GPS Civil Signal Monitoring Trade Study Report
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DEPARTMENT OF TRANSPORTATION

GLOBAL POSITIONING SYSTEM (GPS) CIVIL SIGNAL MONITORING (CSM) TRADE STUDY REPORT

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Executive Summary

This GPS Civil Signal Monitoring (CSM) Trade Study has been performed at the direction of DOT/FAA Navigation Programs as the agency of reference for consolidating civil monitoring requirements on the Global Positioning System (GPS). The objective of this trade study is to develop recommendations to DOT leadership on viable paths for achieving the requisite monitoring of GPS broadcast signals used by civil agencies. Civil unique GPS signal monitoring needs have been consolidated into the GPS Civil Monitoring Performance Specification (CMPS). The trade study activity examined alternatives including use of the Next Generation Operational Control System (OCX) segment as well as Non-OCX elements for implementing civil signal monitoring, completed a comparative evaluation of the OCX/Non-OCX/hybrid alternatives available, and documented assumptions and risks associated with the trades.

The CMPS 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 (SPS-PS), 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). The implementation of a civil signal monitoring system that satisfies these requirements will allow operators and users to continuously verify that performance standards and commitments on civil use of GPS broadcast signals are achieved and inform the operators if action needs to be taken. To the extent practicable, each CMPS-defined metric is traceable to one or more specifications or commitments of performance. In cases where the metric is an indirect measurement of performance, the connection between the metric and the standard is explained and the threshold and/or goal necessary to achieve acceptable performance provided.

The CMPS also addresses operational needs such as timeliness of notification or action, archiving of key data and events to support future improvements in GPS service, and retrieval of performance data and events to respond to external queries about actual GPS service levels.

The CMPS is a requirements document and does not postulate or dictate 'how' civil monitoring will be performed nor does it address the monitoring system architecture. The objective of the CMPS was to provide the current requirements for monitoring of the GPS signals for use by the U.S. Government in planning GPS development efforts. As a result, many of the requirements contained in the CMPS may be incorporated into the OCX, while other requirements may be allocated to other government entities for implementation.

Based on evaluations of key metrics including risk, requirements, cost, and integration with operations, this trade study recommends a hybrid system. 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. To implement this alternative, OCX requirements would be accomplished through the existing OCX acquisition process while Non-OCX requirements would be phased into operational procedures as a progression from Navigation Analyst support, to GPS Operations Center (GPSOC), to potentially 2nd Space Operations Squadron (2 SOPS) technical orders for operational control of GPS broadcast signals used by the civil community.

This recommendation effectively places a cut-line on the Civil Signal Monitoring (CSM) rough order of magnitude (ROM) cost estimate prepared by the OCX contractor. Those requirements above the cut-line would be boarded by the GPS Directorate onto the OCX baseline. The residual requirements would then be satisfied by acquisition and maintenance of a Non-OCX system. Specifically the recommendations are:

1. Submit a request for proposal to Raytheon for buying P1-P2 with an option for P3 requirements
2. Submit a request for proposal to NASA JPL for buying and maintaining the Non-OCX element with SQM monitoring
3. The civil community should engage with Air Force Space Command 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.

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1 SCOPE

1.1 SCOPE

The CSM Trade Study examines viable Trade Study Alternatives for implementing civil monitoring as described in the GPS Civil Monitoring Performance Specification (CMPS), assesses the cost effectiveness and risks of each, and summarizes the results for determining a course of action.

1.2 INTRODUCTION

The Trade Study team considered two operational methods for civil signal monitoring (CSM). One is implementation under the Next Generation Operational Control System (OCX). The other is use of a CSM system provided by a civil government agency, which we are calling the Non-OCX system. One such Non-OCX system proposed is the Global Differential GPS (GDGPS) service operated by NASA JPL, although this service could be provided by other federal agencies.

In performing this Trade Study, we use information supplied by the US Air Force GPS Directorate (GP) and by NASA JPL to assess capabilities, cost, operational impacts, and risk.

1.3 BACKGROUND

1.3.1 CSM Mission

In order to fulfill its mission, the Global Positioning System must both provide signals and services to support user positioning, navigation, and timing services. Monitoring of those signals is necessary so that operators and users are aware that the service is meeting its stated commitments. The GPS Civil Monitoring Performance Specification (CMPS) is the document adopted by civil federal agencies to identify the requirements for implementing civil signal monitoring.

The CMPS 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. In cases where the metric is an indirect measurement of performance, the connection between the metric and the standard is explained and the threshold and/or goal necessary to achieve acceptable performance provided.

The CMPS also defines the scope and range of monitoring needs not directly traceable to the key 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). The CMPS also addresses the need for archives of key data and events to support future improvements in GPS service and to respond to external queries about actual GPS service levels.

The CMPS addresses the current L1 C/A signal and the GPS Standard Positioning Service (SPS) provided via that signal. It also includes the L2C and L5 signals and semi-codeless use of the GPS signals, along with the planned L1C signal.

In this document, civil signal monitoring is defined to incorporate the following key elements:

- Metrics verification – verification that signal and service performance meets commitments made in SPS Performance Standard, interface specifications, and other government specifications
- Operations notification and situational awareness– timely notification to satellite operators of real-time GPS anomalies and situational awareness of civil signal performance
- Civil user notification and situational awareness – notification to civil authorities and agencies or GPS anomalies and situational awareness of civil signal performance
- Signal quality monitoring – assessment of carrier waveform and code performance to ensure within designated limits
- Archive – archival of CSM reports and data for retrieval by satellite operators and civil authorities
- Signal monitoring – monitoring of the four civil signals (tracking the codes and verifying the navigation data): L1 C/A, L2C, L5, and L1C

Civil agencies have been working with the US Air Force to implement capabilities identified in the CMPS into the OCX as appropriate. Not all requirements identified in the CMPS are intended to be implemented in the OCX.

CSM is expected to be used by the following groups:

- Satellite operators in the 2 SOPS. Used for assessing current performance and providing actionable data for operating the constellation.
- Navigation analysts (day shift) in 2 SOPS and support contractors. Used for investigations into satellite performance and resolving anomalies.
- User support Triad personnel, comprised of the GPSOC, US Coast Guard Navigation Center (NAVCEN), and FAA National Operations Control Center (NOCC). Used in providing support to constituent users.
- Constellation managers. Used by those determining which satellites for placement in the constellation and which to replace.
- Civil authorities. Used by civil authorities in evaluating constellation mission performance for civil signals and reporting on ability to meet U.S. Government service commitments.

1.3.2 Requirements

Requirements for CSM come from the CMPS. The CMPS was initiated by the Acquisition Liaison for Civil Applications at the GPS Directorate (SMC/GPC), but was later amended and completed by an interagency group of civilian and military agencies, called the Signal

Monitoring Working Group. This group, formed in part to address GPS Directorate concerns that a defined operational concept for CSM was needed, met between 2008 and 2010 to examine signal monitoring for OCX and beyond, and to answer questions posed by USAF personnel such as: What does "signal monitoring" mean? What is being done for situational awareness? What/whose data is being used? and Who is responsible for each component of GPS signal monitoring?

While the CMPS stipulates civil requirements for monitoring the civil signals, it does not prescribe the solution for implementation. The Trade Study is one phase of determining the path toward implementation.

The CMPS allocates its requirements to the following groups to fulfill mission needs:

- System Performance – service commitments largely derived from the GPS SPS Performance Standard
- Civil Signal Monitoring – verification of ranging codes, signal quality monitoring, verification of semi-codeless commitments, and verification of the navigation message
- Non-broadcast Data Monitoring – verification of GPS status information provided to users, including almanacs, Notice Advisory to Navstar Users (NANU), and operational advisories
- Reporting and Notification – reporting anomaly and status information to satellite operators and civil agencies
- Analysis and Data Archiving – retention and archive access of monitoring data and analysis
- Infrastructure – information assurance, reliability, and system status requirements
- Operations Integration – integration into satellite operations to meet operational needs

1.3.3 High-level Functional Architecture

At a high-level, a multi-tier implementation of the CSM is considered, comprised of elements from both the OCX and a Non-OCX CSM. Each of these two architectural components will be able to accomplish some but not all of the CMPS requirements. The OCX portion will have the advantage of being able to implement monitoring that enables real-time response by operators to anomalies. However, this version is constrained by funding limitations permitting only a fraction of the total 193 CMPS requirements set to be implemented, namely those deemed "fully satisfied" or "with high satisfaction" in the OCX baseline [Reference 2]. Within this Trade Study report, we will use the term "Highly Satisfied" for CMPS requirements that the OCX baseline is able to accomplish "with high satisfaction". The Non-OCX portion is intended to satisfy most of the requirements not able to be accomplished in the OCX CSM.

The "Fully Satisfied" and "Highly Satisfied" requirements were divided into twelve categories with priorities categorized by civil stakeholder for the OCX cost estimate to support selection of highest priority features for available funds, as shown in Table 1.3-1. Thus for example, if funding only permits three categories to be implemented, then OCX would incorporate requirements from categories P1 through P3. As another example, if funding permits six categories to be implemented, then OCX would incorporate requirements from categories P1 through P6.

Table 1.3-1 CMPS Requirements categorized by civil stakeholder priority

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	

NASA JPL has proposed implementing the Non-OCX CSM using their GDGPS. Under their approach, they will be able to implement all CMPS requirements, except for the following:

- CMPS 3.1.3.b - Verify 95% Signal in Space user range error (URE) for zero age of data (ZAOD) < 6 m. This requires access to OCX Kalman filter output which is not available to JPL.
- CMPS 3.2.3.a,b - Verify that L2 and L1 are modulated with same P(Y) code and nav message. This requires a classified receiver which is not available to JPL.
- CMPS 3.8.a - Incorporate CSM results into GPS operations. As currently envisioned, the CSM design proposed by JPL cannot be incorporated into GPS operations at 2 SOPS.
- CMPS 3.2.2.a,b,c,d,e,f,g,h – Verify the terrestrial and orbital received power is at or above thresholds.

1.3.4 Lower-level Components

Within each set of requirements for OCX and Non-OCX CSM solutions, further refinements are made. The OCX requirements are aggregated by priority subsets based on inputs collected in the study, including additional input on criticality, cost, operational considerations, and overlap with the Non-OCX CSM.

The Non-OCX requirements have been split into two groups, those involving observables which existing reference receivers in the GDGPS network provide and a smaller group not available from the current reference network. JPL's design of a Non-OCX CSM system placed options between these two CMPS requirement groups labeled "Easy" and "Hard". The original design left open the question of make or buy receivers to meet the "Hard" requirements in the CMPS. In consultation between the Study team and JPL, the requirements in the "Hard" set are further narrowed to CMPS 3.2.1.a,b,g,h,k,lo-r; 3.2.2.w-aa. The outcome here is premised on the acceptance of a buy (rather than make) of the reference receiver as the NovAtel G-III for the "Hard" option.

1.3.5 Operational Concepts

In examining operational paths for applying CSM, we consider how personnel at the 2 SOPS customarily respond to anomalies. In some cases, immediate action is taken to remediate failed signals. In other cases, teams are formed to investigate anomalies and propose actions.

For operators to take immediate action on anomalous signals, the anomaly must be evident through the baseline command and control system, and there must be a clear path for action defined in standard operating procedures. Operators are trained to deal with anomalies and the operational concept for CSM must adhere to existing operational processes. Alternatives explored in this study range from providing a secondary terminal which can be used on an as-needed basis for assessing civil signal performance to a primary terminal with operational training and procedures which are used by operators for taking designated actions for specific anomalies.

2 CSM TRADE STUDY METHODOLOGY

This section describes the methodology used in performing this trade study on the civil signal monitoring (CSM) system.

2.1 CSM TRADE STUDY OPTIONS

A set of implementation Options is selected that represents either proposed or likely choices for implementation from the OCX and Non-OCX elements. These options are comprised of solutions and costs identified by OCX/Raytheon (RTN) and NASA JPL.

Raytheon delivered its proposed solutions and estimated costs in the following forms:

1. Special Study on Implementing Civil Signal Monitoring, CSM Implementation, CDRL A064-008, 24 May 2012 [Reference 2]
2. Presentation, 21 Nov 2013, Follow-On Civil Signal Monitoring Special Study, Rough Order of Magnitude, GPS-13.175.KG [Reference 3]
3. Rough Order of Magnitude Response to Civil Signal Monitoring Study, Attachment G, Follow-On CSM Implementation Plan, 10 Dec 2013 [Reference 4]

NASA JPL delivered its proposed solutions and estimated costs in the following forms:

1. Presentation, 31 Jan 2014, 'Leveraging the Global Differential GPS System for Cost Effective and Rapid Implementation of CSM, Proposal Outline', [Reference 5]
2. Revised Estimate, 5 Mar 2014, 'Leveraging the Global Differential GPS System for Cost Effective and Rapid Implementation of CSM: Proposal Outline, Revised Estimate' [Reference 15]

The information provided by NASA JPL for use of its GDGPS as a CSM monitor network is "representative" of a Non-OCX solution, but may not in fact be the monitoring system chosen. While there are other candidate monitoring systems that could be used as a Non-OCX solution, for the purposes of this study, the NASA JPL technical and cost data will be used as a proxy for a Non-OCX monitoring system.

The options considered in this trade study are below.

OCX:

1. RTN P2 – all Fully Satisfied and Highly Satisfied requirements up through Priority P2
2. RTN P3 – all Fully Satisfied and Highly Satisfied requirements up through Priority P3
3. RTN P6 – all Fully Satisfied and Highly Satisfied requirements up through Priority P6
4. RTN 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 fulfill CMPS requirements excluding SQM requirements identified as "Hard" by JPL
6. Non-OCX with SQM – Use of Non-OCX monitoring to fulfill CMPS requirements including those SQM requirements which can be accomplished using a NovAtel G-III receiver

In addition to the Trade Study Options identified, we also present set of requirements and cost identified in the May 2012 Raytheon Implementation Plan [Reference 2] as a point of reference.

The OCX proposed approaches identified above could cover up to 127 of the CMPS requirements (67%) if fully implemented. The Non-OCX proposed approaches could cover up to 175 of the CMPS requirements (93%) if fully implemented.

2.2 Trade Study Alternatives

The Trade Study Alternatives are combinations of the Trade Study Options chosen to assess the possible solutions. These alternatives are given in Table 2.2-1 where the first four are OCX or Non-OCX only implementations and the last four are hybrid implementations of the different Options

Table 2.2-1 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 - RTN P6			x			
2 - RTN P12				x		
3 - Non-OCX without SQM					x	
4 - Non-OCX with SQM						x
5 - RTN P2 + Non-OCX with SQM	x					x
6 - RTN P3 + Non-OCX with SQM		x				x
7 **-** RTN P6 + Non-OCX without SQM			x		x	
8 - RTN P3 + Non-OCX without SQM		x			x	

2.3 Top-Level CSM Architecture

Viewed from a high level, the CSM architecture comprises both the native OCX capability and a Non-OCX CSM capability. This architecture is illustrated in Figure 2.3-1. A block-by-block description from upper-left to lower-right follows.

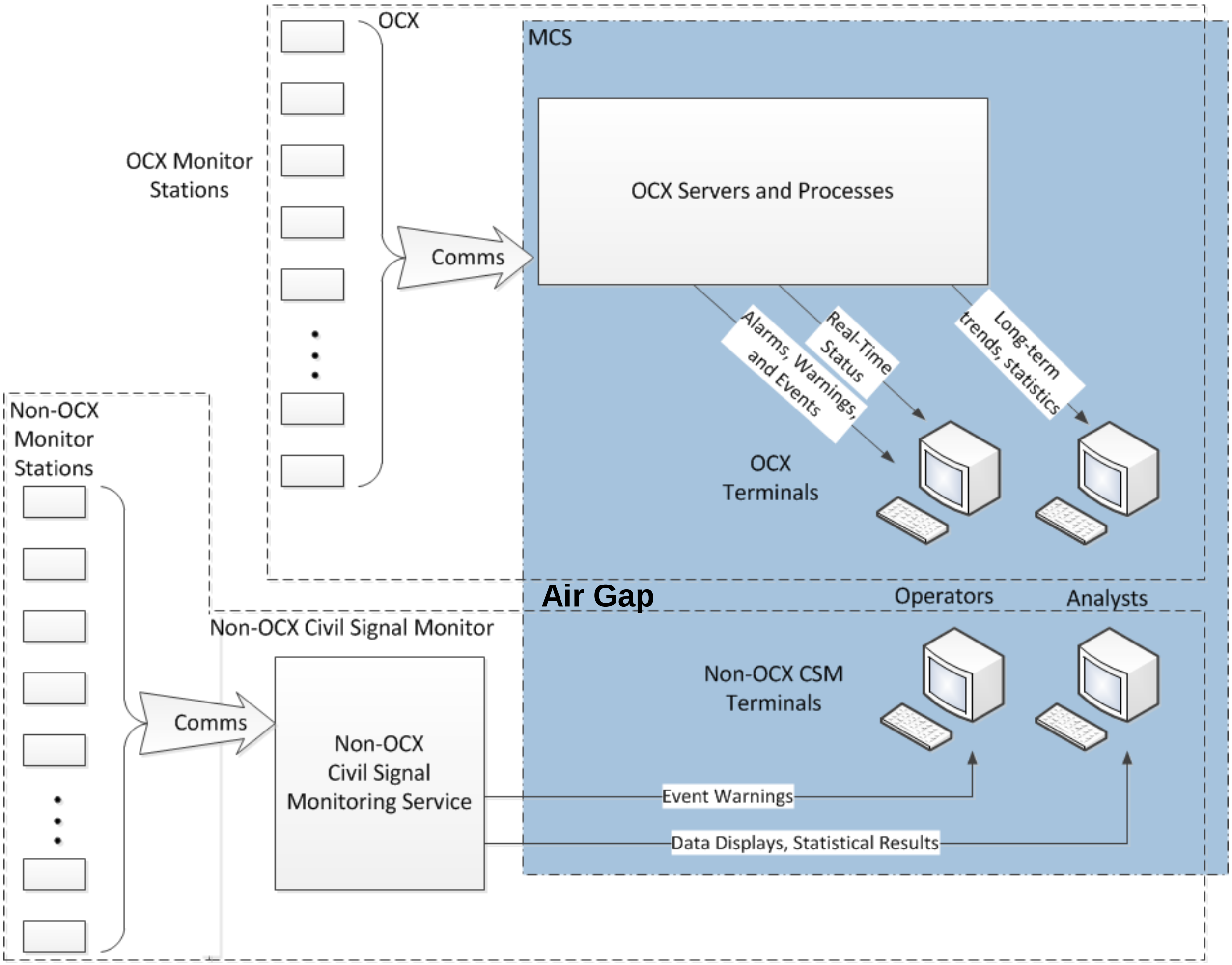

Figure 2.3-1 CSM Top-Level Architecture

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 MSN monitor stations, and the FAA WAAS reference stations.

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 actions that must be taken by the operator. 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 removed 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 analysts will have access to both the native OCX and Non-OCX CSM 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 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 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 analyst. Time-histories of past results will be available from the archive on request. For example, if the 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.

This high-level functional architecture diagram is not intended to suggest design details. The detailed design would be driven by the specific requirements that are to be addressed by a given implementation.

2.4 CSM Trade Study Evaluation Categories

Four criteria are selected for evaluating each of the Trade Study Options: integration with operations, requirements, cost, and risk. Each of these categories is discussed in sections following.

2.4.1 Integration with Operations

Civil signal monitoring per the CMPS requirements encompasses two competing objectives. The first is civil agency accessibility to the performance statistics accumulated by the civil signal monitoring system (CSMS). The second is operator notification of time sensitive events or warnings. For the purposes of considering operational integration, the CMPS requirements set is divided into 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. The reverse is true for the Non-OCX implementation. 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 CSMS is likely to provide a more viable solution. In Sections 3.2 and 4.2 below, we identify aspects of CSMS operational integration particular to the two Categories.

We summarize essential characteristics of 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 Triad (NOCC/NAVCEN/GPSOC) of all alerts and warnings monitored by the CSMS
5. daily report to the 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 CSMS 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 where a plurality of broadcast civil signals will be observable long before the coverage of those signals will support navigation.

2.4.2 Requirements

This category is used to assess the degree of fulfillment of CSM capability within each Trade Study Option. This is done by evaluating the number of CMPS requirements that are fulfilled by each Trade Study Option as viewed within a set of subcategories. The subcategories chosen are as follows.

- Metrics verification – this assessment is broken into three groups of equal value. The first is the percentage of the total 189 CMPS requirements that are fulfilled (derived from 193 total CMPS requirements excluding 4 that were dropped from the OCX list during the Follow-on Civil Signal Monitoring Special Study [Reference 3]: 3.1.2.a,b, 3.2.1.f, 3.2.4.1.h). The second is the percentage of the 33 requirements derived from the SPS Performance Standard that are fulfilled (3.1.1 through 3.1.8). The third is the percentage of the 127 requirements derived from Interface Specifications that are fulfilled (3.2.1.a-m,o-q, 3.2.2.a-l, q-v, 3.2.3.c,d, 3.2.4, 3.4.a-d, 3.5.b).
- Operator notification and situational awareness – this assessment is broken into two groups of equal value. The first is the timely response to anomalies which consists of the percentage of the categories in CMPS Table 3.5-1 with response times under five minutes which have been met. The second is the percentage of the 126 requirements identified as real-time requirements that have been met. (CMPS 3.1.4.a-d; 3.2.1.a-e,g-r; 3.2.2.m-aa; 3.2.3.a-d; 3.2.4.1.a-y; 3.2.4.2.a-w; 3.2.4.3.a-r; 3.2.4.4.a-t).
- Civil user notification and situational awareness – this assessment is the percentage of the 3 CMPS requirements involving notification (3.5.b, 3.5.d,e) that are fulfilled.
- Signal quality monitoring – this assessment is the percentage of the 32 CMPS requirements relating to SQM (3.2.1.n through 3.2.1.r, 3.2.2.a through 3.2.2.aa) that are fulfilled.

- Archive – this assessment is the percentage of the 5 CMPS requirements relating to archiving and retrieving archived data (3.6.a, b, c, f, g) that are fulfilled.
- Signal monitoring – this assessment is broken into two groups. The first is the percentage of 65 L1 C/A, L2C, and L1C CMPS requirements that are fulfilled (3.2.4.1.a-y, 3.2.4.2.a-w, 3.2.4.4.a-t). The second is the percentage of the 19 L5 CMPS requirements that are fulfilled (3.2.4.3.a-s).

The subcategories are each assigned the weights in Table 2.4-1.

Table 2.4-1 Subcategory Weights

Subcategory	Weight
Metrics Verification	10
Ops notification & situational awareness	10
Civil Users notification & sit. awareness	10
SQM	10
Archive	10
Signal monitoring	10

The weighting method assumes each category is equal in weight, except for signal monitoring. Weighting of the monitoring requirements on the L1 C/A, L1C, and L2C signals are combined and given a weight of 6. The monitoring requirements on the L5 signal are given an independent weight of 4 to acknowledge that the generation of the L5 signal on the satellite vehicle is a distinct path whereas the L1 C/A, L1C, and L2C signals are generated through a unified path. When used in determining the degree of fulfillment, the weightings are normalized to result in scores that range from zero through one hundred.

For each of the Trade Study Alternatives, a Trade Study Alternative Score is computed to assess the Alternative's fulfillment of the requirements subcategories. This Trade Study Alternative Score is a percent of fulfillment of the requirements (# of requirements fulfilled divided by total number of requirements in the subcategory) weighted by the subcategory weight. The resulting Trade Study Alternative Score is a number between 0 and 100 representing the degree of fulfillment of the requirements for each Trade Study Alternative.

A sensitivity analysis was performed to assess the variance that occurs from large swings in the weightings. Our investigations uncovered that while weighting did result in noticeable differences in the degree of fulfillment for each of the Trade Study alternatives, it did not affect the rank outcome of the assessments for the Trade Study alternatives.

2.4.3 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 [Reference 8] 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 this 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 this 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 [Reference 9] 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% [Reference 10].

We use three types of cost construction in this report.

1. Then-Year dollars ($TY), which represent budgeted costs with inflation properly accounted for. Reference [Reference 11] is used as the source for the nominal rate of inflation.
2. Base Year dollars ($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 will use $TY in this report when discussing development costs. We will use $BY when discussing operations and maintenance (O&M) costs, and we will use $PV and NPV when comparing trade study alternatives.

2.4.4 Risk Methodology

We assume a standard risk assessment in which a risk is described, likelihood and impact of the stated risk is evaluated, and the overall risk gauged. An overall guide based on FAA experience is provided in Figure 2.4-1.

Level	Likelihood	Description	Probability
A	Low: Not Likely	Existing approach and processes will effectively avoid or mitigate the risk, based on standard practices.	0% < Prob. <= 20%
B	Minor: Low Likelihood	Existing approach and processes may mitigate the risk, with minimal oversight based on similar cases.	20% < Prob. <= 40%
C	Moderate: Likely	Existing approach and processes may mitigate the risk, but alternative approach(es) may be required.	40% < Prob. <= 60%
D	Significant: Highly Likely	Existing approach and processes cannot mitigate the risk, but different approach(es) might.	60% < Prob. <= 80%
E	High: Near Certainty	Existing approach and processes cannot mitigate the risk; no known processes or alternatives are available.	80 % < Prob. < 100%

Likelihood	1	2	3	4	5
E	5	13	20	22	25
D	4	12	15	21	24
C	3	11	14	17	23
B	2	7	9	16	19
A	1	6	8	10	18
	Impact				

Level	Impact	Technical **	Schedule **	Cost **
1	Low: Program/ portfolio success not impacted.	Technical goals will still be met.	Schedule will still be met.	0% < Cost increases <= .1%
2	Minor: Negligible impact to program/ portfolio success.	Minor performance shortfall (within acceptable limits); no design or process change needed.	Schedule slip but able to meet key dates with additional activities or effort; critical path not affected.	.1% < Cost increases <= 1%
3	Moderate: Limited impact to program/ portfolio success.	Moderate performance shortfall; workarounds available, with minor design or process change needed.	Some key dates missed; workarounds available; critical path not affected.	1% < Cost increases <= 5%
4	Significant: Program/ portfolio success could be jeopardized.	Unacceptable performance; workarounds available, with significant design or process change needed.	Critical path affected; workarounds available; major milestones not affected.	5% < Cost increases <= 10%
5	High: Program success in doubt.	Unacceptable performance; workarounds not available.	Cannot achieve major milestones; rebaseline required.	Cost increases > 10%

Figure 2.4-1 Risk assessment guidelines used in this report

As a rough gauge across options we use $30M as a basis for assessing cost risk. If the impact of a risk is $5M, for example, then the percent impact is about 17% and the Impact is High.

3 OVERVIEW OF OCX CSM IMPLEMENTATION

The DOT/FAA funded a study by Raytheon to provide a rough order of magnitude (ROM) cost estimate to implement into the OCX those CMPS requirements cited as "fully satisfied" and "highly satisfied" in Raytheon's CSM Implementation plan [Reference 2]. Subsequent to that initial CSM implementation plan, Raytheon was funded to provide an updated ROM, delivered in December 2013, for implementation of CSM capability on a graduated scale by priority, depending on the funding available. Table 1.3-1 identifies the requirements to be implemented in each priority category. The cost figures used here were provided in the Raytheon ROM estimate of December 2013 [Reference 4].

3.1 OCX CSM REQUIREMENTS

The trade study team examined the prioritized requirements, and assessed their ability to fulfill the civil signal monitoring services described in the CMPS. This assessment is described in sections following.

3.1.1 Criticality of Requirements

In order to better assess the criticality of the requirements in the OCX priority categories, Trade Study team members were asked to further assess the significance of placing the requirements included in the Raytheon ROM specifically within the OCX element. Note that this exercise was not meant to re-sort the priority of CMPS requirements previously accomplished, but rather to ask team members where they might "draw the line" given limited resources available for accomplishing all 12 of the priority groups. Table 3.1-1 identifies the results, with a number showing how many of the respondents identified the priority group as higher and lower. There were five total respondents. Note that P1-P3 requirements are largely deemed critical to include in the OCX implementation. There is no strong support for keeping the remainder within the OCX element.

Table 3.1-1 Trade Study Team Assessment of Requirements Criticality

Priority Level	Higher Priority Requirements	Lower Priority Requirements
P1	5	
P2	5	
P3	3	
P4		1
P5	1	
P6	1	
P7		1
P8		1
P9		1
P10		2
P11		2
P12		2

3.1.2 Requirements Evaluation

The degree of fulfillment for priority levels of the OCX ROM is assessed and displayed in Table 3.1-2. For each of the six categories, a value is assigned between 0 and 10 indicating the degree of fulfillment. These category values are then weighted equally and used to compute a Trade Study Option Score that ranges between 0 and 100. Priorities P1 through P3 are each assessed due to the high criticality given these as explained in the previous section. Priority P4 is included simply because it is the next level beyond the last priority category deemed critical. Priority P6 is included since it the last priority category included in the Raytheon ROM that is below the $30M cut line. Priority P12 is included to bracket the cost estimate of the Raytheon ROM to implement all Fully Satisfied and Highly Satisfied requirements. Finally, the results of the May 2012 ROM assessment to implement all CMPS requirements are included to bracket the full cost estimate by Raytheon.

Table 3.1-2 Fulfillment of OCX Priority Categories

Description	P1	P2	P3	P4	P6	P12	May-12 Reference Point
Trade Study Option Score	**10**	**27**	**41**	**43**	**46**	**61**	**95**
Metrics verification	0.5	2.8	2.8	3.0	4.1	6.9	9.4
Operations notification/situational awareness	5.5	7.5	7.5	7.5	7.7	8.6	9.6
Civil user notification/situational awareness	0.0	0.0	0.0	0.0	0.0	0.0	10.0
Signal quality monitoring	0.0	0.0	0.0	1.3	1.9	4.4	8.1
Archive	0.0	0.0	8.0	8.0	8.0	8.0	10.0
Signal monitoring	0.0	6.0	6.0	6.0	6.0	8.9	9.8

From Table 3.1-2, we see there is negligible difference in fulfillment between priorities P2 through P6. The largest jumps occur between P1 and P2, P2 and P3, and between P6 and P12.

3.2 OCX CSM Integration into Operations/Implementation

SMC/GP will integrate OCX civil signal monitoring into satellite operations, in coordination with the 2 SOPS. It will integrate technical capabilities into the baseline software and command and control systems, and will develop technical orders, standard operating procedures, training materials, and standards, which will be used to incorporate CSM into crew position and support staff duties. The CSM data/metrics will be available to navigation analysts providing support to operators.

The OCX CSM does have some shortfalls in meeting the required integration of CSM with the satellite operations. The key shortfall is OCX inability to provide immediate reporting of alerts and warnings to the Triad (NOCC/NAVCEN/GPSOC). Although the OCX is planned to provide a daily report to the Triad, this report is not the detailed report of daily statistics contemplated by the CMPS, rather it is an abbreviated summary report. Likewise, the OCX has not identified any plans for providing other periodic reports of specified performance statistics.

3.3 OCX CSM COST

In this section we provide cost estimates for various RTN options. It should be noted that 'Civil Requirements' under interagency agreement between DOT and DoD includes GPS civil support to SMC/GP on the order of $3M per year, primarily staff activities. This activity is essential to maintaining a GPS Civil presence and more specifically to providing technical and material resources, as well as an oversight function, directly to the decision-making process on signal monitoring. However, these costs are exogenous to the current trade study.

OCX cost estimates for this trade study are based entirely on the rough order of magnitude (ROM) cost estimate provided under special study contract by RTN [References 4, 12]. It is important to note that the cost estimates provided by RTN as an outcome to these studies only has the fidelity of a ROM. The actual bid costs under a formal proposal could be higher or lower than the ROM estimates. Further, since the contract vehicle will likely be cost plus award fee (CPAF) there is a risk that the actual costs could be higher than the bid costs.

The basis of the RTN cost estimate is not provided here since it involves proprietary data and the introduction of proprietary data would limit the dissemination of this report. This section is divided into three subsections

1. Description of options
2. Assumptions
3. Cost estimate results

3.3.1 OCX CSM Cost Options

We consider the following four OCX options in this trade study:

1. P1-P2
2. P1-P3
3. P1-P6
4. P1-P12

The cost structure in the ROM estimate as a function of the priority levels is explicitly cumulative meaning that selection of any given priority level must include all higher priority levels.

We also consider, as a reference point, the estimated cost to implement all the CMPS defined [Reference 1] requirements that RTN felt could reasonably be met by RTN per the special study published May 2012 [Reference 2]. This cost reference point is listed in Table 5.4-1 for informational purposes only.

3.3.2 OCX CSM Cost Assumptions

We make the following assumptions with respect to the OCX cost estimate

1. No OCX O&M costs charged to Civil Requirements after deployment.
2. No systems engineering & integration (SE&I), Aerospace Corporation, or MITRE costs charged to Civil Requirements.

3. The OCX Baseline will assume full responsibility for the following activities which were not estimated by Raytheon:
    a. Deployment of CSM into the operational environments (Master Control Station and Alternate Master Control Station),
    b. Maintenance of labs and operational facilities (SITL and TSF),
    c. Providing availability in the SITL (System Integration and Test Lab aka: Integration Lab) for CSM technical order and training development as well as training delivery,
    d. Providing availability in the TSF (Transition Support Facility aka: Integration Lab) for CSM integration and test (Site Acceptance Testing).
4. OCX CSM development costs are paid for in $FY2015 and $FY2016.
5. RTN costs are reflected incrementally in bid P1-P12. If we skip a requirement in P1-P12, we cannot assume that all costs are accounted for in the total cost.
6. We take RTN cost estimates at face value.

3.3.3 OCX CSM Cost Estimate Results

This section provides cost estimates for the RTN options in this trade study. The results are taken directly from [Reference 4] and are shown in Table 3.3-1.

Table 3.3-1 OCX development, and operations and maintenance cost estimates for the four options considered.

Option	FY2015 development cost in M$TY	FY2016 development cost in M$TY	O&M cost in each year of the lifecycle in M$BY	Description
P1-P2	3.4	3.4	--	Most CMPS real-time messaging requirements met
P1-P3	4.2	4.2	--	P1-P2 plus archival
P1-P6	15.0	15.0	--	P1-P3 plus 24-hour performance displays, select message timing verification in real-time, relative C/N, and SQM
P1-P12	23.1	23.1	--	URRE, URAE, UTCOE, PDOP, URE, absolute power, constellation performance and navigation message timeliness

P4 includes ‘container’ costs that are specific to standing up “Fullerton labs, segment SE (system engineering), and I&T (integration and test)” [Reference 12]. Apparently these Fullerton capabilities will be ramped-down after completion of Block 1 if not required to support specific CSM capabilities, for example, P4 and P6.

As a reference point for all cost estimates we consider the May 2012 ROM cost [1] provided by RTN for all CMPS requirements that could reasonably be met by OCX. In the RFC 67 and RFC 106 study report [Reference 2], RTN indicated that 13 CMPS requirements could not be met. The remaining 162 requirements were projected by RTN to cost $101.5M (RFC 67) + $48.2M (RFC 106) = $149.7M on a ROM basis, or $133M NPV. The identified 162 requirements covered by RFC 67 and RFC 106 would be completed in Block 3; with partial completion of some requirements in Block 2.

We consider the question as to whether this ROM estimate represents a floor or ceiling to the probable actual cost to implement the full set of CMPS requirements that are identified as feasible for OCX. We do not know exactly how the RFC 67 SLOC count is partitioned between P1-P12 and the remaining requirements, but we can examine the RFC 67 cost basis and compare to the P1-P12 cost basis. This analysis was conducted and the conclusion is that the RFC 67 ROM cost estimate represents a floor, and not a ceiling, for the likely actual cost to implement. Therefore, at a minimum the cost to implement the full set of CMPS requirements that are identified as feasible for OCX is approximately $150M in $TY, or $133M NPV. We assume that these development costs include P1-P12 as a subset; and development would nominally take four years; across Blocks 2 and 3.

3.4 OCX CSM Risk

Technical and Cost risks have been identified and are illustrated in the Risk Matrix in Table 3.4-1. These risks are explained in succeeding sections.

Table 3.4-1 OCX CSM Risk Categorization Matrix

Likelihood					
			R3a		
			R3d		R3c
	R3b				
	Impact				

3.4.1 OCX CSM Technical Risk

There is a risk that the CSM provider misunderstands the intent of the CMPS and either (a) implements something that does not address a requirement, or (b) implements something that goes farther than intended. Either direction results in a loss of scarce resources and impacts cost and/or schedule. Despite several conversations with RTN, we continue to discover misunderstandings. Mitigation: (a) the implementers have access to subject matter experts that can interpret the government intent (b) the government insists on in-depth review of the algorithms and the form of the results prior to significant implementation effort. This risk extends to all priorities P1 through P12. Due to past experience and the proposed path of RTN, we see this risk as Highly Likely. If it does occur, its significance is rated Moderate. [Risk R3a]

3.4.2 OCX CSM Cost Risk

The cost risk associated with P1 through P3 is likely Low. This is because it essentially involves taking existing OCX measurements, comparing, thresholding, and displaying to the operator. This has already been accomplished end-to-end on Block 1 for select measurements; so it should be a relatively well-defined process. [Risk R3b]

There is a risk associated with use of the Fullerton facility in OCX development. If schedule delays occur in Block 2 OCX, whether specific to CSM or not, there could be a ripple effect that could necessitate extended use of the Fullerton facilities and the impact would be the accrual of additional container costs to use the facility. This risk extends to P4, P6, P7, and P9 whether collectively or individually. The likelihood is assessed as Likely based on prior OCX experience. Block 1 and Block 2 development overlapped to a considerable degree with ready to transition to operations for the two blocks separated by about 9 months. If we combine this with the Block 2 schedule timeline and known Fullerton costs on WAAS we can conjecture that the cost to stand-up Fullerton amounts to about $800K per month. Delays in OCX schedule could translate directly into costs accrued on a month-by-month basis. Maximum delays are conjectured to be on the order of 6 months (two quarters), nominal delays 3 months (one quarter), and 80th percentile bound delays would then be about 4.8 months. This translates into 4.8 months x $800K/mo = $3.84M, or about 13% of base. The Impact is therefore High. The overall risk is High. [Risk R3c]

P5 has cost risk in going from the current 5^{o} grid to the 1^{o} grid desired by the civil community. We address this risk by assuming that the current 5^{o} grid is the baseline implementation in P5 rather than a 1^{o} grid. We rate this risk as Likely, but only extends to Priority P5 and above. Its impact is Moderate. [Risk R3d]

4 OVERVIEW OF NON-OCX CSM IMPLEMENTATION

NASA JPL maintains the GDGPS network as a worldwide monitoring system for all of the GPS civil signals. Figure 3.4-1 displays the location of GDGPS reference stations. GDGPS's strength in detecting anomalies such as those specified for monitoring in the CMPS is the density of the reference network. One limitation of GDGPS, however, is that the system is external to the operational control of GPS, and thus not integrated into mission operations. The operational concept for making operators aware of anomalies has not been worked out. This is discussed in more detail in Section 4.2, Integration into Operations.

JPL provided the following background on GDGPS in their design concept for a CSM system.
Robust tracking network

- 75+ global tracking sites deployed, controlled, operated, and maintained by JPL
    - The network is either fully owned by NASA or secured through long-term international agreements and contracts
    - GDGPS hardware and software fully owned and controlled by JPL
    - Decades of site stability, quality, and continuity
    - Highly resilient to the loss of data from any country
- 125+ sites equipped with geodetic-quality receivers and reporting data in real-time
    - Operated by a variety of foreign agencies (e.g., ESA, BKG, GA)
    - Provide additional level of redundancy and diversity

Monitoring GPS with 25-fold redundancy on average with the GDGPS network alone

- Enables strong majority voting schemes for high reliability
- Resilience to spoofing demonstrated during OCX PRDA

Monitored signals: CA, P1&P2 (semi-codeless), L2C, L5

- Phase and pseudo-range at 1 Hz; 1 second latency
- Navigation message bit-by-bit (LNAV and CNAV)
- SNRs

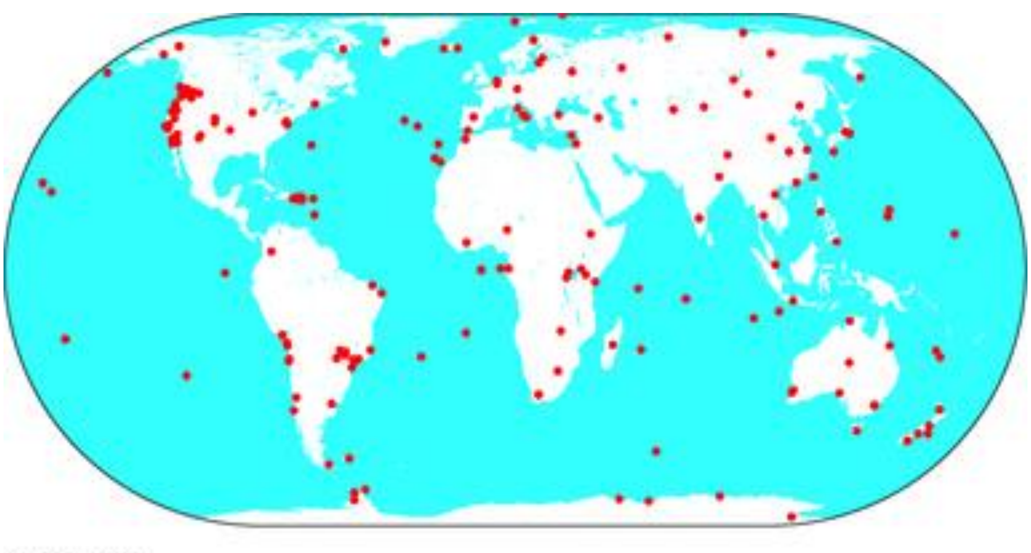

Figure 3.4-1 GDGPS Tracking Sites

Furthermore, JPL has provided a design option that would use the NovAtel G-III receiver in specific CSM monitoring stations for satisfying some of the CSM functions. This study treats the JPL design concept assertions on satisfaction of CMPS requirements with the same level of acceptance as those assertions made by the RTN ROM.

4.1 NON-OCX CSM REQUIREMENTS

JPL states they are able to incorporate all CMPS requirements with the exception of four:

CMPS 3.1.3.b - Verify 95% SIS URE for zero age of data (AOD) < 6 m. This requires access to OCX Kalman filter output which is not available to JPL.

CMPS 3.2.3.a,b - Verify that L2 and L1 are modulated with same P(Y) code and navigation message. This requires a classified receiver which is not available to JPL.

CMPS 3.8.a - Incorporate CSM results into GPS operations. As currently envisioned, the CSM proposed by JPL cannot be incorporated into GPS operations at 2 SOPS.

In addition, based on further consultations with JPL, and civil observations with respect to the utility of the WAAS reference receiver (NovAtel G-III) rather than building a custom receiver, the eight absolute power monitoring requirements were excluded:

CMPS 3.2.2.a,b,c,d,e,f,g,h – Verify the terrestrial and orbital received power is at or above thresholds.

Where the G-III receiver does not support these power assessments, such monitoring functions would need to be performed by a calibrated measurement system.

4.1.1 Non-OCX CSM Requirements Evaluation

In their proposal, JPL self-certifies their ability to meet CMPS requirements. They also provide a spreadsheet listing each CMPS requirement and their assessment as to whether they could implement it or not. Based on this input, the trade study team assesses the ability of the GDGPS to fulfill the requirements of the CMPS. The degree to which the JPL GDGPS solution fulfills CMPS requirements is provided in Table 4.1-1. For each of the six categories, a value is assigned between 0 and 10 indicating the degree of fulfillment. These category values are then weighted equally and used to compute a Trade Study Option Score that ranges between 0 and 100.

Table 4.1-1 GDGPS Fulfillment of CSM

Description	Without SQM	With SQM
Trade Study Option Score	**80**	**86**
Metrics verification	8.9	9.4
Operations notification/situational awareness	4.3	4.9
Civil user notification/situational awareness	10.0	10.0
Signal quality monitoring	4.7	7.5
Archive	10.0	10.0
Signal monitoring	9.9	9.9

4.2 NON-OCX CSM INTEGRATION INTO OPERATIONS

The Non-OCX implementation is envisioned to provide at least two types of operator screens: a screen for satellite operators to use in monitoring the signals, and a screen for analysts to use in assessing signal performance.

The Non-OCX CSM is not expected to be used to direct operators to take action on an SV. Instead, it will be used to inform operators to corroborate any reports with the OCX system and then to follow standard operating procedures.

The Non-OCX implementation makes CSMS data/metrics available to navigation analysts serving a support role to the satellite operators. It also provides immediate reporting of alerts and warnings to the Triad (NOCC/NAVCEN/GPSOC) of all alerts and warnings monitored by the CSMS, as well as daily and periodic (monthly/quarterly/annually) reports of specified performance statistics.

2 SOPS operators and analysts in the current GPS operations center are able to access Internet connected unclassified computers (called NIPRNet display) on the operations floor. For this to be integrated into regular operations, however, several programmatic steps must first take place.

1. Air Force Space Command (AFSPC) leadership must provide clear direction through the chain of command to fulfill civil signal monitoring using a Non-OCX system.
2. Standard operating procedures must be developed to provide unambiguous direction to operators on actions to take in the event of CSM alerts, warnings, and events.
3. Training and standards/evaluation guidance must be provided, including documentation.

4.3 NON-OCX CSM COST

In this section we provide cost estimates for various Non-OCX options. These estimates are based on rough order of magnitude (ROM) costs provided by JPL in two separate presentations [References 5,13]. It is important to note that the cost estimates provided by JPL as an outcome to these studies is ROM only. The actual bid costs under a formal agreement could be higher or lower than the ROM estimates. The risk of additional cost liability is low given the overall role of JPL.

The detail behind the JPL cost estimate is not presented here. These costs include system engineering, design, development, documentation, and test. The basic monitoring network and framework that JPL intends to use to meet CMPS requirements already exists; and is already operating with partial funding by NASA. The CSM costs estimated by JPL are essentially an add-on to these base costs. The cost estimates provided by JPL are taken at face value. This section is divided into three subsections

1. Description of options
2. Assumptions
3. Cost estimate results

4.3.1 Non-OCX CSM Cost Options

As noted in above Section 4.1, JPL states that they can meet all CMPS requirements with the exception of those requiring an L1P(Y) receiver – two requirements – and access to the OCX filter output – one requirement. The L1P(Y) receiver would no longer be required once a full constellation of satellites with L5 is available. JPL also states they cannot independently incorporate CSM information directly into GPS operations. We assume that a near-term Non-OCX implementation can meet all CMPS requirements exclusive of the four 'impossible' requirements. We also assume that JPL will not need to meet CMPS requirements for absolute signal power measurements.

Two Non-OCX options are considered in this trade study
1. Non-OCX without signal quality monitoring (SQM)
2. Non-OCX with SQM

4.3.2 Non-OCX CSM Cost Assumptions

We make the following assumptions with respect to the OCX cost estimate
1. Non-OCX CSM development and deployment costs paid for in $FY2015 and $FY2016
2. JPL cost proposals are used as the basis for the Non-OCX cost estimate
3. JPL cost estimates in [Reference 5] and [Reference 13] are taken at face value
4. CMPS requirements specific to SQM are met by the Non-OCX system using the NovAtel G-III receiver
5. Non-OCX options will be implemented via Web-based interface. Cost of user console equipment for Non-OCX capabilities is not included in this estimate
6. JPL cost estimates have margin/risk dollars included in the base cost estimate.

4.3.3 Non-OCX CSM Cost Estimate Results

This section provides cost estimates for the Non-OCX options in this trade study. The results are taken directly from References [Reference 5], [Reference 13], and [Reference 15] and are provided in Table 4.3-1.

Table 4.3-1 Non-OCX development, and operations and maintenance cost estimates for the two options considered.

Non-OCX Option	FY2015 development cost in M$TY	FY2016 development cost in M$TY	O&M cost in each year of the lifecycle in M$BY	Description
Non-OCX without SQM	1.50	1.50	3.05	Non-OCX without absolute power measurements or SQM
Non-OCX with SQM	2.33	2.33	3.33	Non-OCX without absolute power measurements plus world-wide G-III receiver network to support SQM

The JPL cost estimates include 'margin' to account for uncertainty. In the case of the Non-OCX without SQM option, JPL already took their code count estimate and doubled it in the base cost estimate. In addition, JPL has stated that the measurement data is already available and all that remains is to set up the calculation and display the results – a well-understood process. The uncertainty lies in the screen displays. It is highly likely that these displays will evolve as the system is put to use.

We retain the ‘margin’ in the JPL cost estimate, however, we assume that this margin is at the discretion of Civil Requirements. These dollars should be targeted towards specific activities whether at JPL or elsewhere by way of refining and improving user screens, funding training and operating procedure development if needed, refining algorithms, and so on. These discretionary funds amount to approximately $330K.

The JPL cost estimate assumes that the NovAtel G-III receiver [Reference 6] is incorporated into 20 stations in order to satisfy SQM requirements. The civil community informed JPL that the G-III provides the functionality required in the receiver element to meet the CMPS designated SQM requirements.

4.4 NON-OCX CSM RISK

Technical and Cost risks have been identified and are illustrated in the Risk Matrix in Table 4.4-1. These risks are explained in succeeding sections.

Table 4.4-1 Non-OCX CSM Risk Categorization Matrix

Likelihood					
				R4b	
				R4c	
	R4d R4e		R4a		
	Impact				

4.4.1 Non-OCX CSM Technical Risk

There is a risk that the CSM provider misunderstands the intent of the CMPS and either (a) implements something that does not address a requirement, or (b) implements something that goes farther than intended. Either outcome results in a loss of scarce resources and impacts cost and/or schedule. As a result, it is likely misunderstandings will be discovered, just not the same ones. It is recommended that whichever organization proceeds with whatever set of requirements, (a) the implementers have access to subject matter experts that can interpret the government intent (b) the government insists on in-depth review of the algorithms and the form of the results prior to significant implementation effort. Mitigation: This is highly mitigated by JPL’s proposed collaborative approach in implementation. Due to the proposed path of JPL, we see this risk as Not Likely. If it does occur, its significance is rated Moderate. [Risk R4a]

Integration into Operations has been discussed on several occasions. If the CSM results aren't available to the operational staff for use in prompting action, the effectiveness of CSM will be greatly reduced. From JPL's comments and a 2 SOPS support contractor's explanations of how current JPL data feeds are used today, this may be a more tractable matter than initially thought. However, it is not clear whether the current supporting role of the JPL data is officially accepted as part of the process or simply proven through experience. Further exploration through direct discussion with 2 SOPS will mitigate this risk, as well as the development of a simplified design for unambiguous action, training plan, standard operating procedures, evaluation criteria, and traceability to the metrics that it supports. If Non-OCX data is not properly integrated into operations, the risk is considered Significant. The Likelihood of this occurring is considered Likely. [Risk R4b]

AFSPC HQ is not expected to authorize use of an external CSM as a primary means for conducting mission operations. For civil monitoring to be integrated into 2 SOPS, AFSPC must provide clear direction that this is part of the mission, and that they do allow use of external CSM for managing the civil only signals. Mitigation: the integration of JPL data into 2 SOPS will need to be socialized through AFSPC/A3 or A5 by the civil liaison to AFSPC. If this guidance is not provided, the success of CSM using Non-OCX resources is greatly diminished, and the risk is Significant. The ability to overcome this risk will take significant effort, but presuming the AF will work with the civils, this can be addressed. The likelihood therefore is rated Low Likelihood. [Risk R4c]

4.4.2 Non-OCX CSM Cost Risk

We assume that JPL has all the necessary measurement data needed to meet its requirements and all that remains to develop comparison and threshold calculations. The overall risk is assessed as Low in this regard. [Risk R4d]

Screen development has considerable uncertainty around it; particularly if operator displays are needed. Screen displays do not have to be developed in only in FY2015 and FY2016, but rather can be established over an extended period of time. The base annual O&M costs combined with risk mitigation dollars (10%) as needed should adequately address this risk. [Risk R4e]

5 CSM TRADE STUDY

This section describes the trade study alternatives examined, explaining the trade space, and the evaluations.

5.1 CSM TRADE STUDY SUMMARY

The Trade Study considers features of value and costs and risks to implement those features. The features considered in the trade are generally summarized in the requirements sections. That said, there are several capabilities that deserve special discussion, two of which relate to the key categories discussed in Section 2.4.1 above.

Real-time Response: A priority for the civil community has been having the satellite operators aware of a problem quickly enough to take corrective action. For this reason, a number of requirements are identified as being detected within 1 minute, along with the requirement that all events be reported to the satellite operators as part of their normal operational duties (reference CMPS 3.5.a and c). These relate directly to Category 1requirements discussed in Section 2.4.1

Reporting to civil agencies: An essential part of CSM is not only that operators are notified, but also that notifications be reported to civil agencies (CMPS 3.5.b, d, 3.6.f). These relate directly to Category 2 requirements discussed in Section 2.4.1

Signal Quality Monitoring: While SQM is a desired feature per the CMPS, it is costly to implement. Any of the options under OCX implementation only satisfy a small subset of the SQM requirements. With regard to the Non-OCX implementation, the cost-effectiveness in satisfying the SQM requirements does decrease somewhat due to the added receiver element.

5.1.1 CSM Trade Study Assumptions

In performing this study there are several pieces of information we do not have. For this reason, we proceed with the trade study based on assumptions.

1. Tech orders, training, and standards/evaluation will be provided by SMC/GP at no cost to the civils
2. SE&I services for implementing CSM into the baseline will be provided by SMC/GP at no cost to the civils

5.2 CSM TRADE STUDY TRADE SPACE

We consider the following Trade Study Alternatives:

1. **RTN P6** – OCX fulfillment of requirements up through Priority P6
2. **RTN P12** –OCX fulfillment of requirements up through Priority P12
3. **Non-OCX without SQM** – Use of Non-OCX monitoring without SQM capability to fulfill CMPS requirements
4. **Non-OCX with SQM** – Use of Non-OCX monitoring to fulfill CMPS requirements
5. **RTN P2+Non-OCX with SQM** –OCX fulfillment of Priority P2 combined with Non-OCX fulfillment of CMPS requirements with SQM capability
6. **RTN P3+Non-OCX with SQM** –OCX fulfillment of requirements up through Priority P3 combined with Non-OCX fulfillment of CMPS requirements with SQM capability

7. **RTN P6+Non-OCX with SQM** – OCX fulfillment of requirements up through Priority P6 combined with Non-OCX fulfillment of CMPS requirements with SQM capability
8. **RTN P3+Non-OCX without SQM** – OCX fulfillment of requirements up through Priority P3 combined with Non-OCX fulfillment of CMPS requirements without SQM capability

5.2.1 CSM Trade Study Requirements Model

The Trade Study considers the eight Trade Study Alternatives identified in Section 5.2. The Trade Study Alternatives, along with their associated Trade Study Scores calculated using the model described in Section 2.4.2, are given in Table 5.2-1.

Table 5.2-1 Trade Study Alternative Capability Scores

Trade Study Alternatives	Trade Study Alternative Score
Alt 1 - RTN P6	46
Alt 2 - RTN P12	61
Alt 3 - Non-OCX without SQM	80
Alt 4 - Non-OCX with SQM	86
Alt 5 - RTN P2+Non-OCX with SQM	94
Alt 6 - RTN P3+Non-OCX with SQM	94
Alt 7 - RTN P6+Non-OCX without SQM	90
Alt 8 - RTN P3+Non-OCX without SQM	89

From this table we see that Alternative 5 and Alternative 6 have the highest degree of fulfillment with a 94% fulfillment level. Alternative 1 has least fulfillment, fulfilling only 46% of the weighted CMPS requirements.

5.2.2 CSM Trade Study Integration into Operations Model

For any of the alternatives involving Non-OCX CSM, the integration of a Non-OCX CSM into satellite operations is expected to be phased in a stage at a time, with an analyst terminal initially provided to introduce CSM functionality to operators and analysts. Once this capability is accepted by 2 SOPS, then increased operational functionality will be introduced, having unambiguous alerting of anomalies with recommended actions to be taken by the operator within the OCX system. It is expected that Non-OCX terminals will be used only as secondary sources, alerting operators to check for corroborative indicators on the OCX system, and will not be used stand alone to cause operators to take action on satellites.

For alternatives relying on OCX only, integration with the satellite operators will be performed by SMC/GP.

5.2.3 CSM Trade Study Cost Model

In this section we present results of a cost effectiveness analysis across all trade study alternatives. The basis for cost effectiveness calculations is presented in Section 2.2.3 of this report. Trade study alternatives are built from various combinations of OCX and Non-OCX options.

NPV calculations are based on convolving the discount rate with costs documented in Sections 3.3.3 and 4.3.3. A plot of PV by year is shown in Figure 5.2-1~~Figure 5.2-1Figure 5.2-1~~. NPV is the cumulative PV over the entire life-cycle. These calculations do not include risk mitigation costs for any of the alternatives. They represent vendor proposals at face value. These are illustrated in Table 5.2-2.

Table 5.2-2 Cost analysis of trade study options using net present value (NPV).

Alternative	NPV in M$PV	Options					
		OCX P1-P2	OCX P1-P3	OCX P1-P6	OCX P1-P12	Non-OCX w/o SQM	Non-OCX w SQM
1	27.7						
2	42.7						
3	45.0						
4	50.5						
5	56.8						
6	58.3						
7	72.8						
8	52.8						

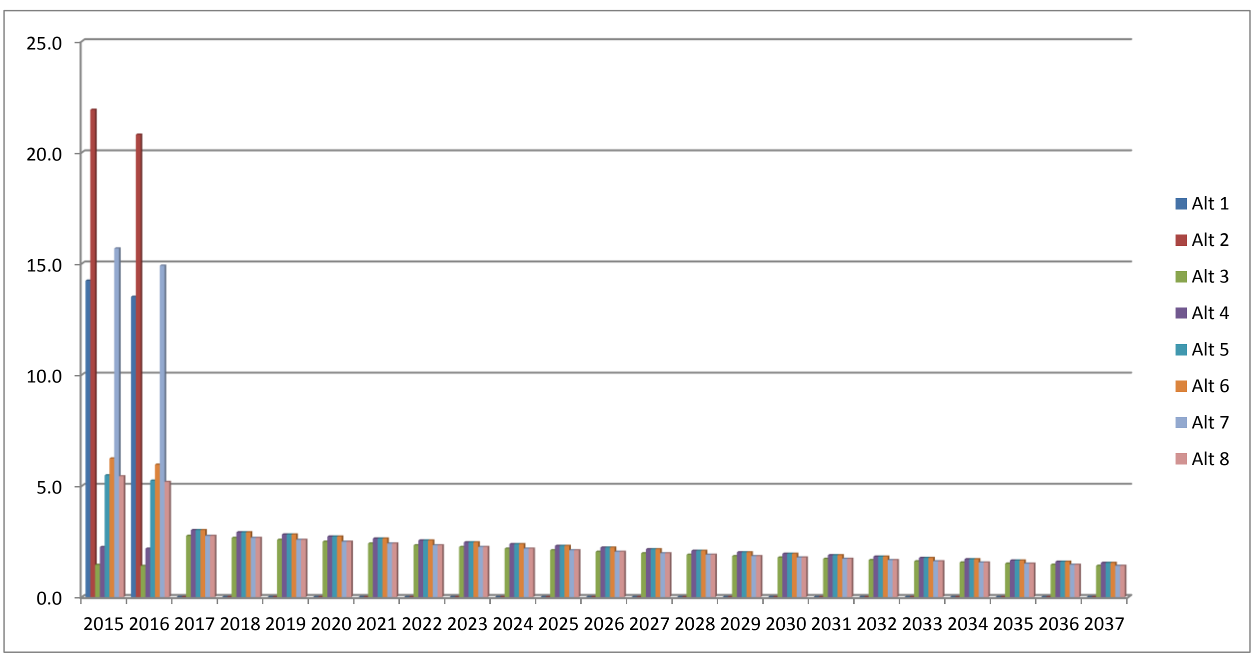

Figure 5.2-1 Plot of present value (M$PV) over time for each of the trade study alternatives.

We are, of course, concerned with budget requirements. The budget dollars ($TY, which includes inflation adjustment) over the next five years, and the life cycle cost (LCC) of the system are provided in Table 5.2-3, and displayed in Figure 5.2-2~~Figure 5.2-2Figure 5.2-2~~.

Table 5.2-3 Budget dollars (M$TY) for trade study alternatives.

Alternative	FY2015 M$TY	FY2016 M$TY	FY2017 M$TY	FY2018 M$TY	FY2019 M$TY	FY2015-19 M$TY	LCC M$TY
1	15.00	15.00	0.00	0.00	0.00	30.0	30.0
2	23.10	23.10	0.00	0.00	0.00	46.2	46.2
3	1.50	1.50	3.22	3.29	3.35	12.8	85.3
4	2.33	2.33	3.52	3.59	3.66	15.4	94.6
5	5.73	5.73	3.52	3.59	3.66	22.2	101.4
6	6.53	6.53	3.52	3.59	3.66	23.8	103.0
7	16.50	16.50	3.22	3.29	3.35	42.8	115.3
8	5.70	5.70	3.22	3.29	3.35	21.2	93.7

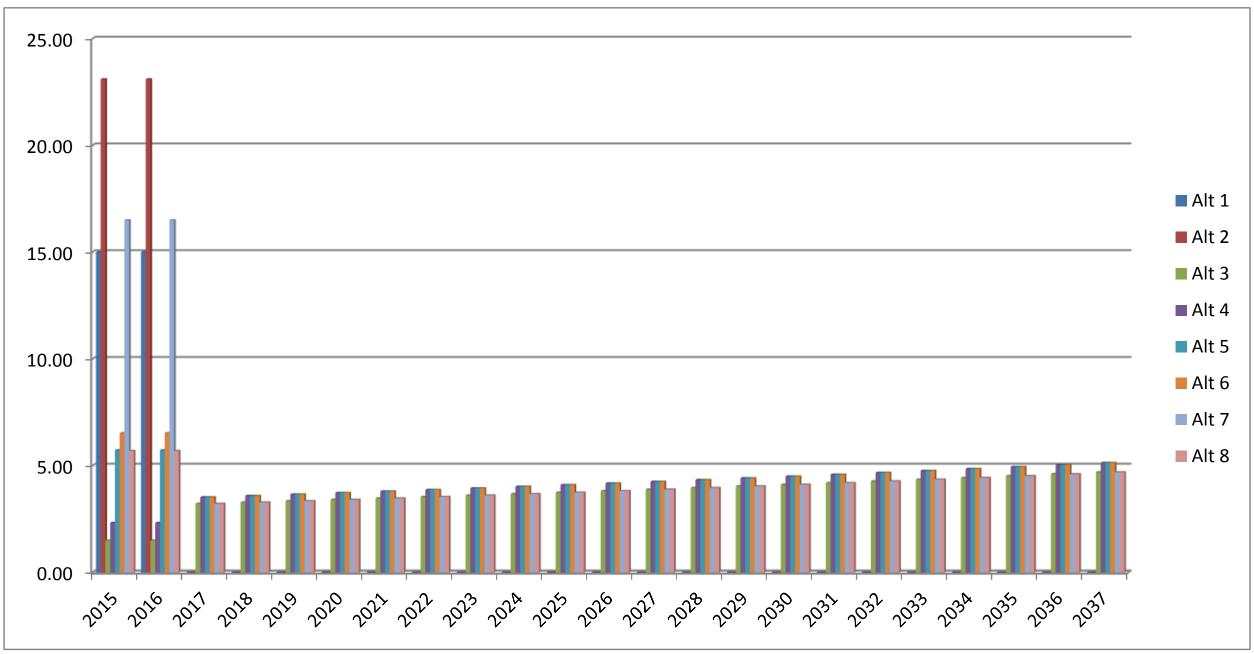

Figure 5.2-2 Plot of budget dollars (M$TY) over time for each of the trade study alternatives.

The cost discussion to date takes available cost data at face value without adjustment. There are several areas of potential adjustment to consider. The first is the cost risk discussed in Section 3.4.2 associated with the potential for OCX cost overruns. This is an obvious risk exposure on a

CPAF contract experiencing 46% overrun to date. The estimated cost risk mitigation to take this into account is an additional $3.84M for OCX P4 and P6 priorities.

Another cost adjustment is OCX P10 which is allocated to absolute power measurements. This can be more cost-effectively undertaken elsewhere and should be removed. If we assume that removing P10 out of sequence does not impact P11 and P12 cost, then the associated cost reduction is $1.43M.

Table 5.2-4 Impact of Cost Adjustments

Alternative	NPV in M$PV	Description
1	31.3	Includes $3.84M P4, P6 cost risk adjustment
2	44.9	Includes $3.84M P4, P6 cost risk adjustment minus P10
3	45.0	
4	50.5	
5	56.8	
6	58.3	
7	76.6	Includes $3.84M P4, P6 cost risk adjustment
8	52.8	

5.2.4 CSM Trade Study Risk Model

Risks for each of the Trade Study Options are identified in Sections 3.4 and 4.4. These risk assessments are allocated to each of the Alternatives as shown in Table 5.2-5.

Table 5.2-5 Summary Risks by Alternative

Alternative	Risk
1	R3a, R3b, R3c, R3d
2	R3a, R3b, R3c, R3d
3	R4a, R4b, R4c, R4d, R4e
4	R4a, R4b, R4c, R4d, R4e
5	R3a, R3b, R4a, R4b, R4c, R4d, R4e
6	R3a, R3b, R4a, R4b, R4c, R4d, R4e
7	R3a, R3b, R3c, R3d, R4a, R4b, R4c, R4d, R4e
8	R3a, R3b, R4a, R4b, R4c, R4d, R4e

5.3 CSM Trade Evaluation

In terms of meeting requirements as a function of cost, the evaluated alternatives are within a relatively narrow band of effectiveness in meeting CMPS requirements versus net present value cost. This holds true over a wide variation in assumptions (sensitivity analysis). Essentially, for the alternatives under consideration, the more one is willing to pay, the more capability one acquires in rough proportion to cost.

5.4 CSM Trade Summary Discussion

This section collects the results into a matrix summarizing the results. It describes evincive data, such as which Trade Study Alternatives provide the highest cost/effectiveness ratio or least risk.

The trade study team compared the level of requirements fulfillment to the projected costs (unadjusted net present value). These are summarized in Table 5.4-1 and illustrated in Figure 5.4-1.

Note that none of the solutions is able to fully satisfy all of the CMPS-defined 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 5.4-1 Cost-effectiveness Assessment

Trade Study Alternative	Weighted Score	Cost $M (NPV)	Effectiveness / NPV
Full CMPS (RTN ROM of May 2012, for reference only)	95	133.0	0.7
Alt 1 - RTN P6	46	27.7	1.7
Alt 2 - RTN 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 - RTN P2+Non-OCX with SQM	94	56.8	1.7
Alt 6 - RTN P3+Non-OCX with SQM	94	58.3	1.6
Alt 7 - RTN P6+Non-OCX without SQM	90	72.8	1.2
Alt 8 - RTN P3+Non-OCX without SQM	89	52.8	1.7

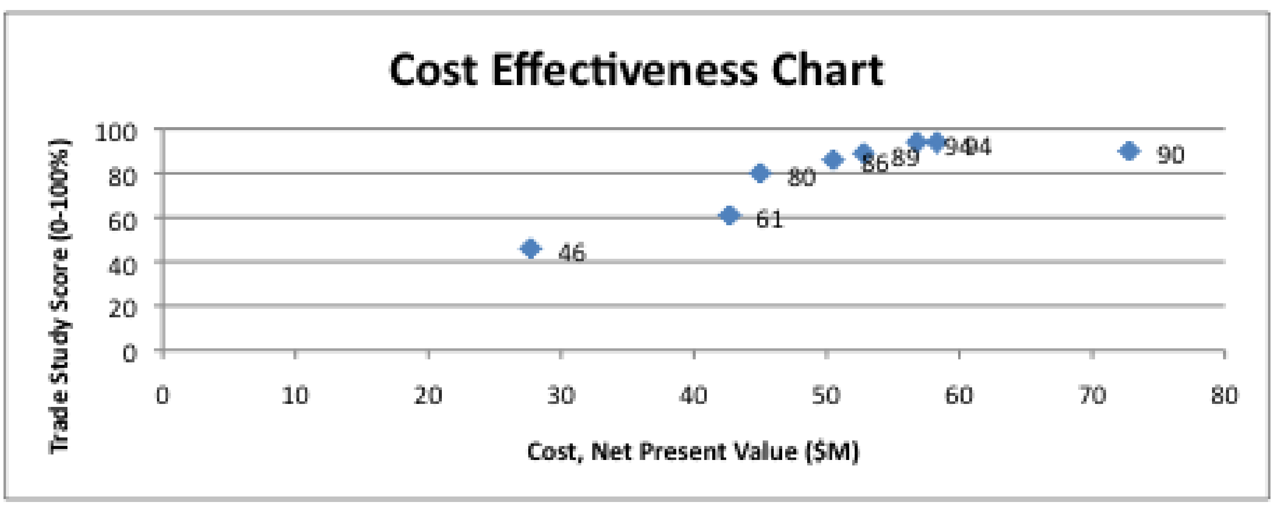

Figure 5.4-1 Plot of cost (NPV $M) versus effectiveness score for the eight alternatives analyzed.

In determining a "best" course of action, we consider alternatives that are able to provide a most cost-effective solution for each of the following categories:

1. Metrics verification – verification that signal and service performance meets commitments made in SPS Performance Standard, interface specifications, and other government specifications
2. Operations notification and situational awareness – timely notification to satellite operators of real-time GPS anomalies and situational awareness of civil signal performance
3. Civil user notification and situational awareness – notification to civil authorities and agencies or GPS anomalies and situational awareness of civil signal performance
4. Signal quality monitoring – assessment of carrier, code and navigation message performance to ensure within designated limits
5. Archive – archival of CSM reports and data for retrieval by satellite operators and civil authorities
6. Signal monitoring – monitoring of the four civil signals: L1 C/A, L2C, L5, and L1C

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 AFSPC 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 Section 2.4.1, 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 this trade study is to pursue Alternative 5 by submitting a request for proposal from the OCX vendor for P1-P2 with an option for P3 and submit a request for proposal from the Non-OCX vendor for an implementation including SQM.

5.5 CSM Trade Study Recommendations

Based on evaluations of key metrics including risk, requirements, cost, and integration with operations, this trade study recommends a hybrid system. 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. To implement this alternative, OCX requirements would be accomplished through the existing OCX acquisition process while Non-OCX monitoring would be phased into operational procedures as a progression from Navigation Analyst support, to GPS Operations Center, to potentially 2nd Space Operations Squadron technical orders for operational control of GPS broadcast signals used by the civil community.

This recommendation effectively places a cut-line on the Civil Signal Monitoring rough order of magnitude cost estimate prepared by the OCX contractor. Those requirements above the cut-line would be boarded by the GPS Directorate onto the OCX baseline. The residual requirements would then be satisfied by acquisition and maintenance of a Non-OCX system. Specifically the recommendations are:

1. Submit a request for proposal to Raytheon for buying P1-P2 with an option for P3 requirements
2. Submit a request for proposal to NASA JPL for buying and maintaining the Non-OCX element with SQM monitoring
3. The civil community should engage with Air Force Space Command 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.

6 REFERENCE MATERIAL

This section identifies reference material used in preparation of this trade study.

[1] GPS Civil Signal Monitoring Performance Specification, DOT-VNTSC-FAA-09-08, 30 April 2009
[2] Raytheon Company, Special Study on Implementing Civil Signal Monitoring, CDRL A064-008, 24 May 2012
[3] Raytheon Company, Follow-On Civil Signal Monitoring Special Study, Rough Order of Magnitude, GPS-13.175.KG, 21 Nov 2013
[4] Raytheon Company, Follow-on Civil Signal Monitoring (CSM) Special Study Report, CDRL A064.012.002, 10 December 2013
[5] Yoaz Bar-Sever, Larry Young, and George Purcell, 'Leveraging the Global Differential GPS System for Cost Effective and Rapid Implementation of CSM: Proposal Outline', 7 February 2014
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[10] http://www.treasury.gov/resource-center/data-chart-center/interest-rates/Pages/TextView.aspx?data=yield
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[13] Larry Young, 'JPL's GPS Receiver Program and Development Process', NASA/JPL, 7 February 2014
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[15] Yoaz Bar-Sever, Larry Young, and George Purcell 'Leveraging the Global Differential GPS System for Cost Effective and Rapid Implementation of CSM: Proposal Outline, Revised Estimate', NASA/JPL, 5 March 2014.

7 ABBREVIATIONS

Following is a list of abbreviations used in this document.

AFSPC	Air Force Space Command
CMPS	GPS Civil Monitoring Performance Specification
CSM	Civil signal monitoring
CSMS	Civil signal monitoring system
DOT	Department of Transportation
FAA	Federal Aviation Administration
GDGPS	Global Differential GPS
GPSOC	GPS Operations Center
IA	Information assurance
JPL	Jet Propulsion Laboratory
LCC	Life cycle cost
MSN	Monitor Station Network
NASA	National Aeronautics and Space Administration
NAVCEN	US Coast Guard Navigation Center
NGA	National Geospatial-Intelligence Agency
NIPRNet	Non-classified Internet Protocol (IP) Router Network
NOCC	National Operations Control Center
NPV	Net present value
OCX	Next Generation Operational Control System
ORD	Observed range deviation
OST-R	Office of Secretary of Transportation – Research
PDOP	Position dilution of precision
PRDA	Program Research & Development Announcement
PV	Present value
ROM	Rough order of magnitude
RTN	Raytheon Company
SE&I	Systems Engineering & Integration
SMC/GP	Space & Missile Systems Center GPS Directorate
SQM	Signal quality monitoring
SV	Space vehicle
URAE	User range acceleration error
URE	User range error
URRE	User range rate error
USAF	United States Air Force
UTCOE	Universal coordinated time offset error
VPN	Virtual private network