Benefit-Cost Assessment Refresh

The Use of eLORAN to Mitigate GPS Vulnerability for Positioning, Navigation, and Timing Services

Final Report

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## Executive Summary

In June 2004 the Volpe National Transportation Systems Center provided a “Benefit-Cost
Assessment of The Use of LORAN To Mitigate GPS Vulnerability For Positioning, Navigation, And Timing Services,” to the Undersecretary of Transportation.

This report updates Volpe’s 2004 assessment based on real-world events in the interim period coupled with an ever-growing world-wide dependence on GPS-provided PNT services for more and more applications. It is important to note that there are two kinds of data used in this analysis: costs and benefits. As in 2004, our approach has been to get costs as accurately as possible, and sample the benefits. Thus, our study provides a conservative, lower bound to the benefit-cost ratio. The true ratio can only be higher. While it is beyond the scope of this refresh, costs of a GPS outage for other infrastructure will be significant. The disruption of the electric power grid due to a loss of GPS timing, for example, might be in the range of 20 to 30 times the effects estimated here for transport-related consequences.

The Volpe Center also recognizes that user equipment costs certainly should be addressed in a study integrating GPS and eLORAN. For the purposes of this analysis, chip sets integrating GPS and eLORAN capability are assumed to be part of the GPS equipage, with eLORAN representing a minor share of this cost. The cost of the additional antenna has been correctly added to this list.

Although this report only addresses civil applications of GPS and eLORAN, it is understood that military uses of GPS may also benefit from the availability of eLORAN provided PNT services.

The enhanced LOng RAnge Navigation system (eLORAN) remains a viable, cost-effective back up for GPS. It is currently the only non-satellite Positioning, Navigation, and Timing (PNT) system that has been tested and can provide a multi-modal back up for the PNT services GPS provides. Given the growing importance of and dependence on PNT services, it is increasingly cost-beneficial to provide back up to those services. The commercial services dependent on GPS PNT services have grown into markets that were previously unforeseen. There is little doubt that this trend will continue.

In summary, this report concludes:
• The benefits of eLORAN exceed the costs by a factor of about 13:1 if, in 15 years, eLORAN backs up just one high-impact GPS outage.
• The LORAN infrastructure has already been significantly upgraded to achieve eLORAN capability as a result of ten years of Congressional support and $160M of funding. It is already operating and the newer, state-of-the-art components remain, so it is available for the cost of completion of the modernization.
• Perhaps the greatest benefit of all is that a robust back-up to GPS-provided PNT services makes GPS a less desirable target, and reduces the risk that it would be attacked at all.

1 See, “The Economic Impacts of the August 2003 Blackout,” Electricity Consumers Resource Council,
2 LORAN is an abbreviation for “LOng RAnge Navigation;” GPS is an abbreviation for “Global Positioning System.”


4 This report addresses civil applications of GPS and LORAN. However, it is understood that military uses of GPS may also benefit from the availability of LORAN.

5 See, for example, the discussion in “Uncertainty and Technological Change,” by Nathan Rosenberg, pp. 91-110, in Technology and Growth, Conference Proceedings, Federal Reserve Bank of Boston, June 1996.

6 Throughout this report, outage refers to the making the GPS unusable due to jamming (spectrum denial), spoofing (making a satellite appear to be in a position or time it is not), or there is an insignificant number of satellites for the application.

7 Economists prefer comparing the net benefits of alternative investments. In this case, however, the comparison is not between provision of GPS back up through eLORAN or an alternative, but rather, is there a case that an eLORAN back up is cost beneficial. In that case a benefit-cost ratio in excess of unity is required to make that case.

8 LORAN continues to provided a means of PNT services for multimodal and multipurpose PNT applications e.g., coastal navigation, enroute flight and communications timing.


10 “Modernized” is the preferred term. The modernization includes a change from vacuum tube technology transmitters, to lower operational costs by using the more robust solid state technology. In addition, recent enhancements put modernized LORAN on the threshold of providing PNT services that can adequately perform the GPS backup function in many key civil applications.


14 “Time interval” relates to frequency, an important parameter connected with clock and network synchronization. Thus, GPS, LORAN and atomic clocks, among other devices, provide precise time and time interval (PTTI) services.

15 Electric power distribution is managed by making synchronized measurements at high frequency across wide areas of the power grid. A good, widely available PTTI source is required to synchronize the measurements to high precision.

16 See, for example, the descriptions of the importance of timing and time interval services in, “Global Positioning System Timing Criticality Assessment – Preliminary Performance Results,” Carroll, J. and Montgomery, K., presented at the 40s Annual Precise Time and Time Interval (PTTI) Meeting.


18 LORAN is a terrestrial system, while GPS is space-based. LORAN provides a long wave, high power signal, while the GPS signal has low power and a short wavelength. Thus, GPS requires a direct line-of-sight between the satellites and the user antenna, while LORAN offers better penetration into tree canopies, urban canyons, and building interiors. The shorter wavelength GPS has relative to LORAN, however, is the basis for the greater accuracy provided by GPS.

19 Mothballing has been suggested as a stop-gap alternative. However, the speed with which existing facilities age both functionally (as technology advances) and physically (many current stations are remote and exposed to extreme weather conditions) make stasis an unrealistic option. In addition, user equipment would not likely be available. It is doubtful industry would embark on development of user equipment for “mothballed” equipment. Lastly, the salvage value of such a “time capsule” approach is likely to be very small.

20 The one year range varies between $32.41 and $147.27 as of this writing, with one forecast a year out at $59 per barrel. See www.oil-price.net for updates. Other sources include the Department of Energy’s Energy Information Administration, at www.eia.doe.gov/, which forecasts out to 2030. Also, a recent study of the benefits of GPS for personal trips and the resulting gasoline savings, valued at $543 per driver.

21 OMB Circular A-94 provides guidance on the conduct of Benefit-Cost Analyses (BCA). It can be found at [http://www.whitehouse.gov/omb/circulars/a094/a094.html](http://www.whitehouse.gov/omb/circulars/a094/a094.html).


23 NextGen is the FAA’s plan to modernize the U.S. National Airspace System through 2025. Through NextGen, the FAA is addressing the impact of air traffic growth by increasing NAS capacity and efficiency while improving safety, reducing environmental impacts and increasing user access to the NAS.


25 In many of these systems GPS is a single point of failure node.


27 See, “The Case for eLORAN,” Basker et al., General Lighthouse Authorities of the United Kingdom and Ireland, May 8, 2006, which describes mitigating the risk of revenue loss and public confidence from road user charge apps. The availability of cheap jamming solutions available to the public will contribute to the likelihood that they are used.

28 DSRC means Dedicated Short-Range Communications.

29 ITS International, January/February 2009, p. 43.


31 The average rate of growth posited for telecom was about 9.5 percent through the study period, and the actual rate of growth for 2005 was 14 percent.


34 Declines in population density moving out from city centers will reduce the numbers affected, if jamming is assumed to be located close to the center of populations to maximize the effect.

35 See the article on GPS JamFest testing in the July/August 2008 edition of Inside GNSS.


41 See, for example, “The Case for eLORAN,” Basker, et al., General Lighthouse Authorities of the United Kingdom and Ireland, May 8, 2006.


44 Most of the present LORAN infrastructure already has eLORAN components.

45 These costs reflect the full operation, maintenance, and upgrades associated with each alternative. They are in 2009 dollars, with discounting to NPV done at the OMB determined rate of 1.8 percent. They are expressed in millions.
Economists strongly prefer comparing the net benefits of alternative investments. In this case, however, the comparison is not between provision of GPS backup through eLORAN or an alternative, but rather, is there a case that an eLORAN backup is cost beneficial. In that case a benefit-cost ratio in excess of unity is required to make that case.


It is no longer a question of if a GPS outage occurs. Rather, it is a question of when, and how prepared we are to mitigate its impact.


The risk of an event can be defined as a likelihood coupled with an accompanying consequence. In the case of natural risks, such as fire or flood, likelihood and consequence are generally considered independent. In the case of planned events, consequence is instead a consideration in the decision to attack a target. The likelihood is addressed via the plans to mitigate GPS interference. (See, Position, Navigation, and Timing Interference Detection and Mitigation Plan, DHS, 2006.)

This applies to the civil users of GPS and to a lesser degree the military uses. The degree to which it affects military users is not considered in this analysis.

See, for example, the working paper by Richard de Neufville, Kenichi Hodota, Joseph Sussman, and Stefan Scholtes, “Using Real Options to Increase the Value of Intelligent Transportation Systems,” December 2008.


The concept of a so-called “smart” baseline refers to making intelligent and reasonable decisions about the continued operations of the system under study, in the absence of detailed future budget plans. This would include, for example, making prudent and necessary repairs and upgrades, without fundamentally changing the nature or mission of the system.


**Introduction**

The June 2004 Volpe LORAN2 Benefit-Cost Analysis, “Benefit-Cost Assessment of The Use Of LORAN To Mitigate GPS Vulnerability For Positioning, Navigation, And Timing Services,” was a response to a limited question:

> “Given the need to provide a GPS backup, is an enhanced LORAN more cost-beneficial than not having enhanced LORAN?”

This report is an update to the results of that report. However, based on the real-world events during the interval between that report’s release and the preparation of this one, the premise of the earlier report, “if a GPS outage occurred” is replaced by “when a GPS outage occurs.” This change in perspective, coupled with an ever-growing dependence on GPS for more and more civil applications, reinforces the need to re-visit the original question.

Over the last five years, the list of applications depending on positioning, navigation and timing (PNT) information (i.e., those applications that use GPS) has grown beyond the most optimistic predictions. New applications were
expected, of course, and unanticipated applications are in fact part of the innovation process. Largely unforeseen, however, was the creation of an entire industry providing “mobility apps,” which utilize GPS and leverage the growth in the number and capabilities of wireless phones and other handheld devices. The acronym LBS, for location-based services based on these devices, was recently coined to describe this market. This has helped reinforce the perspective that GPS is an enabling technology, with PNT being described as more of a “superstructure” than a separate infrastructure for the economy.

In addition, the often critical need for precise time and frequency cannot be emphasized enough. This need applies not only to the transportation sector, but also to networks, telecommunications and electric power (see Appendix B, which contains background material on timing, and on some aspects of aviation and maritime operations.). The increase in application and continued dependence on GPS and the various services it enables brings with it the potential for concomitant losses, should the GPS service become unavailable. The 2004 benefit-cost analysis described potential scenarios for GPS outages and their consequences. These scenarios and additional scenarios of actual events are examined in this update to determine if the benefits of enhanced LORAN (eLORAN) to mitigate the impact of the GPS outages are, as before, valid and significant. In doing the analysis both planned and unplanned outages are described, with unplanned or intentional outages leading to the largest consequences, and hence the largest benefits if these are mitigated by the back-up system.

Benefits from eLORAN continue to accrue to civilian GPS users, the majority of whom use location-based services (LBS). This application was not in the earlier report, since LBS had not yet emerged as an industry. There were various services envisioned at the time the 2004 report was written, such as canes for the blind equipped with GPS and street maps. Mobile phones with GPS existed, but only as locators for emergency 911 calls. Since then, LBS and mobility apps have blossomed. This and other changes since the first Benefit-Cost Analysis are described immediately following the Background section.

This benefit-cost analysis (BCA) refresh of the 2004 analysis applied OMB standards coupled with conservative assumptions on benefits accruing to GPS users who could also use eLORAN. The conservatism means in part that many quantifiable benefits were not included, and, although they were described, their benefits were not added to the quantified benefits.

Maintaining the conservative approach from the previous study, the updated benefit-cost ratios have increased. Using eLORAN to mitigate the impact of a loss of GPS PNT capabilities is therefore more cost-beneficial, relative to the 2004 results.

For the case of the Intentional High Impact outage scenario taking place in 2020, the present value of avoiding such a loss is estimated at $4.3 billion. This is a benefit to cost ratio of 13, and the net benefit in this case is $4.0 billion. The benefit-cost ratio has increased over the last version of this report due to the increased dependency in the
In summary,

- Benefits of a backup exceed eLORAN costs for significant outages and are close to costs for one moderate outage
- As reliance on GPS grows, the potential benefit of a backup correspondingly increases
- eLORAN offers transportation sectors continuity of operations across modes
- PNT benefits accrue to critical infrastructure and provision of network services (including power grid, communications and emergency response)
- By limiting the consequences of an outage, availability of a backup reduces the attractiveness of GPS as a target

The main body of the report follows.

**Background**

LORAN has a long history as a successful navigation system, principally through its longest running incarnation, LORAN-C. LORAN-C, still operating, has provided mariners with positioning, navigation and timing services prior to GPS. As GPS became more capable (e.g., more complete constellation and updated satellites), and finally ubiquitous, LORAN use waned. The events of 9/11 and the information presented in the Volpe GPS Vulnerability study underscored a need to examine GPS applications and their vulnerabilities. This ultimately led to support for the modernization of the LORAN system that will ultimately lead to an enhanced system, eLORAN. Today, LORAN-C has been significantly upgraded to what is called “modernized” LORAN.

While LORAN-C has been perceived by some to be an outmoded technology superseded by GPS, in truth, its updated form eLORAN can provide PNT services on par with GPS. Thus, eLORAN has the ability to provide loss mitigation for GPS, as well as the ability to provide supplemental PNT service where GPS does not reach, such as within buildings. eLORAN is currently the only non-satellite PNT system developed and tested, that can provide effective back up for most of the PNT services GPS provides. The technical capabilities of eLORAN have been described in detail in reports such as the FAA-sponsored research on LORAN enhancement and the National Institute of Standards and Technology.

**PNT Services**

The value provided by positioning and navigation services is understood intuitively by anyone who has ever needed directions. These services underpin the functioning of modern economies, and their use is integral to all critical infrastructures. Timing and
frequency services are likewise ubiquitous throughout the economy, and are necessary to the functioning of all networks, for example, as well as the transportation and electric power distribution sectors. GPS provides a reliable and costless source of this service to 50 million civil users directly, and indirectly to virtually all citizens who use the infrastructure of a modern society13.

PNT timing services affect applications that require accurate knowledge of precise time and time interval (PTTI).14 These services range from the “clocks” in the Internet managing the data packets to controlling the electric utility system.15 It has often been noted that the successes of the services provided by GPS are such that operators of the systems that depend upon this information are unaware of how the information from multiple sources is blended. From a user perspective, they really don’t need to know - it just works. From a critical infrastructure support perspective, however, it is important that adequate knowledge of service delivery methodology, reliability, maintainability, continuity of service, integrity of information, etc., be thoroughly vetted and well understood. This report and the previous version consider some of the consequences of the PNT source failing to work, and describe the benefits of maintaining PNT services.

Electric power distribution is managed by making synchronized measurements at high frequency across wide areas of the power grid. A good, widely available PTTI source is required to synchronize the measurements to high precision. In addition, modern communications also depends on precisely segmenting and sharing frequencies and time availability, to increase the number of users and the quality of service. This multiplexing capability is quickly lost when the time signals upon which everything is synchronized are lost. Hence, it can be difficult to communicate using networks lacking sufficiently accurate clocks and modern, secure equipment.16,17

**Mitigating the Loss of the GPS Signal**

The desirability, indeed necessity, of providing a means to mitigate the impact of a loss of GPS is not in doubt. The technical case for LORAN (or eLORAN) stems from the ability of LORAN to provide most of the required PNT services, and provide them in a manner that is also complementary to GPS. The latter feature increases eLORAN’s attractiveness as a GPS back up.18

The financial case considered in this benefit-cost analysis is limited to the economic impact of the loss of GPS availability absent mitigation. Since LORAN has a long history, this simplifies some of the tasks associated with cost estimation. eLORAN builds incrementally on known capabilities. It involves adding capabilities that have been tested, thus reducing greatly the related technical uncertainties and resulting costs that are part of a benefit-cost analysis. The major cost uncertainties involve decommissioning costs related to site remediation.19 Other cost assumptions relate to the various alternatives. For example, assumptions which involve the relocation of two Alaskan LORAN stations, the amount of and schedule for improvements, and resulting cost avoidance are described.
The principal benefits accruing to eLORAN derive from its ability to continue the provision of services to GPS users during a loss of the GPS signal. These are the PNT services, which comprise positioning, navigation and timing, and are used to protect and manage critical infrastructure. PNT services include every facet of the modern economy. The loss of efficiency gains in marine shipping and logistics management, for example, account for the majority of the savings attributed to positioning and navigation. The communications services include time-stamped automatic financial transactions and direct communication of voice and data over the radio spectrum or the Internet, the latter enabling the growth in LBS. Aviation has become a major consumer of GPS services, as well. Quantified benefits under consideration also include cost avoidance due to investments in technology, as well as savings from shutting down LORAN entirely.

Perhaps the greatest non-quantifiable benefit of the existence of a back up at all, also described in the earlier report, is that a practical, seamless, near-transparent back up for GPS effectively reduces the risk of GPS being purposely attacked. This is a desirable quality in a PNT back-up service, since it offers a broad resilience to many GPS-related threats. Whether satellites are removed from the GPS constellation due to a hostile act or an inadvertent equipment failure jams a signal, PNT services would remain intact.

Differences between this report and the prior version

Scope

As part of refreshing the earlier analysis, the alternative LORAN configurations and their costs were revisited, assumptions were checked and adjusted where required, and associated data elements were updated as needed. The outage scenarios used in the earlier report remain intact. One update concerning the scenarios was to ensure they reflect realistic examples of the results of jamming trials and actual events concerning the latency of the precise time. A primary interest of this update was to provide a wider discussion of the potential benefits and their sources than was previously attempted. As in the earlier report, a thorough evaluation of all sources of benefit from GPS is outside the scope and resources of this report. However, as GPS becomes increasingly ubiquitous it is worthwhile to describe, even qualitatively, the significant areas in which dependence upon GPS gives rise to benefits from using a back up.

Price level and discounting

The change in price levels and dollar values was made to ensure that prices are expressed
in 2009 terms. Similarly, the discount rate, previously set by OMB at 3 percent, is now 2.75 percent.

**Cost of Fuel**

The cost of oil is a principal component of operating costs for transportation. In 2004 the price of oil was around $35 per barrel (or in today’s dollars, about $39), but recently experienced historic volatility as it rapidly approached $140. It then experienced an even faster decline, and currently sits a bit above $50 per barrel at the world price and $49 in the U.S. The cost per barrel continue to be volatile, and has recently also been below $40, or essentially back to 2004 price levels, a result of the worst economic downturn since the Great Depression. Since oil is such a significant contributor to the operating costs of all modes of transportation, and savings in such costs are a key component of the benefits of GPS, the price of oil affects the future benefits imputed to eLORAN.20

**Benefits**

The principal benefits accruing to eLORAN operation derive from its ability to continue providing services to GPS users during a loss of the GPS signal. These are the PNT services, consisting of positioning, navigation and timing, and are used to protect and manage critical infrastructure. In many applications, GPS is a single point of failure. PNT services involve every facet of the modern economy. They reach across all modes of transportation, and significantly impact timing services in other key areas such as communications and electric power distribution. The loss of efficiency gains realized through GPS-based applications in marine shipping and logistics management, for example, account for the majority of the savings attributed to positioning and navigation. The communications services include time-stamped automatic financial transactions and direct communication of voice and data over the radio spectrum or the Internet, the latter enabling the growth in LBS. Aviation has become a major consumer of GPS services as the use of the Wide Area Augmentation System (WAAS), ADS-B and other enhancements to navigation are adopted to bring about more efficient aircraft operations. Benefits also under consideration include the costs avoided due to shut down. This is in accordance with the procedures for benefit-cost analysis outlined in the Office of Management and Budget’s (OMB) Circular A-94.21

Most of the above benefits can be quantified in dollar terms. The improved robustness an effective PNT back up brings to GPS is a desirable quality since it offers a broad resilience to many GPS-related threats. Whether the GPS constellation has the requisite number of correctly orbiting satellites22, or satellites are destroyed due to a hostile act, or an inadvertent equipment failure jams a signal, PNT services would remain intact.

**Aviation benefits**
The benefits of GPS PNT services provided by GPS will accrue through the implementation of improved procedures based upon improved knowledge of aircraft position. These will permit more direct routing of flights, higher operating densities, and result in reduced operating costs and less passenger time spent in transit. Delays also will be reduced. These efficiencies are still being quantified as part of the Next Generation (NextGen) investment process.23

Previously, benefits were attributed to aviation by building up flight plans, imputing equipage rates, and determining savings from improved positioning that were based on phase of flight. This bottom-up approach was conservative in the sense that these efficiencies did not spill over into the aviation system at large. At the same time, mitigation of the delays that propagate through the network is one of the most analyzed areas in aviation. Less is known about the actual efficiency gains on NextGen from direct routing, for example, that lead to the reduction in delays, although reducing aviation delays tends to play a small part in the overall national impact. To better reflect the gains to aviation due to GPS services, therefore, we examine the operational savings in using a GPS/eLORAN integrated system in general aviation and regional aircraft, as well as in some larger aircraft. Pilots of smaller craft will be able to select and fly to alternate airports, including those currently without indigenous NAVAID support, either when GPS is disrupted or when congestion begins to delay the major carriers. In addition, since eLORAN is intended to provide non-precision approach capability throughout the CONUS, aircraft can choose to fly more direct point-to-point operations, even during periods when GPS service is disrupted.

Aviation benefits cannot be realized without a decision for full eLORAN deployment. It will take several years for industry to develop and validate suitable avionics standards. Operators would not be expected to retrofit for eLORAN capability alone. eLORAN aviation capability would most likely be achieved through integrated GPS/SBAS(WAAS)/eLORAN and future dual-frequency Global Navigation Satellite System (GNSS)/eLORAN capable avionics. Most GPS and GPS/SBAS avionics are not upgradeable in their current configurations. Industry’s non recurring avionic development and aircraft integrations costs for an integrated receiver are significant. The industry time to market for new integrated avionics will depend upon current market demand for SBAS and the timeline for future GNSS capabilities.

Operators will avoid replacing avionics until they perceive benefits that exceed the costs. Benefits are primarily achieved by equipment that enables new operational capabilities. Robust availability of GPS and backup conventional navigational aid infrastructure do not provide operators an incentive to reequip with eLORAN capable avionics.

While the positive impact on congestion would be considerable, and hard to quantify without detailed simulations of alternative route structures, the larger picture of current aviation delays is instructive.

Aviation delays are a much-studied phenomenon. A recent study by the Congressional
Joint Economic Committee finds that in 2007, $40.7 billion in congestion costs was incurred in the U.S. Almost twenty percent of domestic flight time was wasted in delay. The NextGen program is designed to alleviate delays through direct routing and improved operational procedures as a result of GPS-based improvements in aircraft positioning and navigation performance. Some of these costs can be viewed as transfers, and as such are not appropriate in a benefit-cost analysis. The $19.1 billion in additional operating costs incurred by the airlines and the $12 billion in value of time lost to passengers found in the analysis of over ten million scheduled flights is still considerable. Benefits of using a GPS back up accrue based on the ability to maintain efficiencies gained through GPS.

**Maritime Benefits and World Trade**

Earlier results were based upon the levels of maritime trade, and the benefits of more efficient transit with GPS. Trade continued at a robust rate of increase until the recent recession, which resulted in port activity being reduced by roughly one-third. Again, the valuation of benefits of a back up hinge upon the continuation of services at forecast levels of the activities being supported. Thus, while reasonable forecasts of global trade are based on a rebound of the world economy, it is important to also point out that the forecast errors surrounding these are, generally, not known. These uncertainties are likely asymmetric, however, with a greater potential for an increase in oil prices and trade, rather than further decreases. This makes the overall assessment of benefits conservative.

It is prudent, therefore, in the face of these uncertainties, to leave the analysis of this sector intact, and limit the update to reflect changes consistent with the updated price levels. It is also worthwhile to emphasize the mechanisms through which additional maritime benefits accrue, in addition to those related to flow of maritime commerce. These include many GPS-dependent systems, which themselves contribute to safe, secure, effective and efficient maritime commerce, in addition to efficient routing, tracking, scheduling, etc., by providing situational awareness, safety and security. Some of these GPS-dependent systems are:

- Automatic Identification System (AIS)
- Long Range Identification and Tracking (LRIT)
- Maritime Safety and Security Information System (MSSIS)
- Search and Rescue Satellite Aided Tracking (SARSAT)
- Ship Security Alert System (SSAS)
- Global Maritime Distress & Safety System (GMDSS)

These systems are critical to specific activities such as search and rescue operations. They also have more general application, such as enabling Maritime Domain Awareness (MDA). Some are interdependent among each other. All of these applications, however,
are dependent on GPS, and they are key components of MDA and national security. While it is beyond the scope of this refresh of the earlier BCA to determine the benefits of MDA, it is still a non-quantified benefit of GPS, and hence of using a GPS back up.

**Landside benefits**

These would include roadway applications such as applications of tolling and collection of vehicle mile travelled (VMT)-based fees. Applications continue to multiply. The worldwide market for roadway uses is now envisioned as 20 percent of the total land market, with “most of the rest,” around 75 percent, coming from LBS. These applications become key as the gas tax becomes less viable as the principal source of road revenues in the U.S. The possibility of loss of service (and revenue) from GPS-reliant services points to the benefit of using a back up.

**Roadway**

Tolling services are more widely available than when the first report was written in 2004, and congestion pricing and pricing based on VMT has gone from concept to testing. In Europe, DSRC may be overtaken by space-based services. Similar evaluations may be done in U.S. This will likely open new markets for GPS services. Likewise, the creation of LBS and the value derived from direct routings, as described above, have greatly expanded since the 2004 BCA report.

**Telecommunications**

The earlier Volpe BCA report used extant trends in telecommunications to forecast the value of those services, hence the benefit to preventing their disruption. The industry grew approximately 50 percent faster than was assumed in the 2004 analysis, and thereafter spawned new products and services which coalesced into the location-based services industry. A conservative approach to benefits estimation was used throughout, with market penetration of cell phones capped at 80 percent. The actual rate of market penetration for 2008 was 85.7 percent. Likewise, the estimated U.S. population at that time was almost 295 million, whereas the actual population reached over 306 million. The result of updating these figures is a ten percent increase in the current user base, and the opening of revenue streams from new services. Industry expectations are for growth in voice at about the rate of inflation, with data traffic expected to increase by 14 percent annually over the next eight years. These contribute to significant increases in the estimated benefits over the study period, with a faster growing user base growing revenues faster than we had forecast.

**Technical considerations and implications for scenario design**
The scenarios described in the previous BCA report were based upon the then-current understanding of the likely available jamming equipment. Our previous scenarios had posited ranges for outages from 50 miles to 200 miles for the largest intentional outage. The results of recent field tests indicate that even low power, ground based jammers can cover a range of perhaps 250 miles. When jammers are used in concert, as described in the most severe scenario, this could easily increase the coverage area by a factor of ten, with a smaller increase in the underlying population affected. It should be noted that smaller jammers are readily available (at a cost of less than $50.00) to deny GPS in a more localized area. We retain our outage footprints from the previous analysis, while noting that this is a conservative approach. The use of jammers in these applications could seriously disrupt first response operations as well as other security applications, which are disruptions not considered in the analysis. Scenarios not considered relate to those resulting from specific spoofing or insufficient constellation causes.

We had conservatively estimated that the Code Division Multiple Access protocol (CDMA) would not be affected by time loss until about a week after initiation. This estimate proved to be very conservative based on the subsequent experience of DOD-hosted GPS jamming tests and other recent experiments in maritime jamming of GPS. As a result, the lag between GPS disruption and loss of time synchronization is reduced from 3 days to as little as an hour or less.

Critical Infrastructure Protection

In addition to the telecommunications and transportation sectors described above, the electric power grid and financial services sectors are significantly dependent upon PNT for timing services.

As described in the earlier report, increases in effectiveness and efficiency of the electric power grid are possible because of the highly accurate timing services provided by GPS, which increases dependency on GPS. While the risks posed by loss of the timing through intentional or unintentional loss of these services is beyond the scope of a this benefit-cost analysis, it is reasonable to examine the comparative statics of the situation in 2004 and an understanding of what the electric grid will likely evolve into during the analysis period. The investment in Smart Grid technology is an acceleration of the process by which advanced management of the grid will enable new efficiencies and new services. These will create additional benefits, which, while difficult to quantify, accrue to the timing services provided by an eLORAN back up.

Providing precise timing and synchronization to the financial sector was described in the previous BCA report as a benefit that could be obtained using a PNT system such as eLORAN. Since the last BCA report was written, it was confirmed that loss of CDMA synchronization can occur within as little as about 30 minutes. The extent of disruption to the financial services sector, and the ripple effect through the rest of the economy, is difficult to judge, but could be significant in rough proportion to the timing precision required. In addition, the potential impact of a loss of confidence in these systems would
be difficult to judge, and would have to be weighed against the practical difficulties in continuing business in a different manner.

**Quantifiable and Non-Quantifiable Benefits**

Typically in benefit-cost analyses the non-quantifiable benefits are relegated to a brief mention, and since they do not lend themselves to expression in the final calculation, the bottom line “net benefit” inevitably leaves the non-quantifiable benefits on the sideline. In addition, the level of mitigation capability should GPS not be available is also not always quantifiable. It is incumbent upon both the authors and readers of the report, however, to consider both these sources of benefit. In the case of GPS, the list of applications continues to grow, and an entire mobility industry has grown up since the first study was written in 2004. As has been discussed, GPS is a critical enabling technology, and the quantifiable side of the discussion omits the value of continued growth of these applications into new applications; rather, it examines the magnitude of the loss to the current services should GPS be unavailable.

Many of the most significant applications described, for example in the maritime domain, relate to safety of life and property, national security, as well as the efficiency of the economy. While we quantify benefits to commerce, the other benefits are also significant. In the case of first responders, for example, timely response to the site of an automobile crash, hazardous materials spill, or impending detonation of a dirty bomb, requires support from PNT services. The required communications are also dependent upon GPS. These benefits, while significant, are not captured in a quantifiable manner, and are only incorporated by reference.

**The state of PNT practice**

Reliance upon GPS continues to grow, and with it reports of occasional failures due both to erosion of basic navigational skills and to increasing threats. GPS services are generally so reliable that they allow the navigator’s experience in the more traditional means of navigation to atrophy. GPS information is often accepted as ground truth, even when it is faulty and should be disregarded. This high level of acceptance is a mark of the success of GPS, but it is also a new source of vulnerability. An alternate PNT source utilizing the same output display, obviating the need to break focus on GPS-like information, has an added cognitive benefit; it will be used and interpreted more correctly than an alternative requiring a user’s acceptance of a GPS signal failure.

**Retaining world leadership in PNT**

As a result of a series of decisions made over decades, the United States has attained world leadership in providing PNT services. LORAN and eLORAN were invented here. GPS was invented here. While some other nations are launching their own satellite
constellations, there remains a natural tendency to look to the policies of the U.S. for guidance. The case for eLORAN as a back up to GPS has been made and accepted in the world community, and retention of the leadership role in PNT depends not only on having the best GPS constellation, but on having the most accurate and most robust PNT service possible.\textsuperscript{41} Global trade, global communications, energy provision, indeed the fabric of the economies of the developed and developing worlds, depend upon U.S. PNT services, not just for accuracy, but for reliable service. Efficiency gains from GPS can be lost for a short time, and their effects can be compensated for in many cases. For an increasing number of GPS applications, however, the loss of timing means a total loss of service. Robustness requires that when a service outage occurs, due to planned or unplanned events, the consequences be well managed. It is for this reason that a plan was developed to mitigate interference to GPS with backup PNT services.\textsuperscript{42} World leadership in PNT requires also that there be an adequate back up, and that this be linked to standards in place with our trading partners.

The alternatives examined are described next, along with the relevant assumptions and associated costs.

**Baseline and Alternatives**

The alternatives examined cover a range of possible outcomes for LORAN, and include shutdown as well as the complete build-out of an eLORAN system with complete CONUS and Alaska coverage. These are described briefly below, and in greater detail in Appendix A.

The baseline against which the alternatives are measured consists of LORAN-C operation through fiscal year 2023 (FY2023), based on the current U.S. position as described in the 2008 Federal Radionavigation Plan\textsuperscript{43} and current USCG plan budget. If not otherwise specified, costs are assumed to incur according to a “smart” baseline principle, which assumes making intelligent and reasonable (usually cost minimizing) decisions about the continued operations of the system under study, in the absence of detailed future budget plans. In the baseline, 24 LORAN-C LorStas (“LORAN stations”) continue to operate through 2023, and thus incur all the LORAN-related support costs. In addition to replacement of equipment and the de-staffing of all transmitter stations, Attu and Port Clarence are moved inland to take advantage of access to commercial power. We include tower replacement, based on expected service life, assuming these decisions minimize operating costs while retaining operational capabilities.

The alternatives are:

Alternative 1 describes the case in which LORAN is terminated in all due haste. This alternative thus incurs no costs other than for operation and maintenance (O&M) through 2009, and shutdown starting in 2010. No upgrades or moves are considered.
Alternative 2 provides for continuation and building upon the current baseline to provide partial eLORAN capability, maintaining current operations and capabilities, plus filling the central U.S. LORAN coverage gap. Thus, 25 LORAN-C LorStas continue to operate through 2023, and carry all the LORAN-related support costs. Further, we assume de-staffing at the Alaska LorStas and various enhancements.

Alternative 3, likewise, includes Alternative 2 plus full eLORAN capability, with 25 eLORAN LorStas operated thru FY2023, and including all the LORAN-related support costs. LORAN enhancements include Shoal Cove infrastructure repair, legacy SSX replacement, de-staffing transmission stations, and other enhancements described in the appendix. Attu and Port Clarence are moved inland to take advantage of commercial power, and tower replacements are included based on the expected service life.

**Costs**

The costs of the baseline and alternatives are as follows. The costs are the discounted sum of the relevant expenditures to support the baseline and each alternative described in Appendix A, for the period under study, the 15 year period from 2009 to 2023.

Baseline: Continue current operation $573.0 million

Alternative 1: Terminate LORAN $318.2 million

Alternative 2 Fill Mid-Continent Gap $600.3 million

Alternative 3: Full eLORAN $655.9 million

These are not budget costs - they have been discounted to express their present values and then summed. While appropriate to a benefit-cost analysis, since this facilitates comparison to the present value of benefits, it reduces their usefulness for budget purposes. Real undiscounted costs are shown in Appendix C. See Figure 1.

The benefits of cost avoidance are the sole benefits of shutting down LORAN. As described above, it will cost $573 million to continue LORAN on its current path of incremental upgrades and replacement. Terminating LORAN is estimated to cost $318.2 million, thus continuing the current operations can be accomplished over the study period for the incremental cost, or $254.8 million (NPV).

Likewise, full eLORAN capability is estimated to cost $655.9 million (NPV) over the study period, for an incremental cost of $337.7 million over discontinuing LORAN, and
for $82.9 million compared to the cost of continuing the current operation, in NPV terms.

Various outage scenarios and their consequences are taken up next.

![Figure 1: Total Cost Breakdown](image)

**Outage Scenarios**

The scenarios remain the same as in the previous analysis. The outages in the scenarios under study last from one day to one month, and posit jamming from a fifty-mile radius up to 200 miles. This report updates these in order to reflect the current understanding of the impacts of GPS outages, based on recent data for telecommunications growth in the economy, as well as the latency of synchronization.

As can be seen in Table 1, the outage scenarios used are not as severe as one could
imagine, based on historical precedent. They are designed to represent plausible, not necessarily probable, outcomes.

**Benefits**

As stated previously, the benefits of eLORAN derive from the ability to maintain various capabilities in the event of a GPS outage. Hence, the benefits accrue to GPS users, not users of LORAN per se.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Site</th>
<th>Range</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-Intentional</td>
<td>Typical city</td>
<td>100 miles</td>
<td>one week</td>
</tr>
<tr>
<td>Intentional – Low</td>
<td>High impact city</td>
<td>50 miles</td>
<td>one day</td>
</tr>
<tr>
<td>Intentional – Moderate</td>
<td>High impact city</td>
<td>100 miles</td>
<td>one week</td>
</tr>
<tr>
<td>Intentional - High</td>
<td>5 maximum impact regions</td>
<td>200 miles</td>
<td>one month</td>
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</table>

The table below summarizes the updated benefits for outage scenarios occurring during the years specified. These benefits are year-specific, since the growth in the economy adds to the user base, which adds to the benefits of backup. On the other hand, discounting future streams of benefits works to reduce the numbers slightly when they are presented as present values.

**Table 2 – Benefits if Outage Mitigation for Selected Years (in millions of 2009 dollars, discounted)**
As can be seen in Table 2, the benefits of mitigating a single severe (Intentional – High Impact) outage outweigh the discounted sum of costs for the eLORAN system, over the 15-year study period. More descriptions of the benefits and costs are presented in the next section.

### Analysis

The benefits of having a GPS back up in place are sensitive to the time period during which various scenarios take place. Our analysis, as before, thus considers the benefits of backing up a loss of GPS occurring at different times during the analysis period.

For example, recall the incremental cost of developing full eLORAN capability over the study period - $337.7 million (NPV). This cost can be weighed against the benefit (in NPV terms) of avoiding the losses associated with a GPS PNT outage. For the case of the Intentional High Impact outage taking place in 2020, the present value of avoiding

<table>
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<th>2016</th>
<th>2020</th>
<th>2023</th>
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<td>Unintentional</td>
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<td>10.3</td>
<td>9.4</td>
<td>8.8</td>
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<tr>
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<td>12.4</td>
<td>11.6</td>
<td>10.8</td>
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<td>Intentional-Medium Impact</td>
<td>269.0</td>
<td>255.0</td>
<td>242.2</td>
<td>229.4</td>
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<tr>
<td>Intentional-High Impact</td>
<td>4,796.3</td>
<td>4,558.8</td>
<td>4,258.8</td>
<td>4,109.6</td>
</tr>
</tbody>
</table>
such a loss is estimated at $4.3 billion. This is a Benefit to Cost ratio of about 13, and the net benefit in this case is $4.0 billion.\textsuperscript{46} The benefit-cost ratio has increased over the last version of this report due to the increased dependency upon GPS PNT in the economy.

Previously, two medium impact outages were required to reach a determination that provision of a back up would be cost beneficial. While one of these outages does not meet that test, two outages exceed the costs of the system.

These benefits are due to mitigation of losses in efficiency and loss of service provision to sectors of the economy representing the modes of transportation (land, sea and air) and the telecommunications services provided to cell phone users through voice and data subscriptions. The chart in Figure 2 displays relative shares of the source of benefit from the Intentional – High Impact scenario. These are by no means the only sources of benefit. As in the previous study, these benefits are sampled to be representative of the effects mitigated by a back up system. Other studies have estimated the consequences to other economies for selected outages from a GPS loss, and have placed values on the loss of the power grid, for example, which was not attempted for this analysis.\textsuperscript{47} Possible environmental consequences due to loss of critical infrastructure were not considered but, like national security, are substantial non-quantified benefits of a well-functioning critical infrastructure.

**Conclusion**

This assessment represents another look, five years on, at benefit-cost portion of the larger effort to assess the applicability of eLORAN as a cost-beneficial backup to GPS. The benefit-cost approach was to accurately determine costs and conservatively estimate benefits against a range of possible GPS outage scenarios. An outage is defined by the number of locations, the radius of outage, and the duration of outage. Of these, the most significant factor is duration of outage. Because eLORAN’s protection against a single high-impact outage event in 15 years produces a benefit-cost ratio in the range of 13, this assessment concludes that eLORAN is a cost-beneficial back-up to GPS. In particular, the following points are made:

- The benefits of eLORAN exceed the costs by a factor of about 13 if, in 15 years, LORAN backs up one high-impact GPS outage.
- The benefits of eLORAN exceed costs if, in 15 years, two moderate-impact intentional GPS outages are backed-up by eLORAN.
• The benefits of eLORAN do not approach the costs for backing-up the low-impact or unintentional GPS outage scenarios.

• Legacy LORAN is already operating, largely capitalized, and the newer state-of-the-art components remain, so eLORAN would be available for the cost of completion of the recapitalization, modernization and operating the system. That is, the time, cost and administration to initiate and develop a new system need not be expended.

• Perhaps the greatest benefit of all is not measurable. A strong back-up makes GPS a less desirable target, and reduces the risk that it would be attacked at all.

eLORAN would be, therefore, a viable cost-effective back up for GPS. It is currently the only non-satellite PNT system that has been tested and can provide multi-modal back up for the PNT services GPS provides. Given the increasing importance of and dependence on PNT services, it is increasingly cost-beneficial to provide back up to those services. Since 2004, when the first Benefit-Cost Analysis was written, the commercial services for GPS have grown into markets that were unforeseen at that time. There is little doubt that this trend will continue. The dependence of large portions of the economy on GPS PNT services remains the fundamental rationale for a viable PNT alternative, in the event of a GPS outage. While it is beyond the scope of this report, costs of a GPS outage from other infrastructure will be significant. The disruption of the electric power grid
due to a loss of GPS timing, for example, might be in the range of 20 to 30 times the effects estimated here for transport-related consequences.

GPS outages occur on a regular basis. The outages posited here, however, are of larger duration and size than the typical previously observed outages, since they are meant to represent the outcomes of a coordinated attack.

On the non-commercial side, the need for infrastructure protection continues, including a back up for GPS. The importance of GPS services to national security, through programs such as Maritime Domain Awareness (MDA), for example, has also not been quantified here. The benefits to these programs, however, are nevertheless substantial.

Consistent with the previous BCA report, the benefits of eLORAN, Alternative 3 have increased in line with the growing importance of PNT to the economy. The benefits derive from an incremental investment, which consists of continuation of current LORAN O&M costs, plus the costs of the enhancements to provide full eLORAN capabilities. Since LORAN is largely in place, these enhancement costs are provided for an incremental cost of approximately one quarter of the O&M costs, which makes eLORAN a cost effective back up to GPS.

It is anticipated that, by removing the uncertainty surrounding continued Federal support for eLORAN as a back up to GPS, sufficient interest would exist in supplying integrated GPS/eLORAN user equipment that such systems would become a de facto standard. Purchasers of such equipment would thus benefit from a built-in back up capability.

As previously noted, a back up for GPS reduces the risk of willful jamming by directly addressing and reducing the consequence of such an action. This effectively removes much of the risk of GPS jamming, by reducing or removing the consequence of such an action. Simply put, system resiliency through existence of a backup PNT source such as eLORAN is a major deterrent to an intentional GPS jamming threat.

**Further work**

The state of the practice for benefit-cost analysis and program evaluation continues to evolve. The value from adding flexibility to project design has traditionally been difficult to quantify, and generally has been treated as an additional cost, without adequate attention paid to the benefits of preserving options. That value may come from an additional expenditure that enables the owner to add capacity more cheaply later on, for example, or, from deferring expenditures until such time as the demand is realized. Real options analysis is one methodology that has been evaluated for projects and programs in such cases. One benefit of such an approach is that it overcomes the problem of using average values in interpreting systems that involve interactions of many components, leading to non-linear outcomes. Determining the option value of eLORAN, by explicitly taking into account the interaction among the many components of the infrastructure that are affected, would be a significant undertaking, but would better reflect the actual value.
from a GPS PNT back up. Such work is being done and is extending the practice of benefit-cost analysis.

Appendix A
Assumptions and Alternatives

General Assumptions

System: U.S. LORAN System (the U.S. Government does not pay for the operations of LorSta in other countries)

Duration of study: 15-yr life-cycle cost, from FY2009 to FY2023

Dollar base: FY09 dollars

Discount rate: 2.75% (interpolated from rates described in OMB Circular A-94, Appendix D)

Capital cost distribution: evenly spread over the duration of the length of the particular task

Move Attu to and Port Clarence (PC) (circa 2010): includes upgraded transmitter, signal control equipment, and environmental cleanup and remediation (moved over from Enhancement)

LORAN Enhancement Elements
  • Shoal Cove (pressing infrastructure repair for sustainment)
  • Legacy Solid-State Transmitter Replacement
  • Two-Way Satellite Time Transfer
  • De-staffing of transmitting stations
    o Develop Performance Work Statement & Bid Package
    o CONUS site hardening
    o Alaska site hardening
  • Tok: upgrade transmitter & signal control equipment
  • Shoal Cove: Environmental Impact Statement
  • Shoal Cove: upgrade transmitter and signal control equipment
  • Recapitalize LORAN monitor network and information control and operating system
  • LORAN Data Channel Monitor Sites (56)
  • LORAN Monitor Network Environmental Impact Statement
  • Port Surveys
  • Coverage expansion: 1 mid-continent station
  • Project Administration

Any costs budgeted for FY08 or earlier are assumed to be sunk costs

Alternative-Specific Assumptions
Baseline (LORAN-C operation through FY23, based on the current U.S. position as per the 2008 Federal Radionavigation Plan and current USCG plan budget. If not otherwise specified we assume costs are incurred according to a “smart” baseline principle):

- 24 LORAN-C LorSta continue to operate through 2023
- Include all the LORAN related support costs.
- No LORAN-C LorSta shut down
- ALS operations in all LorSta (de-staffing at the ALS LorSta)
- LORAN Enhancements: Shoal Cove (SC) infrastructure Repair, Legacy SSX Replacement, and De-staffing Transmission Stations
- Attu and PC will be moved inland to take advantage of access to commercial power (we include the costs of new stations and the decommission costs of the old stations)
- Include tower replacement, based on the expected service life (we include LSU)

Alternative 1 (Terminate LORAN ASAP):

- 24 LORAN-C LorSta thru FY09.
- Include all the LORAN-related support costs.
- Shut down all 24 LorSta starting FY10
- No ALS operations
- No LORAN enhancements
- No Attu and PC moves
- No tower replacement

Alternative 2 (Baseline plus fill in mid-continent gap):

- 25 LORAN-C LorSta continue to operate through 2023
- Include all the LORAN related support costs.
- ALS operations in all LorSta (de-staffing at the ALS LorSta)
- LORAN Enhancements: Shoal Cove Infrastructure Repair, Legacy SSX Replacement, De-staffing Transmission Stations, and one mid-content LorSta
- Attu and PC will be moved inland to take advantage of commercial power (include the costs of new stations and the decommission costs of the old stations)
- Include tower replacement, based on the expected service life (include LSU)

Alternative 3 (Alternative 2 plus full eLORAN capability):

- 25 eLORAN LorSta thru FY2023
- Include all the LORAN related support costs.
- No shut down
- ALS operations in all LorSta (de-staffing at the ALS LorSta)
- LORAN Enhancements: Shoal Cove Infrastructure Repair, Legacy SSX Replacement, De-staffing Transmission Stations, one mid-content LorSta, Two-Way Satellite Time Transfer, Tok transmitter and signal control equipment, SC environmental impact statement, SC transmitter and signal control equipment, Monitor network and information control, and OS, LDC Monitor Sites (56), LMN Environmental Impact Statement, Port Survey, and Project Administration
- Attu and PC will be moved inland to take advantage of commercial power (we include the costs of new stations and the decommission costs of the old stations)
- Include tower replacement, based on the expected service life (include LSU)
Appendix B

Timing, Aviation Operations, and Maritime Domain Awareness

Timing

GPS is the dominant distribution source for time and frequency in the U.S. and throughout the world, and the telecommunications industry relies heavily on GPS to meet its performance requirements. GPS can provide time accurate to within 0.1 µsec and frequency accurate to about $1 \times 10^{-13}$ after 1 day of averaging. Because of its worldwide availability at very low cost, many applications and industries now use GPS exclusively as their time and frequency source, making them very vulnerable to GPS disruptions. It is generally agreed that backups and alternatives are needed to protect the national time and frequency infrastructure from the consequences of a GPS outage.

The LORAN enhancement known as eLORAN includes improvements in the key transmitter equipment, the distribution of differential corrections, and new time and frequency equipment. Using three cesium atomic clocks at each transmitter station, eLORAN can provide time synchronized to within 0.02 µsec of Universal Coordinated Time – Stratum 1 performance comparable to, but fully independent of GPS. Calibrated receivers that apply the differential corrections were shown in tests to recover time accurate to within 0.1 µsec.

Aviation Operations

Reviewer comments from FAA show concern about whether eLORAN user equipment costs are understated. The purpose of this refresh of the 2004 report is to replicate the methodology while updating cost and benefit numbers with the existing methodology and most key assumptions. The perspective has been that PNT user equipment costs certainly should be addressed in a study integrating GPS and eLORAN. For the purposes of this analysis, chip sets integrating GPS and eLORAN capability are assumed to be part of the GPS equipage, with eLORAN representing a minor share of this cost. The cost of the additional antenna has been correctly added to this list.

Maritime Domain Awareness

Maritime Domain Awareness (MDA) is a feature of Maritime Situational Awareness, which depends more increasingly on use of GPS. Maritime situational awareness (C.Dubay, Office of MDA, USCG) is based principally on systems such as Long Range Identification and Tracking (LRIT) and the Automatic Identification System (AIS). LRIT, used by maritime nations on a global basis, provides IMO (International Maritime Organization)-mandated ship information. LRIT is strongly dependent on GPS, as is the AIS, used by roughly 60 countries worldwide.
Appendix C

Detailed Costs (Discounted, in FY09 $K) for Baseline and Alternatives

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<td>39,018</td>
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## Appendix D

**Detailed (Undiscounted) Benefits by Scenario and Sector**

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