO/01798, February 10, 2005.
12. M. Tran and C. J. Hegarty, "Performance Evaluations of the New GPS L5 and L2 Civil (L2C) Signals," ION-NTM-2003, Institute of Navigation, January 2003.