Navigation and Landing Transition Strategy

Prepared By:
The Office of Architecture and Investment Analysis, ASD-1
Federal Aviation Administration
Washington, D.C.
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U.S. Department
of Transportation
**Federal Aviation
Administration**

Office of the Administrator

800 Independence Ave., S.W.
Washington, D.C. 20591

INFORMATION MEMORANDUM TO THE DEPUTY SECRETARY

From: Monte R. Belger, FAA Acting Administrator MRB 8-21-02
267-8111

Prepared by: David L. Olsen, Navigation System Engineer, ASD-100
358-5440

Re: Navigation and Landing Transition Strategy Report

SUMMARY

Attached is the Federal Aviation Administration's (FAA) *Navigation and Landing Transition Strategy*. This report defines the satellite navigation transition strategy that considers the vulnerability of the Global Positioning System (GPS) and describes proposed requirements for a backup for navigation and landing for the National Airspace System (NAS). The report represents the starting point for discussions with the users on the timing of transition, deployment of instrument procedures based on satellite navigation, and the schedule for discontinuing ground-based navigation aids.

BACKGROUND

This report also serves as the input to the Department of Transportation's action plan to maintain the adequacy of backup systems for critical transportation applications in which GPS is being used. The FAA strategic transition ensures that an appropriate mix of systems is described that addresses GPS vulnerabilities.

The aviation user community participated in a full-day meeting on May 7 on the strategy. Participants were also provided an opportunity to comment on a draft report. The Air Transport Association, Northwest Airlines, Southwest Airlines, and Delta Air Lines provided clarifying comments. The Aircraft Owners and Pilots Association (AOPA) provided substantive comments around the need to provide incentives to its members before removing any ground-based navigation aids. AOPA also requested that research continue on developing a nonprecision approach capability for Loran-C. The National Business Aviation Association emphasized the need to not group all general aviation operations together, since many of its members have capabilities that meet or exceed those of air carriers. On June 4, the Department of Defense Policy Board on Federal Aviation was briefed. NAS user information has been incorporated in the strategy. A major comment theme concerns adequate time to transition to satellite navigation on the order of 5 to 7 years for air carriers and up to 10 years for the military and general aviation.

The FAA will begin commissioning GPS augmentation systems and procedures starting in 2003 for NAS-wide operations from en route navigation through precision approach. The navigation strategy focuses on sustaining safety during GPS disruption for operations in instrument weather conditions and recovery of aircraft operating within an interference area. Sufficient ground-based navigation aids are to be retained to meet this safety responsibility. Navigation equipment currently used by the Department of Defense is retained for homeland defense. Sufficient navigation infrastructure must also be retained for capacity and efficiency to continue commercial flight operations. Continuing operations by air transportation in the presence of interference is the best deterrent to the deliberate disruption of satellite navigation.

Efforts continue on Loran-C as a redundant backup to GPS. Loran-C is an independent source of navigation and timing that is not subject to the interference vulnerabilities of GPS. Loran is available and has the potential to meet the requirements of a nonprecision approach and may also provide an independent communications channel for corrections to the GPS in the same format as delivered by the Wide Area Augmentation System (WAAS). While it is technically advantageous to offer an Area Navigation (RNAV) backup to GPS, there are several issues that must be resolved. Loran-C must first be able to provide a nonprecision approach. There must be a long-term commitment made (with its associated investments) to the continuation of Loran, and a market must be created for incorporating Loran into the GPS/WAAS avionics. There is a great deal of market risk. When all of these issues are considered, the FAA cannot, by itself, justify continuation of the investment in Loran for navigation. However, the combined benefits associated with other modes of transportation and support of use for timing applications may be sufficient justification to continue the provision of Loran services.

FOLLOW-UP

We will use the FY 2003 *Federal Radionavigation Plan* to transition from this strategy to policy.

Attachment

The Deputy Secretary

REVIEWED __________

COMMENTS __________

DATE __________

Executive Summary
Federal Aviation Administration
Navigation and Landing Transition Strategy

This report defines the satellite navigation (Satnav) transition strategy that considers the vulnerability of the Global Positioning System (GPS) and describes proposed requirements for a backup navigation and landing capability for the National Airspace System (NAS).

This report also provides the Federal Aviation Administration's (FAA) input to the Department of Transportation's action plan to maintain the adequacy of backup systems for critical transportation applications in which GPS is being used. The FAA Satnav strategic transition ensures that adequate ground-based navigation aids (Navaids) are maintained and that the appropriate mix of systems is described that addresses GPS vulnerabilities. The transition time is through the full deployment of the next generation of GPS (GPS III), which brings improvements that address elements of the current vulnerabilities. The FAA will begin commissioning GPS augmentation systems and procedures starting in 2003 for NAS-wide operations from en route navigation through precision approach.

The navigation strategy focuses on sustaining safety during GPS disruption for operations in instrument operations and recovery of aircraft operating within an interference area. Sufficient ground-based Navaids are to be retained to meet this NAS safety responsibility. Navigation equipment used by the Department of Defense is retained for homeland defense. Sufficient navigation infrastructure must also be retained for capacity and efficiency to continue commercial flight operations. Continuing operations by air transportation in the presence of interference is the best deterrent to the deliberate disruption of satellite navigation.

The transition to Satnav is dependent upon the increased service provided over existing ground-based Navaids in instrument meteorological conditions with operations continuing in the presence of interference. The FAA is not in a position to support the development and deployment of Satnav and to also re-capitalize the entire existing ground-based infrastructure, making Satnav just another layer of navigation. The FAA is recommending the sustainment of a reduced number of existing Navaids to provide both a redundant and backup capability for en route navigation, nonprecision approach, and precision approach.

Redundancy is defined as being able to navigate apart from the airway structure using area navigation (RNAV). A backup capability is dependent on flying directly between retained ground-based Navaids.

The FAA will sustain the existing network of distance measuring equipment to provide a redundant RNAV capability. A reduced set of very-high frequency omni-directional range and non-directional beacon systems will be retained, described as the minimum operating network, to support a backup capability suitable for recovery of aircraft not equipped with a redundant RNAV capability. Many Category I ILS's will be retained to fulfill precision approach capabilities as a backup to Satnav to ensure safe recovery of aircraft and continued operation of air commerce in the event of GPS interference. All ILS's used to support Category II/III operations will remain in service. The current network of tactical air navigation systems will be retained for the Department of Defense. These actions will effectively reduce the threat to air transportation from the intentional disruption of navigation. The continued development and deployment of diverse L1 and L5 frequencies on the GPS satellites adequately addresses unintentional interference. The exact mix of ground-based navigation aids will need to be defined by specific locations and time for discontinuing services so that the users can assess the impact to their operation and plan their investments in Satnav. This work needs to be completed in 2004.

Efforts continue to examine the applicability of Loran-C for use in the NAS as a redundant backup to GPS. Loran-C is an independent source of navigation and timing that is not subject to the interference vulnerabilities of GPS. Loran is available and has the potential to meet nonprecision approach requirements and may also provide an independent communications channel for corrections to GPS in the same format as delivered by the Wide Area Augmentation System (WAAS). While it is technically advantageous to offer an RNAV backup to GPS, there are several issues that must be resolved. Loran-C must first be able to provide a nonprecision approach. There must be a long-term commitment made—with its associated investments—to the continuation of Loran, and a market must be created for incorporating Loran into the GPS/WAAS avionics. There is a great deal of market risk. When all of these issues are considered, the FAA cannot, by itself, justify continuation of the investment in Loran for navigation. However, the combined benefits associated with other modes of transportation and support of its use for precise timing applications may be sufficient justification to continue the provision of Loran services.

The strategy in this report is not impacted by the European Union's decision to pursue Galileo, an independent satellite navigation system. While the Galileo signals could further improve how robust satellite navigation is to unintentional interference, they would not mitigate intentional interference, as their power levels are very similar to GPS (L1 and L5).

Transition Chronology

Summer 2002	DOT Pos/Nav task Force completes the multi-modal navigation capability assessment
October/November 2002	GPS Outage En Route Simulation (GOERS)
December 2002	DOT Pos/Nav Task Force recommendations on multi-modal navigation mix to the Secretary
December 2002	Secretary’s decision on Loran continuance
2002 – 2008	Phase 1 Loran Upgrade ($158.3 M)
Summer 2003	GPS Outage Terminal Simulation (GOTS)
December 2003	Commissioning of WAAS with LNAV/VNAV approaches
March 2004	GPS/WAAS LPV approaches
March 2005	GPS/LAAS first production unit commissioned
2005	GPS Block IIF and IIR launches begin with L5 (no increased power) – IOC (18 satellites) by 2013 (includes GPS III)
2005	Notice of proposed rulemaking for redundancy and backup in Class A airspace
2005	Third WAAS communications satellite
2007	Final rule on Class A airspace
2007	Begin replacing VOR’s that are to be retained as part of a minimum operating network – continues through 2012
2008	First GPS III satellite launch – continues through 2019 – carries higher power L5 – IOC (18 satellites) by 2013 to 2016
2010	Begin Phase II of Loran modernization ($11.5 M) – continues through 2015
2010	Begin reduction of ILS Category I infrastructure – retaining at least one ILS at airports supporting the backup strategy
2010	Begin removing VOR’s not part of the minimum operating network
2014	Victor Airways and Jet Routes phased out
2015	ILS Category II/III at end of service life

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1.0 Purpose

This report defines the satellite navigation (Satnav) transition strategy that considers the vulnerability of the Global Positioning System (GPS) and describes proposed requirements for a backup for navigation and landing operations. The report sets the strategic framework for the next edition of the Federal Radionavigation Plan, defines the Federal Aviation Administration's (FAA) approach to decommissioning ground-based Navaids, and modifies the architecture for the National Airspace System (NAS).

This report also serves as input to the Department of Transportation's (DOT) action plan to maintain adequate backup systems in which GPS is being used for critical transportation applications. This action plan is submitted in response to a vulnerability study prepared by The DOT's Volpe National Transportation Systems Center.[1] This study noted that GPS is susceptible to unintentional disruptions from atmospheric effects, signal blockage from buildings, and interference from communications equipment, as well as to potential deliberate disruption. The study contained recommendations that have been accepted by the FAA and endorsed by the Secretary of Transportation. The most relevant recommendations from the study are:

> *Public policy must ensure, primarily, that safety is maintained even in the event of loss of GPS. This may not necessarily require a backup navigation system for every application. Of secondary but immediate importance is the need to blunt adverse environmental or economic impacts. The focus should not be on determining the nature of the backup systems and procedures, but on which critical applications require protection.*
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> *Because requiring a GPS backup will involve considerable government and user expense, it is recommended that the transportation community determine the level of risk each critical application is exposed to, what level of risk each application can accept, the costs associated with lowering the risk to this level, and how such costs are to be funded.*

The FAA Satnav transition strategy ensures that an adequate and appropriate mix of backup systems is maintained to mitigate GPS vulnerabilities through 2020.

The backup systems focus on three main goals in the event of GPS disruption: safely recovering aircraft; sustaining capacity and efficiency of commercial flight operations; and retaining navigation equipment used by the Department of Defense (DOD) for

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[1] The August 2001Volpe report, *Vulnerability Assessment of the Transportation Infrastructure Relying on the Global Positioning System,* is available through the Coast Guard Navigation Center website at http://www.navcen.uscg.gov

homeland defense.[2] Continuing operations by air transportation in the presence of interference is a significant deterrent to deliberate the disruption of satellite navigation.

2.0 Relationship to DOT POS/NAV Recommendations on Multi-modal Navigation Transition

This report provides the FAA's recommendations to the Secretary of Transportation on navigation transition as part of a larger navigation review. The DOT Positioning and Navigation (POS/NAV) Executive Committee has the leadership responsibility for recommending to the Secretary the right mix of navigation systems for all modes of transportation. The POS/NAV Executive Committee is charged with overseeing a Radionavigation Systems Task Force to develop recommendations on the navigation capabilities investment strategy for the most appropriate mix of radionavigation systems, from both a capabilities and cost perspective, to satisfy radionavigation requirements for at least the next 10 years. Where feasible, the requirements of non-transportation users of Federal radionavigation systems will be considered.

The work of the Task Force is divided into two phases. Phase I is anticipated to complete a capabilities assessment by summer 2002. Phase II will develop a recommendation on the future mix of Federal radionavigation systems and provide a report to the Secretary of Transportation by the end of calendar year 2002.

3.0 Concept of Operations for Navigation and Landing

The aviation community is transitioning from highly structured air traffic control to Free Flight. Free Flight is a continuing process that removes restrictions to current flight operations while improving flight safety, capacity, and efficiency. The NAS must migrate from navigation based on Victor and Jet Route airway structures to area navigation (RNAV) apart from the airway structures. Satnav provides an RNAV capability. The overall objective of RNAV, whether it be provided by augmented satellite navigation or derived from aircraft flight management systems (FMS), inertial reference systems (IRS), or FMS/IRS in combination, is to remove the restrictions imposed by reliance on ground-based navigation aids and the restrictive electronic "railroad tracks in the sky." The use of augmented GPS produces instrument approach procedures that provide vertical guidance, reducing the risk of controlled flight into terrain.

This change to RNAV opens up more airspace for use by aircraft, increases options for arrivals and departures, and reduces separation requirements—and hence increases

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[2] Navigation aids used by DOD will be retained for national security. Currently, the DOD uses tactical air navigation (TACAN) systems for en route navigation and nonprecision approaches. Additionally, the DOD is developing the Joint Precision Approach and Landing System (JPALS). JPALS is a ground-based augmentation system for GPS that will enable the use of GPS for precision approaches. The FAA intends to sustain all of the current TACAN systems used by the military for navigation and landing. The DOD will define the timing and policy for when to reduce dependence on ground-based Navaids. DOD will use the Federal Radionavigation Plan to define such a transition to Satnav. In the interim, TACAN, ILS, and radar guided precision approaches will bridge the transition to Satnav.

capacity—in portions of the airspace. Navigation and landing in the NAS is migrating to required navigation performance (RNP) operations. Under RNP, the total navigation system performance is used to approve procedures or operations based on the capability of the pilot, the aircraft and the supporting navigation infrastructure to meet specific performance tolerances. RNP is a metric of performance for use in aviation navigation and is intended to facilitate the use of diverse navigation systems.

RNP is defined in terms of cross-track displacement and along-track position errors relative to a defined flight track. As an example, a route designated as RNP-2 means that the aircraft must be capable of navigating within two nautical miles either side of centerline (95%). An approach procedure designated as RNP-0.3 means that the aircraft must be capable of navigating within 3/10th of a nautical mile on either side of centerline. Detailed requirements for RNP operations are under development.

The use of RNAV (RNP-0.5) can produce instrument approach minima (ceiling and visibility) equal or lower than minima associated with VOR or nondirectional beacon (NDB) nonprecision approaches (NPA). When supported by GPS augmented by the Wide Area Augmentation System (WAAS), the Local Area Augmentation System (LAAS), or GPS integrated with an IRS, RNAV accuracy is better than the accuracy of ground-based navigation aids. GPS can support RNP at and below 0.3.

As WAAS and LAAS are fielded and users equip, satellite navigation (including GPS/IRS integration for some aircraft) will become the fundamental system used for RNAV operations. Airspace will be converted to an RNAV-based structure, eliminating inefficient routes based on the location of ground-based navaids, increasing the diversity of arrivals and departures, and providing approaches with vertical guidance to all runways at our nation’s airports. Using vertical guidance during approach operations increases safety by reducing the risk of controlled flight into terrain.

In the event of interference to GPS, navigation must revert to other means. Commercial operations essential to our nation’s economic vitality must continue uninterrupted. General aviation operators may choose to retain navigation equipment in their aircraft with the ability to continue to navigate, or could avoid flying in the area of interference. General aviation operators that are dependent on Satnav and are operating in instrument weather conditions when a disruption occurs must request radar vectors to reach visual conditions or to fly clear of interference.

4.0 Satnav Vulnerabilities

All radionavigation aids are susceptible to both unintentional and deliberate interference. Virtually all of the interference against ground-based Navaids has been caused by unintentional radiation from radio transmitters. The diversity of ground-based navigation aids has assured that interference has not been a threat to safety or efficiency. Additionally, today’s network of ground-based Navaids mitigates disruption associated with the loss of a single Navaid.

Satnav presents a different situation. GPS produces a weak signal that can be interfered with by low-power transmitters, and interference can affect a large area. Two recent incidents illustrate this vulnerability:

- In 2000, test equipment at the Rome Air Development Center interfered with GPS signals over New York and disrupted GPS RNAV operations in New York Air Route Traffic Control Center (ARTCC) airspace. A number of aircraft, including air carrier aircraft, reported a loss of RNAV capability. Although safety was not affected, this disruption forced these aircraft to revert to ground-based Navaids.
- In 2001, an aircraft manufacturer was conducting tests of a military helicopter's systems using a signal generator without required coordination with the FAA. The device was inadvertently left on, effectively disrupting GPS navigation for approximately 180 miles around Phoenix, Arizona. It took the FAA five days to locate the emitter and get it turned off.

Unintentional interference can occur from sources other than systems designed specifically to jam GPS. This type of disruption occurs because of interference to the single civil frequency for GPS, L1, at 1575.42 MHz. A second civil frequency, L5, broadcasting at 1176.45 MHz, will be implemented to support safety-of-life operations, including aviation navigation. The L5 signal will be broadcast with more power than the L1 signal. This spectrum diversity and increase in power effectively remove unintentional interference from causing safety or efficiency impacts. In the event of interference on L1, signals from L5 can be used. The L5 frequency is expected to become available beginning in 2005, and to be available from a minimum of 18 satellites by 2013.

Intentional interference cannot be overcome through frequency diversity, because a ground or airborne emitter could generate interference on multiple frequencies. The interference could be continuous or intermittent. Interference does not present an unacceptable safety risk. In the event of interference, avionics lose navigation capability and notify the pilot of that loss. Interference during an instrument approach in the weather would cause the pilot to execute a missed approach, navigating either by a backup navigation capability or by radar vectors provided by an air traffic controller.

Intentional interference is expected to be targeted at disrupting air commerce. If commercial aviation has sufficient backup capability to continue to operate in the presence of interference, the threat is significantly diluted. This is not unlike the situation today with ground-based Navaids. Deliberate interference to ground-based Navaids is rare because it does not produce the desired disruption of air commerce. However, interference to GPS may not have aviation as its only target. As the use of GPS spreads to other segments of the economy, the possibility exists that interference attacks will be directed elsewhere and air commerce must continue.

Threat assessments have not identified near-term risks to GPS operations, but have identified the technologies and tactics that could be used to disrupt GPS signals. The technology needed to jam GPS is readily available. Disruption scenarios have been discussed openly, but the threat itself remains extremely low. This is not to say that at some future date a credible threat will not materialize.

The strategy in this report is not impacted by the European Union's decision to pursue Galileo, an independent satellite navigation system. While the Galileo signals could further improve how robust satellite navigation is to unintentional interference, they would not mitigate intentional interference as their power levels are very similar to GPS (L1 and L5).

5.0 Backup to Satellite Navigation

In defining a strategy to cope with disruptions to satellite navigation, three levels of capabilities are used as illustrated in Figure 5.1. On the left side there is minimal protection, and on the right there is redundancy. As the capabilities increase, the operational disruption to air transportation goes down and the likelihood of deliberate acts and consequences are reduced. The reduction of the threat to aviation as a target is attained through continuing operations of commercial aviation, law enforcement, and the military.

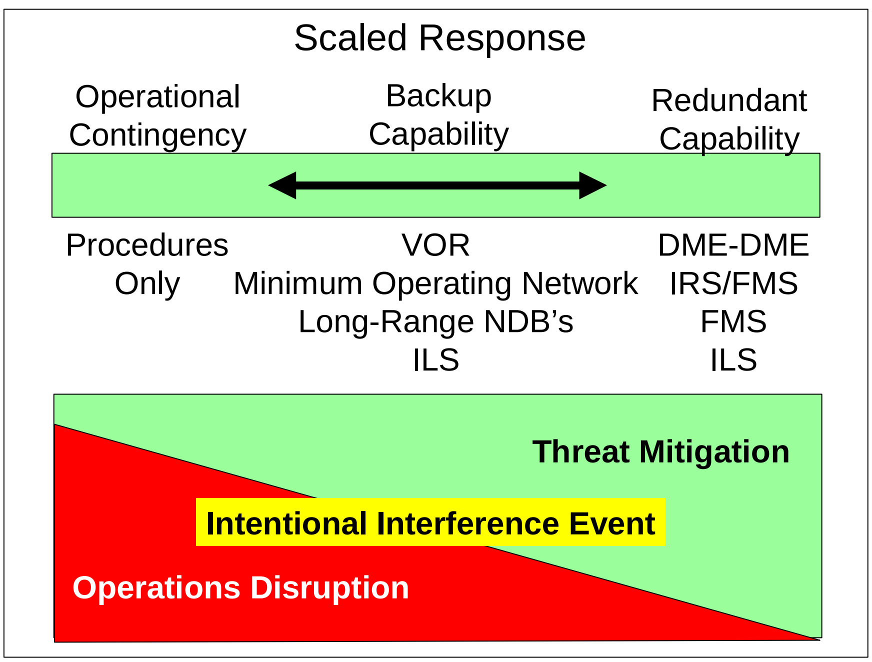

Figure 5.1 Scaled Response with Three Levels of Backup Capabilities

Redundant Capability – a capability where interference has no effect on flight operations and navigation and landing capabilities are similar to what can be accomplished using Satnav. Aircraft with a redundant capability would be able to fly using RNAV, conduct RNAV approaches, and fly precision approaches to landing under instrument flight rules (IFR) in instrument meteorological conditions (IMC). Aircraft with a redundant capability may file a flight plan and fly out of, through, or into areas of known interference.

Backup Capability – a capability where Satnav interference will affect flight operations by requiring reliance on ground-based Navaids for navigation and landing under IFR operations in IMC. Interference with Satnav will require filing and flying routes, procedures and approaches based on ground-based Navaids, primarily VOR. Aircraft that carry a backup capability may not be able to land at the planned destination, but will have an adequate number of airports that they can divert to and land safely. Aircraft with a backup capability may file a flight plan and fly out of, through, or into areas of known interference. Flights in areas of Satnav interference must plan to use routes defined by ground-based Navaids.

Operational Contingency – a capability that relies on specific operational contingency procedures to safely recover aircraft at the onset of interference and to restrict IFR flights. These procedures may preclude flight operations in IMC conditions, while allowing continued operations in visual weather conditions. Access to certain airspace would be denied during a Satnav interference event. Aircraft subject to operational contingency procedures will not be allowed to file a flight plan to fly out of, through, or into areas of known interference in weather requiring IFR operations.

5.1 Redundant Capabilities Supported by Retained Ground-based Systems

Redundant capabilities allow the pilot to continue operating in the presence of interference using the same navigation techniques, with guidance coming from systems other than GPS.

The redundant RNAV capabilities that will be supported include:

- GPS/IRS – With no position updates available from ground-based Navaids, redundant capability is time-limited. An example would be the loss of GPS in oceanic airspace. The IRS can continue to provide sufficient navigation for the separation standards used in the airspace. The IRS precession will introduce error over time, but still remain within tolerance for a period of time dependent on the operation.
- DME/DME – By receiving multiple DME signals with good geometry, the FMS can derive sufficient position information to support RNAV for en route navigation through nonprecision approach.

Both of these capabilities are typically integrated in an aircraft in the FMS. The redundant capability allows pilots to continue to fly their planned flight track and use similar approach and landing ceiling and visibility minima in the presence of interference.

Loran may also provide a redundant RNAV capability. Loran has already demonstrated sufficient performance for en route navigation over most of the nation, but must also provide a nonprecision approach capability to be considered an acceptable backup to GPS. The feasibility of Loran to provide an RNAV nonprecision approach capability is being evaluated.

Additional detail on each of these services is provided below.

5.1.1 Precision Approach – ILS

For redundancy, the FMS can be used for approach and landing. However, the RNAV approach derived from DME position updating is not adequate for landings conducted in low visibilities requiring precision approach procedures. The FAA will retain ILS on a reduced number of runways for the more demanding low-visibility cases where interference is occurring.

All of the current ILS facilities supporting Category II/III operations[3] will be retained on existing runways and new systems will be added where needed to support Category II/III operations to new runways at delay-constrained airports. New ILS installations will continue until the GPS/LAAS capability can support Category II/III operations at these airports. When that happens, the precision approach infrastructure will be re-assessed based on the GPS signals, power, and receiver robustness available at that time. Any resulting changes to the transition strategy will be published in the Federal Radionavigation Plan.

The number of Category I ILS's in the continental United States will be reduced from the current 933 systems. The FAA will remove excess ILS's at the end of their service life, retain the approach lighting systems, and replace the ILS's with GPS-based approaches augmented either by WAAS or LAAS. At least one ILS will be retained on the primary runway at those airports necessary for recovery of aircraft during an interference event. Pilots landing in areas of GPS interference can fly an RNAV arrival procedure to an ILS final approach segment, receive radar vectors to an ILS final, or fly the published ILS approach.

5.1.2 GPS/IRS

The integration of GPS and IRS can provide a robust RNAV system. When data from the two sensors are integrated so that the inertial performance is continually calibrated in-flight, the performance of the IRS is significantly improved. The period of time that RNAV operations can be supported after loss of GPS depends on a number of factors, including the RNP for the operation, the manner in which the systems are integrated, and the aircraft trajectory prior to the loss of GPS. The principle advantage of GPS/IRS as the

[3] Instrument landing systems are provided to support three categories of precision approach procedures—Category I, II and III. Generally, the Category II and Category III capability is available from the same system, but the required airport runway markings, lighting and signage are different. There is a significant cost difference for the airports between Category I and Category II or III.

redundant capability is that it is autonomous in the aircraft and does not rely on any external Navaids.

5.1.3 DME/DME

The FAA will retain at least the current network of 930 DME locations to support FMS operations. This network enables position updates and RNAV (through ranging with multiple DME's) without reliance upon GPS. Aircraft can continue to navigate en route independent of Satnav. Nonprecision approaches can be flown to landing at many airports. The DME network is sufficient to provide a redundant capability for aircraft with FMS or FMS/IRS. Aircraft can be safely recovered in interference areas and continue near-normal operations while flying through areas of known interference to GPS.

DME/DME ranging operations are dependent upon the geometry of DME's relative to the aircraft. At low altitudes (typically, when near an airport) the number of DME's in view decreases and navigation accuracy can be degraded. The FAA may need to expand the DME network to provide a redundant RNAV capability for terminal area operations at major airports.

One of the most challenging operations for a redundant service are departure procedures. The coverage of DME at low altitude is not sufficient to guarantee adequate updating of the IRS. Aircraft without IRS integration may experience departure restrictions in the event of interference. Aircraft that integrate IRS may also experience some restrictions. This is because the precision of the aircraft's IRS position drifts over time. The IRS position can be set at start of taxi out, checked against a known point at the runway entrance, and subsequently updated after takeoff. Therefore, a takeoff delay leading to a drift in the IRS and/or lack of supporting DME systems can result in inadequate accuracy to properly fly a departure procedure. The FAA will need to evaluate coverage from the surface to approximately 1,000 feet and upgrade the IRS update locations on airports. Users must know performance limits for their individual navigation systems given various updating scenarios. The inability to depart during GPS interference would be for those rare locations where terrain is a factor and radar departures are not available today. While there are published departure procedures for many airports, most departures include a takeoff and climb on runway heading with radar vectors being provided. Radar vectors would continue to provide sufficient redundancy until receiving an update in position from DME during an interference event.

5.1.3 Loran

The FAA and DOT are assessing the capability of Loran to provide an RNAV redundant service. In order to be considered as a viable alternative, Loran will need to provide at least an RNP-0.5 nonprecision approach capability. The DOT is expected to make a decision on whether or not to retain Loran by the end of 2002.

5.2 Backup Capabilities

The planned backup capability will be operationally less robust than the redundant capability. The objective of the planned backup capability is to allow continued safe navigation and landing in an interference environment using existing avionics, but with less efficiency than with a redundant capability. A minimum operating network of VOR's and long-range NDB's will be retained in the NAS as a backup capability. Pilots who encounter interference to Satnav will be able to tune a ground-based Navaid, proceed to that Navaid and either continue the flight or land. Efficiency is lost due to requirements to fly from one Navaid to the next. The network of retained VOR's and long-range NDB's are designed to recover aircraft safely, not support a route structure for routine navigation.

Pilots may choose to retain one VOR receiver for use as a backup. The coverage criteria used for the minimum operating network in the continental United States is based on line-of-sight reception from at least one VOR when at 5,000 feet or more above ground level (AGL). To assure safety, the existing VOR structure will be retained in the mountainous terrain of the west, in Alaska and Hawaii, and at offshore locations. Pilots can file a flight plan for IFR departure from an airport, proceed direct to the VOR, then fly outbound to the next VOR, and continue until clear of the interference area. Once clear of interference, the flight can transition back to RNAV using GPS.

For Alaska and certain offshore areas like the Gulf of Mexico, the FAA will also retain and operate the long-range NDB's. These Navaids allow the pilot to identify position, and fly to the stations, bringing the aircraft within reception range of an airport VOR for landing.

Both the VOR and the long-range NDB backups are retained for recovery of aircraft that are caught in an interference event. The network retained is not practical for routine en route navigation, but provides the ability to navigate to an airport VOR and fly a nonprecision approach or intercept an ILS. Also, with a VOR receiver, a pilot can tune to an ILS frequency and fly a localizer-only approach. Additionally, if terminal radar services are available, pilots can be vectored to the ILS.

5.3 Operational Contingencies

Pilots operating under Federal Aviation Regulation Part 91 may elect to not carry redundant or backup avionics, opting instead to accept operational restrictions when appropriate. A key operational restriction will be that aircraft cannot rely on Satnav in areas of known interference. Therefore, pilots without a redundant or backup navigation capability could not fly out of, through or into an interference area on an IFR flight plan or in IMC. Visual flight rule (VFR) operations could be conducted in a region of interference. Pilots will be expected to use visual reference with the ground and dead reckoning to navigate in visual meteorological conditions (VMC).

In the event of interference, operational contingencies will be exercised. Aircraft without a redundant or backup navigation capability will revert to VFR operations (weather permitting) or be vectored out of the region of interference. All GPS/WAAS equipment is required to have an automatic dead reckoning capability that will assist in this transition.

As the threat of intentional interference rises, the FAA may elect to restrict access to certain airspace. One of the threat scenarios involves intermittent interference. In this case, even though an active interference event is not underway, the FAA may need to limit flight operations by aircraft without a redundant or backup capability. The basis of this restriction is the uncertainty of the ability to sustain navigation, the inability to support procedural separation in absence of navigation, and the increased workload in a radar environment to handle aircraft incapable of navigation.

5.4 Planned Restrictions in Class A and B Airspace

Class A airspace includes the airspace at and above Flight Level 180. The FAA will propose a rule that will require either a backup capability relying on a minimum operating network of VOR's or a redundant capability (IRS or DME/DME). The reason is that in the initial onset of an interference event, controller workload will rise and aircraft may need to be placed in a holding pattern to control short-term demand and assure safe separation. Aircraft require navigation to be able to hold. Since a likely intentional interference scenario is at a major urban center, this ability to hold in the en route airspace will allow controllers to adjust demand on the terminal airspace through routing and holding in the en route airspace. Such a rule will need to be in place by 2007 with a 3 to 5 year transition and is expected to have little impact on the users since most aircraft operating in the airspace are already equipped.

As aircraft are routed to a VOR or vectored out of the interference area, and the controller workload is stabilized, normal flows of aircraft with redundant or backup navigation can be reestablished. An interference event should be no more significant than a summer thunderstorm that requires momentary adjustments in demand to assure safe separation. Temporary flight restrictions (TFR) will be used in the event of interference in Class B airspace around congested terminals for aircraft that do not have redundant or backup capabilities. These restrictions are targeted at reducing controller workload to assure safety. At the onset of an interference event, there may be both VFR and IFR traffic in the airspace. Aircraft that are not carrying at least a VOR will be cleared from the interference areas of Class B airspace if warranted by traffic volume. VFR traffic will be directed away from Class B airspace, and IFR traffic will be vectored out of the interference area. No departures will be allowed for aircraft equipped with just Satnav capabilities from airports within the interference area. No IMC landings will be possible in the interference region without at least a backup capability. Those aircraft with a backup capability will be vectored to establish a course to a VOR for landing or for navigation through the area traveling from VOR to VOR. Pilots can also expect radar vectors to an ILS for landing if so equipped.

TFR's will have an impact on those pilots who decide to rely on operational contingencies to address a Satnav interference event. Since such interference events are likely to be rare, a pilot may decide to not carry a backup capability. If the pilot is operating out of an airport within Class B airspace, at the onset of interference, there will likely be departure restrictions imposed, both for VFR and IFR traffic. However, as flight operations stabilize, VFR departures could resume. Pilots wanting to fly through Class B airspace would continue to be denied access, unless their destination was a nearby airport within that airspace. Certain VFR and IFR RNAV corridors would be closed, since pilots would be unable to navigate along the routes in presence of interference. Aircraft caught on these routes at the start of interference would be vectored along the flight path until out of the airspace or clear of the interference area.

TFR's for handling GPS interference would be pre-defined and uniform across the NAS. This would assure that both pilots and controllers would understand the restrictions, apply and comply with them uniformly, and restrictions could be quickly lifted when the interference event ends.

TFR's may be imposed in Class B airspace based on imminent, credible threats. Scenarios that could require issuance of TFR's include events where intelligence or security agencies have identified a threat, where there are multiple intermittent interference events that have previously occurred, or where military training or testing activities may cause interference.

5.5 Operational Scenarios

Interference events can range from a low-power nuisance area near an airport to large area interference created by a powerful airborne emitter. The response by the FAA and the pilot will vary with the event. Appendix B provides examples of interfering events and scenarios built around likely sources of interference.

6.0 Performance Requirements

The transition to Satnav for aviation navigation is made possible by the use of GPS, GPS/WAAS and GPS/LAAS. The International Civil Aviation Organization (ICAO) has adopted performance standards for these systems. These standards, dubbed SARPS (Standards and Recommended Practices), became effective in November 2001, with the publication of ICAO Annex 10, Volume 1, Amendment 76. Satnav may be used for all phases of flight including terminal-area navigation (e.g., departure procedures and standard terminal arrival procedures), en route flight, and instrument approach procedures (e.g., nonprecision approaches, approaches with vertical guidance and Category I precision approaches). It is expected that the FAA's LAAS will eventually support Category II and III precision approaches, however, additional research and development will be required before these systems are fielded.

The FAA's WAAS will begin providing service for IFR operations in 2003. WAAS will improve the accuracy, integrity, availability and continuity of the GPS Standard Positioning Service (SPS) such that certain aircraft (general aviation) may use GPS/WAAS as the only required radionavigation system. RNAV instrument approach procedures based on lateral and vertical navigation criteria (LNAV/VNAV) use Satnav for the lateral component and barometric altimeter guidance for the vertical component of the approach. The integrity and accuracy of WAAS allow Satnav to be used for vertical guidance on these instrument approaches. By September 2003, RNAV approach charts will also begin to include a procedure based on a new lateral precision with vertical guidance criteria (LPV) that takes better advantage of WAAS accuracy and integrity, using WAAS for both the lateral and vertical guidance. Both LNAV/VNAV and LPV criteria allow descents as low as 250 feet AGL, when visibility is as low as ¾ mile.[4] LPV approaches attain 250 feet and ¾-mile visibility at approximately 80% of the runways in the NAS, while LNAV/VNAV approaches reach the same minima at only 20% of the runways. Figure 6.1 illustrates the difference between the performance required for LPV and LNAV/VNAV approaches.

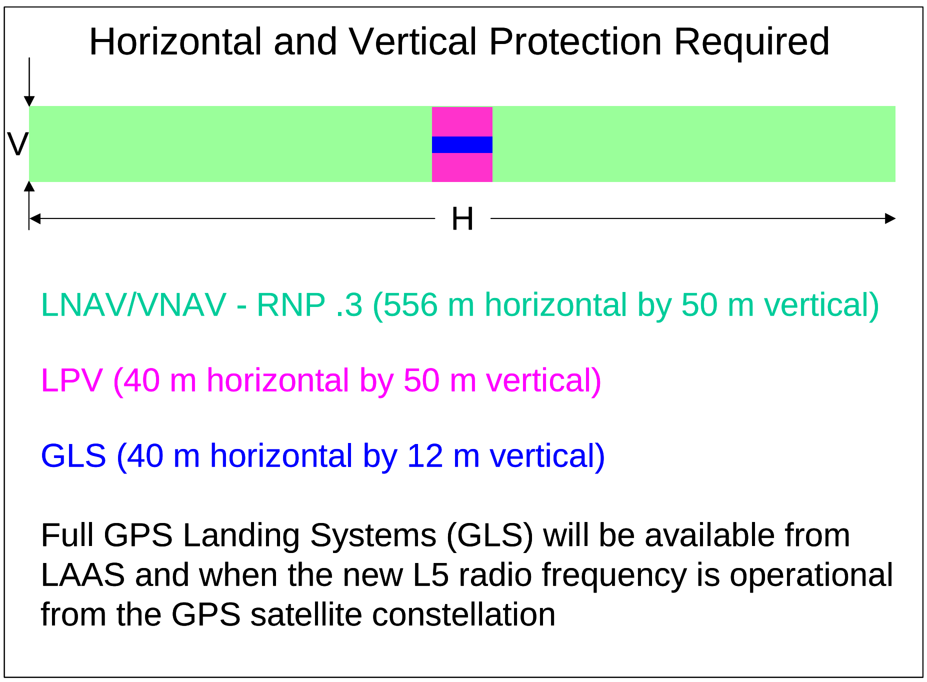

Figure 6.1 Horizontal and Vertical Integrity Limits for GPS/WAAS LPV

The integrity improvement associated with the LPV criteria is significant. The reduction of the lateral limit from 556 meters to 40 meters not only opens up more runways that would otherwise be constrained by terrain or obstacles, it also allows for lower ceilings on the approach compared to what is possible with an NPA based on VOR.

As can be seen from the figure, GPS augmented by WAAS significantly increases the number of runway ends with LPV that could have reduced minima over what can be attained today with LNAV/VNAV. Figure 6.2 illustrates the number of runways that would meet LPV performance.

[4] LNAV/VNAV and LPV visibility minima may be as low as ½ mile when an appropriate approach lighting system is installed.

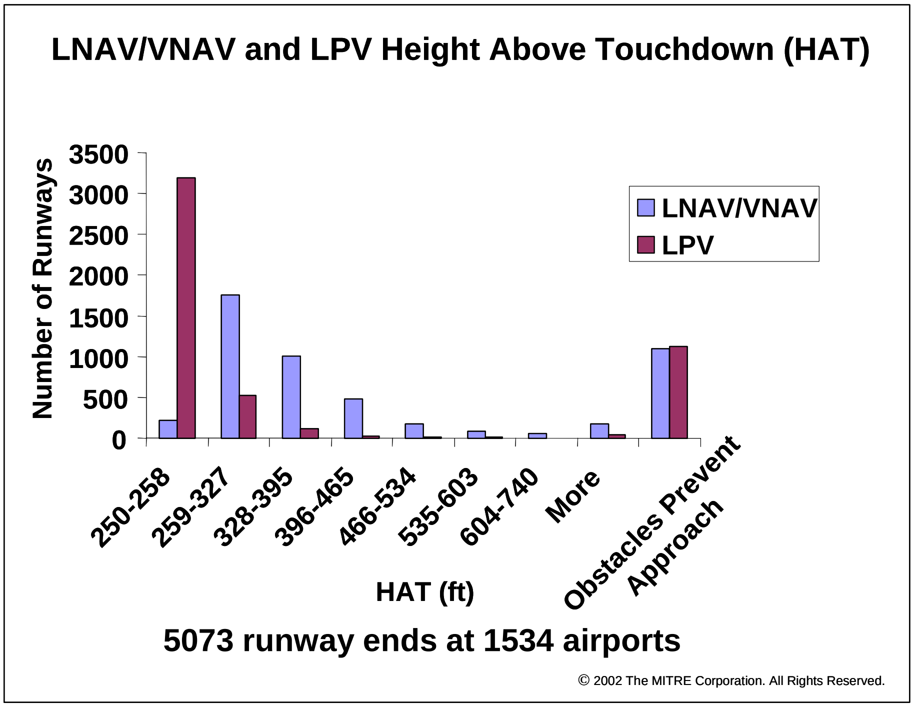

Figure 6.2 Comparison of LNAV/VNAV and LPV

6.1 Technical Performance of Satellite Navigation and Backup Navigation Systems

Performance requirements are defined in terms of horizontal and vertical accuracy, integrity, time-to-alert to an anomaly, continuity risk, and availability. Integrity is discussed in terms of notification of hazardously misleading information (HMI). Integrity is how reliable the signal is for use in navigation and landing, and if unreliable, then how long it takes to alert the pilot.

6.1.1 Requirements on the Navigation Function Provided by the Composite of All Navigation Systems

This section specifies the technical performance requirements (accuracy, integrity, availability, and continuity) on the total navigation function provided by signals-in-space from the composite of the augmented satellite navigation system and the backup navigation systems.

The performance of the navigation function based on the total (composite) set of navigation signals-in-space (satellite-based and non-satellite-based) must be met as indicated in Table 6.1.

Table 6.1 Navigation Performance Requirements

Operation	Accuracy (horizontal 95%) (Note 1)	Accuracy (vertical 95%) (Note 1)	Integrity (probability of HMI) (Notes 2, 3)	Time-to-alert (Notes 2,4)	Continuity Risk (1 – Continuity) (Note 5)	Availability (Note 6)
En Route	3.7 km	NA	10^{-7}/hr	1 min	10^{-4}/hr to 10^{-8}/hr	0.99 to 0.99999
Terminal	0.74 km	NA	10^{-7}/hr	15 sec	10^{-4}/hr to 10^{-8}/hr	0.999 to 0.99999
LNAV (NPA)	220 m	NA	10^{-7}/hr	10 sec	10^{-4}/hr to 10^{-8}/hr	0.99 to 0.99999
LNAV/ VNAV	220 m	20 m	2×10^{-7}/ approach	10 sec	8×10^{-6}/ 15 sec	0.99 to 0.999
LPV	16 m	20 m	2×10^{-7}/ approach	10 sec	8×10^{-6}/ 15 sec	0.99 to 0.999
APV-II	16 m	8 m	2×10^{-7}/ approach	6 sec	8×10^{-6}/ 15 sec	0.99 to 0.999
GLS/CAT I	16 m	6 m to 4 m	2×10^{-7}/ approach (150 sec)	6 sec	8×10^{-6}/ 15 sec	0.99 to 0.99999
CAT II and IIIa	6.9 m	2 m	10^{-9}/ 15 sec	1 sec	4×10^{-6}/ 15 sec	0.99 to 0.99999
CAT IIIb	6.2 m	2 m	10^{-9}/ 30 sec (lateral) 10^{-9}/ 15 sec (vertical)	1 sec	2×10^{-6}/ 30 sec (lateral) 2×10^{-6}/ 15 sec (vertical)	0.99 to 0.99999

NOTES for Table 6.1

1. Accuracy requirements for En Route through GLS/CAT I (except for LPV) have been taken from the signal-in-space performance requirements in ICAO Annex 10, Vol. I (Amendment 76), Table 3.7.2.4-1. ICAO Annex 10 notes that for Category I, the value of 4 m is based upon ILS specifications and represents a conservative derivation from ILS specifications. Accuracy requirements for Category II through IIIb were taken from RTCA/DO-245 for the height or longitudinal position where requirements are the most stringent.
2. Integrity requirements for En Route through GLS/CAT I (except for LPV) have been taken from the signal-in-space performance requirements in ICAO Annex 10, Vol. I (Amendment 76), Table 3.7.2.4-1. Integrity requirements for Category II through IIIB, including probability of HMI and time-to-alert, were taken from RTCA/DO-245 (except that the exposure times for Category IIIb appear for lateral and vertical appear to be reversed in that document).

3. The definition of the integrity requirements includes an alert limit against which the requirement can be assessed. These alert limits are as follows:

Operation	Horizontal Alert Limit	Vertical Alert Limit
En Route	4 nm	NA
Terminal	2 nm	NA
LNAV (NPA)	1 nm	NA
LNAV/VNAV	0.3 nm	50 m (not applicable for barometric-VNAV)
LPV	40 m	50 m
APV-II	40 m	20 m
GLS/CAT I	40 m	12 m – 10 m
CAT II	17.3 m	5.3 m
CAT III	15.5 m	5.3 m

These values have been taken from ICAO Annex 10, Vol. I and RTCA/DO-245. Alert limits for Category I vary depending on whether guidance is used below the lowest Category I decision height of 200 ft. It is desirable to be able to use the signal below the decision height of 200 ft in VFR conditions in order to maintain pilot currency for certain types of approach operations.

4. Time-to-alert requirements for terminal, LNAV, APV-II, GLS/CAT I were taken from ICAO Annex 10, Vol. I (Amendment 76), Table 3.7.2.4-1. Time-to-alert requirements for Category II through Category IIIb were taken from RTCA/DO-245. Time-to-alert for LNAV/VNAV and LPV have been assumed to be those of the ILS Category I localizer. The Time-to-alert for en route was based on an assumption that aircraft may be in mountainous terrain.
5. Continuity requirements for En Route through GLS/CAT I are from GNSS signal-in-space requirements of ICAO Annex 10, Vol. I (Amendment 76), Table 3.7.2.4-1. Annex 10 notes that a range of values for continuity requirements are given for en route, terminal initial approach, NPA, and departure operations, because the continuity requirement is dependent upon several factors including the intended operation, traffic density, and complexity of airspace. Continuity requirements for Category II through IIIb were taken from RTCA/DO-245.
6. Availability requirements for En Route through GLS/CAT I were taken from ICAO Annex 10, Vol. I (Amendment 76), Table 3.7.2.4-1. Availability requirements for Category II through Category IIIb were taken from RTCA/DO-245.

6.1.2 A Candidate Allocation of Total Navigation System Requirements Between Satellite Navigation and Non-Satellite-Navigation Components

For any given flight operation, accuracy and integrity requirements (including the probability of hazardously misleading information and time-to-alert) are the same for all systems. Note 3 of Table 6.1 noted that the Vertical Alert Limit could vary depending on whether the system needs to support operations below the decision altitude/height in VFR conditions in order to support pilot currency for certain types of approach operations.

Specific availability requirements for an area or operation should be based upon the following direct considerations:

- Traffic density
- Alternate navigation aids
- Primary/secondary radar surveillance coverage
- Air traffic and pilot procedures
- Duration of outages

Availability requirements may be allocated between Satnav and non-Satnav systems. As described in Section 5.0, general aviation operators will be able to choose if they want to carry a redundant or backup navigation system. To support these users and to capture the efficiency of Satnav, a minimum threshold availability requirement of 0.9999 is used for en route through nonprecision approach operations. The higher availability objective is 0.99999. The availability of a redundant or backup navigation service is driven by the need to continue efficient air commerce in the event of interference. As such, an availability threshold of 0.999 is applied. Note that these availabilities are not required at every location in the NAS due to the factors described above, but it is not practical to specify location-specific availability requirements for a wide-area system.

The availability requirement for precision approach is 0.99 to 0.99999 depending on the traffic level at a particular airport, the probability that weather is below minima at a particular airport, and on operational restrictions associated with an alternate airport. The availability of ILS is expected to remain constant or improve, and is not specified.

6.1.3 Expected User Equipage

Users are expected to equip with Satnav and ground-based navigation avionics according to the needs of the type of operations conducted. Table 6.2 shows the expected aircraft equipage for en route navigation through nonprecision approach:

Table 6.2 Likely Civil User Equipage for En Route Through Nonprecision Approach

	Add	*Retain*
Current Avionics	***Satnav***	***Ground-based Navigation Backup***
FMS with inertial	**GPS/inertial (or GPS/WAAS)**	**FMS (DME/DME or inertial) RNP/RNAV**
FMS No inertial	**GPS (or GPS/WAAS)**	**FMS (DME/DME) RNP/RNAV**
No FMS or inertial	**GPS/WAAS**	**(1) VOR or (2) Loran RNAV or (3) Operational Contingency**

Expected future equipage for en route through nonprecision approach is likely to be influenced mostly by current navigation equipage. For example, aircraft with FMS that use DME/DME sensor inputs to conduct RNAV operations will be able to use GPS (or GPS/WAAS) as additional sensor input, while retaining DME/DME as a redundant capability. Aircraft without FMS or inertial can add GPS/WAAS capability and optionally retain VOR as a backup capability or rely on operational contingencies.

Table 6.3 shows the aircraft equipage expected for precision approach services:

Table 6.3 Likely Civil User Equipage for Precision Approach

	Add	*Retain*
Current Operations	***Satnav***	***Ground-based Navigation Backup***
Scheduled Operations Large Airports	**GPS/LAAS** 200 feet and ½ mile	**ILS** **Cat I/II/III**
Scheduled Operations Many Airports	**GPS/WAAS** 250 feet and ½ mile with approach lights	**ILS/Cat I** 200 feet and ½ mile
Unscheduled Operations Many Airports	**GPS/WAAS** 250 feet and ¾ mile without approach lights	**(1) ILS/Cat I or** **(2) Operational Contingency**

The expected future equipage for precision approach is likely to be influenced mostly by future operational needs. For example, for scheduled operations into the busiest airports where maximizing access is important, users would likely equip with GPS/LAAS and retain ILS as a redundant capability. Aircraft operating with an extensive route structure may elect to equip with GPS/WAAS to take advantage of low LPV minima and increased flexibility on multiple runways. Many airports will not have LAAS capabilities. Unscheduled operations into many possible airports could be adequately served for precision approach by GPS/WAAS alone.

6.2 DME Retention

Current plans are to retain full capability for DME/DME navigation in the continental United States. This will include all VORTAC, VOR/DME and ILS/DME. Figure 6.3 depicts DME coverage for 930 existing VOR/DME's and VORTAC's. The available ILS/DME and TACAN provision of DME would be in addition to this coverage.

The DME coverage is very dense at en-route altitudes, where pilots are within range of three or more DME's most of the time. However, coverage at lower altitudes is less dense, especially when considering the geometric requirements for DME/DME position solutions.[5] Accordingly, in the future it may be desirable to add some DME's near certain airports to assure adequate DME/DME RNAV capability at lower altitudes. Also, in the future it may be desirable to remove some DME's that produce redundant en route coverage and do not enhance low altitude coverage at airports where DME/DME navigation is used.

[5] The accuracy of a DME/DME position solution depends upon the angle between the Navaids from the perspective of the aircraft. An "include angle" between 30 and 150 degrees is generally required for the position solution to be valid.

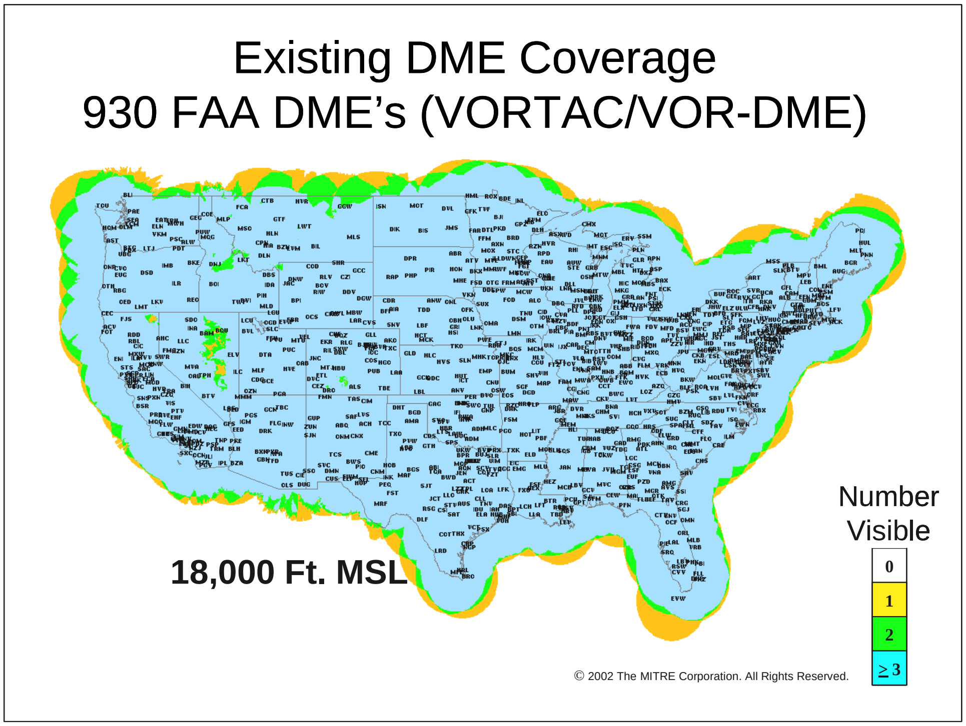

Figure 6.3 Coverage of Existing VORTAC's and VOR/DME's at 18,000 Ft. Mean Sea Level

6.3 VOR Retention

The current VOR service in the continental United States is very dense, even at fairly low altitude. Figure 6.4 shows the coverage of the 1,008 VOR's that cover the continental United States out of the total 1,033 VOR's in the NAS. One objective of retaining VOR's is to provide en route coverage at and above 5,000 feet AGL in non-mountainous areas, and to retain existing coverage in mountainous areas to support general aviation in the event of Satnav interference. A second objective of VOR coverage is to provide landing aids at airports, either for a nonprecision approach or for guidance to an ILS approach.

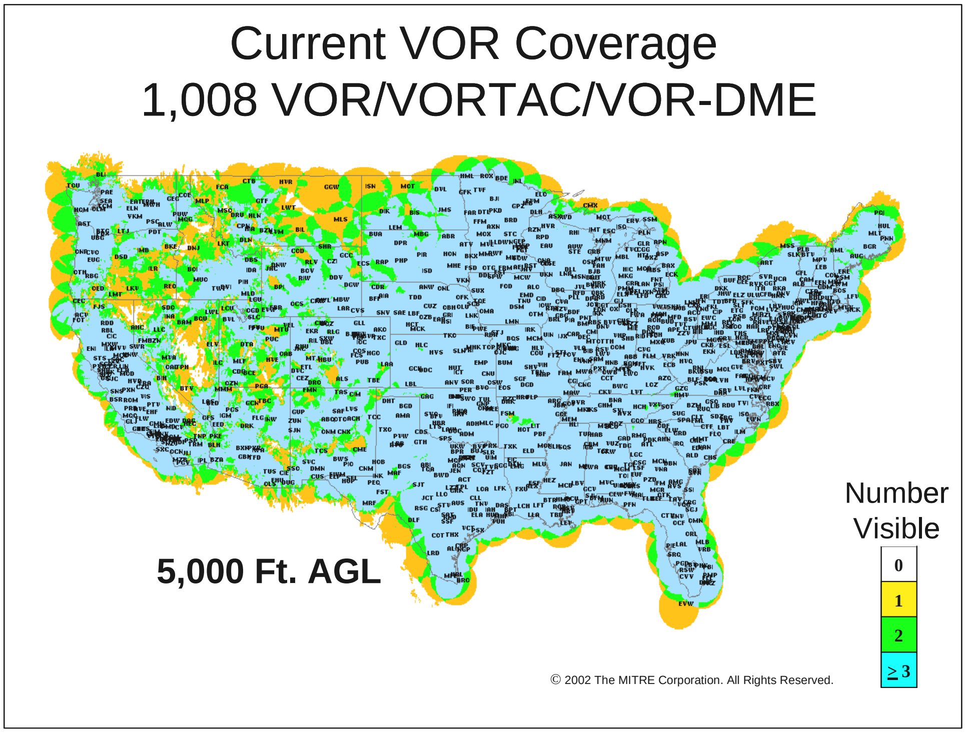

Figure 6.4 Current VOR Coverage at 5,000 Ft. AGL

To estimate required coverage for VOR as a backup to Satnav, the 200 busiest airports were selected based on the number of instrument operations. These airports represent approximately 92% of the instrument operations performed in the NAS, and nearly all are served by a radar approach control. A VOR serving each airport was selected and used as the initial basis for a hypothetical list of VOR's to be retained. Over 60 of these airports were not served by a VOR approach, although a VOR was often near the airport and served another airport. A total of 177 existing VOR's were retained to serve the 200 airports and the airspace near them. After selecting the 177 VOR's, additional existing VOR's were added to provide coverage at 5,000 feet AGL. In mountainous areas, nearly all VOR's are to be retained. Where a VOR did not provide a nonprecision approach, another nearby VOR was substituted that did provide an approach. In addition, some VOR's were added to enable a nonprecision approach (i.e., some nonprecision approaches require multiple VOR's). This added 294 VOR's to the hypothetical list of VOR's to be retained, for a total of 471 VOR's. See Figure 6.5.

A comparison of Figures 6.4 and 6.5 shows the areas that "lost" VOR coverage. One can note that using the reduction to the hypothetical set of 471 VOR's reduced redundant coverage, but little or no actual coverage was lost. Some of the VOR's depicted in Figure 6.5 do not serve an airport. As much as possible, these VOR's will be replaced with VOR's that provide an instrument approach capability at an airport to facilitate landing. As the FAA begins to replace existing VOR's that have approached the end of their service life, VOR's in the minimum operating network will be fully replaced. An opportunity exists to relocate VOR's to improve airport coverage, to deal with restrictions imposed due to obstructions that block signals, and to adjust coverage.

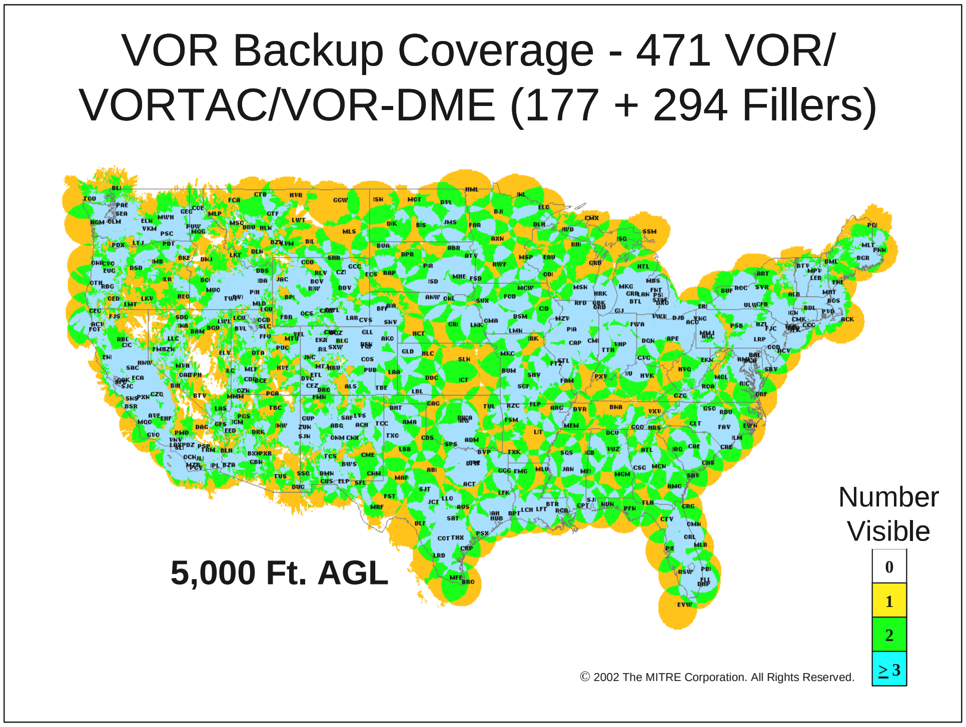

Figure 6.5 Coverage of 471 Existing VOR's at 5,000 Ft. AGL

The VOR's in the NAS comprise a patchwork that grew over time. VOR's were established to support Victor Airways, Jet Routes and arrival and departure procedures for airports. The evolution to Satnav eliminates the need for such routes and procedures, since users of RNAV can fly either the current airspace structure using waypoints or enjoy more freedom of movement in the same airspace. A backup system of VOR's that will be called the minimum operating network is just that, a backup, not the principal means of navigation in the airspace.

The FAA intends to turn off unnecessary Navaids, replace those used as part of the minimum operating network, and provide for both en route backup and the ability to land using a nonprecision approach for at least 200 airports. Not every airport needs a backup, since interference is not expected to be NAS-wide. The FAA plans to begin removal of VOR services in 2010 and complete the transition by 2014. During this time, airways will be discontinued—or redefined as RNAV airways where operationally desirable—and airspace opened for more RNAV flights.

It should be noted that all the VOR's in Alaska would be retained at least until a decision is made on statewide deployment of Capstone[6] technology beyond the research phase.

6.4 ILS Retention

Approximately 1,275 ILS's are installed throughout the NAS (including localizer-only installations), with 671 different airports served in the continental United States.

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[6] The Capstone program is demonstrating advanced communications, navigation and surveillance concepts in Alaska.

Approach lights are installed to support most of these ILS's. There are 117 ILS's that provide Category II or Category III service. Until LAAS attains the capability for Category II/III approaches, all of the Category II/III ILS's will be retained and more may need to be added to accommodate new runway operations at larger airports.

Many Category I ILS's will be retained to fulfill precision approach capabilities as a backup to Satnav. Serving as a backup, it is not necessary to retain all ILS's. As airports transition to Satnav approaches, the FAA will decommission ILS's which are not necessary as part of the redundant navigation system and are no longer cost-beneficial to retain. LPV approaches using GPS/WAAS are expected to enable the elimination of a number of ILS units starting in 2010. In these instances, approach lighting will be retained so that the LPV visibility minima are the same as currently available with the ILS. For airports designated as landing locations for redundant or backup capabilities, at least the primary runway (most used in IMC) will retain its ILS. At large capacity-constrained airports, most ILS's will be retained to ensure adequate arrival and departure capacities in the event of interference. Here, pilots will fly either an RNAV or VOR approach to an ILS final, or receive radar vectors. Category I ILS's will not be removed from airports until WAAS or LAAS approaches have been commissioned at those airports.

6.5 Loran Retention

Loran-C, as operated by the U.S. Coast Guard, is used for navigation by multiple modes of transportation and for precise timing and frequency applications. Due to the uncertainty of continued operations and the rapid growth in GPS use, the user base is declining. In the 1980's the Coast Guard and FAA jointly conducted an expansion of the Loran infrastructure to close a mid-continent coverage gap. This project was completed in 1990. Although originally intended to support nonprecision instrument approach procedures, Loran-C could not meet the required operational performance. The system has therefore been limited to supporting VFR flights and as a supplemental system for IFR en route navigation.

The successful transition of the Loran-C system from its current state to providing a redundant capability to GPS is dependent upon:

- Demonstrated performance in support of nonprecision approaches
- Completion of work efforts to verify and improve integrity performance
- Reduced market risk in production of suitable avionics through development of the necessary standards
- A decision on the long-term continuation of Loran-C and support of the associated infrastructure funding
- Changes in Coast Guard policies and procedures to enhance the operation of the Loran infrastructure
- A multimode transportation and timing user base willing to support continuation of the infrastructure

7.0 Risk Mitigation

7.1 Operational Effects of GPS Outages

An Experiment Working Group (EWG) has been formed to help identify the operational effects of a GPS outage in reduced ground-based Navaid environments. Various FAA organizations and labor unions are represented on the EWG. The National Air Traffic Satellite Operational Implementation Team recommended that air traffic control human factors issues be identified and appraised prior to or during any national implementation of advanced RNAV. The EWG has determined that the controller's ability to manage an outage situation, particularly interference, should be studied in a real-time environment. The need for two separate simulation environments, en route and terminal, has been identified. Both simulations will be conducted at the William J. Hughes Technical Center (WJHTC):

- GPS Outage En Route Simulation (GOERS) - The simulation, scheduled for the October/November 2002 timeframe, will only address issues related to GPS outages in the en route environment. Three adjacent sectors from a selected ARTCC airspace will be used for the simulation. The scenarios will consist of moderate to heavy traffic, a complex route structure, high levels of controller coordination and interaction, a diverse mix of traffic that includes a high concentration of general aviation aircraft, and limited routine use of vectoring. The results of this en route study are intended to assess the impact of a GPS outage on controller workload, identify operational issues that may arise as a result of a GPS outage, and to incorporate lessons learned from the GOERS study into the planned terminal simulation study.
- GPS Outage Terminal Simulation (GOTS) - The GOTS simulation reflects primarily the same scope and assumptions as in GOERS, with the exception that the use of vectoring is prevalent within the terminal airspace during a GPS outage. It is expected that this study, scheduled for the 2003 timeframe, will help define necessary procedures and possible flight restrictions needed in the event of an outage in congested airspace.

Results from the GOERS and GOTS studies will be analyzed to determine what measures, if any, need to be taken to lessen the impact of a GPS outage. Simulation findings will be published. The need for future simulation studies incorporating the enhancements of the WAAS and the LAAS will be determined following the commissioning of those systems.

7.2 Interference Detection and Response

The FAA is expanding its capabilities to detect interference in advance of reducing ground-based Navaids. Recent interference events have demonstrated that the response time to locate and shut down emitters is measured in days. The ability to restore Satnav services must have a goal of service restoral in a few hours. Improving the detection capabilities using radio frequency interference equipment will be necessary. Airborne capabilities exist with the FAA flight inspection aircraft, but dispatch of these aircraft cannot be justified for every event. Since interference impacts are multi-modal, there is a need to define more deliberate response procedures and activities, involving multiple government agencies.

7.3 Spectrum Diversity

The addition of L5 to the GPS signal provides a redundant, diverse frequency that will effectively remove the risk of unintentional interference on L1 or L5 from being a safety of flight problem. If interference occurs on one channel, the other remains available. The L5 frequency will be first introduced on the GPS block IIF satellite launch in October 2005. However, 18 satellites must have the L5 capability before it becomes useful in avionics receivers. This is not projected to occur before 2013. For the GPS III program, consideration is being given to increasing the civil signal power to further mitigate interference concerns. At least through 2013, unintentional interference will remain a risk to Satnav.

7.4 Training

Pilots, controllers, and other transportation users of Satnav must be trained in the nature of interference events, the procedures to be followed in the event of loss of Satnav, and how to assist in identifying the interference area and volume. Pilots who have a redundant capability require less training than those that rely on the minimum operating network of VOR’s and long-range NDB’s. Personnel responsible for detection and elimination of interference events must be trained on procedures to follow. Military personnel engaged in training where GPS jamming is to be conducted must be trained in proper coordination, notification and the implications on navigation to transportation. The recommendations in the Volpe report, *Vulnerability Assessment of the Transportation Infrastructure Relying on the Global Positioning System*, identified training as a key element to responding to the vulnerability of GPS.

7.5 Anti-jamming Technologies

While the FAA supports efforts to define improvements in avionics that leverage DOD-developed technologies for anti-jamming, aviation is global. Any technologies that could not be exported have little application. Likewise, the FAA must be price sensitive, since a significant portion of the general aviation community could not afford sophisticated antennas or signal processing. As anti-jamming capabilities mature, the FAA will need to evaluate the benefits relative to implementation cost in avionics and work with industry to modify avionics standards accordingly.

8.0 Satnav Transition

The FAA will begin the operational use of augmented GPS in 2003. Un-augmented GPS is being used today for supplemental navigation, update of inertial navigation systems, and other low-fidelity applications. The basic GPS signal-in-space must be augmented to realize performance equivalent to that available with the current infrastructure of ground-based Navaids. WAAS and LAAS will provide precision instrument approach procedures at more runways throughout the NAS, increase the precision of navigation, support improved integrity and availability of navigation and landing, and reduce avionics requirements. A commensurate reduction in pilot training requirements should also be realized. This training reduction comes through the consolidation to two types of instrument approach procedures—RNAV(RNP) and precision augmented GPS/ILS approaches. Consistent with the backup strategy laid out in Section 5.0, general aviation instrument pilots flying aircraft not equipped for RNAV/RNP would continue to train on VOR nonprecision approaches.

8.1 GPS/WAAS Transition

The GPS/WAAS is primarily focused on providing en route navigation and precision landing (lateral and vertical guidance) to: 1) improve safety by reducing controlled flight into terrain on approach, 2) increase the approach procedures possible to more runway ends than available today, and 3) support RNAV en route for aircraft that are not capable of inertial navigation and/or flight management systems.

WAAS uses a system of ground stations to provide necessary augmentations to the GPS navigation signal. A network of precisely surveyed ground reference stations is strategically positioned to collect GPS satellite data across the country including Alaska, Hawaii, and Puerto Rico. Using this information, a message is developed to correct any signal errors. These correction messages are then broadcast through communications satellites to receivers on the aircraft using the same frequency as GPS.

WAAS is designed to provide the additional accuracy, availability, and integrity necessary to enable users to rely on GPS for all phases of flight, from en route through a GPS landing system (GLS) approach for all qualified airports within the WAAS coverage area. This will provide a capability for the development of more standardized precision approach procedures, missed approach procedures, and departure guidance for approximately 4,100 runway ends and hundreds of heliport/helipads in the NAS. WAAS will also provide the capability for increased accuracy in position reporting, allowing for more uniform and high-quality worldwide air traffic management. International standards for satellite-based augmentation systems are in place through ICAO, and Europe, Japan, India and others are actively pursuing WAAS-compatible systems.

In August 2000 the FAA announced the availability of the WAAS for some aviation uses and all non-aviation uses. The 21-day stability test that had been conducted prior to this declaration demonstrated required system stability, allowing immediate use of the WAAS signal by a broad range of users. WAAS continues to be developed to provide the integrity required for safety-critical applications. The WAAS is not currently approved for aircraft navigation under IFR, but continues to move toward operational approval, expected by December 2003. Initial operational capability (IOC) will be declared after system deployment and testing is completed. Avionics standards are already in place, and manufacturers are developing receivers.

WAAS improves basic GPS accuracy to approximately 2 meters vertically and horizontally, and provides important integrity information about the entire GPS constellation. WAAS provides benefits beyond aviation to all modes of transportation, including maritime, highways, and railroads. WAAS is already being used in many different applications including agriculture, surveying, marine and military operations, and scientific and engineering data collection. WAAS has become an integral part of its users' guidance systems, with recreational boating as a prime example. Several manufacturers are supplying low-cost (under $500) systems for navigation with WAAS corrections and repeatable accuracy of 2.5 meters.

When WAAS attains IOC in 2003, it will immediately provide service to previously commissioned LNAV/VNAV approaches, and new LPV approaches will begin to be published. Additional geostationary communications satellites will still be needed to increase communications redundancy. With only two satellites providing the WAAS service, failure or relocation of either satellite would make WAAS unusable over a significant portion of the United States.

A third WAAS satellite is needed to complement the two existing INMARSAT satellites and provide a redundant capability to protect against service disruption if one of the existing satellites is rendered useless. The request for proposals was issued in June 2002, and the satellite is anticipated to be in operation by mid-2004.

Relocation is part of the normal replacement of these satellites. During a relocation evolution, the existing satellite is taken out of service and moved out of the assigned orbit position while a new satellite is guided into place. This process can take several weeks, and during that time the WAAS functionality would be unavailable from the assigned orbit position. One of the current WAAS satellites may need to be relocated before a third WAAS satellite is operational. The consequence would be loss of coverage.

Section 10.1 describes the Loran Data Channel (LDC) that could be used to broadcast the WAAS message. If a decision is made to continue operating the Loran system, and if the LDC is implemented, this could provide a secondary channel for conveying the WAAS message to users. The primary beneficiaries would be non-aviation users whose path the to geostationary WAAS satellites may sometimes be blocked by structures or terrain. However, as discussed in Section 10, there is an issue of user acceptance of Loran as a redundant navigation and timing service.

8.2 GPS/LAAS Transition

The GPS/LAAS has five design goals:

- Develop a precision approach capability equivalent to ILS Category I/II/III
- Provide multiple runway coverage for precision approaches
- Develop advanced approach procedures (curved and segmented) to avoid obstacles, support complex airspace, and meet noise reduction objectives
- Provide remote coverage and gap filling for areas where WAAS performance is inadequate, and
- Support surface movement precision navigation

Augmentation with LAAS includes multiple receiving ground stations on the airport that process GPS information similar to the WAAS reference stations and then broadcast the corrections and integrity information to the aircraft through a very-high frequency (VHF) data link.

The FAA expects to award a development and production contract for LAAS Category I systems by September 30, 2002. The contract will provide for the completion of the Category I system design, procurement of ten limited-rate-of-initial-production systems, and five one-year options to procure 15 - 40 production systems each year. The first LAAS Category I system is scheduled for commissioning in March 2005. A decision to proceed with LAAS Category II/III is scheduled for early in 2005 following development of avionics standards and completion of technical studies on Category II and III design and performance requirements.

8.3 Avionics Transition

The time required to shift users from dependence on ground-based Navaids to Satnav differs with the users. The DOD requires approximately 9 years from the start of transition to complete fleet retrofit. Space and weight limits on fighter aircraft may impede the transition. The DOD will use the Federal Radionavigation Plan to convey their transition schedule and their continuing need for ground-based Navaids.

Civil aviation is driven to equip by an improved business case, access, or in some cases competitive advantage. The FAA does not plan to regulate carriage of Satnav. Forward fit (new aircraft) with new capabilities is easier to support than retrofit of existing fleets. The air carriers estimate that a 5 to 7 year transition is necessary to retrofit because the change out of avionics should be done when the aircraft is removed from revenue service for major overhauls.

General aviation is driven more by cost and access. Assuming there is real benefit for equipping with Satnav and they can understand what impact the transition has on access to more runways and airports, then they will begin to equip. Incentives are essential to general aviation. They must get better service in terms of airspace access and landing capabilities. It should be noted that general aviation is not one class of operators, but many, ranging from high-end business jets to home built aircraft. Each has a particular price-point at which they would invest. For business aircraft, they prefer to buy new capabilities at the purchase time of the aircraft and will retrofit when there is a business case to do so.

A significant portion of the general aviation community flies under visual conditions and does not need a backup; they have it already with dead reckoning and ground reference. They have invested in hand-held GPS units and use them routinely for navigation. The segment of general aviation pilots that conduct instrument flights will transition after they see the avionics options from the manufacturers, have decided how transitioning will benefit them personally, and FAA has provided some relief in the carriage of other avionics. Many cockpits have limited space and to accommodate panel mounted Satnav, something has to go. A reasonable assumption for general aviation transition is approximately 10 years from the time that approach procedures are available from augmented GPS.

This transition can be accelerated if access changes are made. An example would be to implement more RNAV flight corridors through Class B airspace, providing approach procedures at more general aviation airports sooner, and reducing the cost of avionics and training requirements.

Figure 8.1 provides a summary of the navigation and landing transition. The current number of Navaids is shown on the left and an approximate future number on the right for comparison. Decisions to remove specific Navaids have not been made.

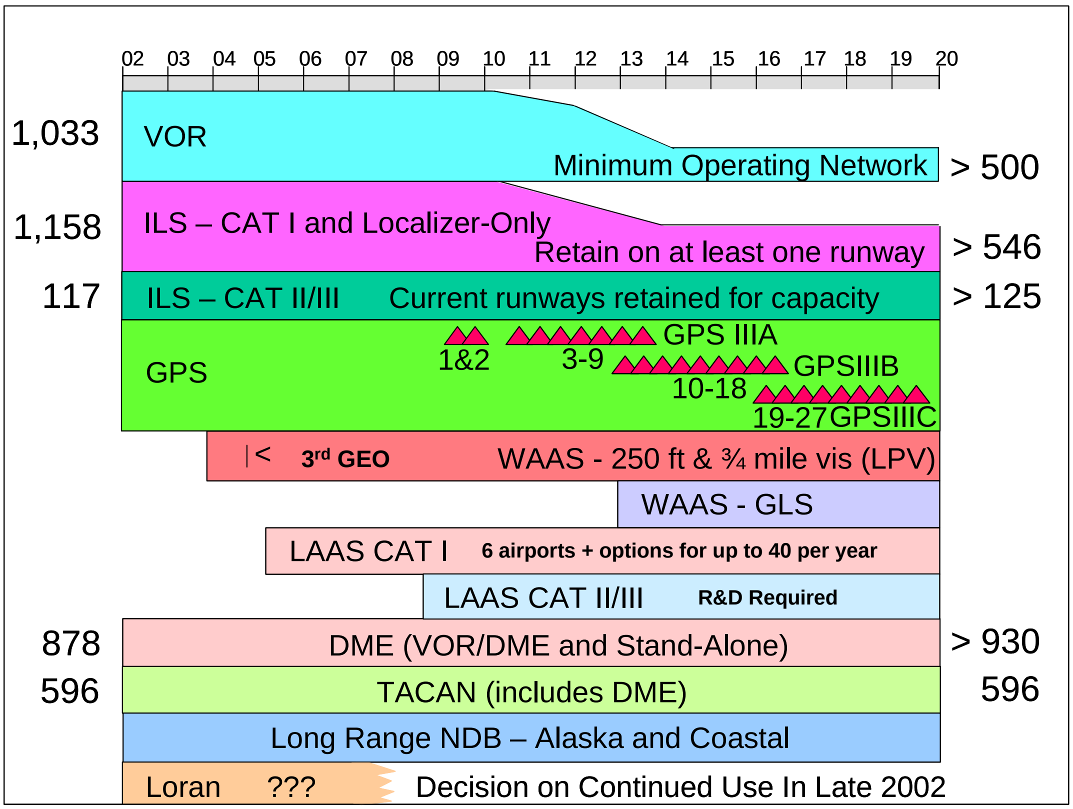

Figure 8.1 Navigation and Landing Timeline

The reduction in the number of VOR's starts slowly in 2010, removing some VOR's that do not support airports and that are in place today to route aircraft along redundant flight paths. The Victor Airway VOR's can be reduced starting in 2010 because the airspace needs to be opened up to allow the increased use of RNAV routes. By 2014 the Victor Airway and Jet Routes are eliminated for en route navigation, and the VOR's that are retained support the minimum operating network used as a backup to Satnav. Between 2007 and 2012, the FAA replaces those VOR's identified as part of the minimum operating network.

Reduction in the number of Category I ILS's can start in 2010. By this time, WAAS LPV and LAAS procedures will have been available for 5 years. Multiple ILS's are typically installed on airports served by commercial aviation. General aviation airports most often have a single ILS. Since at least one ILS is retained at airports supporting the backup strategy, the impact of removal is primarily borne by commercial aviation. The air carriers are migrating to RNAV approaches and expect to use a combination of WAAS and LAAS, and by 2010, the LAAS acquisition contract is in the last year of its option and most of the Category I LAAS units will have been deployed.

Many Category I ILS's have exceeded their service life and have had service life extensions. The FAA will need to begin a replacement program for the older ILS units as early as 2005. This replacement will need to focus on those aging ILS's on the primary runway.

Most of the Category II/III ILS's were deployed in the 1990's and, with service life extensions, can continue to operate well past 2015. There is no reduction in Category II/III ILS's until LAAS is able to deliver equivalent service and vulnerability concerns are addressed. The precision approach infrastructure will then be re-assessed based on the GPS signal power and receiver robustness available at that time. A reduction in the number of Category II/III ILS's may then be considered.

As shown in Figure 8.1, WAAS will be upgraded to provide a redundant service on L5 and to support dual-frequency WAAS users to achieve GLS performance.

9.0 Precise Timing

Both GPS and Loran-C can provide precise time for user applications. Time transfer is the process of comparing two sources of time to synchronize clocks.

GPS is synchronized to coordinated universal time (UTC), which is an international atomic time standard (based on cesium-133) with leap seconds added for variable Earth rotation. Precise time can be determined from GPS through the use of carrier-phase time transfer to a precision of ten picoseconds and an accuracy slightly less than one nanosecond. GPS time is adjusted for each satellite through reference to the U.S. Naval Observatory's master clock and the uplink of synchronization corrections. As a comparison, the WWV high-frequency radio broadcast is only accurate to a few milliseconds. Loran-C has a precision of 100 nanoseconds and an accuracy better than 300 nanoseconds.

The WAAS satellites are also synchronized to UTC and, like the GPS satellites, can be used for carrier-phase time transfer. Because they are in geosynchronous orbit, the WAAS satellites offer advantages over the GPS satellites themselves. Users at fixed locations can employ low-cost high-gain directional antennas to enhance the WAAS signal level and mitigate interference that might deny the signal to mobile users with omni-directional antennas. As a result, time transfer can continue uninterrupted in many signal interference scenarios. WAAS therefore has potential as a diverse backup for the delivery of UTC.

The Loran-C system is also synchronized to UTC. Loran-C is organized into chains consisting of a master station and three to five secondary stations. Each station has a suite of three cesium time standards that maintain signal timing within 100 nanoseconds of UTC. The requirement for Loran-C synchronization is supported by public law[7]. There has been a long-standing use of Loran for precise timing applications.

9.1 Precise Timing Uses

The following applications exemplify the uses of precise time:

Communications and Information Technology
Cell phones and pagers
Large bandwidth data transmission
Network Time Protocol (NTP)
Satellite communications systems
Military communication systems

Surveillance
Space debris monitoring
Space orbit and reentry monitoring
Missile launch detection and tracking
Nuclear explosion detection

Science and Engineering
Power grid synchronization
Generation of UTC
Very Long Baseline Interferometry
Pulsar observations
Neutrino detectors
Black hole research
DOD and civilian laboratories
Earth rotational measurement
Ionosphere measurement
Troposphere measurement

The U.S. Naval Observatory estimates that there are over two million direct users of NTP and an unknown number of secondary users. NTP is used to synchronize local and wide are networks, in banking and the stock markets, for the time stamping of documents like court filings and patents, and for general home and office use.

10.0 Role of Loran-C

10.1 Background

Loran-C has been promoted as a possible backup to GPS. Loran was originally developed for the U.S. Air Force to support all-weather bombing. Its operation was transferred to the U.S. Coast Guard in the 1950's where it enjoyed widespread use in the coastal areas of the United States. Under agreements between the United States and Canada, and between the U.S. Coast Guard and the FAA, coverage was expanded to provide radionavigation service for U.S. coastal waters to include complete coverage of the continental U.S. as well as most of Alaska. Twenty-four U.S. Loran-C stations work in partnership with Canadian and Russian stations to provide coverage in Canadian waters and in the Bering Sea. Loran-C provides accuracy better than 0.25 nautical miles for suitably equipped air,

[7] Public Law 100-223, "Airport and Airway Safety and Capacity Expansion Act of 1987," December 30. 1987.

land and marine users within the published areas of coverage. Users can return to previously determined positions with an accuracy of 50 meters or better using Loran-C in the repeatable mode. Advances in technology have allowed greater automation of Loran-C operations. New technology has allowed the Coast Guard to establish centralized control of the Loran-C system at two locations. The application of new receiver technology has improved the usability of the system.

The current Loran-C operational policy is that while the Department of Transportation continues to evaluate the long-term need for continuation of the system, the Government will continue to operate the system in the short term. The Government has committed to giving users reasonable notice if it concludes that Loran-C is not needed or is not cost effective, so that users will have the opportunity to transition to alternative Navaids. By the end of 2002, the Secretary of Transportation is expected to decide on the continuance of Loran-C. Current Loran-C system sustainment activities are leading to improved synchronization with UTC. New digital receiver technology supports improved accuracy and coverage. Loran-C will continue to provide a supplemental means of navigation for en route flight and terminal-area navigation. Current Loran-C receivers do not support nonprecision instrument approach operations.

Loran-C avionics equipage is currently estimated at 18,200 VFR and 8,700 IFR installed units. These numbers are down substantially from the nearly 200,000 installed units estimated in the early-to-mid 1990's. The decline has occurred as the result of using hand-held GPS receivers or removing Loran-C units to gain space for the installation of panel-mounted GPS avionics. With the uncertain future of Loran, equipment manufacturers are hesitant to invest, and at least for aviation, the market is virtually nonexistent.

The Coast Guard has developed a three-phase Loran-C re-capitalization program. Phase I is designed to extend system operation through 2008, Phase II re-capitalizes the system through 2015, and Phase III looks beyond 2015. Each phase improves upon the system and services that exist today. The estimated cost of the program is $237 M (Phase I - $158 M, Phase II - $12 M, and Phase III - $67 M).

The Coast Guard has also provided estimates for several options to improve Loran service:

- Infrastructure improvements include enhancing services by using uninterruptible power supplies, adding additional secondary factor (ASF) data collection to improve correction of the signals in the receivers, and adding additional stations ($52 M).
- The Loran Data Channel (LDC) can be used to broadcast the GPS differential corrections and integrity information contained in the WAAS message ($39 M). The advantage of this add-on would be the uninterrupted delivery of GPS corrections to marine and terrestrial users whose path to the geostationary WAAS satellites may sometimes be blocked by structures or terrain.
- The Coast Guard would invest approximately $11 M to modify facilities and improve remote monitoring, allowing staff reductions at some stations.

The primary beneficiaries would be non-aviation users whose path to the geostationary WAAS satellites may be momentarily blocked by buildings or terrain.

Loran is the best theoretical backup to GPS. It provides an RNAV backup for an RNAV system, making navigation and landing procedures consistent between GPS and the backup. However, the current Loran-C system does not provide the required capability. An enhanced Loran capability requires new avionics, and may require modifications to the transmitted signal structure. Depending on the extent of the signal enhancements, the current installed base of Loran-C avionics might remain useable for en route operation or could be rendered obsolete. For Loran to become viable in the aviation community, it would need to be integrated with a GPS or GPS/WAAS avionics package, and the benefits would need to outweigh the infrastructure costs of a delayed transition from VOR.

10.2 Performance Requirements

For Loran to be a backup, it must support nonprecision approaches. Minimum and target performance requirements have been identified. The difference between minimum performance (required) and targeted performance is the desire for Loran to support RNAV RNP 0.3 operations so that training and approach procedure development can be aligned with a consistent capability across the NAS. Table 10.1 summarizes the requirements that Loran must meet to be considered a useful backup for aviation.

Table 10.1 Minimum and Target Loran Performance Requirements

Performance Requirement	Value
Accuracy (minimum)	796 meters
Accuracy (target)	220 meters
Monitor Limit (minimum)	926 meters
Monitor Limit (target)	556 meters
Integrity	10^{-7}/hour
Time-to-alert	10 seconds
Availability	99 percent
Continuity of Service	99.99 percent

10.3 Challenges to Meeting Requirements

For Loran to provide a redundant backup to GPS, it must be able to support nonprecision approach operations. The issues surrounding the acceptance of Loran can be viewed in four general areas: Federal policy and user acceptance, operational policy, transmitting equipment re-capitalization, and user equipage.

The uncertainty around Loran’s future has not been conducive to user or industry support of the system even though advances in technology have opened the door for improved transmitting and receiving equipment. Federal policy would need to be revised to include an extension of service well beyond 2015 and the associated funding to re-capitalize the system. If a policy decision is made to terminate continued use of Loran-C, then early termination saves the further commitment of resources. The FAA would stop further engineering development to achieve a nonprecision approach capability.

Although the U.S. Coast Guard has made considerable effort to support the use of Loran by all transportation modes, limitations in transmitting equipment and a focus on the marine user community have precluded changes in operating policies that could optimize the system to meet aviation's need for nonprecision approaches. These changes include operational control and monitoring methods, control tolerances, and maintenance policies. Changes in operational policies and procedures are possible once the initial phase of the system re-capitalization is complete. The Coast Guard is supportive of these changes.

The current Loran-C transmission capability cannot support the signal-in-space requirements for a redundant capability to GPS. Upgrades would need to continue as described in Section 10.1.

The existing Loran-C receivers used in aviation are not capable of meeting the expected requirements for minimum operational performance. Technical and economic issues continue to be obstacles to attaining adequate performance and acceptance of the technology for a nonprecision approach. These obstacles include:

- Precipitation static (p-static)
- Hazardously Misleading Information (HMI)
    - Cycle slip
    - Additional secondary factor bias errors due to signal propagation
- Availability shortfalls
- Coverage shortfalls
- Declining customer base

P-static results from the discharge of the static electricity that accumulates when an aircraft flies through precipitation. This is similar to the static you hear from lightning storms on the AM broadcast band. Without proper discharge from the aircraft,[8] static builds up and then discharges suddenly, causing static noise to exceed the signal. As a result, Loran can become unreliable in the very weather conditions in which it is most needed. Considerable progress has been demonstrated in verifying the improved performance provided by magnetic-field (H-field) antenna technology for Loran receivers. While tests have shown that an H-field antenna can improve the signal-to-noise ratio in high static-discharge conditions, flight tests of this technology in weather conditions or static loading tests have not yet been conducted. The FAA's William J. Hughes Technical Center plans to conduct antenna tests this year.

[8] Static wicking devices are commonly installed on the trailing edges of aircraft surfaces to help reduce p-static.

As a result of a March 2002 meeting between the FAA and the Coast Guard, it was agreed to form a Loran Integrity Performance Panel (LORIPP), similar to the integrity panel formed for WAAS and including some of the same technical experts. The panel is examining the risks of HMI. Two leading HMI contributors are the cycle slips caused by a combination of random effects (signal-to-noise ratio effects and transmission jitter) and bias errors (transmission offset and ASF errors), and improper definition of the ASF corrections. Cycle slips can yield over 3,000 meters of error but are easy to detect using technologies very similar to the receiver autonomous integrity monitoring (RAIM) algorithms used in GPS avionics.

ASF errors are caused by propagation of the signal across the Earth's inhomogeneous surface, plus some temporal variation. The temporal variation, although significant, may not require seasonal calibration. A one-time calibration of each airport, with periodic validation using flight inspection aircraft, may be sufficient to characterize the required ASF corrections. Early airports will need to have intense calibration procedures. As experience is gained with ASF data collection, models can be refined to reduce the calibration requirements. In any case, ASF corrections will need to be incorporated in the receivers and may require periodic update.

The LORIPP is 90 percent confident that enhanced Loran will be able to provide RNP 0.3 integrity over virtually the entire continental United States and much of Alaska. However, there are potential coverage shortfalls around the San Diego area, through sections of the Midwest, and above the Brooks Range in Alaska. There may be a need to add transmitters near the Great Lakes and on the Yucatan Peninsula. To improve coverage above the Brooks Range requires a transmitter in the Prudhoe Bay area. The Coast Guard has proposed moving the station at Attu to Prudhoe Bay. The approximate $12 M cost is included in the add-ons identified in Section 10.1. Costs for new transmitters in the Great Lakes region and the Yucatan Peninsula have not yet been determined. This 90 percent confidence does not extend to the p-static issue. Additional performance information is needed to assure confidence in the H-field antenna.

Current Loran-C navigation availability is 0.997, based on the performance of a chain of Loran stations.[9] To provide a stand-alone capability, Loran must meet en route navigation through nonprecision approach requirements with an availability of 0.999 to 0.9999. If a Loran sensor is integrated with GPS/WAAS avionics, the required Loran availability could be lower, since GPS and Loran are independent systems. The LORIPP is proposing use of all-in-view receiver technology to attain the higher availability. This is a new receiver that uses algorithms that derive position from any set of Loran-C transmitters received, independent of the Loran chain configuration.

To solve coverage shortfalls, three new stations would be needed as discussed above. The existing Canadian Loran stations would also be needed to meet coverage requirements. If

[9] Individual Loran-C stations have an availability of 0.999. The signals from a triad of three stations are required for a position solution, yielding an availability of 0.997.

Canada decides to discontinue Loran, the United States would need to consider assuming the cost of continued operation and re-capitalization.

There is a risk whether receiver manufacturers will invest in the development of Loran technology. This uncertainty has resulted from the declining Loran customer base and a growth in marine GPS navigation equipment that includes either the Coast Guard differential correction technology[10] or, more recently, WAAS technology. In the marine market, GPS/WAAS units with display mapping are running between $400 and $1,000 retail, competing with future Loran equipage. Without the benefit of multi-modal use and leveraging the economies of scale, the market for future Loran receivers is uncertain. A stand-alone all-in-view receiver is being built today; however, aircraft panel-space limitations and general aviation cost constraints lead to a conclusion that for aviation to be part of that economy of scale, the avionics would need to be integrated as just one sensor in a GPS/WAAS/Loran package. The estimated additional cost to add Loran to GPS/WAAS is on the order of $800 to $1,200.

10.4 VOR Transition With Loran

The LORIPP needs another 15 to 21 months of analysis to determine whether Loran can support nonprecision approaches, including definition of the ASF characteristics. An estimated 18-month effort would then be needed to develop standards for an integrated GPS/WAAS/Loran receiver. Avionics could be introduced by 2007, but there is no assurance that a market will develop. Assuming a 5- to 7-year transition for general aviation to equip with integrated GPS/WAAS/Loran avionics, then the planned VOR phase-down could begin in 2014. This is four years later than if Loran were not retained and VOR’s alone formed the general aviation backup infrastructure. A 2014 VOR reduction would also coincide closely with the expected operational date for the new GPS L5 civil signal. The integrated GPS/WAAS/Loran avionics standards would also support L5, which significantly reduces the impact of unintentional interference.

Under this scenario, the FAA must maintain the full complement of VOR’s until the integrated GPS/WAAS/Loran equipment is available. This delay may require the FAA to replace more VOR’s than would otherwise be necessary, only to follow with their removal at a later date. Introduction of Loran as a redundant system would follow a decision by the Department of Transportation to continue operating Loran, and would then delay equipage with GPS/WAAS avionics by many users who would wait until 2014 to equip.

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[10] The Coast Guard has installed a coastal network of differential GPS stations using a medium-frequency data link to broadcast corrections and integrity information to suitably equipped users. This Nationwide Differential GPS (NDGPS) network is being expanded to cover the entire U.S. The system design is based on maritime requirements and lacks the software design assurance and integrity algorithms needed to meet aviation requirements.

11.0 Loran Tradeoff Space

The tradeoff space for Loran is between Loran and the extent of the VOR backup network. Assuming technical performance issues can be resolved and the users accept Loran as a better backup than VOR, then eventually fewer VOR's would be needed in the system. VOR's would be retained primarily at commercial airports where they would be used to supplement DME-DME position determinations for FMS-equipped aircraft.

A high percentage of aircraft would need to be equipped with a Loran backup before the FAA could reduce VOR's below the minimum operating network described in Section 6.3. Instead of reducing to a level of approximately 500 VOR's, the number could be closer to 250. The difference of 250 VOR's has a re-capitalization cost of approximately $375 M. This exceeds the Government Loran re-capitalization costs. On the user side, there are approximately 217,000 general aviation aircraft. Assuming that 60 percent would carry GPS/WAAS and engage in IFR operations, the added avionics cost above their investment in GPS/WAAS would be between $104 M and $156 M. In addition, the cost of the delayed transition would need to be determined.

If only a low percentage of aircraft equip with Loran, then the FAA would need to retain the minimum operating network of approximately 500 VOR's. The investment made in the Loran ground infrastructure would primarily benefit the other modes of transportation and precise timing users.

12.0 Next Steps

Several near-term actions supporting the transition strategy have been identified. These actions continue to refine the transition, provide users with information on timing of key investment actions, and support navigation service improvements.

1. As discussed in Section 5.4, the FAA intends to issue a rule governing required equipment to be carried in Class A airspace. This rule would apply to civil aircraft operating at or above Flight Level 180. A notice of proposed rulemaking will be issued in 2005, and a final rule in 2007. Precursors to this rule development include the update of the benefit/cost analysis for Satnav that considers retention of the necessary ground-based Navaids to support redundant and backup capabilities, and definition of which Navaids are to be retained by specific location. In September 2002, the WAAS program baseline will be updated for performance, cost, schedule, and qualitative benefits. The quantitative analysis on Satnav benefits with WAAS will be completed by end of calendar year 2003. Cost elements associated with the third geostationary satellite will be known and the approximate number of retained ground-based Navaids will be defined. This information will support user business case development.

   The FAA, in collaboration with the aviation community, will identify criteria, timeframes and locations for removal of ground-based Navaids and produce a site list and date for discontinuance of services provided by these Navaids in 2004, consistent with Satnav capabilities.

2. As of the April 2002 charting cycle there were 3,339 RNAV approaches published in the NAS. An estimated 600 LNAV/VNAV approaches will be published by July 2003. By September 30, 2002 the FAA will publish the criteria for development of LPV approaches. Starting in September 2003, all new RNAV approaches will carry LPV minima where there is a benefit to doing so. Approximately 40 LPV approaches will be published by September 2003. The FAA will investigate ways to accelerate the development of LPV approaches and will review changes needed to add LPV minima to existing LNAV/VNAV approach procedures.

3. The update of Advisory Circular 90-94, *GPS Operations*, will be released in May 2003 and will contain operational guidance on GPS and WAAS use, in advance of commissioning of WAAS.

4. WAAS will attain initial operational capability for use en route through precision approach using LNAV/VNAV by December 2003.

5. As discussed in Section 7.2, there is a need to significantly improve national response to GPS interference events. The FAA will ask the Interagency GPS Executive Board (IGEB) to pursue the issue of response to interference events. The IGEB should define Government roles and responsibilities, set criteria for response, and define the command and control aspects of eliminating interference. In the interim, the FAA will continue its investment in radio frequency interference detection equipment and its development of a rapid response capability. The more challenging issue remains law enforcement. To this end, the FAA's Office of Spectrum Policy and Management is working with the Transportation Security Administration (TSA) to develop a memorandum of agreement, and then have assistance agreements in place with local law enforcement organizations to assist in terminating interference events.

6. The current Technical Standard Order for GPS/WAAS receivers (TSO-C146) does not include the standards for adding L5. The FAA will implement the necessary program changes to support a modification of TSO-146 that would add the second civil frequency. This will allow the avionics manufacturers to offer an expansion capability and avoid a two-step transition for the users.

7. There is uncertainty amongst the user community on operational approvals for use of GPS for VFR operations. No approvals are required for use in VFR; however, there is a lack of standards and training on the safe and efficient use of hand-held GPS receivers for VFR operations. The FAA will ask the Air Safety Foundation to develop recommended guidelines on the use of GPS that the FAA can endorse. These guidelines will subsequently stimulate training in proper use of GPS, including consideration of the need for interference strategies.

8. The Terminal Area Operations Aviation Rulemaking Committee (TAOARC) has recently formed a general aviation implementation subgroup. The FAA will ask the TAOARC to charge this new subgroup with identifying and prioritizing locations where VFR and IFR RNAV routes are requested through Class B and special use airspace. Once this list is identified, the FAA will plan the development and charting of these routes. The introduction of RNAV routes is a significant incentive for equipping with GPS for low-altitude flight operations. A GPS interference event should be no worse than a delay event caused by weather.

13.0 Recommendations

The transition to Satnav is dependent upon the increased service that Satnav provides over existing ground-based Navaids and the continuation of safe IMC operations in the presence of interference. The FAA is not in a position to support the development and deployment of Satnav and to also re-capitalize the entire existing ground-based infrastructure, making Satnav just another layer of navigation. The FAA is recommending the sustainment of a reduced number of existing Navaids to provide both a redundant and backup capability for en route navigation, nonprecision approach, and precision approach.

The FAA will sustain the existing network of DME's to provide a redundant RNAV capability. A reduced set of VOR's and long-range NDB's will be retained, described as the minimum operating network, to support a backup capability. At least one ILS will be retained at airports where this service is provided today, unless the ILS is not necessary as part of the backup service and traffic use does not justify a requirement for continued and uninterrupted service. The current network of TACAN's will be retained for the DOD. These actions effectively reduce the threat to air transportation from the intentional disruption of Satnav services. The continued development and deployment of diverse L1 and L5 frequencies on the GPS satellites adequately addresses unintentional interference. The exact mix of ground-based Navaids will need to be defined by specific locations and time for removing systems so that the users can assess the impact to their operation and plan their investments in Satnav. This work needs to continue in FY 2003 with the goal of publishing a site-specific list of the Navaids to be turned off, including dates, in 2004.

13.1 Multiple Means of Determining GPS Corrections

There are some additional recommendations for the DOT to consider. The FAA recommends that the determination of GPS corrections be consolidated across all of transportation and the DOT take national leadership in providing differential corrections as a national asset, like GPS is a national asset supported by the DOD. The FAA and Coast Guard investments in differential correction need to be leveraged to reduce future costs. Separating the derivation of the correction from distribution should produce economies in terms of staffing, maintenance of ground stations, and equipment development. If the Coast Guard moves to the future Department of Homeland Defense, then consideration should be given to creating a national differential correction function within the FAA, leveraging our investment in GPS. Differential correction information could travel across a network for distribution to users by multiple transmitters. The FAA needs both a satellite communications distribution (WAAS) and a VHF communications (LAAS). The Coast Guard is supporting marine beacons with medium frequency transmissions. Centralized differential correction monitoring and control is recommended to assure quality and responsiveness to all users.

The FAA will continue to operate the WAAS network, and the differential corrections derived can be distributed in other information formats for other modes of transportation and delivered to the end users by means other than satellite communications.

13.2 Detection and Enforcement

The FAA will be well positioned to locate sources of interference. Continued investment in radio frequency interference equipment helps improve detection. Our current experience with locating and discontinuing interference sources in days must shrink to a matter of hours. A goal has been set, in consultation with the aviation user community, to detect and eliminate interference within six hours. This goal needs to be attained by 2007. The rationale for the six hours comes from representative time required to clear an airport following a snowstorm and still accomplish flight activities on that day.

Interference detection can be improved significantly by adding technology. However, the processes associated with legal actions taken to shut down the interference source needs to be examined across the Department. In the past, there has been good cooperation from the Federal Communications Commission and the Department of Justice, but not with the response time needed as transportation becomes increasingly dependent on Satnav. There may be a role for the Transportation Security Administration and the Office of Homeland Defense. The FAA will initiate actions with the IGEB to structure recommendations on how to pursue interference events.

13.3 Continuation of Loran

Loran must be able to provide nonprecision approaches to be an acceptable backup. Technical issues must be resolved, standards developed, and avionics manufactured in an uncertain market. Part of that market risk is the uncertainty of continuing Loran. By itself, the FAA cannot justify the investment when the number of VOR receivers is so high and the number of Loran receivers is not only low, but the current installed base is not acceptable for IFR operations. The FAA recommends that the Department consider the risks and the capital costs in weighing the Loran decision.

The technical opportunities that Loran provides include an add-on capability to broadcast WAAS differential corrections for other modes of transportation. The combined benefits from the other modes and support of use for precise timing applications may be sufficient justification to continue the provision of Loran services. If the DOT decides to continue operating Loran, the FAA will accelerate work on integrity and antenna research and start developing standards for an integrated GPS/WAAS/Loran avionics capability. If the DOT decides to discontinue Loran service in the future, the FAA will discontinue further development work in trying to get Loran to the point where it will support IFR operations.

Navigation Transition Strategy

Appendix A
List of Acronyms

AGL	Above Ground Level
ARTCC	Air Route Traffic Control Center
ASF	Additional Secondary Factor
DME	Distance Measuring Equipment
DOD	Department of Defense
DOT	Department of Transportation
EWG	Experiment Working Group
FAA	Federal Aviation Administration
FMS	Flight Management System
GOERS	GPS Outage En Route Simulation
GOTS	GPS Outage Terminal Simulation
GLS	GPS Landing System
GPS	Global Positioning System
GPS III	the next generation of GPS
H-Field	magnetic-field
HMI	Hazardously Misleading Information
ICAO	International Civil Aviation Organization
IGEB	Interagency GPS Executive Board
IFR	Instrument Flight Rules
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
INMARSAT	an international maritime satellite service provider
IOC	Initial Operational Capability
IRS	Inertial Reference System
JPALS	Joint Precision Approach and Landing System
km	kilometer
LAAS	Local Area Augmentation System
LDC	Loran Data Channel
LNAV/VNAV	lateral and vertical navigation criteria
LORIPP	Loran Integrity Performance Panel
LPV	lateral precision with vertical guidance criteria
M	Million (in dollars)
m	meter
MHz	Megahertz
MSL	Mean Sea Level
NAS	National Airspace System
Navaids	navigation aids
NDB	Nondirectional Beacon
NDGPS	Nationwide Differential GPS

nm	nautical mile
NPA	Nonprecision Approach
NTP	Network Time Protocol
POS/NAV	Position and Navigation
RAIM	Receiver Autonomous Integrity Monitoring
RNAV	Area Navigation
RNP	Required Navigation Performance
SARPS	Standards and Recommended Practices
Satnav	satellite navigation
sec	second
SPS	Standard Positioning Service (GPS)
TAOARC	Terminal Area Operations Aviation Rulemaking Committee
TFR	Temporary Flight Restrictions
UTC	Coordinated Universal Time
VFR	Visual Flight Rules
VHF	Very-High Frequency
VMC	Visual Meteorological Conditions
VOR	VHF Omni-directional Range
WAAS	Wide Area Augmentation System
WJHTC	William J. Hughes Technical Center

Navigation Transition Strategy

Appendix B
GPS Interference Scenarios

The following scenarios have been developed to illustrate typical operational responses in the event of GPS interference. These scenarios consider both VFR and IFR operations and IFR operations in IMC. The scenarios are built around departure, en route, arrival, and landing. Each scenario is representative of the expected types of interference. To date, all interference events have been caused by either the DOD or contractors conducting work for DOD.

Departure

Interference has occurred that affects airspace in the San Francisco Bay area. Weather at the San Francisco International Airport (SFO) requires instrument departures. Weather at Palo Alto is VMC. Aircraft that do not have a backup or redundant capability will not be allowed to depart SFO since pilots must be able to navigate. Departures at Palo Alto will also be affected. IFR traffic will need to re-file their flight plan route based on the backup minimum operating network of VOR's or continue as filed with the redundant RNAV capabilities. VFR departures heading north into Class B airspace would be restricted. Aircraft departing to the south under VFR could continue to depart and use visual reference to the ground.

Aircraft departing San Francisco, Oakland, San Jose and other towered airports served by the Northern California TRACON could expect to climb on runway heading for radar vectors to either a VOR or to a point where the redundant navigation capabilities could establish position using VOR/DME or DME-DME. Some temporary delays would occur at the inception of the interference event while controllers worked to vector aircraft in IMC conditions to the backup VOR network or to landing with either a VOR or ILS.

A temporary flight restriction would be imposed for operations in the Class B airspace. Aircraft without a backup or redundant capability would be restricted from entering the airspace. Initially, this would include both IFR and VFR operations. As the condition stabilized, VFR departures may be permitted based on workload, extent of the interference area, and the surrounding weather. If visual reference to the ground can be maintained to areas clear of interference, then VFR departures would be authorized.

En Route

A large area of Kansas, Missouri, and Nebraska are affected by intermittent interference. The interference seems to be centered on the Kansas City area. Air traffic controllers have identified the volume of the affected area and have used a new tool to map and display the area. Pilots who were flying at the time of the interference helped to define the impacted airspace volume by squawking a specific code on their transponder to indicate they did not have a valid GPS signal. Their position and elevation were plotted and contours of interference were generated on the controller’s display.

Aircraft operating with RNAV with redundancy to Satnav would not be affected by interference, but would be made aware of the interference event as controller workload may change. Aircraft operating with the backup using the minimum operating network of VOR’s would be rerouted by flying direct to the VOR’s through the area. The majority of en route traffic continues due to the requirement to carry either a backup or redundant capability for operations at FL 180 and above.

Aircraft operating below FL 180 who do not have a backup or redundant capability must remain VMC. These pilots will also need to avoid flight through airspace with TFR’s. Pilots operating on an IFR flight plan in VMC conditions who lose navigation will be expected to terminate IFR services and land at an airport still in VMC. Pilots should not enter weather without the ability to navigate. Aircraft who are navigating by Satnav only at the time of interference and operating in IMC will need to be vectored through the weather and interference area to either a VMC airport or clear of the interference to resume Satnav.

Aircraft who have not yet entered the interference area and who do not have a redundant RNAV or backup capability can be routed in VMC or IMC conditions around the affected area. Aircraft who have yet to depart would be expected to avoid the interference area through their flight plan. Aircraft who are dependent upon Satnav for navigation and landing and have no backup capability will not be allowed to enter an area of interference under IFR.

A scenario exists where the pilot is operating IMC using Satnav and not in radar contact. The minimum operating network of VOR’s supports this situation. When the pilot loses Satnav the VOR receiver can be turned on. The pilot is expected to contact air traffic control and request direct to the VOR being received. If no VOR is received, then the pilot will request a climb up to as high as 5,000 feet AGL. At least one VOR will exist within 75 miles line-of-sight of any location in the contiguous 48 states. Pilots will report their position relative to the VOR received and amend their clearance. Controllers will assign an altitude along a route direct to the VOR to avoid terrain. Pilots can re-plan their route of flight from VOR to VOR until out of the interference area or to landing at a designated airport served by a VOR or with a VOR to ILS transition for landing.

For aircraft operating offshore and in Alaska, the long-range NDB’s are used to establish a bearing to the station. This information is used to home in on the station until a suitable VOR can be received.

Approach

Aircraft in the terminal airspace around Kansas City at the time are operating in IMC with clouds at about 2,800 feet, with breaks in the overcast. Aircraft operating VMC below the overcast are requested to stay VMC and land if they do not have a backup capability. Aircraft in IMC are vectored to an ILS approach, a localizer only approach or to a VOR for a non-precision approach. Aircraft with a redundant RNAV capability will be radar

vectored to an ILS or cleared for an RNAV approach. Little impact will be experienced with the high ceiling and visibility.

Since this interference event is intermittent, controllers may set the arrival procedures based on the assumption that Satnav is unavailable. The impact to those with redundant capabilities would be negligible, but for those relying on the VOR network there may be delays in arrivals as arrival paths are established and aircraft are vectored to these paths. TFR's would be in place to restrict traffic not capable of navigation.

If visibility were low, VFR operations would not be occurring. Radar vectors would be used to direct aircraft to an ILS approach. If the weather were below localizer-only minima and the pilot only had a VOR backup, the pilot would receive initial vectors to the IFR alternate that would need to be at or above the minima the pilot is capable of flying.

Landing

Interference is centered on Atlanta, Georgia and many airports are affected. Weather is 600 feet ceiling and one-mile visibility. The landing phase in the presence of interference is reliant on ILS, ILS localizer, VOR or an RNAV approach. At least one runway at multiple airports in the area will have an ILS approach. At the instant interference occurs, aircraft on the approach would lose integrity of the signal and execute a missed approach. These aircraft would then be vectored to an ILS precision approach, a VOR non-precision approach or an RNAV approach to landing. Pilots who only have Satnav would need to be vectored either to VMC conditions for landing or clear of the interference area. Since interference is line-of-sight, it could affect aircraft as far away as 80 miles at altitudes of 5000 feet AGL and below. . If the emitter of the interference were airborne, this distance would be greater. Pilots who rely solely on Satnav should flight plan to have a VMC airport within the fuel reserve carried for the IFR operation.

In areas where radar services are not provided, pilots would need to execute a missed approach without benefit of course guidance until clear of terrain and able to receive a VOR or a DME-DME update of position. Once navigation is reestablished, the pilot can execute another approach and landing. There is a safety problem for the pilot who elects to not have any backup and operate in IMC conditions in a non-radar environment. The pilot must know the terrain and climb in the missed approach based upon dead reckoning. In mountainous terrain where radar coverage at low altitudes is poor this is not a safe condition. Pilots who routinely fly IMC is such terrain should carry a backup.

Summary of Phoenix Interference Event

On December 13, 2001 an outdoor antenna test facility at Apache Field installed new antenna testing software. As part of the initial checkout of the software, a frequency span that included the GPS frequency was being used. On December 14, the verification test was conducted throughout that Friday. Unfortunately, the operator had inadvertently left the system on and left for the weekend. On December 14 the FAA needed to issue a Notice to Airmen of unreliability of the GPS signal-in-space for an airspace area of 180 nautical miles around Phoenix, Arizona. The FAA had received numerous pilot reports of the interference and begun searching for the source of interference.

Following the use of a flight inspection aircraft flown in from Oklahoma City, the source of interference was narrowed to the Boeing facility. Boeing's Apache Control was notified on December 17 at 6 pm about the possibility that the signal was coming from their facility. Boeing began a search of their facility throughout the evening and into the following day. At start of work on December 18 the source was identified at the antenna range and shut off. The FAA flight check aircraft flew over the area on December 18 and confirmed the interference was now terminated.

In the aftermath of the event it was determined that the new testing software, following its azimuth scan of an antenna, will remain fixed at the highest end of the spectrum selected for the frequency scan. In this case that was the GPS frequency.

The normal FAA response to interference events is to use radio frequency interference vans equipped with equipment to triangulate an interference signal. In this case, the van was located in Los Angeles at the regional office. The decision to drive to Phoenix was not made and a flight check aircraft was dispatched on the following Monday. From the time of locating the area of the interference, it took 13 ½ hours to find the actual source.

Other events have shown similar results. The following is a list of examples:

Rome, New York	L1-Interference: Impacted aircraft only. DOD inadvertently left test equipment on
Fort Bragg, North Carolina	L1-Interference: Impacted aircraft only. DOD failed to coordinate proper frequency use for Marines exercise.
St Louis, Missouri	L1-Interference: Impacted aircraft only. DOD contractor inadvertently left test equipment on.
San Juan, Puerto Rico	L1/L2-Interference: Impacted WAAS reference station only. Program failed to coordinate satellite phone installation separation from WAAS antennas.

San Juan, Puerto Rico	Military FPS-117 Radar emissions generating spurious signals within L2 pass band.
Birmingham, Alabama	L1-Interference: Impacted aircraft only hospital lighting emissions interfere with GPS signals on approach procedure.
Billings, Montana	L2-Interference: Impacted WAAS reference station only. FPS-117 radar generating spurious emissions within L2 pass band.
Juneau, Alaska	L2-Interference: Impacted WAAS reference station only. Airport personnel failed to coordinate Airport Wireless Lighting Control System installation separation.

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Navigation Transition Strategy

Appendix C
List of VOR's Used for Modeling
Minimum Operating Network

Location	State	LOC ID	Type
DECATUR	AL	DCU	VOR/DME
MONTGOMERY	AL	MGM	VORTAC
BROOKLEY	AL	BFM	VORTAC
VULCAN	AL	VUZ	VORTAC
DRAKE	AR	FYV	VOR
FLIPPIN	AR	FLP	VOR/DME
FORT SMITH	AR	FSM	VORTAC
LITTLE ROCK	AR	LIT	VORTAC
RAZORBACK	AR	RZC	VORTAC
TEXARKANA	AR	TXK	VORTAC
WALNUT RIDGE	AR	ARG	VORTAC
BARD	AZ	BZA	VORTAC
BUCKEYE	AZ	BXK	VORTAC
COCHISE	AZ	CIE	VORTAC
DOUGLAS	AZ	DUG	VORTAC
DRAKE	AZ	DRK	VORTAC
FLAGSTAFF	AZ	FLG	VORTAC
GILA BEND	AZ	GBN	VORTAC
GRAND CANYON	AZ	GCN	VOR
KINGMAN	AZ	IGM	VOR/DME
LIBBY	AZ	FHU	VOR
NOGALES	AZ	OLS	VOR/DME
PAGE	AZ	PGA	VOR/DME
PEACH SPRINGS	AZ	PGS	VORTAC
PHOENIX	AZ	PXR	VORTAC
SAN SIMON	AZ	SSO	VORTAC
ST JOHNS	AZ	SJN	VORTAC
STANFIELD	AZ	TFD	VORTAC
TUBA CITY	AZ	TBC	VORTAC
TUCSON	AZ	TUS	VORTAC
WILLIE	AZ	IWA	VORTAC
WINSLOW	AZ	INW	VORTAC
ARCATA	CA	ACV	VOR/DME
AVENAL	CA	AVE	VORTAC
BIG SUR	CA	BSR	VORTAC

Location	State	LOC ID	Type
BISHOP	CA	BIH	VOR/DME
BLYTHE	CA	BLH	VORTAC
CHICO	CA	CIC	VOR/DME
CLOVIS	CA	CZQ	VORTAC
CRESCENT CITY	CA	CEC	VORTAC
DAGGETT	CA	DAG	VORTAC
EL NIDO	CA	HPY	VOR/DME
FORT JONES	CA	FJS	VOR/DME
FORTUNA	CA	FOT	VORTAC
GAVIOTA	CA	GVP	VORTAC
GOFFS	CA	GFS	VORTAC
HANGTOWN	CA	HNW	VOR/DME
IMPERIAL	CA	IPL	VORTAC
JULIAN	CA	JLI	VORTAC
LOS ANGELES	CA	LAX	VORTAC
MANTECA	CA	ECA	VORTAC
MENDOCINO	CA	ENI	VORTAC
MISSION BAY	CA	MZB	VORTAC
MORRO BAY	CA	MQO	VORTAC
NEEDLES	CA	EED	VORTAC
OAKLAND	CA	OAK	VORTAC
OCEANSIDE	CA	OCN	VORTAC
PALM SPRINGS	CA	PSP	VORTAC
PALMDALE	CA	PMD	VORTAC
PANOCHE	CA	PXN	VORTAC
PARADISE	CA	PDZ	VORTAC
POGGI	CA	PGY	VORTAC
POMONA	CA	POM	VORTAC
RED BLUFF	CA	RBL	VORTAC
SACRAMENTO	CA	SAC	VORTAC
SALINAS	CA	SNS	VORTAC
SAN FRANCISCO	CA	SFO	VOR/DME
SAN JOSE	CA	SJC	VOR/DME
SAN MARCUS	CA	RZS	VORTAC
SAUSALITO	CA	SAU	VORTAC
SEAL BEACH	CA	SLI	VORTAC
SHAFTER	CA	EHF	VORTAC
THERMAL	CA	TRM	VORTAC
VAN NUYS	CA	VNY	VOR/DME
AKRON	CO	AKO	VORTAC
ALAMOSA	CO	ALS	VORTAC

Location	**State**	**LOC ID**	**Type**
BLUE MESA	CO	HBU	VOR/DME
COLORADO SPRINGS	CO	COS	VORTAC
CONES	CO	ETL	VOR/DME
CORTEZ	CO	CEZ	VOR/DME
DENVER	CO	DEN	VOR/DME
DOVE CREEK	CO	DVC	VORTAC
DURANGO	CO	DRO	VOR/DME
FALCON	CO	FQF	VORTAC
GILL	CO	GLL	VORTAC
GRAND JUNCTION	CO	JNC	VORTAC
HAYDEN	CO	CHE	VOR/DME
HUGO	CO	HGO	VORTAC
KREMMLING	CO	RLG	VORTAC
LAMAR	CO	LAA	VORTAC
MEEKER	CO	EKR	VOR/DME
MOAB	CO	OAB	VOR
MONTROSE	CO	MTJ	VOR/DME
PUEBLO	CO	PUB	VORTAC
RED TABLE	CO	DBL	VOR/DME
RIFLE	CO	RIL	VOR/DME
ROBERT	CO	BQZ	VOR/DME
SNOW	CO	SXW	VOR/DME
THURMAN	CO	TXC	VORTAC
TOBE	CO	TBE	VORTAC
HARTFORD	CT	HFD	VORTAC
WASHINGTON	DC	DCA	VOR/DME
CRAIG	FL	CRG	VORTAC
CROSS CITY	FL	CTY	VORTAC
DOLPHIN	FL	DHP	VORTAC
FORT LAUDERDALE	FL	FLL	VOR/DME
KEY WEST	FL	EYW	VORTAC
LEE COUNTY	FL	RSW	VORTAC
MELBOURNE	FL	MLB	VOR/DME
ORLANDO	FL	ORL	VORTAC
ORMOND BEACH	FL	OMN	VORTAC
PALM BEACH	FL	PBI	VORTAC
PANAMA CITY	FL	PFN	VORTAC
SAUFLEY	FL	NUN	VOR
ST PETERSBURG	FL	PIE	VORTAC
TALLAHASSEE	FL	SZW	VORTAC
ALMA	GA	AMG	VORTAC

Location	State	LOC ID	Type
ATLANTA	GA	ATL	VORTAC
COLUMBUS	GA	CSG	VORTAC
HARRIS	GA	HRS	VORTAC
MACON	GA	MCN	VORTAC
SAVANNAH	GA	SAV	VORTAC
CEDAR RAPIDS	IA	CID	VOR/DME
NEWTON	IA	TNU	VORTAC
FORT DODGE	IA	FOD	VORTAC
LAMONI	IA	LMN	VORTAC
MASON CITY	IA	MCW	VORTAC
SIOUX CITY	IA	SUX	VORTAC
BOISE	ID	BOI	VORTAC
BURLEY	ID	BYI	VOR/DME
COEUR D'ALENE	ID	COE	VOR/DME
DONNELLY	ID	DNJ	VORTAC
DUBOIS	ID	DBS	VORTAC
IDAHO FALLS	ID	IDA	VOR/DME
MALAD CITY	ID	MLD	VOR/DME
MOUNTAIN HOME	ID	MUO	VOR
MULLAN PASS	ID	MLP	VOR/DME
NEZ PERCE	ID	MQG	VOR/DME
POCATELLO	ID	PIH	VORTAC
SALMON	ID	LKT	VOR/DME
TWIN FALLS	ID	TWF	VORTAC
CAPITAL	IL	CAP	VORTAC
CHAMPAIGN	IL	CMI	VORTAC
CHICAGO O'HARE	IL	ORD	VOR/DME
DAVENPORT	IL	CVA	VORTAC
NORTHBROOK	IL	OBK	VORTAC
PEORIA	IL	PIA	VORTAC
JANESVILLE	IL	JVL	VORTAC
FORT WAYNE	IN	FWA	VORTAC
INDIANAPOLIS	IN	VHP	VORTAC
POCKET CITY	IN	PXV	VORTAC
TERRE HAUTE	IN	TTH	VORTAC
DODGE CITY	KS	DDC	VORTAC
GOODLAND	KS	GLD	VORTAC
HAYS	KS	HYS	VORTAC
HILL CITY	KS	HLC	VORTAC
LIBERAL	KS	LBL	VORTAC
SALINA	KS	SLN	VORTAC

Location	State	LOC ID	Type
WICHITA	KS	ICT	VORTAC
CINCINNATI	KY	CVG	VORTAC
FALMOUTH	KY	FLM	VOR/DME
LEXINGTON	KY	HYK	VORTAC
LOUISVILLE	KY	IIU	VORTAC
BATON ROUGE	LA	BTR	VORTAC
DOWNTOWN	LA	DTN	VORTAC
LAFAYETTE	LA	BTR	VORTAC
LAKE CHARLES	LA	LCH	VORTAC
MONROE	LA	MLU	VORTAC
RESERVE	LA	RQR	VOR/DME
BOSTON	MA	BOS	VORTAC
NANTUCKET	MA	ACK	VOR/DME
BALTIMORE	MD	BAL	VORTAC
SALISBURY	MD	SBY	VORTAC
BANGOR	ME	BGR	VORTAC
KENNEBUNK	ME	ENE	VORTAC
MILLINOCKET	ME	MLT	VOR/DME
PRESQUE ISLE	ME	PQI	VORTAC
PRINCETON	ME	PNN	VOR/DME
BATTLE CREEK	MI	BTL	VORTAC
DETROIT	MI	DXO	VOR/DME
FLINT	MI	FNT	VORTAC
GIPPER	MI	GIJ	VORTAC
GRAND RAPIDS	MI	GRR	VOR/DME
HOUGHTON	MI	CMX	VOR/DME
HOUGHTON LAKE	MI	HTL	VOR/DME
IRONWOOD	MI	IWD	VORTAC
LANSING	MI	LAN	VORTAC
MUSKEGON	MI	MKG	VORTAC
PONTIAC	MI	PSI	VORTAC
SAGINAW	MI	MBS	VOR/DME
SALEM	MI	SVM	VORTAC
SAULT STE MARIE	MI	SSM	VORTAC
SCHOOLCRAFT COUNTY	MI	MBL	VOR/DME
ALEXANDRIA	MN	AXN	VOR/DME
BEMIDJI	MN	BJI	VORTAC
DULUTH	MN	DLH	VORTAC
ELY	MN	ELO	VOR/DME
HUMBOLDT	MN	HML	VORTAC
INTERNATIONAL FALLS	MN	INL	VORTAC

Location	State	LOC ID	Type
GOPHER	MN	GEP	VORTAC
LACROSSE	MN	LSE	VORTAC
REDWOOD FALLS	MN	RWF	VORTAC
BUTLER	MO	BUM	VORTAC
FARMINGTON	MO	FAM	VORTAC
FORISTELL	MO	FTZ	VORTAC
RIVERSIDE	MO	RIS	VORTAC
KIRKSVILLE	MO	IRK	VORTAC
SPRINGFIELD	MO	SGF	VORTAC
ST LOUIS	MO	STL	VORTAC
SUNSHINE	MO	SHY	VOR/DME
BIGBEE	MS	IGB	VORTAC
GULFPORT	MS	GPT	VORTAC
JACKSON	MS	JAN	VORTAC
MERIDIAN	MS	MEI	VORTAC
SIDON	MS	SQS	VORTAC
BILLINGS	MT	BIL	VORTAC
BOZEMAN	MT	BZN	VOR/DME
COPPERTOWN	MT	CPN	VORTAC
CUT BANK	MT	CTB	VORTAC
DILLON	MT	DLN	VOR/DME
DRUMMOND	MT	DRU	VOR
GLASGOW	MT	GGW	VOR/DME
GREAT FALLS	MT	GTF	VORTAC
HAVRE	MT	HVR	VOR/DME
HELENA	MT	HLN	VORTAC
KALISPELL	MT	FCA	VOR/DME
LEWISTOWN	MT	LWT	VORTAC
LIVINGSTON	MT	LVM	VORTAC
MILES CITY	MT	MLS	VORTAC
MISSOULA	MT	MSO	VOR/DME
WHITEHALL	MT	HIA	VORTAC
FORT MILL	NC	FML	VOR/DME
FAYETTEVILLE	NC	FAY	VOR/DME
GREENSBORO	NC	GSO	VORTAC
NEW BERN	NC	EWN	VOR/DME
RALEIGH/DURHAM	NC	RDU	VORTAC
WILMINGTON	NC	ILM	VORTAC
BISMARCK	ND	BIS	VOR/DME
DEVILS LAKE	ND	DVL	VOR/DME
DICKINSON	ND	DIK	VORTAC

Location	State	LOC ID	Type
FARGO	ND	FAR	VORTAC
JAMESTOWN	ND	JMS	VOR/DME
MINOT	ND	MOT	VORTAC
WILLISTON	ND	ISN	VORTAC
AINSWORTH	NE	LNK	VOR/DME
ALLIANCE	NE	AIA	VOR/DME
GRAND ISLAND	NE	GRI	VORTAC
MCCOOK	NE	MCK	VORTAC
LINCOLN	NE	LNK	VORTAC
OMAHA	NE	OVR	VORTAC
O'NEILL	NE	ONL	VORTAC
SCOTTSBLUFF	NE	BFF	VORTAC
SIDNEY	NE	SNY	VORTAC
BERLIN	NH	BML	VOR/DME
LEBANON	NH	LEB	VOR/DME
MANCHESTER	NH	MHT	VOR/DME
ATLANTIC CITY	NJ	ACY	VORTAC
TETERBORO	NJ	TEB	VOR/DME
WOODSTOWN	NJ	DQO	VORTAC
ALBUQUERQUE	NM	ABQ	VORTAC
ANTON CHICO	NM	ACH	VORTAC
BOLES	NM	BWS	VOR/DME
CARLSBAD	NM	CNM	VORTAC
CIMARRON	NM	CIM	VORTAC
CHISUM	NM	CME	VORTAC
COLUMBUS	NM	CUS	VOR/DME
CORONA	NM	CNX	VORTAC
DEMING	NM	DMN	VORTAC
FARMINGTON	NM	FMN	VORTAC
GALLUP	NM	GUP	VORTAC
LAS VEGAS	NM	LVS	VORTAC
OTTO	NM	OTO	VOR
PINON	NM	PIO	VOR
SILVER CITY	NM	SVC	VORTAC
SANTA FE	NM	SAF	VORTAC
SOCORRO	NM	ONM	VORTAC
TAOS	NM	TAX	VORTAC
TRUTH OR CONSEQUENCES	NM	TCS	VORTAC
TUCUMCARI	NM	TCC	VORTAC
ZUNI	NM	ZUN	VORTAC

Location	State	LOC ID	Type
BATTLE MOUNTAIN	NV	BAM	VORTAC
BEATTY	NV	BTY	VORTAC
BOULDER	NV	LAS	VORTAC
BULLION	NV	BQU	VOR/DME
COALDALE	NV	OAL	VORTAC
ELY	NV	ELY	VOR/DME
HAZEN	NV	HZN	VORTAC
LAS VEGAS	NV	LAS	VORTAC
LOVELOCK	NV	LLC	VORTAC
MINA	NV	MVA	VORTAC
MORMON MESA	NV	MMM	VORTAC
MUSTANG	NV	FMG	VORTAC
SOD HOUSE	NV	SDO	VORTAC
TONOPAH	NV	TPH	VORTAC
WELLS	NV	LWL	VOR
WILSON CREEK	NV	ILC	VORTAC
WINNEMUCCA	NV	INA	VOR/DME
ALBANY	NY	ALB	VORTAC
BINGHAMTON	NY	CFB	VORTAC
BUFFALO	NY	BUF	VOR/DME
CALVERTON	NY	CCC	VOR/DME
CARMEL	NY	CMK	VOR/DME
CARARSIE	NY	CRI	VOR/DME
DEER PARK	NY	DPK	VOR/DME
ELMIRA	NY	ITH	VOR/DME
KENNEDY	NY	JFK	VOR/DME
KINGSTON	NY	IGN	VOR/DME
LA GUARDIA	NY	LGA	VOR/DME
PLATTSBURGH	NY	PLB	VORTAC
ROCHESTER	NY	ROC	VORTAC
SYRACUSE	NY	SYR	VORTAC
WATERTOWN	NY	ART	VORTAC
AKRON	OH	ACO	VOR/DME
ZANESVILLE	OH	ZZV	VORTAC
DAYTON	OH	DQN	VOR/DME
DRYER	OH	DJB	VORTAC
WATERVILLE	OH	VWV	VOR/DME
YOUNGSTOWN	OH	YNG	VORTAC
ARDMORE	OK	ADM	VORTAC
GAGE	OK	GAG	VORTAC
TULSA	OK	TUL	VORTAC

Location	State	LOC ID	Type
WILEY POST	OK	PWA	VOR/DME
WILL ROGERS	OK	IRW	VORTAC
ASTORIA	OR	AST	VOR/DME
BAKER CITY	OR	BKE	VOR/DME
CORVALLIS	OR	CVO	VORDME
DESCHUTES	OR	DSD	VORTAC
EUGENE	OR	EUG	VORTAC
KIMBERLY	OR	IMB	VORTAC
KLAMATH FALLS	OR	LMT	VORTAC
KLICKITAT	OR	LTJ	VORTAC
LAKEVIEW	OR	LKV	VORTAC
NEWPORT	OR	ONP	VORTAC
NORTH BEND	OR	OTH	VORTAC
PENDLETON	OR	PDT	VORTAC
PORTLAND	OR	PDX	VOR/DME
ROGUE VALLEY	OR	OED	VORTAC
ROME	OR	REO	VORTAC
ROSEBURG	OR	RBG	VOR/DME
WILDHORSE	OR	ILR	VOR/DME
ALLEGHENY	PA	AGC	VOR/DME
ALLENTOWN	PA	FJC	VORTAC
ERIE	PA	ERI	VORTAC
HAZLETON	PA	HZL	VOR
LANCASTER	PA	LRP	VORTAC
MONTOUR	PA	MMJ	VORTAC
NORTH PHILADELPHIA	PA	PNE	VOR
PHILIPSBURG	PA	PSB	VORTAC
RAVINE	PA	RAV	VORTAC
PROVIDENCE	RI	PVD	VORTAC
CHARLESTON	SC	CHS	VORTAC
GREENWOOD	SC	GRD	VORTAC
COLUMBIA	SC	CAE	VORTAC
GRAND STRAND	SC	CRE	VORTAC
SPARTANBURG	SC	SPA	VORTAC
ABERDEEN	SD	ABR	VOR/DME
BUFFALO	SD	BUA	VOR
DUPREE	SD	DPR	VORTAC
MITCHELL	SD	MHE	VOR/DME
PIERRE	SD	PIR	VORTAC
RAPID CITY	SD	RAP	VORTAC
SIOUX FALLS	SD	FSD	VORTAC

Location	**State**	**LOC ID**	**Type**
WATERTOWN	SD	ATY	VORTAC
WINNER	SD	ISD	VOR
CHOO CHOO	TN	GQO	VORTAC
DYERSBURG	TN	DYR	VORTAC
MEMPHIS	TN	MEM	VORTAC
NASHVILLE	TN	BNA	VORTAC
VOLUNTEER	TN	VXV	VORTAC
ABILENE	TX	ABI	VORTAC
AMARILLO	TX	PNH	VORTAC
AUSTIN	TX	CWK	VORTAC
BEAUMONT	TX	BPT	VOR/DME
BONHAM	TX	BYP	VORTAC
BROWNSVILLE	TX	BRO	VORTAC
CHILDRESS	TX	CDS	VORTAC
CORPUS CHRISTI	TX	CRP	VORTAC
COTULLA	TX	COT	VORTAC
COWBOY	TX	CVE	VOR/DME
DALHART	TX	DHT	VORTAC
DALLAS/FORT WORTH	TX	TTT	VORTAC
EL PASO	TX	ELP	VORTAC
FORT STOCKTON	TX	FST	VORTAC
GREGG COUNTY	TX	GGG	VORTAC
HOBBY	TX	HOU	VOR/DME
HUMBLE	TX	IAH	VORTAC
JUNCTION	TX	JCT	VORTAC
LAREDO	TX	LRD	VORTAC
LAUGHLIN	TX	DLF	VORTAC
LLANO	TX	LLO	VORTAC
LUBBOCK	TX	LBB	VORTAC
LUFKIN	TX	LFK	VORTAC
MARFA	TX	MRF	VOR/DME
MC ALLEN	TX	MFE	VOR/DME
MIDLAND	TX	MAF	VORTAC
PALACIOS	TX	PSX	VORTAC
SALT FLAT	TX	SFL	VORTAC
SAN ANGELO	TX	SJT	VORTAC
SAN ANTONIO	TX	SAT	VORTAC
TEXICO	TX	TXO	VORTAC
THREE RIVERS	TX	THX	VORTAC
WACO	TX	ACT	VORTAC
WICHITA FALLS	TX	SPS	VORTAC

Location	**State**	**LOC ID**	**Type**
BONNEVILLE	UT	BVL	VORTAC
BRYCE CANYON	UT	BCE	VORTAC
CARBON	UT	PUC	VOR/DME
CEDAR CITY	UT	CDC	VOR/DME
DELTA	UT	DTA	VORTAC
FAIRFIELD	UT	FFU	VORTAC
HANKSVILLE	UT	HVE	VORTAC
LOGAN	UT	LGU	VOR/DME
LUCIN	UT	LCU	VORTAC
MILFORD	UT	MLF	VORTAC
MYTON	UT	MTU	VORTAC
OGDEN	UT	OGD	VORTAC
PROVO	UT	PVU	VOR/DME
SALT LAKE CITY	UT	SLC	VORTAC
ST GEORGE	UT	OZN	VOR/DME
VERNAL	UT	VEL	VOR/DME
ARMEL	VA	AML	VORTAC
CAPE CHARLES	VA	ORF	VORTAC
GLADE SPRING	VA	GZG	VOR/DME
MONTEBELLO	VA	MOL	VOR/DME
NORFOLK	VA	ORF	VORTAC
PULASKI	VA	PSK	VORTAC
RICHMOND	VA	RIC	VORTAC
ROANOKE	VA	ROA	VORTAC
BURLINGTON	VT	BTV	VORTAC
MONTPELIER	VT	MPV	VOR/DME
BATTLE GROUND	WA	BTG	VORTAC
BELLINGHAM	WA	BLI	VORTAC
ELLENSBURG	WA	ELN	VORTAC
HOQUIAM	WA	HQM	VORTAC
MOSES LAKE	WA	MWH	VOR/DME
OLYMPIA	WA	OLM	VORTAC
PAINE	WA	PAE	VOR/DME
PASCO	WA	PSC	VOR/DME
PULLMAN	WA	PUW	VOR/DME
SEATTLE	WA	SEA	VORTAC
SPOKANE	WA	GEG	VORTAC
TATOOSH	WA	TOU	VORTAC
WALLA WALLA	WA	ALW	VOR/DME
WENATCHEE	WA	EAT	VOR/DME
YAKIMA	WA	YKM	VORTAC

Location	State	LOC ID	Type
BADGER	WI	BAE	VORTAC
EAU CLAIRE	WI	EAU	VORTAC
GREEN BAY	WI	GRB	VORTAC
HORLICK	WI	HRK	VOR/DME
MADISON	WI	MSN	VORTAC
RHINELANDER	WI	RHI	VORTAC
CHARLESTON	WV	HVQ	VORTAC
CLARKSBURG	WV	CKB	VORTAC
BIG PINEY	WY	BPI	VOR/DME
BOYSEN RESERVOIR	WY	BOY	VORTAC
CHEROKEE	WY	CKW	VOR/DME
CHEYENNE	WY	CYS	VORTAC
CODY	WY	COD	VOR/DME
CRAZY WOMAN	WY	CZI	VOR/DME
DUNOIR	WY	DNW	VORTAC
FORT BRIDGER	WY	FBR	VOR/DME
GILLETTE	WY	GCC	VOR/DME
JACKSON	WY	JAC	VOR/DME
LARAMIE	WY	LAR	VORTAC
MEDICINE BOW	WY	MBW	VOR/DME
MUDDY MOUNTAIN	WY	DDY	VORTAC
NEWCASTLE	WY	ECS	VOR
RAWLINS	WY	RWL	VOR/DME
RIVERTON	WY	RIW	VOR/DME
ROCK SPRINGS	WY	OCS	VORTAC
SHERIDAN	WY	SHR	VORTAC
WORLAND	WY	RLY	VOR/DME