



THE INTERAGENCY GPS EXECUTIVE BOARD

STEWARDSHIP PROJECT #204

GPS L1 Civil Signal Modernization (L1C)

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1.0 Executive Summary

The objective of this document is to report the findings of the L1 Civil Signal Modernization (L1C) Stewardship Project (Technical Project #204) to the Interagency GPS Executive Board (IGEB) in support of policy decisions about whether or not to endorse a 4th civil signal on the Navstar Global Positioning System (GPS). The report also provides support for decisions about what characteristics are most important for this potential new civil GPS signal.

The IGEB funded this project in August of 2003 to provide recommendations (based both on technical work and stakeholder feedback) on whether or not a modernized civil signal (L1C) could and should be added at L1. Because of funding restrictions, the objectives and the results were limited to:

1. Determine if it would be possible, technically, to insert a new civil GPS navigation signal at the L1 frequency in addition to the C/A code, P(Y) code, M code, and Interplex code.
 - **Our technical team evaluated this issue and concluded it is possible to add L1C while maintaining a constant transmitted signal amplitude and preserving “flex” power control options.**
2. Determine if a broad and representative range of civil GPS experts and users want L1C in addition to the current C/A code.
 - **Based on small group presentations followed by questionnaires to centers of GPS expertise, including U.S. government agencies, GPS equipment manufacturers, and university departments specializing in GPS applications, 55 responses were received from around the world. The survey result is unambiguous that L1C is desired, even at the expense of a slight reduction in the C/A signal power.**
3. Determine what L1C signal characteristics would be most desirable for the widest range of user applications. In particular, two key characteristics were evaluated:
 - a. Modulation waveform, with the options being BOC(1,1) and BOC(5,1).
(Note: BOC(1,1) was accepted as the modulation template through EU/US negotiations during the course of this project. At one time the Galileo team was evaluating subtle alternatives to BOC(1,1). If a better modulation is found which meets the EU/US agreements on signal compatibility, the U.S. should be prepared to implement it instead of BOC(1,1). However, such a replacement would have to be studied very carefully, justified thoroughly, and is very unlikely.)
 - **The survey result is clear that most experts prefer BOC(1,1) for all L1C potential applications.**
 - b. Message data rate and content, with the options being 25, 50, and 100+ bits per second (bps)

- **The answer is clear, although with less unanimity, that L1C should provide a data rate of 25 bps with no additional messages. This optimizes signal robustness for all applications. An equal number of requests were made for a higher data rate, although for at least three different and conflicting requirements, not all of which could be accommodated concurrently. This recommendation leaves differential GPS signals, integrity messages, long duration orbit and clock parameters, or simply faster orbit and clock parameters to other communication services, which either exist now or are rapidly developing, and which are better suited to these specialized tasks.**

Had the originally requested funding been available, this project would have next addressed specific technical design issues in order to prepare high-level L1C signal recommendations to guide development and documentation of L1C signal details, including:

- A proposed specific method of adding L1C to the existing suite of L1 signals
- Details of the recommended modulation waveform, e.g., BOC(1,1)
- A recommended code generation method, and recommended code lengths, for each of the two L1C signal components
- A recommended forward error correction algorithm and additional message content if needed

Should additional funding be made available, we recommend these follow-on actions and would be pleased to continue our work:

- Contact all the survey respondents and additional interested parties, asking them to review this report in order to fully validate or, if necessary, slightly modify its conclusions
- Perform technical studies to determine how best to incorporate the L1C signal
- Review forward error correction (FEC) options to determine if changing from the current L2C and L5 standard would be worth the potential improvement in error rate
- Propose specific code generation methods and code lengths for each L1C signal component
- Prepare a top level signal description to enable the Interface Control Working Group (ICWG) to develop detailed specifications
- Interact with the GPS/Galileo interoperability working groups to optimize the worldwide civil user benefits while protecting allied military effectiveness

This IGEB Stewardship Project has been successful in establishing the feasibility, desirability, and some of the key characteristics of an L1C signal. The processes used to reach these conclusions included (a) assembly of a technical team to conduct analyses and then reach conclusions during a two-day meeting at the GPS Joint Program Office (JPO), (b) public presentations and papers that supported the overall goals of the project, answered questions, and elicited feedback, (c) individual technical presentations to GPS experts in government agencies, GPS companies, and at universities to obtain specific recommendations on an L1C questionnaire, and (d) interviews with user groups to determine the benefits GPS now provides and what improvements would be most helpful to their applications. This report documents the processes,

the materials created, the results obtained, and the conclusions and recommendations reached, as delineated at the beginning of this Executive Summary.

The L1C team wishes to express its thanks to the IGEB Senior Steering Group (SSG) and the Director's office of the IGEB Executive Secretariat for enabling this study and for guidance during this nearly year-long effort. We also are particularly grateful for the time and effort of the many organizations and their staff who participated in the expert group briefings and responded with meaningful answers, comments, and suggestions. Without this volunteer work, from around the world, the project could not have succeeded. Through it all, it was gratifying to find clear answers to important questions about the future of GPS.

Finally, it is important to highlight the splendid working relationship between the GPS JPO and the USGS. Both parties worked cooperatively to fully protect national security interests while providing civil users the best possible service. This project has been an excellent example of dual-use GPS stewardship.

2.0 Introduction

GPS is in the midst of a radical, albeit gradual, transformation. From launch of the first GPS satellite in 1978 through all of 2003 there have been only three navigation signals on only two frequencies. With these signals, GPS has completely changed how the world navigates. However, over the next several years the number of navigation signals will increase from three to seven and the number of frequencies from two to three. In addition, the new signals will have substantially better characteristics, including a pilot carrier, much longer codes, the use of forward error correction, and a more flexible message structure with much better resolution. New and modern civil signals will be on L2 and on the new L5 frequency. The current GPS modernization plan, however, leaves the L1 frequency with only the outdated C/A signal for civil applications. With the addition of L1C, all three GPS frequencies would then provide a modernized civil signal, completing the GPS modernization process.

There is good reason to concentrate attention on L1. Today it carries C/A, the only civil GPS signal. In the future, even with new and modern L2 and L5 signals, L1 is expected to remain the most important civil frequency. This is primarily because it is less affected by ionospheric refraction error than L2 or L5. (L1 has only 61% of the L2 error and 56% of the L5 error.) This inherent advantage relative to L2 and L5 helps motivate the basic goal of this project.

The L1C project was initiated to determine whether it would be technically possible to add L1C to an already crowded suite of L1 signals, to determine whether GPS users could use and would welcome L1C, and to determine what L1C characteristics would be most valuable for the broadest range of GPS users. This report documents the activities, the presentation materials, the processes used, the results we have obtained, and the conclusions we have reached.

Section 3.0, immediately below, reviews the Project Objectives. It recognizes that the objectives had to be narrowed because of funding restrictions, and it defines the steps that would have been taken next without these restrictions (or that can be taken next if funds become available).

Section 4.0 then provides a description of the processes used to achieve these objectives. The overview in Section 4.1 includes a review of supporting activities, including multiple presentations, literally around the world. Section 4.2 then describes the evaluation process used to determine whether L1C technically can be added to the other L1 signals. Section 4.3 defines the process of reaching out to a wide range of worldwide GPS experts, defining the L1C issues through multiple presentations to small government, industry, and academic centers, and obtaining valuable answers and comments from the overwhelming majority. Section 4.4 describes the parallel process of interviewing many GPS users to determine how GPS is valuable and what improvements they would most appreciate.

Section 5.0 presents and evaluates the expert interview results. Included in Section 5.1 is a discussion of the technical evaluation of the GPS L1 signal structure to determine whether one more signal can be added, while retaining the required characteristics of a constant amplitude composite signal and the ability to control the allocation of power to each individual signal. Section 5.2 reports the results from the expert surveys, statistically evaluating the source of the responses, whether the experts support the addition of L1C, which modulation is preferred by the experts, the apparent data rate dilemma, and how the dilemma was resolved. Section 5.3 summarizes the signal recommendations based on the expert interviews.

Section 6.0 provides an overview of user signal requirements by market segment. It then summarizes results from informal user group interviews. Users were asked why and how GPS is useful and important now and what improvements would be most appreciated.

Section 7.0 presents the Project Conclusions and Recommendations, and Section 8.0 offers acknowledgements to the key participants.

This report also includes a large number of attachments. These include most of the presentation materials used during the project. Of particular importance are:

- Attachment 6.0 Presentation given to most of the GPS experts, explains the issues and the options
- Attachment 6.1 Questionnaire the experts were asked to return with answers and comments
- Attachment 7.0 The 55 individual responses to the questionnaires
- Attachment 8.0 Review of user group needs and perspectives

3.0 Project Objectives

The objectives have been narrowed since this project was first proposed in August 2003. There are two reasons for this. First, the funding was about half what had been requested, so we de-scoped accordingly, reducing our planned level of effort on both the technical work and stakeholder feedback work. Second, the U.S. and the European Union (EU) commenced and recently completed negotiations about the compatibility of Galileo L1 signals with both military and civil GPS signals. As part of these negotiations, the U.S. Department of State offered that the U.S. would implement a new signal on L1 with BOC(1,1) modulation if Europe would do the same on Galileo. Although there is room for both sides to deviate somewhat from this particular

modulation, as long as the compatibility requirements are met, the specific modulation question was no longer as important a question for this project to resolve.

Therefore, the narrowed L1C project objectives have been to:

1. Determine technical feasibility of adding another civil GPS navigation signal at the L1 frequency in addition to the C/A code, P(Y) code, M code, and Interplex code signals.
2. Determine, by means of presentations and interviews, if a broad and representative range of civil GPS experts and users want an L1C in addition to the current C/A code.
3. Determine what L1C signal characteristics would be most desirable for the widest range of user applications. In particular, two key characteristics were evaluated:
 - a. Modulation waveform, with the options being BOC(1,1) and BOC(5,1) (Note: BOC(1,1) was chosen as the preferred modulation template through US/EU negotiations during the course of this project, although there is room for further evaluation and a different agreement by both parties.)
 - b. Message data rate and content, with the options being 25, 50, and 100+ bps
4. Prepare a high-level L1C signal specification to guide development of the signal details, including:
 - c. A proposed method of adding L1C to the existing suite of L1 signals
 - d. A recommended modulation waveform, e.g., BOC(1,1)
 - e. Recommended code generation and code lengths for the two L1C signal components
 - f. Recommended data rate, forward error correction, and additional message content if needed

Objectives 1, 2 and 3 have been accomplished to the extent possible with resources available, on time and on budget. The 4th objective has not been realized due to limited resources. The following section describes the methods we used to achieve the first three objectives.

4.0 Process Description

4.1 Overview

Three main activities were used to achieve the project objectives. The first was to determine the feasibility of adding another signal to the already crowded L1 signal structure. Ever since the start of GPS there have been two signals at L1, the C/A code and the P(Y) code, which are transmitted in phase quadrature. A key objective has always been for the composite signal to have a constant amplitude in order to maximize transmitter efficiency. Thus, to add the two components of the new military M code required some clever engineering. Chip by chip multiplexing of the M code is used to provide both a data signal component and a data-less, or pilot carrier, signal component in a single bi-phase composite signal. To achieve a constant transmitted signal amplitude, a fourth “Interplex” signal was then introduced. Therefore, to add the two components of an L1C signal while maintaining a constant amplitude was seen as quite a challenge. This activity also assessed the potential interference of L1C to legacy C/A receivers, recognizing that full backward compatibility is essential. After considerable preliminary work, a

two-day technical meeting was held early in the project to address L1C feasibility as well as other issues related to design and implementation of the L1C signal (see Section 4.2).

The second activity was to obtain feedback from GPS experts around the world on whether or not, and – if so – how *best* to configure an L1 modernized signal. Based on this expert input, recommendations would be made on what specific L1C characteristics would best serve the worldwide user base. Section 4.3 describes this process and Section 5 describes the results.

The third activity was to obtain feedback from GPS user communities about the benefits GPS now provides and what improvements would be most helpful to their applications. We did not expect technical guidance from these interviews, but it was important to get an overall impression of what applications were being served, what was working well, and what type of improvements would be most beneficial.

The following sections explain these three activities in more detail, but before that it also is important to characterize the scope of related meetings, presentations, and papers which supported the overall goals of this project. For example, multiple presentations were made to inform stakeholders about the L1C Project, to answer their questions, and to elicit their feedback. This effort began at the 42nd CGSIC meeting forum on 8 September 2003 in Portland, Oregon (Attachment 1.0). Immediately after the CGSIC meeting the presentation was continuously shown at the USCG NAVCEN booth throughout ION GPS-2003 and a document which combined the presentation with a questionnaire (Attachment 1.1) was made available. Subsequently, *GPS World* published an article introducing the L1C Project to the global GPS user community (Attachment 1.2).

Additional major L1C presentations included the following, all of which are documented in attachments to this report:

- (A) The L1C Project group technical meeting, held at the GPS JPO on 8-9 October, 2003. Material developed for and presented at this meeting led to the GPS System Engineering Forum (GSEF) technical review presentation on 28-29 October, 2003 in Los Angeles, California (Attachment 2.0). See Section 4.2 of this report.
- (B) International Civil Aviation Organization (ICAO) - Air Navigation Conference (ANC), Navigation Systems Panel (NSP); Canberra, Australia Nov. 11, 2003 (Attachments 3.0, 3.1 and 3.2). Presentations and user feedback by Taylor and Dorfler.
- (C) Meeting with the Japan GPS Council (JGPSC) stakeholder group in Tokyo, Japan on 23 January 2004 using the expert group presentation and questionnaire (Attachments 6.0 and 6.1). Presentations and user feedback by Titus and Stansell.
- (D) The International GPS Service (IGS) 10th annual symposium; invited presentation and poster on 3-4 March 2004 in Berne, Switzerland (Attachments 4.0 & 4.1) by Stansell.
- (E) The L1C Project presentations and stakeholder feedback sessions formed a prominent part of the IEEE PLANS conference special session on GPS Modernization on 28 April 2004 at Monterey, California (Attachments 5.1 & 5.2). Presentations and user feedback by Hudnut and Stansell.

We also expect to present our findings at upcoming meetings of the CGSIC, the ION, and other groups during the upcoming year, as requested and as opportunities arise.

A summary and chronology of L1C project presentations and meetings is given in Table 4.1.

Table 4.1 - Chronology of L1C Project Presentations and Meetings:

Date	Event
7 August 2003	Joint L1C team planning meeting (at GPS JPO)
28 August	Joint L1C team planning meeting (at GPS JPO) w/ D. Turner
3 September	Joint meeting with Aerospace for GPS III briefing (at GPS JPO)
5 September	Meeting re. L1C Project with Mr. Mike Shaw (at GPS JPO)
5 Sept. (late a.m.)	Meeting with Aerospace experts on worst case aggregate global interference calculations (at GPS JPO)
8 September	CGSIC 42 nd Meeting: L1C presentation and participation in panel open forum; Mr. Hank Skalski, chairman (Portland) http://www.navcen.uscg.gov/cgsic/meetings/default.htm
10-12 September	ION Meeting L1C display at USCG NAVCEN booth
23 September	Civil IFOR meeting; Mr. Hank Skalski, chairman (DC)
24 September	L1C core group strategy & planning meeting (at GPS JPO)
8-9 October	L1C Project – Initial Technical Meeting (at GPS JPO)
20 October	L1C user meeting with Larry Young, NASA/JPL (at USGS)
28-29 October	GSEF Meeting presentation (at ARINC)
11 November	ICAO ANC NSP, Canberra, Australia
23 January	L1C Meeting with JGPSC, Tokyo, Japan
3-4 March	L1C Presentation & Poster at International GPS Service (IGS) 10 th Annual Meeting, Berne, Switzerland
10 March	CGSIC 43 rd Mtg.: L1C Presentation (Hothem); Arlington, VA http://www.navcen.uscg.gov/cgsic/meetings/default.htm
20 April	Joint team progress review meeting (at GPS JPO)
22 April	L1C Presentation at ION Southern California Section http://www.ion.org/sections/southcalifornia.cfm
28 April	L1C Presentation and Group Interview at IEEE PLANS, session and forum on GPS Modernization, Monterey, California --- all presentations available at http://www.igeb.gov/outreach/
29 June	Joint team progress review meeting (at GPS JPO)
20-21 Sept.	CGSIC Long Beach, CA --- Invited --- L1C Project Final Report (will speak and be an open forum panel participant)

4.2 Technical Feasibility Determination

The L1 frequency now carries two GPS signals, C/A and P(Y). Beginning in 2005, IIR-M satellites will be launched with two additional signals on L1, M code and the Interplex code which is there only to maintain a constant transmitter signal amplitude. Another important requirement on all new satellites is “flex power”, the ability to command a relative power increase or decrease on any of the signal components. With the existing signals and the constraints of constant amplitude and flex power, adding yet another L1 signal could be difficult at best. Therefore, the initial question was whether adding L1C technically was feasible.

To address this question, a team of GPS signal experts was engaged. The technical team included: Dr. John Betz of MITRE; Dr. Charles Cahn, consultant to Aerospace; Dr. Phil Dafesh of Aerospace; Dr. Chris Hegarty of MITRE; Karl Kovach of ARINC; Rich Keegan, GPS industry consultant; and Tom Stansell of Stansell Consulting. After a period of analytical work, preparation of documents, exchange of information, preliminary meetings, etc., a two-day meeting was held on October 8-9, 2003 at the GPS JPO. The L1C Project co-leaders Dr. Ken Hudnut of USGS and 1Lt Bryan Titus of the GPS JPO chaired the meeting and 2Lt Jason Taylor also participated. The meeting was focused on whether or not L1C could be added and if so how best to do so.

4.3 Expert Presentations and Questionnaires

As stated in Section 4.1, the second key activity was to obtain feedback from GPS experts around the world on whether or not, and, if so, how best to configure an L1 modernized signal. Table 4.2 summarizes these technical presentations and shows whether a response was received or not. Both the number (54) and the percent of questionnaire responses to the presentations was very high, although some invitations to receive a presentation were not accepted. The individual questionnaire responses (Attachment 7.0) are worth reviewing.

Table 4.2 - Technical Presentations and Responses

Date	Location	Type	Group & Contact Person	Resp.
09/08/03	Portland, OR	Personal	CGSIC	Y
09/10/03	Portland, OR	Personal	NAVCEN Booth at ION	Y
09/11/03	Portland, OR	Personal	NAVCEN Booth at ION	Y
09/12/03	Portland, OR	Personal	NAVCEN Booth at ION	Y
10/20/03	Pasadena, CA	Personal	JPL	Y
12/15/03	Washington, DC	Personal	US GPS Industry Council	N
12/15/03	Washington, DC	Personal	NASA	N
12/16/03	Washington, DC	Personal	NGS/NOAA (Milbert)	Y
12/19/03	Virginia (2) & California	WEB	U.S. Coast Guard	Y
12/23/03	Moscow, Russia	WEB	Thales (Lyusin)	Y
01/23/04	Tokyo, Japan	Personal	Japan GPS Council Members	Y
02/06/04	New Brunswick, CA	WEB	University of New Brunswick (Langley)	Y
02/10/04	Clifton, NJ	WEB	ITT Aerospace Communications	Y
02/11/04	Sydney, Australia	WEB	University of New South Wales (Rizos)	Y
02/12/04	Dallas, Texas	WEB	NavWard (Ward)	Y
02/27/04	Calgary, Canada	WEB	University of Calgary (Lachapelle)	Y
02/27/04	Stanford, CA	WEB	Stanford University (Enge)	Y
02/27/04	Sunnyvale, CA	WEB	Trimble Navigation	Y
03/03/04	Bern, Switzerland	Personal	Talk & Poster Presentation at IGS Mtg.	N
03/04/04	Bern, Switzerland	Personal	Poster Presentation at IGS Meeting	N
03/10/04	Arlington, VA	Personal	Talk at CGSIC Meeting	N
03/22/04	Olathe, KS	WEB	Garmin (Pemble, Kao)	Y
03/31/04	Calgary, CA, Heerbrugg, CH	WEB	NovAtel (Fenton) & Leica (Euler)	Y
04/08/04	Newport Beach, CA	WEB	RFMD (Warloe, Keegan)	Y
04/09/04	San Jose, CA (+ 2 other sites)	WEB	SiRF (Garin)	Y
04/12/04	Cedar Rapids, IA	WEB	Rockwell Collins (McGraw)	Y

04/22/04	El Segundo, CA	Personal	Southern California ION Section Meeting	N
04/28/04	Monterey, CA	Personal	PLANS Conference	Y
05/14/04	Columbus, OH	WEB	Ohio State University (Brzezinska)	Y
06/29/04	Campbell, CA	WEB	Qualcomm (Krasner)	Y
06/29/04	Lexington, MA	WEB	MIT Lincoln Laboratory	Y
07/02/04	Frederick, MD	WEB	AOPA	Y
07/09/04	Athens, OH	WEB	Ohio University (Braasch)	Y

Almost immediately after the L1C project was approved there were important opportunities to begin technical outreach. Therefore, a technical presentation and a questionnaire (Attachments 1.0 and 1.1) were prepared quickly and taken to the September 2003 CGSIC and ION GPS meetings in Portland, Oregon. Dr. Ken Hudnut participated on a CGSIC GPS Modernization panel and gave the L1C presentation on September 8. During the ION meeting the presentation was continuously shown at the NAVCEN exhibit booth, a stack of questionnaires was available, and Tom Stansell was present to answer questions.

The initial questionnaire was intended to be self-explanatory, showing the presentation material in the left column and questions on the right. These early efforts resulted in a gratifying number of useful responses. The same questionnaire also was used in a technical discussion at the Jet Propulsion Laboratory on October 20, 2003.

By December of 2003 the issues were in better focus and both a new presentation and a simplified questionnaire were created. Minor improvements were made to these documents in the months to follow. The final version of the presentation, with a written explanation for each chart, and the final questionnaire are included as Attachments 6.0 and 6.1. Reading this material will help you interpret the individual questionnaire responses included as Attachment 7.0 and evaluated below.

Table 4.2, above, lists the date of each presentation or other outreach effort, the audience, and whether or not there was a response. It is always difficult to obtain meaningful feedback from a questionnaire, but we are pleased with both the quantity and the quality of responses received.

It should be noted that although many of the presentations were made in person by one of the team members, a large number were presented remotely over the Internet. Some of these were to several sites simultaneously. Each site projected a web browser page on a conference room screen. The presenter controlled which slide was being shown, could move a pointer on the screen, and verbally communicated by speakerphone. For example, on December 19, 2003, a presentation was made simultaneously to U.S. Coast Guard facilities at Alexandria, VA, Portsmouth, VA, and Petaluma, CA. Using the web permitted worldwide participation, including presentations in Australia, Canada, Russia, and Switzerland.

The technical presentations were intended for GPS experts who could provide guidance in what signal characteristics would most benefit their constituents. This included Government agencies and laboratories, GPS companies, and University professors and graduate students. These experts provided valuable feedback from most GPS application perspectives, including land, sea, air, and space, and with requirements ranging from the highest possible precision to the lowest possible cost.

4.4 User Group Interviews

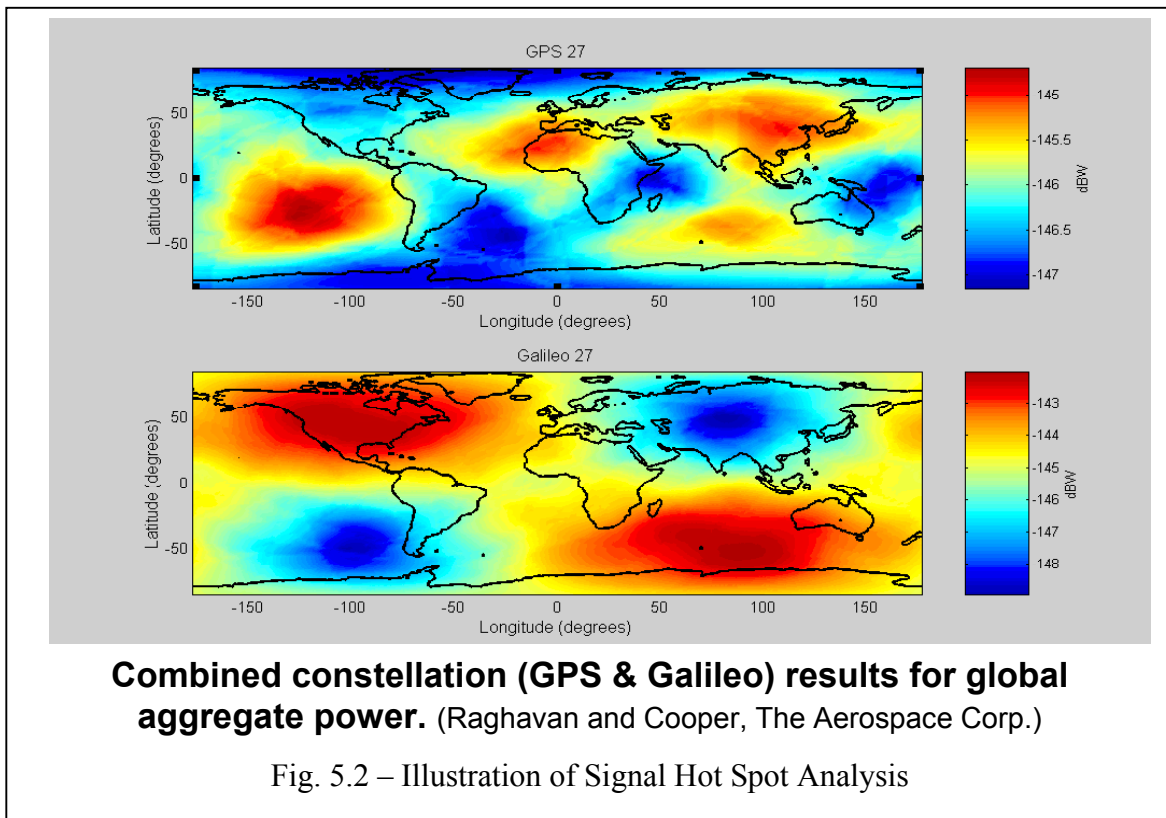
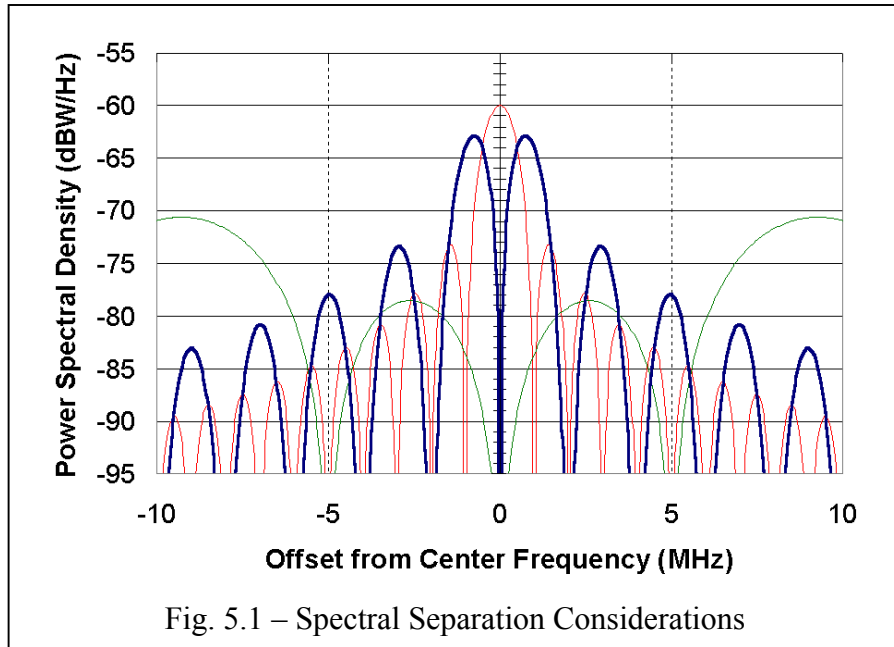
As described in Section 4.1, the third activity was to conduct interviews with user groups in order to gain non-technical feedback on L1C design considerations. Making use of the User Group Guidelines (Attachment 8.1), members of the L1C Project team were asked to identify users and speak with them about the project. Furthermore, additional information was gleaned from reports that had been developed previously for related purposes. The interviews were intended to evoke responses that might either confirm or refute previously understood user interests in the range of possible capabilities of L1C, depending on which signal design parameter is used. For example, users who would benefit most from a low data rate would be those wishing to have better performance in wooded, urban, or even indoor environments. The interviews also were used to capture new considerations about ways in which L1C could better meet the navigation requirements of user groups.

5.0 Expert Interview Results and Analysis

5.1 Technical Feasibility Results

Section 4.2 is a review of the process used to determine whether an additional signal could be added to the already-planned suite of L1 signals. The challenge was not simply to add a new signal but at the same time to maintain a constant total signal amplitude. This is needed to maximize satellite power efficiency. Also, it is important to be able to adjust the relative power level of each signal component (flex power). Several ways were found to achieve these objectives, so the question of technical feasibility was answered in the affirmative.

Another aspect of the study was to evaluate the compatibility of L1C with the existing C/A signal, with the military M code signal, and with potential Galileo signals. Every signal in the L1 band interferes to some degree with all the others. Current civil users do not want L1C to adversely affect performance by significantly raising the noise floor of C/A receivers. National security interests require sufficient spectral separation of L1C from the M code signal, and it also limits the total power of both L1 civil signals combined. As with C/A signals, L1C signals interfere with each other. Therefore, it is important to set power levels with all these parameters in mind. The technical meeting confirmed ways to evaluate these factors and made preliminary assessments. Figure 5.1 illustrates that spectral separation of signals in the L1 band was a very important consideration. Figure 5.2 illustrates that an important part of the analysis was to consider signal “hot spots”, i.e., places on earth where the total power received from all satellites in view reaches a maximum during some part of the day. These are areas where interference between signals is at its worst during part of each day. These calculations not only depend on the satellite orbits but, importantly, they depend on assumptions about the gain of receiver antennas.



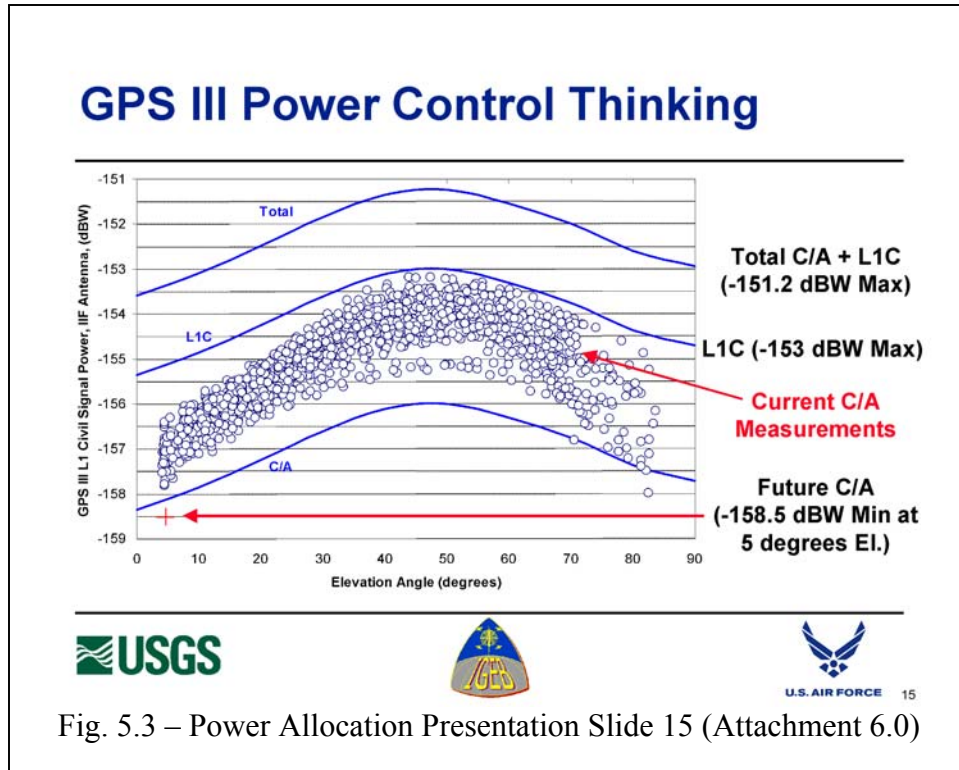


Fig. 5.3 – Power Allocation Presentation Slide 15 (Attachment 6.0)

As a result of these efforts, decisions were reached about which signals and what power levels would best fit the constraints. A summary of these results was presented soon afterwards by Hudnut and Titus, at the invitation of the GPS Systems Engineering Forum (GSEF), at their meeting on October 28-29, 2003 (see Attachment 2.0). Also, Figure 5.3 was developed and has been a key part of the presentation to GPS experts (Slide 15 of Attachment 6.0).

The following paragraphs are a brief summary of the October 8-9, 2003 meeting and its key decisions.

An initial classified session, led by Titus and including nearly all of the participants in the following main meeting, identified the power level and signal modulation options considered acceptable to the U.S. Government. A range of several possible signal modulations was reviewed, and trade-offs were carefully considered. The BOC(1,1) signal modulation arose as being both acceptable and also preferred by most participants as the best overall solution. Signal aggregate power was discussed and reviewed. The evaluation approach and algorithms which had been used by Titus and Betz during negotiations with the EU Galileo team were applied to this analysis as well. It was agreed that L1C would carry at least the same messages that will be carried by L2C and L5.

Discussion of signal structure and modulation options, as well as multiplexing and coding techniques, led to the conclusion that design and implementation of L1C is feasible. Partly because of the 1.5 dB increase in specified minimum C/A signal power, L1C can be added without negative impact on C/A receivers. It was decided that the C/A signal will be continued indefinitely. The promise of a data-less channel and increased power, as well as enhanced GNSS interoperability, were agreed to be main user benefits from a technical standpoint.

It was agreed that user feedback, primarily from technical experts throughout the GPS manufacturing and international community, would be gathered as a next step. Now that a limited and concrete number of questions could be asked, this greatly simplified the questionnaire. That is, the form distributed after our initial presentation (Attachment 1.1) asked for user feedback on a wider range of issues, some of which were decided on at our technical meeting. Following that, we were able to identify just those key few questions upon which user feedback would be most critical to L1C design. So, the interview process was modified and a new questionnaire developed to accompany the technical interview process from this point forward. The new technical presentation (annotated slide set in Attachment 6.0) and questionnaire (Attachment 6.1) became highly effective tools for gaining technical stakeholder input on those questions where a range of options remained open.

After the technical sessions were completed, the meeting participants then discussed and agreed to help with a process of eliciting stakeholder feedback using an approach suggested by Joe Dorfler. The approach is based on his prior experience with similar efforts determining user requirements for WAAS and GPS III. The approach is to gain input from non-technical GPS users, and the results have been developed into the material described in Section 4.4.

5.2 Expert Interview Results

A key element of the L1C project was to interview GPS experts around the world to determine:

- If a broad and representative range of civil GPS experts and users wanted an L1C signal in addition to the present C/A code, although with slightly reduced C/A signal power
- What L1C signal characteristics would be most desirable for the widest range of user applications. In particular, two key characteristics were evaluated:
 - Modulation waveform, with the options being BOC(1,1) and BOC(5,1)
 - Message data rate and content, with the options being 25, 50, and 100+ bps

Attachment 6.0 is an annotated version of the presentation, and Attachment 6.1 is the expert's questionnaire form. This Section 5.2 of the report is an evaluation and analysis of the expert responses, which are individually included in Attachment 7.0. Subsection 5.2.5 of this section offers conclusions and recommendations based on the expert responses.

5.2.1 Response Statistics and Summary

In many cases an organization would create one consolidated response after a presentation. In other cases several people from an organization would respond separately, often with different recommendations. Therefore, it isn't straightforward to imply an organizational response from differing personal responses. In the opposite sense, an organizational response may actually represent the opinion of just one person or, at most, a very few people. Recognizing these difficulties and accepting the potential distortion caused by mixing personal and presumed organizational responses, the following statistics are based simply on the number of responses received. Answers to key questions are summarized in Table 5.1. The headings, from left to

right, are: (1) a reference number, (2) the organization name, (3) the contact person's name, (4) whether attribution is permitted, (5) whether the response favors L1C, (6) which of the two modulation waveforms is favored, and (7) what message bit rate is preferred. A blank cell under Organization or Name shows that the respondent chose no attribution for that information. A blank cell under Modulation or Rate shows that no preference was indicated.

Table 5.1 – Summary of Responses Received

Ref.	Organization	Name	Att.	Favor L1C?	Mod.	Rate (bps)
1	ACRT, Inc.	Godfrey, Cathy Genest	Y	Y		25
2	Air Force Research Laboratory	Sampson, Steven J.	Y	N		
3	AOPA		Y/N	Y		25
4	Rockwell Collins	McGraw, Gary	Y	Y	BOC(1,1)	50 to 100
5	Comm. Research Labs	Hama, Shin'ichi	Y	Y		100
6	ENRI	Ito, Ken	Y	Y		100
7	ENRI	Sakai, Takeyasu	Y	Y		100
8	Evolution Robotics	Schell, Steve	Y	Y		25
9		Kakutani, Kazuaki	N/Y	Y		25
10	Furuno Electric Company	Kawai, Masato	Y	Y	BOC(1,1)	100
11	Furuno Electric Company	Okada, Tsutomu	Y	Y	BOC(1,1)	100
12	Garmin International	Seymour, Jarrod	Y	Y	BOC(1,1)	50
13	ITT Aerospace/Communications	Cangiani, Gene	Y	Y	BOC(1,1)	100
14			N	Y		25
15			N	Y	BOC(1,1)	50
16	JAXA	Kogure, Satoshi	Y	Y	BOC(1,1)	25
17			N	Y	BOC(1,1)	25
18			N	Y	BOC(5,1)	100
19	Leica Geosystems	Euler, Hans-Jurgen	Y	Y	BOC(5,1)	25
20			N	Y	BOC(1,1)	100
21	NASA/JPL		N	Y		250
22	NASA/Shuttle		N	N		100
23	NavCom Technology, Inc.	Hatch, Ron	Y	Y	1,1 or 5,1	100
24	NavCom Technology, Inc.	Knight, Jerry	Y	Y	1,1 or 5,1	100 or ?
25	Navward GPS Consulting	Ward, Phillip W.	Y	Y	BOC(5,1)	25
26	NEC Toshiba Space	Maeda, Hiroaki	Y	Y		100
27	NEC Toshiba Space	Ono, Takeshi	Y	Y	BOC(1,1)	100
28	NEC Toshiba Space	Sagawa, Kazumi	Y	Y	BOC(1,1)	50
29	National Geodetic Survey	Milbert, Dennis	Y	Y	N/A	N/A
30		Iwata, Toshiaki	N/Y	Y	BOC(5,1)	100
31	Nikon-Trimble Co.	Izawa, Mitsuma	Y	?		25
32	NovAtel, Inc.	Fenton, Pat	Y	Y	BOC(5,1)	25
33	Ohio State University	Brzezinska, Dorota	Y	Y	BOC(5,1)	100
34	Ohio University	Braasch, Michael	Y	Y	BOC(5,1)	25

35	Panasonic Automotive Systems	Ishigaki, Toshihiro	Y	Y		100
36	pcisys (?)	Lee, Ron	Y	N		
37	Pioneer Corporation	Ando, Hitoshi	Y	Y		50
38	Pioneer Corporation	Kigure, Yoshiyuki	Y	Y	BOC(1,1)	
39	Qualcomm	Krasner, Norman	Y	Y	BOC(1,1)	100
40	RF Micro Devices (RFMD)	Warloe, Andreas	Y	Y	BOC(1,1)	25
41	SiRF Technology, Inc	Garin, Lionel	Y	Y	BOC(1,1)	25
42	Stanford University	Enge, Per	Y	Y	BOC(1,1)	25
43	Thales Navigation	Lyusin, Sergey	Y	Y	BOC(1,1)	100
44	Thales Navigation	Snow, Robert	Y	Y	BOC(1,1)	50
45	University of New Brunswick	Beran, Tomas	Y	Y	BOC(1,1)	25
46	University of New Brunswick	Wang, Chaochao	Y	Y	BOC(1,1)	25
47	University of New South Wales	Babu, Ravindra	Y	Y	BOC(1,1)	100
48	University of New South Wales	Jia, Xiaodong	Y	Y	BOC(1,1)	25
49	University of New South Wales	Mumford, Peter	Y	Y		25
50	University of New South Wales	Rizos, Chris	Y	Y	BOC(1,1)	100
51	University of Calgary	Lachapelle & Team	Y	Y	BOC(1,1)	50
52	University of Sydney	Quigley, Aaron	Y	Y	BOC(1,1)	25
53	US Coast Guard, C2CEN	Wolfe, Parsons, Cleveland	Y	Y	BOC(1,1)	25
54	US Coast Guard, NAVCEN	Schutzenhofer, John	Y	Y	BOC(1,1)	25
55	Trimble		Y/N			

Note: The last input (Ref. # 55) was received after the following analyses were completed. Therefore, because this input also did not address the specific questions, it was not included in the statistics.

Of the first 54 total responses to the survey, it is interesting to see where in the world they originated. Figure 5.1 shows the distribution. The largest number, but less than half, were from the U.S. The second largest number were from Japan. A number of these were the result of our activities at the September 2003 CGSIC and ION GPS meetings in Portland, OR. A larger number were stimulated by one presentation to multiple companies at the Japan GPS Council (JGPSC) meeting in Tokyo on January 23, 2004. Together the U.S. and Japan produced 80% of all responses. Primarily because of academic interest and a response from NovAtel, Australia and Canada produced the third and fourth largest number of responses. Finally, there was one response from Russia on behalf of Thales Navigation and one from Switzerland for Leica Geosystems.

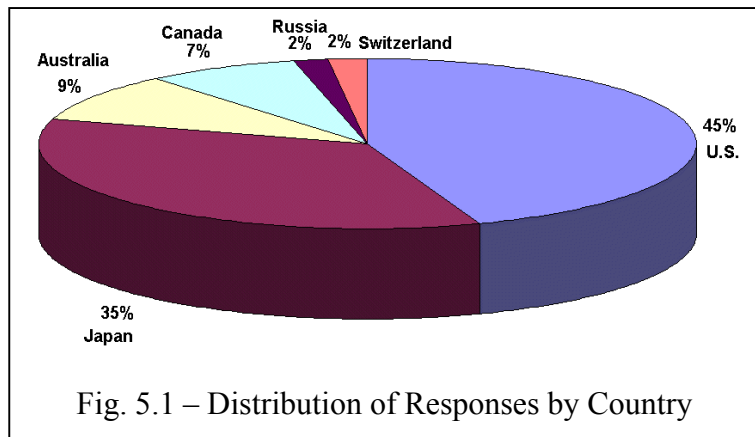


Fig. 5.1 – Distribution of Responses by Country

The lack of response from Europe was not for lack of trying. There were as many, if not more, European companies and delegates at the September ION meeting as Japanese delegates. A number of European companies and universities were invited directly, but there was no response. A paper and a poster display were presented in Bern Switzerland at an IGS meeting during March, 2004 with no results. Perhaps some Europeans considered interest in L1C to be controversial with respect to the Galileo program.

5.2.2 Should L1C be Implemented?

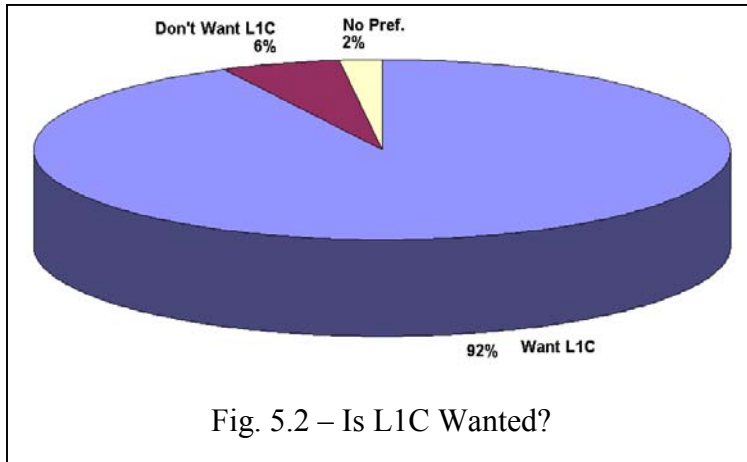


Figure 5.2 shows the distribution of responses to the question of whether a new civil GPS signal should be added at the L1 frequency, even at the expense of reduced C/A signal power, or conversely whether a more powerful C/A signal should be the only civil signal on L1.

The results are overwhelming and unambiguous that Government agencies, GPS manufacturers, and University researchers agree that

L1C is desirable. This is true for all realms of use: Land, Sea, Air, and even Space. (Note there were two different responses from NASA, one from JPL and the other from the Shuttle program. The first wanted L1C and the second didn't, even though the Shuttle response asked for a 100 bps data rate which would be possible only if L1C were implemented.) The full spectrum of user equipment requirements, from the highest precision products to products requiring the lowest possible cost, were favorable to having L1C. The advantages of having a data-less pilot carrier, of having longer codes to reduce or eliminate cross-correlation and narrowband interference problems, of a higher precision and more flexible message structure, and of forward error correction and other message improvements clearly are recognized as desirable improvements for essentially all applications.

The nearly unanimous desire to add L1C is tempered by the insistence that C/A code remain for the indefinite future in order to support many millions of legacy receivers. It would not be acceptable to substitute L1C for C/A, it must be an additional signal. (However, the signal designers must define a way for L1C to continue if, several decades from now, it does become feasible to discontinue the C/A signal. In other words, turning C/A off is not planned but if it were to happen it must not affect what then perhaps could be a billion or more L1C receivers.)

5.2.3 Modulation Preferences

Figure 5.3 shows the distribution of responses to the question of which modulation waveform is preferred for L1C, i.e., BOC(1,1) or BOC(5,1). Fifty percent of the respondents selected BOC(1,1) and 33% had no preference. A relatively small 13% preferred BOC(5,1), and the remaining 4% would be satisfied with either waveform. From a purely statistical perspective, BOC(1,1) is the “winner”. Although this preference may have been greatly influenced by the US/EU agreement to use BOC(1,1) on both GPS and Galileo, a number of the respondents had solid reasons for preferring one waveform over the other, and it is instructive to review some of these comments. Of the seven responses which preferred BOC(5,1), three had supporting comments, which were:

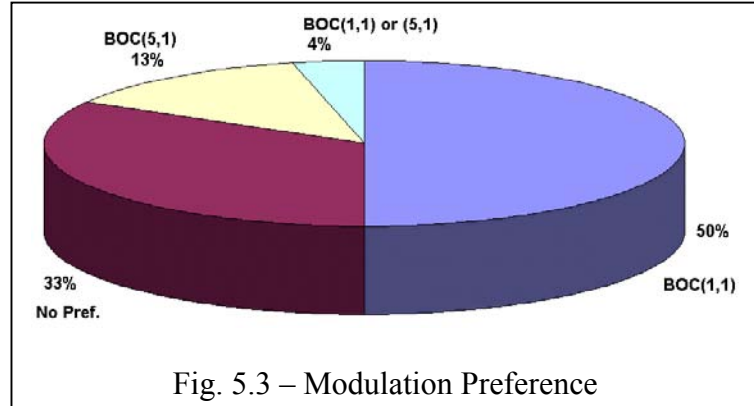


Fig. 5.3 – Modulation Preference

- a) The reason of BOC(5,1), we chose it because it will be able to minimize the interference with present L1 C/A. (Leica Geosystems, Ref. # 19)
- b) Expecting advances in signal processing to continue at the current pace, the implementation of BOC(5,1) will be feasible in the planned time frame for modernization. (Ohio State University, Ref. # 33)
- c) Both the BOC (1,1) and the BOC (5,1) are acceptable. The BOC (5,1) is preferred since it provides less interference both to M-code and the C/A-code and it can offer better code-loop tracking accuracy. (Ohio University, Ref. # 34)

Of the 27 respondents who preferred BOC(1,1), some of the key comments were:

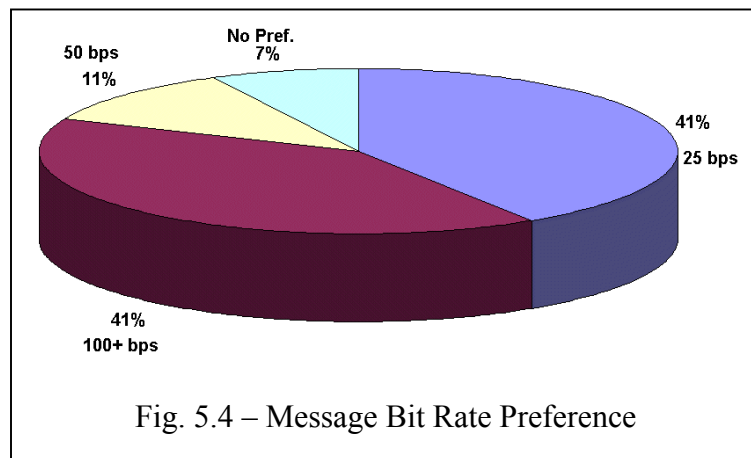
- d) We have concerns that the wider bandwidth of the BOC(5,1) signal would make it extremely difficult to design and produce a practical Navwar prevent notch filter. For this reason, the BOC(1,1) is preferred. (Rockwell Collins, Ref. # 4)
- e) BOC (1,1) appears to be a safe choice at this time based on both technical and political grounds. (Ref. # 20)
- f) BOC(1,1) with 2X Minimum C/A power is a good compromise to improvement in sensitivity in both autonomous and wireless assisted modes. (Qualcomm, Ref. # 39)
- g) Select BOC(1,1) signal since the full bandwidth can be supported by consumer chipsets. The BOC(5,1) has a much wider bandwidth [therefore] requiring a wider Rx bandwidth and higher sampling rate. The BOC(1,1) signal can improve code tracking since there are twice as many code edges than a normal C/A code without the wider bandwidth penalties. (RF Micro Devices, Ref. # 40)
- h) We believe BOC(1,1) is the best modulation scheme for the modern signal because of its lower bandwidth, and therefore lower power consumption. Combined with the longer code

suggested below, it will also support our cross-correlation requirements. (SiRF Technology, Ref. # 41)

- i) On balance, I would expect that BOC(1,1) would be more readily useable by aviation, because of correlation subpeak ambiguities. To my recollection, BOC(1,1) has subpeaks every 150 meters, whereas BOC(5,1) would have subpeaks every 30 meters. Failure to correctly resolve the BOC(1,1) subpeak would be readily detectable by RAIM, but the 30 meter ambiguity may be difficult to detect using RAIM. Hence, it has a greater prospect of hazardously misleading information (HMI). This risk can be offset by using multiple correlation samples per satellite, but this practice increases the cost of the avionics. In addition, the precision advantage of BOC(5,1) is not that important to aviation, because we use carrier smoothing. (Stanford University, Ref. # 42)
- j) BOC(5,1) is undesirable, because wide bandwidth will lead to the following disadvantages for consumer products: a) high sampling frequency and as result bigger power consumption; b) problems with harmonics and digital noise because of wideband RF. (Thales Navigation, Ref. # 43)
- k) In order to have more robust position solutions, the BOC(1,1) signal appears to have better characteristics than the BOC(5,1) because of its more isolated and lower autocorrelation secondary peaks (relative to the main peak), even if this implies a slightly higher multipath impact. It is however likely that in the coming years, new techniques will reduce this impact of multipath to a smaller scale. (University of Calgary, Ref. # 51)

Overall, it seems BOC(1,1) is a safe and effective choice. To choose BOC(5,1) would require much more study and a very convincing rationale. It also would require revision of the current EU/US agreement to use BOC(1,1) as the template for the new L1 signal. Although this is very unlikely, it is not impossible, because BOC(5,1) meets the EU/US negotiated compatibility criteria somewhat better than BOC(1,1).

5.2.4 The Message Data Rate Dilemma



Whereas there is near universal agreement that a modernized L1C signal would be desirable, there seems to be a complete stalemate on the question of message bit rate. As shown by Figure 5.4, 41% of the total responses support a 25 bps data rate and another 41% support 100 bps or higher. Only 11% support retaining the traditional 50 bps rate, and 7% have no preference.

Those who support 25 bps are unified on a single goal, which is to receive the GPS messages under marginal signal conditions, whether those conditions are due to foliage attenuation, weak indoor signals, or if operating in a high interference environment. That the supporters of 25 bps are unified is an important observation and it affects the interpretation of results. Pertinent comments from supporters of 25 bps include:

- 1) L1 C/A is great, but we still have trouble - lots of trouble - under tree canopy, coverage is spotty. Improved use in wooded area important to us. We often work under trees and in urban areas. Indoor use would open up a whole new industry. (ACRT Inc., Ref. # 1)
- 2) Based on the discussions during the briefing, it appears that the new L-1C should focus on the 25bps option. (AOPA, Ref. # 3)
- 3) Improved performance indoors and under foliage would be most desirable. (Evolution Robotics, Ref. # 8)
- 4) The lower data rate (25 bps) is preferred since it extends system performance in low signal-strength environments. The TTFF concerns can easily be eliminated simply by placing a day's worth of ephemeris messages onto the web and other media. (Rockwell Collins, Ref. # 34)
- 5) The 25bps choice is my choice since it makes decoding bits possible at phase lock threshold of the un-modulated carrier component. The downside is that it will take twice as long to get the ephemeris. That is somewhat mitigated by the new message structure being proposed. (RF Micro Devices, Ref. # 40)
- 6) For sensitivity improvement, we would like to go as low as possible in bit rate, 25bits per second. (SiRF Technology, Ref. # 41)
- 7) On balance, I prefer the low data rate alternative, since the highest available data rate of 100 bps would have a hard time supporting aviation time to alarm requirements. Our time to alarm requirement for Category I precision approach is 6 seconds, which probably allows one second for message duration. At 100 bps, this dictates a maximum message length of 100 bits. Of these, 24-32 bits must be used for error detection (parity), and so the messaging efficiency would be at between 68% and 76%, which is low compared to today's systems like WAAS. (Stanford University, Ref. # 42)
- 8) It will be useful to maintain lock in foliated areas. The users who may benefit from that could be land surveyors, automobile navigation users and GPS-equipped cell phone users. (University of New Brunswick, Ref. # 45)
- 9) High speed of data is not the objective of GPS. It can be addressed with satellite communication. (etc.) (University of New South Wales, Ref. # 48)
- 10) I need signals under trees (University of New South Wales, Ref. # 49)
- 11) I chose 25 bps over 50 bps since I feel it is more important to be able to acquire a message in poor signal conditions than having a faster TTFF. (Rockwell Collins, Ref. # 54)

In contrast, supporters of 100+ bps have three completely different and mutually exclusive objectives. The first group wants GPS to provide integrity and/or differential correction messages, much like an SBAS system. Galileo signal designers presumably intend to use their L1 OS signal for this purpose, transmitting messages at 125 bps. Note that comment (6) above from Professor Per Enge of Stanford University suggests that 100 bps may not be adequate for that purpose. Comments from this group include:

- 12) Correction for ionospheric delay and integrity information (new messages) (ENRI, Ref. # 6)

- 13) Ionospheric corrections; Integrity for public transportation; Messaging space allowing regional governments to broadcast serious disaster/weather information to their nations (ENRI, Ref. # 7)
- 14) Forecast of signal outage (similar to NANU); Troposphere delay map like WAAS Iono-Delay Map, but with smaller grid intervals (Furuno Electric Company, Ref. # 10)
- 15) Integrity, more accurate ephemeris data, search and rescue information (new msg's) (ITT Aerospace/Communications, Ref. # 13)
- 16) I believe it wouldn't be a challenge for GPS III to exceed the performance offered by GPS-WAAS. In fact, exceeding the performance of GPS-WAAS would be a good criterion for GPS III to meet. The navigation data rate of 50 bps is adequate for aviation. It may take 100 bps data rate from GPS satellites to match the performance of GPS-WAAS. (Ref. # 20)
- 17) Could add real time differential correction to data to greatly improve user accuracy and integrity. Should the GPS data rate be increased to provide additional messages? Integrity: No DGPS: Yes mainly for added accuracy. With GPS+Galileo, would RAIM be sufficient for integrity? Yes. My applications benefit most from transmitting DGPS corrections via the data message. (NASA JPL, Ref. # 21)
- 18) Self 'differential' corrections, e.g., clock & orbit (new msg's) (NavCom Technology, Ref. # 24)
- 19) Wants integrity and DGPS data in message (NEC Toshiba Space, Ref. # 26)
- 20) Precise ionosphere correction message; integrity message; satellite anomaly should be broadcast immediately via message (NEC Toshiba Space, Ref. # 27)
- 21) Differential corrections, ionosphere in particular (it would make sense if the user receives all the relevant information from one source), integrity information (Ohio State University, Ref. # 33)

The second “group” of 100+ bps supporters is Qualcomm and a Japanese company (without attribution). We believe Qualcomm currently embeds more GPS receivers in cell phones than any other company. Therefore, when Qualcomm speaks we should pay close attention. The Japanese company is a leader in GPS for car navigation. Both would like GPS to send clock and ephemeris parameters which last much longer than 2 hours. The problem is that getting any message at all in urban and indoor environments is extremely difficult. Their thought is that if a user could acquire clock and ephemeris messages which last 8 to 12 hours, then at subsequent times of the day a position fix could be computed even if only code measurements are available. Relevant comments from each response are:

- 22) We have the intention to prolong the period that the ephemeris data are valid for the hot start operation of GPS receivers. We think that this period is about 4 hours from the power off. But we hope that this period will be prolonged 8 or 12 hours later from power off. (Ref. # 18)
- 23) Desire . . . to permit ephemeris period of validity to greatly exceed the approximate 4 hours currently provided. Graceful degradation is O.K. but desire is to at least double the validity period. Extension to well beyond 8 hours is highly desirable. This allows receivers to use the same ephemeris information under weak signal conditions for extended periods of time (ephemeris perhaps received from a land based server). (Qualcomm, Ref. # 39)

The third group of 100+ bps supporters wants no additional messages at all. They want a higher data rate to minimize the time to first fix (TTFF) and also to minimize the time from first acquiring a “fresh” satellite (one for which there is no valid, stored clock and ephemeris data) before it can be used for navigation or for a snapshot position fix. Comments from this group include:

- 24) Faster TTFF will be desirable (Furuno Electric Company, Ref. # 11)
- 25) It would be useful to transmit ephemeris at a faster rate so the TTFF could be reduced (Garmin, Ref. # 12)
- 26) Quick-repeating ephemeris (ex. less than 15 seconds) and almanac (ex. less than 6.25 minutes). (*Note contradictory input in comment 21, although with a similar objective.*) (Ref. # 18.)
- 27) I hope no additional messages. I want to get ephemeris faster. My expectations for new L1C signal are as follows: (1) Reduce effect of interference (2) Improve TTFF. (Panasonic Automotive Systems, Ref. # 35)
- 28) I have placed fast messaging as my preference to help with fast TTFF. (University of New South Wales, Ref. # 50)

Therefore, in contrast to the 41% of respondents who all want a 25 bps data rate to improve system performance in difficult signal conditions, the 41% who want 100+ bps are divided, some wanting extra integrity and accuracy messages, some wanting extra messages to extend the validity interval of the clock and ephemeris parameters, and some wanting no extra messages but a higher data rate to minimize TTFF and time to use a fresh satellite signal. Not to be left out, 11% of the respondents want to continue with the traditional rate of 50 bps. These respondents in general had no strong reason for selecting 50 bps.

5.2.5 Data Rate Analysis and Recommendation

The previous section makes it clear there is a major conflict of interests about how best to enhance the messaging performance of L1C. We believe a simple assessment of these conflicts actually is the best assessment. Figure 5.4 shows that if we consider only those who expressed a preference and then arbitrarily split the group wanting 100+ bps into three equal subgroups: 15% for accuracy and integrity messages, 15% for longer lasting orbit and clock messages, and 15% for faster transmission with no additional messages, then note that 12% would be happy with 50 bps, we see there is no way to reconcile these minority positions. In contrast, 43% of those who expressed an opinion want 25 bps to make the signal more robust and to enhance system

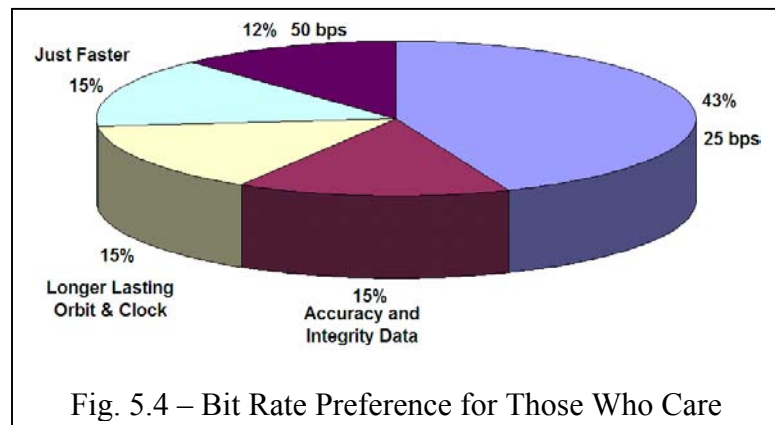


Fig. 5.4 – Bit Rate Preference for Those Who Care

performance under difficult signal conditions. Based on “winner take all”, 25 bps would be the obvious selection. More careful analysis shows this is to be a reasonable outcome.

Take the case of flying toward an area for which the FAA has issued a NOTAM alerting aviators that GPS performance may be unreliable in that region. Let’s assume the GPS receiver will drop lock and stop providing navigation information 50 miles from the center of this region. With a bit rate of 25 bps, loss of message data and loss of lock will occur at about the same 50 mile radius. However, at 100 bps the message data would become unreliable over a 100 mile radius. It is unlikely a certified receiver would be allowed to continue giving navigation information without message reception even if the receiver were locked to the GPS signals and continued to provide pseudorange measurements. At 25 bps the area affected by message loss and by signal drop lock is about the same. At 100 bps the radius affected by message loss is twice as large and the area affected is four times as large. Although for different reasons, the same relative performance issues apply to navigation in forests, along tree-lined roads, and inside buildings.

The penalty for this more robust message performance is that the time required to obtain clock and ephemeris parameters from each satellite is from 36 to 48 seconds as compared with 18 to 48 seconds with C/A today. The quickest time is worse but the longest time is the same. Because certified aircraft receivers now require receipt of two identical messages from a satellite before its signal can be used, the minimum time needed by an aviation receiver to obtain C/A ephemeris and clock data actually is 48 to 78 seconds. Because the modernized message on L1C will have a strong cyclic redundancy check (CRC) and will identify the specific satellite it describes, crosscorrelation problems are eliminated and we expect certified receivers will be allowed to begin using a satellite signal after receiving only one CRC-validated message. Therefore, for aviation, we compare 36 to 48 seconds using L1C at 25 bps with 48 to 78 seconds with C/A today. Not only are the message and drop lock thresholds approximately the same at 25 bps in areas with high levels of interference, the aviation TTFF would be faster with L1C than today.

Integrity and DGPS Messaging

One of our team members is Karl Kovach of ARINC who probably has more experience with GPS messaging issues than any other professional in the field. He was asked to comment on using GPS messaging for some of the desired high rate features. His responses are quoted in the following discussions.

There are problems trying to use GPS messages for integrity and/or for differential GPS (DGPS). With respect to integrity messages, Karl stated: “the sense I have is that most folks are starting to realize that trying to turn GPS III into a clone of WAAS for integrity and DGPS is not such a smart idea. Really, if you think about it - - since WAAS can't meet the 5.2 second [time to alert] requirement with a real-time data link at 250 bps (500 sps), then why would anyone think GPS III can meet it with a real-time data link at 100 bps (200 sps)?” This same perspective is expressed by Professor Per Enge of Stanford University in response # 42 of Attachment 7.0.

SBAS employs a ground station to uplink integrity and DGPS messages to a communication satellite which then re-broadcasts these messages at the GPS L1 frequency to users within its antenna coverage “footprint”. However, there are jurisdictional problems, at least for aviation

navigation. No sovereign nation (or in the case of the EU, group of nations) is willing to relinquish control of aviation in its territory to another sovereign entity. It is unlikely other nations would allow GPS, under U.S. control, to define integrity within their territory. It also seems clear the U.S. Government will not allow other nations to control the signals GPS broadcasts over their sovereign territory. This would be a jurisdictional and logistics nightmare. It is far better for individual nations to use local means to provide integrity and DGPS messages.

Karl Kovach continues: “For integrity, the idea that is starting to take hold is simply to prevent integrity failures right at the source. For satellites, that means a fail-safe clock system like [that] on the IIR birds. For the OCS, that means pre-validating the upload data before uplink. There is an old saying which is appropriate here: ‘An ounce of prevention is worth a pound of cure.’”

Regarding DGPS messages, there are other problems. For example, the DGPS message structure is different for different applications. Single frequency DGPS has different requirements than dual frequency DGPS. Even if these differences can be bridged, local monitor stations would have to forward correction messages to the satellites, which requires either a much larger, worldwide, GPS ground monitor network or for the U.S. to accept and use measurements from international stations. Compared with local means of providing DGPS signals, this seems more cumbersome than it is worth. Furthermore, such a service would directly compete with commercial systems already in place.

It also appears that in the GPS III era, dual frequency autonomous GPS navigation may approach one decimeter accuracy. For most applications, external DGPS will not be necessary. Therefore, it will be used only for quite specialized applications to achieve even better accuracy, and such very high accuracy and specialized applications are not logically supported by a global system.

We conclude that not only is there disagreement about how to use a 100+ bps GPS data rate, it is cumbersome and impractical to use GPS for integrity and differential messages.

Faster TTFF

Two competing methods were proposed to improve TTFF. One was to transmit longer lasting orbit and clock data, and the other was to not transmit additional data but to transmit the required minimum orbit and clock data at a faster bit rate. The groups who wanted this capability were focused on GPS embedded in cell phones or on car navigation applications. The problem is real. Drive out of a city parking lot after a few hours and it often takes many blocks of driving before GPS begins to provide navigation. In some cases it is necessary to stop in an open area for awhile. Driving in obstructed areas can briefly interrupt the signal and thus prevent whole messages from being acquired.

Even if the data were provided at a faster rate, that does not prevent brief outages which prevent reception of whole messages. Furthermore, some satellite signals may not be visible except when passing through an intersection, and this brief time is not adequate to receive a whole message.

It would seem the best solution is to provide users in urban environments with an alternate way to obtain GPS orbit and clock parameters. We agree that orbit and clock information which is valid for 8 to 12 hours or more also would be very beneficial. However, urban environments are where other technologies are emerging which can provide alternate communication links. For example, wireless wideband Internet access is becoming more readily available. By the time L1C could be available on most GPS satellites (perhaps by 2020), such access will be common on cell phones. Automobiles are likely to be equipped with wireless Internet access as well, which could be used not only to provide long duration GPS orbit and clock parameters but also local traffic congestion reports and routing support. A commuter also could use a home Internet connection with a wireless link to the car in the garage to obtain traffic and orbit information in the morning before leaving for work. Long term orbits would still be valid on the commute home that evening. With the vast increase in number of users, there will be commercial incentives to make such navigation and traffic support functions readily available at very low marginal cost.

Karl Kovach suggests there will be no objection for the GPS Control Segment to make long term orbit and clock parameters available over the Internet. The equivalent already is available from the Jet Propulsion Laboratory (JPL) and other computational centers associated with the International GPS Service (IGS).

We conclude that not only is it impossible to agree that the best way to use a 100+ bps data rate is to enhance TTFF, we believe it is functionally better to solve this problem in a more elegant and effective way by using local communication services. Cell phones are communication devices, and the bandwidth of these links is getting faster. Wireless Internet access is proliferating rapidly, and this application could further increase the incentive. Not only will an external solution work better, it can provide other useful information as well, such as warnings about local traffic congestion and suggestions for alternate routing.

5.3 Expert Interview Signal Recommendations

Based on analysis of responses from GPS experts in a wide range of specialties, this L1C project concludes:

1. It is technically feasible to add a modernized civil signal on the GPS L1 frequency.
2. There is a nearly universal desire for an additional, modernized L1 civil signal.
3. The modulation preference clearly is BOC(1,1) rather than BOC(5,1).
4. Although with less unanimity, the best choice of data rate is 25 bps. This optimizes signal robustness for all applications but leaves DGPS, integrity messaging, long duration orbit and clock parameters, and faster orbit and clock parameters to local communication services that are inherently better suited to this task.
5. The following additional tasks are recommended:

- Review this report and its conclusions with the respondents and other interested parties to fully validate or, if necessary, slightly modify the conclusions
- Perform technical studies to determine how best to incorporate the L1C signal
- Review forward error correction options to determine if changing from the current L2C and L5 standards would be worth the potential improvement in error rate
- Propose specific code generators and code lengths for each L1C signal component
- Review waveforms similar to BOC(1,1) which may give slightly better performance
- Prepare a top level signal description to enable the Interface Control Working Group (ICWG) process to develop detailed specifications
- Interact with the GPS/Galileo interoperability working groups to optimize benefits for the worldwide civil user population while protecting national security interests

6.0 Market Segment Signal Needs and User Feedback

This section examines several key segments of the GPS market from the perspective of signal needs. At this time every market segment depends on the GPS C/A code, so in that sense the C/A code has proven to be adequate for all existing applications. However, when companies developed today's products there were no signal options; they could use only the one available signal. GPS modernization will provide two other civil signals, L2C and L5, and GPS III now offers the opportunity to design a new civil signal at L1. Therefore, the present question is what new L1 signal characteristics will best serve the full spectrum of existing and future applications.

Some have suggested that all civil signals should be considered as a package when developing a new L1 signal. In other words, GPS will provide a civil service consisting of at least three signals: C/A at 1575.46 MHz (L1), L2C at 1227.6 MHz (L2), and L5 at 1176.45 MHz (L5). Each of these not only are at different frequencies, they have three different modulation waveforms, two different data rates, and two different message formats. In addition, Galileo is expected to provide similar Open Service (OS) signals at L1 and at L5 (E5a). (Galileo also intends to provide other signals as well, but none of the others shares a frequency with GPS, and access to most could require a user fee. The U.S. Government has made it clear that all civil GPS signals will be provided free of charge to all users, worldwide. Therefore, when developing a new GPS signal it would be inappropriate to take into account anything but the free Galileo OS signals which overlay GPS.) Should L1C, therefore, be developed to enhance the overall package of already-planned GPS and the common OS Galileo signals?

Our answer to the previous question is "no". This is because the largest number of users, by a vast margin, is expected to use only one of the common GPS and Galileo frequencies. In most cases we think this will be L1, although L5 also may be selected for many single-frequency applications. The following section examines the reasons for this conclusion. In either case, if L1C is likely to be used widely for single-frequency navigation, such receivers must rely on that one signal for all its navigation information. It can't take some data from one frequency, other information from a second frequency, etc. Therefore, L1C must be designed to support single frequency navigation applications and, in that sense, be able to function independently of all other GPS signals.

On the other hand, it might be helpful for L1C to have somewhat different characteristics than L5 to give companies a broader range of choices when considering which signal to use for single frequency applications.

6.1 Single-Frequency Applications Dominate

Some will find this assertion troubling. After all, won't technology make dual-frequency receivers practical for all applications, and isn't dual-frequency removal of ionospheric refraction error of vital interest to most users? We believe the answers are "no" and "no".

Until recently car navigation has been the largest GPS application. In the near future, if not already, embedded GPS in cell phones will be the largest application. Consider that, worldwide, between 400 and 500 million cell phones are sold annually. Expected trends are for cell phone sales to climb and for inclusion of GPS to increase. As a result, industry experts believe GPS will be available to a billion worldwide users within the next 15 years. Although the original impetus for GPS was to support the wireless E-911 service, other market forces are pushing the market toward greater use of GPS. For example, recent Nextel ads read: "*WHERE TO TURN FOR DIRECTION. Nextel's GPS-enabled phones get you there with audible turn-by-turn directions.*" GPS offers wireless providers another competitive feature and another source of revenue. It offers subscribers additional safety, directions to and advice about services, a way to remember the way back to favorite places or to record the location of a photograph, and perhaps customers will allow merchants to alert them when near certain stores on an approved list. All of these require more continuous use of GPS.

Car navigation is expected to be the second largest GPS application. There are many millions of car navigators in use today, and the number will grow dramatically over the next decade or two.

When annual production quantities are numbered in the millions, or the hundreds of millions, the dominant consideration is minimum product cost to meet performance requirements. The pressure on embedded GPS makers is to lower the chip cost to well under a dollar, perhaps reaching 25 cents. A large fraction of the overall GPS cost, therefore, is the antenna and the RF bandpass filter, which are substantially less expensive for single frequency reception. In cell phones, the most important antenna function is revenue-producing communication, and communication performance is not being sacrificed to add today's single frequency GPS much less to incorporate a more elaborate two-frequency antenna. When fractions of a penny count and when consumers don't demand it, it's almost inconceivable that dual frequency receivers will ever be used in high volume cell phones. The same cost pressures exist for car navigation, although with less emphasis, so far, to combine a GPS antenna with a cell phone antenna.

If consumers demanded ionospheric refraction correction and were willing to pay for better GPS accuracy, manufacturers would be happy to supply the products. However, unless the improvement is free, as with SBAS (Satellite Based Augmentation System), this isn't happening. SBAS provides differential and ionospheric correction signals at the L1 frequency, so the added cost to have this service in the GPS receiver is practically negligible. Other differential correction signals also are available, but they require an extra receiver, which consumers have shown no interest in buying. Better antennas and wider bandwidth receivers with improved

signal processing can minimize multipath error, but suppliers continue to stress low cost rather than better accuracy. Japan has a network of differential correction stations which provide signals via sidetones on FM broadcast stations. Reception is included in the car radio at negligible extra expense, so the service is in wide use. Such systems also may provide traffic alerts to help navigation routing adapt to local traffic conditions. For the user, this is a low cost way not only to achieve better accuracy but also to obtain a potentially important routing benefit.

The conclusion seems to be that although better accuracy may be desirable, manufacturers and consumers don't perceive it as worth increasing GPS cost or complexity, especially if even better accuracy is available for free, such as with an SBAS signal. (The Wide Area Augmentation System, or WAAS, is the U.S. SBAS, and SBAS is automatically included in almost all current consumer products.) If traffic information plus differential GPS corrections can be broadcast locally, there also would be both a public and a private incentive to incorporate such signals in GPS car navigation products, especially because the consumer also obtains these benefits essentially for free.

Therefore, we conclude that the vast majority of GPS applications will be for consumers and that consumers predominantly will use single frequency GPS receivers. Single frequency GPS receivers thus will vastly outnumber more complex receivers, and the resulting difference in production volume will further increase the cost differential. As a result, the L1C signal must be designed for stand-alone navigation service, providing all necessary information to its users.

6.2 Which will be the Single Frequency of Choice?

Current plans limit the choice of which signal to use for single frequency applications to L1 and L5. This is because improved satellite geometry (more satellites) is an extremely valuable asset, especially in environments where signal blockage by terrain, trees, or buildings is a problem, and these are common problems for most consumer applications. Therefore the ability to use both Galileo and GPS satellites offers a benefit to the user which can't be ignored. Previous paragraphs have established that the vast majority of consumer products will use only one frequency, and the EU is designing Galileo to transmit only two signals which overlap GPS frequencies, namely L1 and L5 (E5a). Therefore, these are the only two signals which will allow use of all GPS and Galileo satellites while retaining the simplicity of a single-frequency design.

There are two key advantages to L5. It is expected to be the most powerful civil GPS and Galileo signal. The minimum received L5 power specification for GPS is between -154 and -154.9 dBW into a circularly polarized antenna. The equivalent L1 C/A code specification today is -158.5 dBW, or from 3.6 to 4.5 dB weaker. (Measurements show that transmitted C/A signals are 1 to 2 dB stronger than the specification, so the practical difference may be only 1.6 to 3.5 dB.) The proposed L1C signal could be specified to have a minimum signal of -155.5 dBW, or only 0.6 to 1.5 dB weaker than the L5 specification. Even so, signal power is extremely important and may drive the signal selection toward L5 for single frequency use.

The second key L5 advantage is signal bandwidth, because it has a 10 MHz (actually 10.23 MHz) code clock rate. This provides 10 dB better rejection of narrowband in-band interference than the 1 MHz C/A code and 5.2 dB better rejection than the BOC(1,1) signal. These can be

important for some applications and, along with more signal power, may drive design decisions toward L5.

The case for L1 rests on three points. The first is the effect of the ionosphere on received signals. At certain latitudes, and especially during times of peak solar storms, scintillation causes signal fading and can cause loss of lock. The problem is more severe at lower frequencies, e.g., L5 versus L1. Probably more important, ionospheric refraction error is inversely proportional to the square of the signal center frequency. Therefore, L5 ionospheric errors always are 1.8 times worse than L1 errors. If the ionospheric error at L1 is 3 meters, at L5 it will be 5.4 meters. L1 provides better single frequency accuracy than L5, even when SBAS ionospheric corrections are applied.

The second key point is the inverse of the L5 bandwidth advantage. The 10 MHz L5 code practically fills the allotted signal bandwidth. Therefore, it is important for the RF filter to be wide enough to accept most of the L5 signal energy but with sharp bandpass skirts to reject out of band interference. This type of filter requires more “poles” and thus is more expensive to manufacture. (Remember that we are talking about a penny of cost being important for consumer applications.) In contrast, the main spectral lobes of a BOC(1,1) signal occupy only the central ± 2 MHz of the ± 10 MHz allotted signal bandwidth. This gives designers the choice to use a wide bandwidth filter with sharp skirts for applications requiring maximum accuracy or, to minimize cost for consumer applications, to use a relatively narrow bandwidth filter with fewer poles and wider skirts. Current consumer GPS products typically use a narrow bandwidth filter to save cost even though better accuracy could be obtained with a wider filter and faster processing circuitry.

Another result of the bandwidth difference between L1 and L5 is that by using a narrower bandwidth RF filter the consumer product can digitally process the signal with a lower clock rate. This may be an important difference for battery powered products such as cell phones. (Today, cell phone power is saved by shutting down the GPS receiver when not in use. Because the initial objective was only for E-911 positioning, GPS is used very seldom. In the future, however, people will begin to expect and to use more continuous navigation services, so concern for battery consumption will increase.) Consider also the wrist watch navigator, where power is even more limited.

Better narrowband interference protection from the 10 MHz L5 code is countered at L1 in two ways. First, it is known that the L5 band contains more interference than the remarkably quiet L1 band. Narrowband interference of current L1 receivers is practically unknown. Second, by using a narrowband RF filter there is less bandwidth exposed to interference. In other words, the filter attenuates many interfering signals that otherwise would affect an equivalent signal in the L5 band.

The final L1 advantage is experience. Many millions of L1 C/A receivers are in use around the world. Receiver companies and end users have vast experience with the L1 band. It will be many years before enough L5 and E5a signals are available to support a robust navigation service. During this time L1 use will continue to expand rapidly. Experience will favor the continued selection of L1 as the single-frequency signal of choice.

Ultimately the market will determine whether L1 or L5 becomes the dominant single-frequency signal. We believe it will be L1. However, even if L5 becomes the ultimate signal of choice, it would be unacceptable to design L1C without the ability to optimally support single-frequency GPS navigation.

6.3 Market Segments

In order to characterize market needs, we characterize the market segments as follows:

Table 6.1 – Primary Market Segments

	Professional & Scientific	Commercial	Consumer
Land			
Marine			
Aviation			

The “professional and scientific” column is intended to stress applications where very high accuracy is required. This includes GIS data collection, land survey, machine control, earthquake, volcano, and structure monitoring, and weather prediction. Although GIS data collection products typically require sub-meter accuracy, the others require accuracy of a centimeter or better. The “commercial” category represents products which are used by companies as a business tool. Such products include truck and taxicab tracking and routing systems, navigation systems for small commercial vessels to supertankers, and aircraft navigation systems for business aircraft to jetliners. By “consumer” products we mean items which are sold to individuals rather than companies. Such products range from GPS embedded in a cell phone to navigation systems for cars, boats, and airplanes.

The following paragraphs discuss likely signal requirements for each major column of the table as well as for some of the rows, e.g., aviation.

6.3.1 Consumer Product Needs for a New Signal

The most important driver for consumer products tends to be achieving the lowest possible cost to achieve competitive performance requirements. For navigation applications, better map displays and routing software are more important differentiators than improved GPS receiver characteristics. For embedded GPS, low power as well as low cost are the drivers. For these reasons, we expect most, although not all, consumer applications will use single-frequency receivers. Because satellite geometry and visibility are so vital to adequate performance, we also expect most consumer products to use both GPS and Galileo on a common frequency. The key exception to single frequency consumer products is likely to be navigation equipment for general aviation, where WAAS support of dual-frequency receivers will significantly improve available accuracy with integrity, availability, continuity, and coverage. These improvements will allow general aviation aircraft to make precision approaches to all approved airports without needing other equipment.

Although the L1C waveform will be chosen by the Government, it seems likely that consumer companies would prefer BOC(1,1) over BOC(5,1). With its narrower bandwidth, BOC(1,1) gives companies the opportunity to choose between L5 for the advantages of a wide bandwidth signal or L1C for the reciprocal advantages of a narrower bandwidth signal. This is an important consideration for very low cost applications, but even general aviation companies probably would prefer BOC(1,1) to avoid any concern about tracking a sub-peak of the BOC(5,1) correlation function.

The most contentious issue is data rate. Four nearly orthogonal needs have been defined. These are: (1) for a high data rate to provide additional accuracy and integrity messages, (2) for a high data rate to minimize the time needed to collect the clock and ephemeris messages and begin using a fresh satellite signal or to begin navigating (TTFF), (3) for a high data rate to provide messages with longer-lasting orbit and clock parameters, such as 8 to 12 hours, so subsequent position fixes don't require reception of a new message, and (4) for a low data rate to maximize the chance of receiving any message at all in challenged signal environments.

These clearly are conflicting requirements, and there is no way to favor one without hurting the others. We must seek a solution which provides the best possible performance to all users, and the key to this may be through other ways to deliver messages.

The data-less or pilot carrier component of L1C is an advantage for all users. This permits receivers in challenged conditions to acquire and track signals at lower S/N levels than would be possible without a pilot carrier. This is an advantage for all applications, but especially for indoor use.

6.3.2 Aviation Signal Requirements

Aviation users are facing a major transition and therefore a dilemma. Unlike other users, certification requirements for aircraft and equipment make it more expensive to upgrade a navigation receiver than simply buying a new product and plugging it in. Every certified aviation receiver today employs the single frequency C/A code. In the future there will be at least three and possibly four civil GPS signals. Galileo will provide signals at L1 and at L5 (E5a), so these two signals will give access both to GPS and to Galileo, practically doubling the number of visible satellites. Galileo also intends to have an E5b signal not only for navigation but also to send integrity data to aviators. Although of limited interest within the U.S., E5b may be mandated in Europe and could require a user charge.

The aviation community recognizes that these major changes are coming, and it is understood that performance will be improved significantly. However, there is very little incentive to make any change until the new options and their advantages are clearly defined, the signals are specified, the services are nearly available, and certified equipment is available at a reasonable price. For example, although WAAS already has been commissioned for use in the U.S., very few certified receivers are available and very few are being installed. Owners don't want to invest in a new receiver just to add single frequency WAAS when another replacement may be desired or required in a few years because of all the new options on the way.

The FAA urged and sponsored development of the L5 signal. The main advantage of L5 for aviation is to permit dual-frequency navigation with both signals (L1 and L5) in Aeronautical Radio-Navigation Service (ARNS) bands. (L2C will be available several years sooner than L5, but it is not in an ARNS band.) Although L5 alone must support navigation if L1 is not available, its 80% larger ionospheric error makes it a significantly less desirable single-frequency signal than L1, even with SBAS corrections. When combined with L1 to eliminate ionospheric refraction errors, aviation performance, especially with SBAS, is greatly improved. (Dual frequency receivers with SBAS support are expected to provide the equivalent of Category I precision guidance.) Therefore, L1 will continue to be the most important signal for aviation, and development of L1C offers a chance to further improve performance.

Some aviation experts have recommended a higher data rate on L1C so GPS can provide integrity and differential correction messages directly, thus eliminating the need for a separate SBAS signal. In contrast, other aviation experts want a very low data rate so L1C remains usable as close to areas for which the FAA has issued a NOTAM alerting aviators that GPS performance may be unreliable in that region. It is important to seek an answer which provides benefit to both points of view. Once again, resolving this conflict of objectives may have to rely on other data sources.

6.3.3 Professional and Scientific Signal Requirements

High precision applications include Geographical Information System (GIS) data collection where half meter accuracy is needed, land survey where centimeter accuracy is required, and machine control where centimeter accuracy under harsh dynamic conditions is needed. Also included is monitoring of structures such as bridges and dams where sub-centimeter accuracy is desired. Finally, this same type of equipment is used for a variety of scientific applications such as volcano and earthquake monitoring, determination of polar motion and continental drift, and atmospheric observations for weather prediction.

With the exception of GIS data collection, all of these applications require dual frequency carrier phase measurements. These are available today using C/A measurements on L1 with codeless or semi-codeless measurements of L2, aided by L1 tracking. A major improvement for these applications is on the way because, for the first time in GPS history, a civil code on L2 (L2C) will be provided. With this code, L2 measurements will be far more robust, and eventually the complex and expensive codeless and semi-codeless circuits no longer will be needed. When L5 becomes available from most satellites, it also will be incorporated. Three frequency receivers are expected to extend the range over which high precision measurements can be made and provide quicker results over conventional distances. These improvements also will be enhanced by access to both GPS and Galileo signals.

Because Professional and Scientific receivers have access to all signals and all messages, and because the primary measurement is of carrier phase, there are no major concerns with any L1C signal option. The primary benefit will be the pilot carrier. Otherwise, there are no problems using BOC(1,1) or BOC(5,1), and with access to all messages there is no particular benefit to a higher or a lower data rate on L1C. The one exception is that accuracy is the most important

consideration for this group. Anything that could be added to the message to further improve accuracy would be welcome.

6.4 User Interviews

Section 4.4 outlined the process whereby user groups would be surveyed to determine their current use of and dependence on GPS and what improvements they would appreciate the most. The approach is documented in Attachment 8.0 and the results are documented in Attachment 8.0. The approach was to identify a potential benefit to users from each main technical improvement expected from L1C. Major established GPS user groups were identified by discipline or interest (see User Benefits Matrix in Table 6.2 below), and *a priori* assessments made of how L1C parameter choices might impact each user group positively. For these cases, an ‘X’ was assigned in this matrix, and an explanation of user potential benefits was created. During the interview process with users, these potential benefits were discussed and validated, and additional comments were elicited by the process.

Table 6.2 – Benefit of Each L1C Improvement to User Applications

L1C Improvement ⇒ Application ↓	Lower Signal Thresholds for Navigation (Power & Dataless Channel)	More Robust Autonomous Navigation (Power, FEC & Data Rate)	Less Susceptible to Interference (Power & Code Structure)	Higher Dynamics Tracking (Power and Dataless Channel)	Reduced Cross- correlation (Longer Spreading Codes)
Location Based Services/Recreation	X	X	X		X
Scientific	X		X		X
Aviation			X		X
Agriculture	X	X		X	X
Surface Transportation	X	X	X		X
Mining & Construction	X	X	X	X	X
Surveying/Civil Engineering	X		X	X	X
Public Safety/Security	X	X	X		X
Timing			X		X
Rail	X	X			X
Space	X				X
Environment	X	X			X
Maritime and Waterways		X	X		X

In Section A of Attachment 8.0, the potential user benefits for each L1C performance enhancement are explained for the non-technical GPS user. Section B is the matrix above, and Section C contains an explanation and user response information for each of the major application areas given in the matrix. For each ‘X’ in the matrix, a description of the potential benefit for that user group is given in Attachment 8.0. In all cases, the users who were

interviewed believed that modernizing L1C would be of positive benefit to them in their GPS applications.

For example, all user groups clearly would benefit from reduced susceptibility to self-interference by adding L1C instead of simply boosting L1 C/A power levels. These user survey data also make it clear that, in particular, a more robust and powerful GPS L1C signal would be very welcome.

The user interviews verified and strengthened our conclusion that L1C would be a valuable asset to GPS and should be implemented.

7.0 Conclusions and Recommendations

We conclude that:

1. L1C is technically feasible,
2. The need for L1C is strongly supported by stakeholders, and
3. Experts prefer the following signal characteristics:
 - a. BOC(1,1) signal modulation
 - b. 25 bps data rate

These three points reflect our primary findings on the first three L1C Project objectives, which were achieved on schedule and on budget, as described in detail within this report (including the documentation provided in the attachments).

Recommendations to the IGEB are as follows:

- 1) Implement L1C as soon as feasible (it makes sense to complete GPS modernization across all three GPS frequency bands)
- 2) Retain C/A indefinitely, but implement L1C such that C/A can be discontinued in the distant future without a negative impact on L1C users
- 3) Implement BOC(1,1) as the L1C modulation. *(At one time the Galileo team was evaluating subtle alternatives to BOC(1,1). If a better modulation is found which meets the EU/US agreements on signal compatibility, the U.S. should be prepared to implement it instead of BOC(1,1). However, such a replacement would have to be studied very carefully, justified thoroughly, and is very unlikely.)*
- 4) Implement L1C with a data rate of 25 bps and with no additional messages. This yields the greatest global benefit by making the signal more robust for all users without sacrificing robustness for the sake of a particular set of users. Therefore, DGPS signals, integrity messages, long duration orbit and clock parameters, and faster orbit and clock parameters should be provided by local or regional communication services which are inherently better suited to these tasks and also may include added value information.

The fourth L1C Project objective, to define the detailed signal specification for L1C, has not been achieved. This work should be done soon, however, in preparation for GPS III acquisition

(e.g., CDD and ICWG processes) and for the next steps in international GNSS cooperation on system interoperability with Galileo and QZSS. We consider this forthcoming technical work to be best addressed by the technical team that has molded L1C up to this point, and this report contains our recommendations for that future work (in the Executive Summary and Section 5.3). We stand ready to continue, resources permitting, and of course pending decisions of the IGEB.

8.0 Acknowledgements:

We greatly appreciate the ideas and time contributed by all questionnaire respondents, and the major in-kind support of all corporations and agencies whose employees participated. We especially acknowledge the JGPSC in Japan and the DOTARS group in Australia for their assistance in distributing and encouraging feedback throughout the duration of the L1C Project.

GPS JPO officers serving under Col Rick Reaser, former Chief GPS Engineer, have guided and provided their input and ideas to the L1C Project. Initially, Maj Pat Harrington and Capt Reginald Victoria were involved in framing and successfully proposing the project. Capt Bryan Titus then brought the L1C Project through its main phases of technical development, while simultaneously working with the international GNSS community to ensure interoperability between GPS and Galileo. Lt Jason Taylor assisted by effectively presenting the L1C Project at the ANC Navigation Systems Panel in Canberra, Australia. During final stages of the project, Col(S) Mark Crews, LtCol Douglas Brown and Capt Dominic Alcocer have seen everything through to completion.

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