GPS Civil Signal Monitoring – Advancing Toward Implementation

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BIOGRAPHY

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Calvin Miles is the GPS Team Lead in FAA Navigation Services. Calvin has over 26 years of experience developing, deploying and approving the design of NAVAIDs with integrity. Those systems include ILS-RMM, VOT, new generation RVR, TLS, three CAT III ILS designs, WAAS, and NCIME. Calvin has worked with GPS III since 1999. He graduated from Harvey Mudd College in 1987 with a degree in engineering.

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ABSTRACT

The Global Positioning System provides user positioning, navigation, and timing service. Fulfillment of this service entails not only performance commitments on the specification and broadcasting of the GPS signals but also monitoring of those broadcast signals so that both operators and users are aware that the service is meeting its stated commitments. The GPS Civil Monitoring Performance Specification (CMPS) has been adopted by civil federal agencies to identify the requirements for civil signal monitoring.

The CMPS is a mature document and defines a set of metrics for assessing GPS performance against standards and commitments defined in official U.S. Government documents such as the Standard Positioning Service Performance Standard, the Navstar GPS Space Segment/Navigation User Interfaces (IS-GPS-200), Navstar GPS Space Segment/User Segment L5 Interfaces (IS-GPS-705), and Navstar GPS Space Segment/User Segment L1C Interfaces (IS-GPS-800). To the extent practicable, each metric defined is traceable to one or more specifications or commitments of performance.

The CMPS also identifies the scope and range of monitoring needs not directly traceable to the key GPS reference documents but expected by civil users. These needs include the ability of the system to detect defects in signal and data, the rapid report of anomalous service behavior to satellite operations for resolution, and notification to users of the causes and effects of such anomalies for their various service types (e.g., positioning, timing, and navigation).

Two key objectives needed to successfully fulfill Civil Signal Monitoring (CSM) are:
1) Direct notification to GPS operators when critical, time sensitive specifications on signals used by the civil community are violated, and
2) Publication of the observed performance level of signals from the GPS service available for civil use.

In some ways—mostly relating to Information Assurance (IA)—these are competing objectives. However, the following six groups of monitor functions are important to both objectives.

a. Metrics verification – verification that signal and service performance meets commitments made in SPS Performance Standard, interface specifications, and other government specifications
b. GPS Operator notification – timely notification to satellite operators of real-time GPS anomalies and situational awareness of civil signal performance
c. Civil user notification – notification to civil authorities and agencies or GPS anomalies and situational awareness of civil signal performance
d. Signal quality monitoring – assessment of carrier waveform and code performance to ensure within designated limits
e. Archive and retrieval – archival of CSM reports and data for retrieval by the GPS operators, analysts, and civil authorities
f. Signal monitoring – monitoring of the four broadcast signals, L1 C/A, L2C, L5, and L1C, accessible to civil users

There are various ways a CSM system may be implemented for the future GPS service. That variety is spanned, roughly, by the allocation of monitoring functions to either the Next Generation Operational Control System (OCX) which is currently under development or a Non-OCX system using other US Government reference networks that observe the GPS signals.

The central theme of the paper is to present the recommended CSM functional architecture with an implementation that leverages both OCX and Non-OCX elements in a complementary fashion to satisfy the two key CSM objectives. Description of architectural allocations of the monitoring functions, operational aspects of implementation, and a cost-effectiveness trade space for implementation alternatives is described. The paper closes with thoughts on the future of CSM, including expected capabilities and milestones.

INTRODUCTION AND BACKGROUND

For more than twenty years, GPS has broadcast three ranging signals in an operational mode: L1 C/A, L1 P(Y), and L2 P (Y) [1,2]. Over that time, non-DoD users have had full access to only one of these broadcast signals. That signal, generally referred to as L1C/A, has not been continuously or generally monitored by the GPS operators under standard operating procedures in the way that the two DoD exclusive signals have been monitored [3].

To compensate for the reduced level of monitoring on the L1C/A broadcast, civilian stakeholders have developed a wide range of monitoring services [4, 5, 6, 7, 8] to enhance the primary GPS functions of positioning, navigation, and timing. Often these services are purpose-specific and, in some cases, involve elaborate systems for notification or even error correction. One of the most sophisticated examples is the FAA's Wide Area Augmentation System [9] (WAAS) which belongs to the group of enhancements referred to as Space Based Augmentation Systems (SBAS) for GNSS. In many of these monitoring systems the L2 carrier signal is also leveraged via semi-codeless tracking [10] to provide an important but tenuous link to the signals which are monitored continuously by the GPS operators.

Contemporary with the development of these non-DoD monitoring services, the US Air Force Space Missile Command (USAF/SMC) is undertaking a broad GPS modernization effort, consisting of GPS III satellites and the Next Generation Operational Control System (OCX). In light of the planned improvements some remedies to the inefficiencies of purpose-specific monitoring services maintained by the US government have been under consideration. In particular, GPS III expands the space segment broadcast to include a set of three new signals, L2C, L5, and L1C, accessible to non-DoD users. The benefit of these new signals and the cooperation across US government agencies on their development is extensive but beyond the scope of this paper. The focus of this paper is to report on the development of opportunities available in OCX to introduce signal monitoring on all GPS broadcast signals available to non-DoD users.

This paper reports on the four key topics of current civil signal monitoring development efforts for the four signals accessible to non-DoD users:

- Overview of the specifications document defining civil signal monitoring which was adopted by the consortium of civilian US government agencies
- Update on the cooperation between the DOT (as representative for the civilian agencies) and the USAF (as the GPS owner) to bring civil signal monitoring into OCX
- Summary of the 2014 DOT CSM Trade Study performed on implementation options for civil signal monitoring architectures
- Status on the CSM implementation process and a look at the expected next steps

CIVIL SIGNAL MONITORING SPECIFICATION

In order to fulfill its mission, the GPS must both provide signals and services to support reliable user positioning, navigation, and timing functions. Monitoring of the GPS signal broadcast is essential to ensure that these functions are meeting stated commitments. The GPS Civil Monitoring Performance Specification [11] (CMPS) is the official document adopted by civilian US government agencies enumerating the specifications that define civil signal monitoring. Initially published as an official DOT document in 2005, the most recent revision of the CMPS was published in 2009.

The CMPS defines a set of metrics for evaluating performance against the published GPS standards and specifications [12, 13, 14, 15]. The defined metrics are traceable to one or more specifications in those standards as a direct observable or if indirectly observable by state algorithm so that the metric can be measured and compared to the threshold and/or goal necessary to achieve the standard. Where the GPS standards are silent or implied on a particular specification, explicit thresholds are stated in the CMPS with reference to originating work.

The CMPS also addresses operational aspects of the civil signal monitoring function such as storage and retrieval of vital monitoring information, timeliness of alerts or warnings of off-nominal or out-of-specification conditions, and use cases for situational awareness and user notification.

In summary, the CMPS is the express consolidation of specifications for a civil signal monitoring function across the four GPS broadcast signals (L1C/A, L2C, L1C, and L5) and the semi-codeless link to the L2 signal accessible to non-DoD users. We refer the reader to the document for the complete expansion of those specifications.

TURNING SPECIFICATIONS TO MONITORING

The work of transforming the collection of civil signal monitoring specifications in the CMPS into a civil signal monitoring system (CSMS) has proceeded in three phases, development of a CSMS architecture that can be linked to the GPS III architecture, allocation of CSMS functions to the GPS III OCX where they are compatible or non-OCX elements where not, and implementation of the CSMS functions in their allocated element.

It is helpful to keep in mind the following entities which are the expected primary consumers of CSMS products.

1. USAF GPS operations personnel (2SOPS)
2. USAF navigation analysts (extra personnel on “day shift” and contract support to 2SOPS)
3. GPS “Triad” [16] personnel (GPSOC/NAVCEN/NOCC)
4. Constellation managers (USAF SMC/GP)
5. Civilian authorities designated with CSMS access

While the CSMS development process has extended for multiple years, we have entered the third phase and are poised to begin implementation of the OCX element of the CSMS first, followed by the implementation of the non-OCX element. In the remainder of this section, we include some discussion on the intermediate steps in the first two phases before turning to the current status and future look.

Before we do, however, let us decompose the monitoring functions by one level. This will help convey the basis used in the recommended OCX/non-OCX allocation of the CSMS architecture.

- GPS operator notification and situational awareness
- Non-DoD stakeholder notification and situational awareness
- Signal monitoring through observation of the L1C/A, L2C, L5, and L1C broadcast signals
- Signal quality monitoring through measurement of the distinct code and carrier waveforms of the L1C/A, L2C, L5, L1C, and L2 semi-codeless signals
- Verification of performance levels against the published signal and service standards
- Archive and retrieval of CSM information by the GPS operators and civil authorities

THE PATH TO CSM: OCX OR NON-OCX

As far back as 2000, the DOT has been exploring the use of non-military assets for monitoring the GPS civil signals. In 2003, under a contract for the Interagency GPS Executive Board (IGEB), the University of Texas Applied Research Laboratories issued a report considering the use of available civilian GPS networks for signal monitoring. These included NASA’s Global GPS Network, International GPS Service Network, FAA Wide Area Augmentation System, and the DOT Nationwide Differential GPS Network [17]. Since then, discussions have been held across federal agencies exploring the use of monitoring networks to perform the civil signal monitoring function. In particular, these discussions have included representatives from the FAA, the National Coordinating Office for Space-Based PNT, the US Coast Guard, the US National Institute of Standards and Technology, and NASA.

With the advent of the OCX acquisition program, the Signal Monitoring Working Group (SMWG) originally formed to draft the CMPS was tasked with engaging GPS Directorate (GP) under interagency agreement between DOT/FAA and USAF/SMC to bring civil signal monitoring into the OCX requirements baseline. The SMWG and GP’s System Engineering & Integration (SE&I) staff conducted the engineering work to draft requirement changes (redlines) and flow those changes down to the OCX architecture and traceability artifacts. Concurrently, GP’s OCX contractor selection was made with the award going to the Raytheon Company (RTN). However, that contract was established before the CMPS specifications were attached as requirements on the OCX implementation.

The DOT as lead civil agency on Space Based PNT matters funded a study through the FAA with the GPS Directorate (GP) to have RTN determine rough order of magnitude (ROM) costs to implement the CMPS specifications as requirements on the OCX contract. In May 2012, RTN delivered their report [18] which included two central pieces of information. The first was an engineering comparison of the 193 CMPS specifications against the OCX baseline requirements [19] at the time to place each CMPS line item into one of five categories of satisfaction, "full", "high", "medium", "low", and "not". The second piece of information was a ROM cost estimate separated into two pools, one for the reference receiver element, formally referred to as RFC-106 but based on the prior SMWG/SE&I work, and another for algorithms and data processing, formally referred to as RFC-67 and also based on the prior SMWG/SE&I work.

Due primarily to funding constraints in the budget environment, DOT acquisition of the complete set of CMPS specifications as requirements on the OCX system was not feasible. The SMWG was again tasked, this time with prioritizing the list of CMPS specifications that fell into only the "fully satisfied" (FS) or "highly satisfied" (HS) categories of RTN's 2012 ROM study in an effort to rationalize the choice of purchased requirements achievable under a given budget. It should be noted that those specifications identified in the "fully satisfied" category were not fully completed and still required additional system engineering, integration, testing, and documentation to bring to completion.

The FS and HS specifications were ranked and divided into twelve priority levels by the civil stakeholders represented on the Signal Monitoring Working Group for the applying available funds to the highest priority items. Table 1 is the consensus priority list itemized by CMPS line item. RTN was asked to apply this prioritization to refresh the ROM estimate with costs itemized by priority level. Thus the "choice" becomes simply a cut-line at the cumulative cost (in prioritized order) up to which funding is available. For example, if funding were to only permit three categories to be implemented, then OCX would incorporate requirements from categories P1 through P3.

The implication here is that fulfillment of all lower priority level items would fall to a Non-OCX element.

Priority ID	Requirement Category	FS	HS
P1	Track codes	3.2.1a, b, c, d, e, g, h, i, j, k, l, m	
P2	Navigation Message	3.2.4.1 b, c, e, f, g, i, l, p, r, t, u, v, w, x 3.2.4.2 a, b, d, k, m, o, s, t, u, v 3.2.4.3 a, b, d, e, f, i, k, m, o, p, r 3.2.4.4 a, b, d, e, f, i, k, m, o, p, q, r	3.2.4.2 e, f, g, i
P3	Archive	3.6a	3.6 b, c, g
P4	C/N0		3.2.2 i, j, k, l
P5	PVT performance	3.2.4.1 a 3.2.4.4 s	3.1.7 c, d, e, f 3.1.8 a, b, c, d 3.2.4.2 p
P6	Signal quality monitoring		3.2.2 w, aa
P7	URRE, URAE, UTCOE		3.1.3 h 3.1.3 f, g
P8	PDOP		3.1.7 a, b
P9	URE		3.1.3 a, b, c, d, e
P10	Absolute power		3.2.2 a, b, c, d, e, f, g, h
P11	Constellation performance		3.1.1 a, b
P12	Timeliness of navigation messages	3.2.4.1 d, j, m, n, o, q 3.2.4.2 c, h, j, l, n, r 3.2.4.3 c, g, j, l, n, q 3.2.4.4 c, g, j, l, n	
N/A	CMPS Reqts that have been dropped	3.1.2 a, b 3.2.1 f 3.2.4.1 h	

Table 1 Prioritized Civil Monitoring Specifications

In mid-2013 NASA JPL approached DOT leadership to request consideration on the use of the Global Differential GPS (GDGPS) network as a means for accomplishing the CSM function possibly as a full CSMS. Early discussions between NASA and FAA subject matter experts on benefits and limitations of GDGPS culminated in a December 2013 briefing to the Space-based PNT Advisory Board. In that briefing, JPL presented an initial survey of GDGPS capabilities against the CMPS specifications. Subsequent to that meeting, DOT/FAA initiated a trade study to explore the use of OCX (RTN ROM) and (JPL ROM) to inform DOT decision-makers on cost effectiveness of implementing a CSMS using either or both OCX and Non-OCX elements. The work was led by DOT/OST-R and a team was formed with representatives from the SMC/GP, DOT/FAA, and the 2nd Space Operations Squadron.

THE CSM TRADE STUDY

The CSM Trade Study team was given six weeks to investigate the trade space, establish a framework for evaluation, and prepare its report. The CSM Trade Study report [20] was delivered March 2014 and briefed to DOT leadership involved in the budget and decision-making process.

The remainder of this section outlines the structure of the trade study and gives the key high-level findings. In the trade study, use of the GDGPS as a CSM monitor network was considered "representative" of a Non-OCX solution. While other monitoring systems exist, for the purposes of the study, the GDGPS technical and cost data provided by NASA JPL addressed the CMPS directly and stands at a level of reliability similar to the RTN ROM.

The trade study has two main dimensions in structuring the trade space: “options” which are bins of coverage on CMPS requirements for the OCX and Non-OCX allocations, e.g. the twelve priority levels projected onto the RTN ROM; and “alternatives” which are combinations of OCX and Non-OCX Options. The six options considered in the trade study are

OCX:

1. OCX P2 – all Fully Satisfied and Highly Satisfied requirements up through Priority P2
2. OCX P3 – all Fully Satisfied and Highly Satisfied requirements up through Priority P3
3. OCX P6 – all Fully Satisfied and Highly Satisfied requirements up through Priority P6
4. OCX P12 – all Fully Satisfied and Highly Satisfied requirements up through Priority P12

Non-OCX:

5. Non-OCX without signal quality monitoring (SQM) – Use of Non-OCX monitoring to satisfy CMPS requirements except SQM items that need new reference receiver design
6. Non-OCX with SQM – Use of Non-OCX monitoring to satisfy CMPS requirements (SQM items satisfied using the NovAtel G-III [21])

An important thing to note is that every one of the six Options contains monitoring requirements that touch all four of the Non-DoD accessible signals (L1 C/A, L2C, L5, L1C). As an informational exercise, the Trade Study team estimated an independent determination of the OCX and Non-OCX abilities to satisfy the CMPS requirements. The OCX proposed approach could cover up to 127 of CMPS requirements (67%) if fully implemented. The Non-OCX proposed approach could cover up to 175 of CMPS requirements (93%) if fully implemented. With this additional perspective (beyond the claims from the two providers), the Trade Study team formed eight CSMS Alternatives as combinations of the Trade Study Options. These Alternatives are listed in Table 2 where the first four are OCX-only or Non-OCX-only implementations and the last four are hybrid implementations of the different Options

Table 2 Trade Study Alternatives

Alternative	Options					
	OCX P1-P2	OCX P1-P3	OCX P1-P6	OCX P1-P12	Non-OCX w/o SQM	Non-OCX w SQM
1 - OCX P6			x			
2 - OCX P12				X		
3 - Non-OCX without SQM					x	
4 - Non-OCX with SQM						x
5 - OCX P2 + Non-OCX with SQM	x					x
6 - OCX P3 + Non-OCX with SQM		x				x
7 - OCX P6 + Non-OCX without SQM			x		x	
8 - OCX P3 + Non-OCX without SQM		x			x	

The Trade Study team evaluated each of the Alternatives against four criteria:

1. Fulfillment of requirements – assessment of the degree of fulfillment of CSM capability within each Trade Study Option. Fulfillment was assessed across six categories: metrics verification, Operator notification and situational awareness, Civil user notification and situational awareness, Signal quality monitoring, Archive, Civil signal monitoring (L1 C/A, L2C, L5, L1C).
2. Cost – a cost estimate for the economic life, the development period, and the reference year for the system under consideration.
3. Risk - risk assessment in which risk is described, likelihood and impact of the stated risk is evaluated, and the overall risk gauged.
4. Integration with Operations – these include actionable alerts for operators, integration of technical capabilities into the baseline software and command and control systems, and development of technical orders, standard operating procedures, training materials, and standards, availability of CSMS data/metrics to navigation analysts, immediate reporting of alerts and warnings to the Triad, daily report to the Triad of daily statistics, periodic reports of specified performance statistics, preparation of standard operating procedures.

CSMS FUNCTIONAL ARCHITECTURE

A high-level architecture was drawn up to reflect the implementation of the OCX and Non-OCX capabilities. This architecture is illustrated in Figure 1. A block-by-block description from upper-left to lower-right follows.

Any CSM architecture must be supported by a large network of data collection sensors (often referred to as monitor stations) that collect the necessary raw measurement data. The exact distribution of the sensors is not critical; however, the collection of sensors ideally achieves continuous multi-station visibility to all GPS satellites, even in the event of single station outages (or preferably even multi-station outages). Examples of such networks include the GPS OCS, NASA GDGPS monitor stations, the NGA Monitor Station Network monitor stations, and the FAA WAAS reference stations.

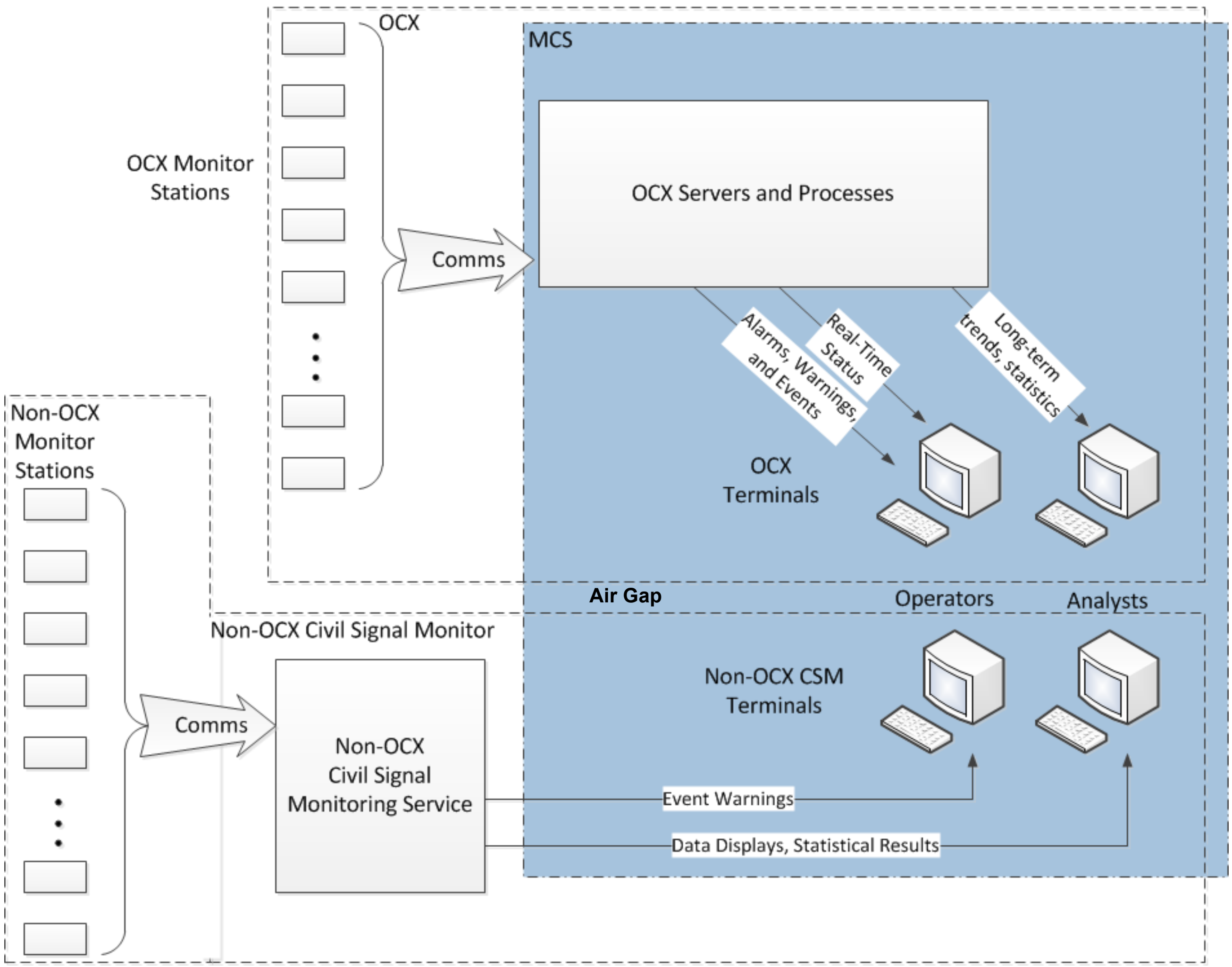

Figure 1 CSM Top Level Architecture

The data collection sensors forward data in near-real-time (<10s latency) to a central processing location. The data communications may be carried over dedicated lines, VPN-over-Internet, or some other means. The key features needed are near-real-time latency, high reliability, and at least a basic level of assurance that the data have not be tampered with while in transit.

The central processing location is required since many of the assessments and analyses to be conducted require simultaneous observations from multiple stations. To that end all data received from the distributed sensors goes through a data reception process that normalizes formats, characterizes the amount of data collected against the amount expected, and calculates desired intermediate results where necessary. The data and intermediate results are then passed in two directions: (1) to an event detection process, and (2) to an archive.

The event detection process is designed to address those CMPS requirements that have detection time requirements in the range of minutes. In general, these are items that indicate some problem in the signal-in-space that will likely be of interest to the satellite operator and can only be addressed by operator action. As a result, the event detection process is a real-time automated operation that detects threshold violations or the occurrence of specific conditions. When such events occur, the event detection process logs the event to the archive and sends a message to the satellite operators.

It is particularly important to note that effective CSM by an organization outside OCX requires some means for the

CSM events to be forwarded in real-time to the satellite operators. In the case of a Non-OCX architecture it is assumed that there is a CSM operator terminal that is not part of OCX, but is somewhere in view of the operators and serves as a remote connection over which the real-time events may be received.

The text labeled "Air Gap" illustrates the fact that the OCX and Non-OCX systems are not physically connected and cannot directly exchange information. This has important ramifications:

- Any CSM reports produced by OCX must be physically copied from OCX in accordance with appropriate information assurance (IA) procedures and imported into the Non-OCX CSM for redistribution to the civil community.
- While the operators and navigation analysts will have access to Non-OCX CSM capabilities as well as OCX capabilities, the results will be presented through separate terminals. This avoids any IA concerns that would arise from attempting to directly import Non-OCX CSM results into OCX; however, the operators will need to look to two places for CSM results which adds operational complexity.

Not all CMPS requirements are real-time in nature. Many requirements need statistical analyses with relatively long averaging times (a day, a month. or a year). In such cases, a set of statistical analysis processes is implemented within the central processing location. Each process is initiated on a timeline consistent with the averaging time and the desired repetition rate. All processes are fed by data from the archive. As statistical results are generated they are stored back into the archive. In that case, the results are not fed directly to the operator, but to the navigation analyst. This is in keeping with the longer-term nature of the results. These results will typically speak to longer term trends that confirm things are going well or indicate a trend that may require action prior to exceeding a threshold. Such results are more likely to be of use to the navigation analysts who can consider what steps are appropriate while keeping in mind that an immediate response may be neither required nor appropriate.

Finally, the central processing center will support “reach-back” into the archive by the navigation analyst. Time-histories of past results will be available from the archive on request. For example, if the navigation analyst wishes to see the URE or observed range deviation (ORD) history for a particular space vehicle (SV) for a particular time frame or to examine the trend of a metric over a period, those data should be available in tabular or graphical form in real-time via a browser interface.

OPERATIONAL ASPECTS

Civil signal monitoring per the CMPS requirements encompasses two competing objectives. One is civil agency access to the performance statistics accumulated by the civil signal monitoring system (CSMS). The other is operator notification of time sensitive events or warnings. For the purposes of considering operational integration, the CMPS requirements set is divided into the following two categories:

Category 1. Those monitoring requirements which result in a direct and timely GPS operator action (within minutes)

Category 2. All other civil monitoring requirements including those for publication of GPS service performance levels

From the operational perspective, Category 1 is part of the GPS signal integrity function whereas Category 2 constitutes a report of GPS system performance. Category 1 requirements include clearly defined steps for operators to follow making these actionable alerts. Category 2 requirements involve providing information to support staff to help guide investigations, making these informational notifications.

A CSMS based exclusively on only one or the other of an OCX or Non-OCX implementation is technically possible; however, the conditions imposed by Information Assurance (IA) on systems used to stimulate operator action and conversely the barriers to releasing unclassified information held on a classified system severely restrict feasible implementation options because of costs associated with IA compliance. The OCX implementation option is, programmatically, easier for Category 1 requirements but limited for Category 2 requirements. Conversely, the Non-OCX implementation is easier for Category 2 requirements but quite difficult for Category 1 requirements.

This inherent preferencing of implementation options against the requirement categories implies that a hybrid implementation of the civil signal monitoring system is likely to provide a more viable solution. In this paper, we identify aspects of CSMS operational integration particular to the two Categories.

We summarize essential characteristics of effectively integrating CSM with satellite operations:

1. actionable alerts for operators, including unambiguous statements of the fault or anomaly, along with clear guidance on steps to take to mitigate the effect
2. integration of technical capabilities into the baseline software and command and control

systems, and development of technical orders, standard operating procedures, training materials, and standards, used to incorporate CSM into crew position duties
3. availability of CSMS data/metrics to navigation analysts serving a support role to the operators
4. immediate reporting of alerts and warnings to the GPS Support Triad (NOCC/NAVCEN/GPSOC) of all alerts and warnings monitored by the CSMS
5. daily report to the GPS Support Triad (NOCC/NAVCEN/GPSOC) of all daily statistics monitored by the CSMS
6. periodic (monthly/quarterly/annually) reports of specified performance statistics
7. preparation of standard operating procedures for satellite operators and/or support staff

Regardless of OCX/Non-OCX implementation, under good engineering practice, integration of the CSMS into operational procedures should follow a phased progression in which the degree of integration increases gradually over time. Such a progression not only increases confidence in CSMS capabilities but also reduces the residual operational risk of faults causing unintended consequences in the operation of the GPS system. This progression also aligns with the availability of civil signals in which a plurality of broadcast civil signals will be observable long before they are monitored to support trusted navigation.

COST METHODOLOGY

The key elements in a cost estimate are the economic life, the development period, and the reference year for the system under consideration. Economic life represents the operational lifetime of the system. Guidance from the FAA [22] indicates that the OCX economic life is 20-years, since OCX is a software-intensive large-scale system.

We assume the development period for any alternative in the Trade Study is two years; with development taking place specifically in FY2015 and FY2016. We further assume that development costs are split evenly between these two years for any alternative. We assume that operations begin in FY2017. The life-cycle of the system is the total time invested in the system; which in this case is 2 + 20 years = 22 years; covering FY2015 through FY2037. We assume that the reference year for economic analysis is FY2014.

We assume that we are only interested in costs that are specifically attributable to Civil Requirements. Costs potentially associated with CSM implementation but borne elsewhere, specifically by the US Air Force or NASA, are not considered in our economic analysis.

A standard metric for comparing costs associated with different alternatives is net present value, or NPV. The key parameter in NPV analysis is the discount rate. We assume that we are conducting a cost effectiveness analysis, as opposed to a benefits analysis. Guidance [23] on the discount rate for a cost effectiveness analysis is to use the Treasury bond yield for a time period roughly corresponding to the sum of the development period and the operational life cycle; which is 22 years in this case. We therefore use the yield for a 20-year Treasury bond as the discount rate, which on 11 February 2014 was 3.42% [24].

We use three types of cost construction in this report.

1. Then-Year dollars ($TY), which represent budgeted costs with inflation properly accounted for.
2. Base Year dollars ($BY), which represent the cost in a given year referenced to the base, or reference year, in this case FY2014. $BY are $TY with inflation taken out.
3. Present Value dollars ($PV), which represents the dollar value in a given after discounting. If d is the discount rate and $\$BY_n$ is the cost in Year n in base year dollars, then the $\$PV_n$ for this specific case is calculated as $\$BY_n/d^n$. NPV is calculated as the sum of $\$PV_n$ over the life-cycle activities by year.

We use $TY in this report when discussing development costs. We use $BY when discussing operations and maintenance (O&M) costs, and we use $PV and NPV when comparing Trade Study alternatives.

COST EFFECTIVENESS ASSESSMENT

The Trade Study team compared the level of requirements fulfillment to the projected costs (unadjusted net present value). These are summarized in Table 3 and illustrated in Figure 2.

Note that none of the solutions is able to fully satisfy all of the CMPS requirements. The hybrid solutions come close but are unable to meet all the time-to-detect requirements of CMPS Table 3.5-1. Further, there is little variation in the cost-effectiveness for the group of alternatives with high effectiveness (score >80%) suggesting that additional criteria can be applied in making a choice.

Table 3 Cost-effectiveness Assessment

Trade Study Alternative	Weighted Score	Cost $M (NPV)	Effectiveness / NPV
Full CMPS (Contractor ROM of May 2012, for reference only)	95	133.0	0.7

Alt 1 - OCX P6	46	27.7	1.7
Alt 2 - OCX P12	61	42.7	1.4
Alt 3 - Non-OCX without SQM	80	45.0	1.8
Alt 4 - Non-OCX with SQM	86	50.5	1.7
Alt 5 - OCX P2+Non-OCX with SQM	94	56.8	1.7
Alt 6 - OCX P3+Non-OCX with SQM	94	58.3	1.6
Alt 7 - OCX P6+Non-OCX without SQM	90	72.8	1.2
Alt 8 - OCX P3+Non-OCX without SQM	89	52.8	1.7

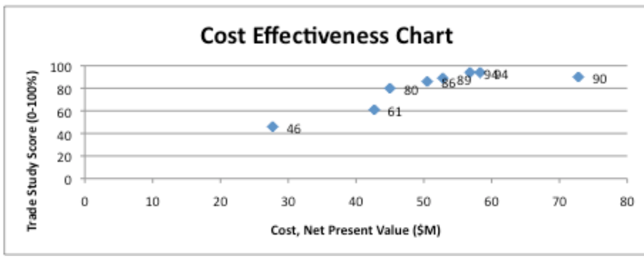

Figure 2 Cost Effectiveness Chart

In determining a "best" course of action, we consider alternatives that are able to provide a most cost-effective solution for each of the categories identified earlier (Key Elements of CSM):

1. Metrics verification
2. Operations notification and situational awareness
3. Civil user notification and situational awareness
4. Signal quality monitoring
5. Archive
6. Signal monitoring

If the decision criterion is to maintain the deployment cost below $30M, then Alternative 1 (RTN P6) is the best choice. However, there is significant risk that the cost to complete P1-P6 will increase above $30M based on OCX development history to date. Further, the SQM capability addressed by P6 is limited to L1 C/A only, so it is not as compelling a capability to acquire. For this assessment, we understand that life-cycle costs will be more than just development costs, however these do not fall within civil CSM funding cost since they will be borne by the USAF in operation and maintenance of the GPS service.

If the decision criterion is to acquire the optimal cost-effectiveness of satisfied requirements, then Alternative 3 (Non-OCX without SQM) is the best choice. As envisaged, this alternative would not provide alerts and warnings to GPS operator displays and it would not provide SQM monitoring.

If the decision criterion is to establish effectiveness in both categories of the key objectives stated in the OPERATIONAL ASPECTS Section, then Alternative 5 (RTN P2 + Non-OCX with SQM) is the best choice. This hybrid pairs the complementary features of the OCX and Non-OCX options and ameliorates their respective deficiencies, specifically OCX's barrier to civil access of monitoring information and Non-OCX's barrier to stimulating GPS operator corrective action on broadcast signals available to the civil community. Because Alternative 5 is more cost-effective that Alternative 6 by only a small margin, the recommendation from the Trade Study is to pursue Alternative 5 from the OCX vendor for P1-P2 with an option for P3 and from the Non-OCX vendor for an implementation including SQM.

TRADE STUDY OUTCOMES

Based on evaluations of key metrics including risk, requirements, cost, and integration with operations, the Trade Study recommended a hybrid system as defined in Alternative 5 or Alternative 6. The hybrid system places as much monitoring capability within the OCX system as is cost-effective and satisfies the balance of the CMPS monitoring requirements with a Non-OCX system which has a remote terminal co-located with the GPS Operators.

As discussed earlier in the paper, this recommendation effectively places a cut-line on the OCX ROM cost estimate. Those requirements above the cut-line would be boarded by the GPS Directorate onto the OCX baseline. The residual requirements that can be achieved by the Non-OCX would then require additional acquisition and maintenance.

A contributing externality with regard to use of the GDGPS as the Non-OCX model is the operational proximity GDGPS holds with current GPS operator procedures. Specifically, GDGPS is the primary reference data provider to the Tactical Analysis Toolsuite for 2 SOPS (TAT2) used by GPS operators and navigation analysts. Regardless of any actual choice on a Non-OCX element it is strongly recommended that the civil community continue active engagement with the USAF to establish operational procedures for GPS control of signals used by the civil community that utilize increasing amounts of Non-OCX monitoring information over time.

CONCLUSIONS AND FORWARD LOOK

The hybrid solutions identified in the Trade Study are good ones with Alternative 5 and Alternative 6 being the best in the authors' opinion. They provide cost-effective coverage of CMPS requirements and at the same time leave significant flexibility in relaxing the cost and schedule burden over time. Further, the more immediate need of having continuous monitoring by the GPS operators on at least some aspect of the L1 C/A, L2C, L5, and L1C signals is achieved.

In looking forward the DOT and SMC/GP have recently (August 2014) completed a new Interagency Agreement under which the CSM requirements acquisition can proceed. The GP is actively working the development of a request for proposal for placing the CSM requirements onto the OCX contract. This RFP is targeted at the P1-P2 requirements with an option for the P3 requirements and answers the most pressing need operator control of the broadcast signals based on CSM.

The complementary function needed directly by civil stakeholders is performance monitoring of the GPS service. Under Alternatives 5 or 6, performance monitoring and reporting is provided by the Non-OCX element and is directly accessible which addresses a long-standing gap in our responsibility (by international agreement) to monitor performance levels. A solid base for moving the Non-OCX element of CSM forward has been established by the formative discussions carried out in the Trade Study effort.

However, we see two significant challenges in successfully improving civil signal monitoring of GPS. The first challenge, which is not new, is funding. Both the OCX acquisition and the Non-OCX acquisition and subsequent operation will require funding at modest but non-trivial levels. This is particularly true of civil agencies which have found pooling of funds to be difficult if not impossible. To the good, we believe that the combination of architecture choices and decreasing infrastructure costs on mature technology such as GPS can make CSM achievable.

The second significant challenge returns to the IA perspective of competing objectives between operator control of GPS and dissemination of GPS performance information. The primary mitigation we see available here is institutional communication. Flow of information, particularly bi-directional, will require strong trust in those aspects of the system where benefits lie commonly in both civil and military interests. Those benefits are often easier to see operationally, but only after official acceptance/agreements are made at the highest level can operations take place.

REFERENCES

[1] 2012 Federal Radionavigation Plan, Section A.2.1
[2] "Global Positioning System Fully Operational", US Air Force Space Command Public Affairs, 17 July 1995
[3] 2012 Federal Radionavigation Plan, Section 3.2.5
[4] 2012 Federal Radionavigation Plan, Section 5.2.4
[5] 2012 Federal Radionavigation Plan, Section 5.2.2
[6] OminSTAR Differential Correction Service, http://www.omnistar.com
[7] NavCom StarFire Differential Correction Service, http://www.navcomtech.com/wps/dcom/navcom_en_US/products/equipment/cadastral_and_boundary/starfire/starfire.page
[8] NASA/JPL Global Differential GPS Service, http://www.gdgps.net
[9] 2012 Federal Radionavigation Plan, Section 5.2.1
[10] 2012 Federal Radionavigation Plan, Appendix E
[11] GPS Civil Signal Monitoring Specification, DOT-VNTSC-FAA-09-08, 30 April 2009
[12] Global Positioning System Standard Positioning Service Performance Standard, 4th edition, September 2008
[13] Navstar GPS Space Segment/Navigation User Interfaces, IS-GPS-200, current edition
[14] Navstar GPS Space Segment/ User Segment L5 Interfaces, IS-GPS-705, current edition
[15] Navstar GPS Space Segment/ User Segment L1C Interfaces, IS-GPS-800, current edition
[16] Civil GPS Service Interface Committee Report, http://www.gps.gov/cgsic/states/2014/halethorpe/hamilton.pdf, 2014
[17] Nationwide Differential GPS System Report, http://www.gps.gov/cgsic/meetings/2010/hernaez.pdf, 2010
[18] Raytheon Company, Special Study on Implementing Civil Signal Monitoring, CDRL A064-008, 24 May 2012
[19] GPS III Control Segment Specification, SS-CS-800, March 2014
[20] Global Positioning System Civil Signal Monitoring Trade Study Report, DOT-VNTSC-FAA-14-06, 6 March 2014
[21] Unit Specification for a Third Generation WAAS Reference Receiver, DTFAWA-09-C-00045, 12 July 2012
[22] FAA, Guidelines for Defining the Required Service Period, Analysis Period, and Economic Service Life, 1996
[23] OMB Circular No. A-94 'Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs'
[24] http://www.treasury.gov/resource-center/data-chart-center/interest-rates/Pages/TextView.aspx?data=yield